PERFORMANCE STUDY FOR INDOOR VISIBLE LIGHT COMMUNICATION SYSTEMS

BY

Shuo Gao

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School of Electrical Engineering and Computer Science
Faculty of Engineering
University of Ottawa

Abstract

The field of Optical Wireless Communications (OWC) has seen rapid development during the recent years. This growing popularity is due to several characteristics of considerable importance to consumer electronics products, such as large bandwidth that is also not having spectrum regulations imposed, low cost, and license free operation. As a branch of OWC, visible light communication (VLC) systems have their own unique advantages, with several new technologies, products and patents having been developed during since the end of last century.

In this research, a VLC system for indoor application is proposed. In this work, we focus on reducing cost, and for that, we had to make appropriate selection of system's components, e.g. modulation, coding, filtering. Our objective was to achieve acceptable bit error rate (BER) performance for indoor use, with a low cost system. Through our research we met this objective.

Our designs were evaluated through computer simulations. The acquired results proved the suitability of the proposed schemes and the performance's degree of dependency on several parameters such as distance, incidence angle and irradiance angle. A software tool was created allowing easy assessment of the communication system. It is using a user friendly GUI through which the user enters the system's parameters and the system outputs the corresponding BER value.

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List of Symbols

B	Bandwidth of signal
c	Speed of light
d/d_{TR}	Distance from transmitter to receiver
$\bar{E}_{bit}$	Average energy per bit
E_g	Band gap energy
E_{pulse}	Energy per pulse
h	Planck's constant
$H(0)$	Channel DC gain
I_B	Average DC photocurrent generated by the shot noise
I_p	Average photocurrent
N	Refractive index
N_o	Single sided noise spectral density
P_{avg}	Average transmitted optical signal power
P_{avgRF}	Average transmitted RF signal power
P_{bottom}	Received optical power at the bottom point of receiver
P_p	Incident optical power
P_{top}	Received optical power at the top point of receiver
q	Charge of an electron
R	Responsively of photodiode
R_b	Bit rate
$T_{s(\psi)}$	The signal transmission of the filter
v	Carrier's frequency
γ	Duty cycle
λ	Center wavelength
Φ	Incidence angle
ψ	Irradiance angle
η_i	Quantum efficiency

η_p	Power efficiency
η_B	Bandwidth efficiency
$\phi_{1/2}$	Semi-angle at half luminance of the LED
ψ_c	FOV at the receiver
ω	Angular frequency
ω_c	Cut-off frequency

Acronyms

2PPM	Two-pulse-position Modulation
ANSI	American National Standards Institute
APD	Avalanche photodiodes
ARIB	Association of Radio Industries and Businesses
AWGN	Additive white Gaussian noise
BER	Bit Error Rate
CENELEC	European Committee for Electro-technical Standardization
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DC	Direct Current
EMI	Electro-magnetic Interference
ESNR	Electric Signal to Noise Ratio
FEC	Forward Error Correction
FET	Field-effect Transistor
FOV	Field of View
FSK	Frequency-shift Keying
GaAs	Gallium Arsenide
GaAlAs	Gallium Aluminum Arsenide
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSI	Geospatial Information Authority
GUI	Graphical User Interface
HeNe	Helium-neon
IC	Integrated Circuit
ICSA	Infrared Communication Systems Association
IEC	International Electrotechnical Commission
IM/DD	Intensity Modulation and Direct Detection
IrDA	Infrared Data Association
ISI	Intersymbol Interference

ITS	Intelligent Transportation System
LAN	Local Area Network
LD	Laser Diode
LED	Light-emmiting Diode
LOS	Line-of-sight
L-PAM	L-level Baseband Pulse-amplitude Modulation
L-PPM	L-level Pulse Position Modulation
L-QAM	L-level Quadrature-amplitude Modulation
M-FSK	Multiple Frequency-shift Keying
M-PSK	Multiple Phase-shift Keying
M-QAM	Multiple Quadrature-amplitude Modulation
NLOS	Non line-of-sight
OFDM	Orthogonal Frequency-division Multiplexing
OOK	On-off Keying
OSNR	Optical Signal to Noise Ratio
OWC	Optical Wireless Communication
PD	Photodiode
PIN	Positive-intrinsic-negative
PSD	Power Spectrum Density
RF	Radio Frequency
RoF	Radio over Fiber
SNR	Signal to Noise Ratio
VLC	Visible Lighting Communication
VLCC	Visible Light Communications Consortium
WLED	White Light Emitted Diode

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Last but not least, I owe to express my special gratitude to my parents whose support and love always gave me courage to face any challenges in my life.

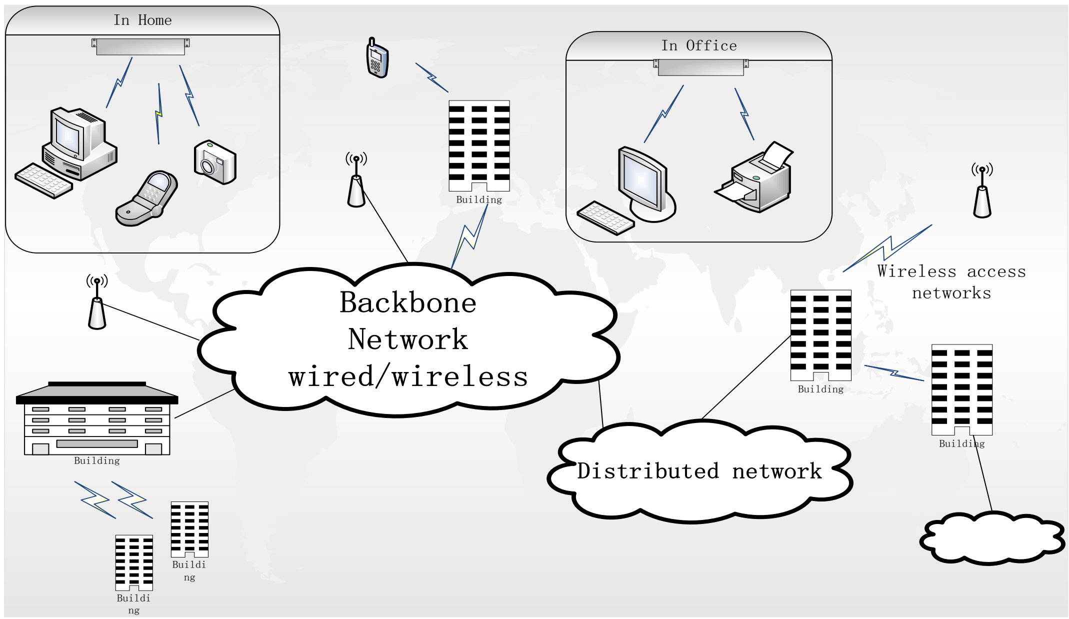
Chapter 1

Introduction

1.1 Background

The proliferation of *ubiquitous computing* and *ambient intelligence* devices and related services has made the necessity for high-capacity, secure wireless telecommunication networks paramount. In an *ubiquitous computing* environment, mobile users expect not only to be able to use their communication devices anywhere, but also have seamless availability of the offered services almost at quality and reliability levels they have when connected through a modern wired network. Use of short communication links allows denser frequency reuse, thus increases capacity, and reduces the chances of a signal to be intercepted. Those wireless networks form access networks, which connect end users to their intermediate service provider [87], are connected to broadband transport and backbone networks (A backbone network is used to interconnect various access and transport networks among themselves and with backbones of other domains [86]). Figure 1.1 provides such architecture. The backbone networks could be of wired or wireless nature. Nowadays, optical fiber networks are usually selected to form the wired backbone networks, due to their high capacity (e.g. 100Gbps has developed by Ciena [75]). WiMAX is considered to be a good candidate for establishing wireless metropolitan and backbone network, but it is more widely used in constructing access networks

[87][88]. Other technologies applied into constructing access networks include Wi-Fi, GSM, CDMA2000, and etc. [87].



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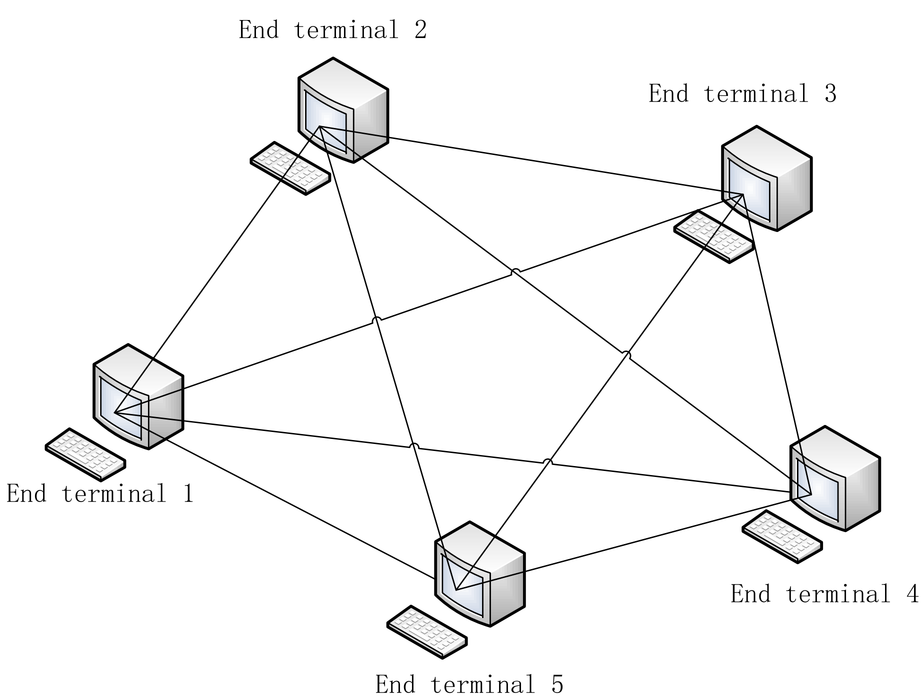

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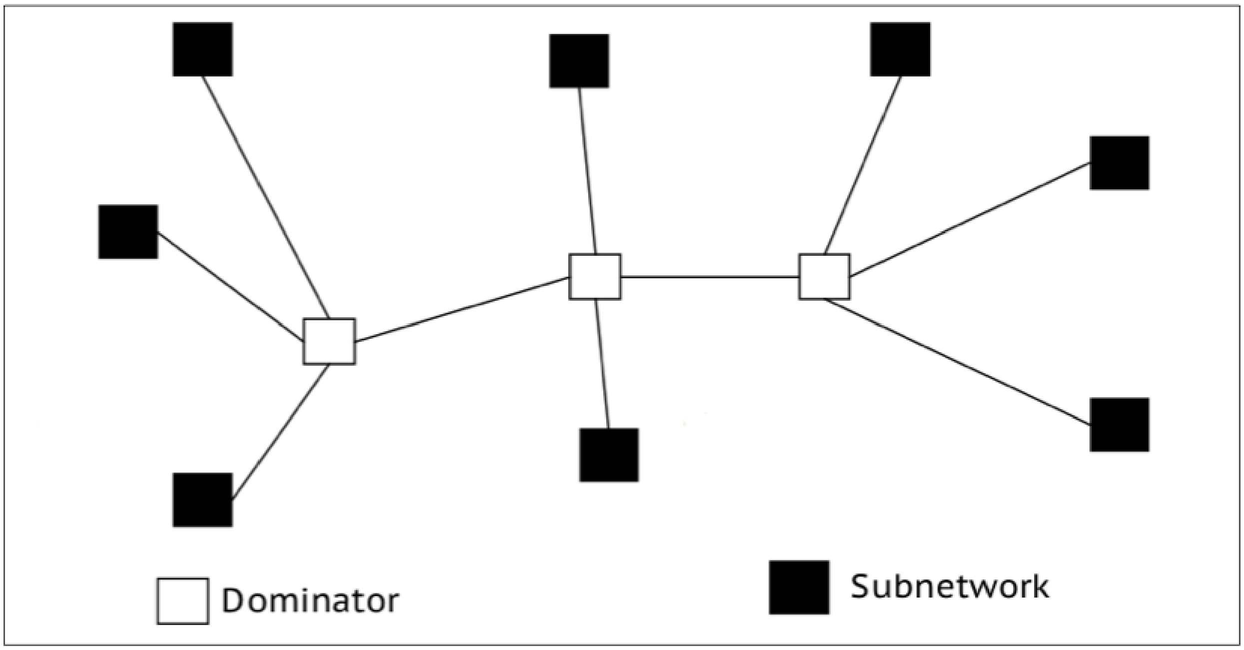


(c)

Figure 1.1 (a) Wired/wireless backbone and wireless access network;
(b)an example of distributed network;
(c) a sample backbone with three dominators

People are always willing to enjoy faster transmission speed. For example in nowadays, high definition video can be accessed from many internet websites, a vast number of people would like to watch one video show while downloading others. In a typical indoor circumstance, almost each individual has his own internet equipment, so larger bandwidth should be utilized in the foreseeable future.

To meet these requirements, high-speed wireless access networks should be available. However, the current technology does not meet expectations. Radio technology, the main wireless communication technology that supports moderate-speed applications such as text, and high-speed service such as video, could satisfy the users to a certain extent, however, existing license-requiring as well as license-free radio frequency bands bellow 10 GHz have become overcrowded, and will not be able to satisfy the needs of the growing user population and growing applications market. Smarter and dynamic use of the bandwidth has been proposed in the form of Cognitive Radio (CR), however the technology is still under development. Should it be proven commercially viable, it will not become broadly used in the consumer products market for another five to ten years. It has to overcome serious challenges, one of them been the additional complexity and processing requirement it adds, which impact negatively cost, size and energy consumption of the user's device. A different approach is to develop viable technology at Extreme High Frequencies (EHF); the spectral range between 30 GHz and 300 GHz [75]. For example, the 20 GHz to 60 GHz band is considered for indoor wireless communication service [76].

The communication systems employing carrier frequency at 60GHz trigger researchers' interests all around the world. There are several factors for this circumstance. First, spectrum band at 60 GHz (a part of millimeter-wave band) is unlicensed. Second, the spectrum at 60GHz still can be used by high-bandwidth commercial wireless communication systems. Third, more bandwidth is available than microwave band communication. However, 60 GHz communication system has its own drawbacks. From [155][156] we can learn that, compared to microwave band communication, "20dB larger free space path loss due to the order of magnitude increase in carrier frequency, 5-30 dB/km due to atmospheric conditions, and higher loss in common building materials". The merits of 60 GHz communication overweigh its shortcomings for close-range gigabit wireless applications.

There have been several standards appeared for 60 GHz communication. For short-range wireless personal area networking (WPAN), WirelessHD [157], IEEE 802.15.3C[158], and ECMA

387 [159] standards have been made, and for next-generation wireless local area networking, IEEE 802.11 ad [160] and WiGig [161] standards are also available.

Many 60 GHz communication systems have been realized by many groups. A system uses differential coded binary phase shift keying modulation and differential demodulation schemes is developed by L. Rakotondrainibe and his colleagues, which can provide 875 Mbps for short-range communication [162]. Their work is supported by the French "Media & Network Clusters". A 60 GHz OFDM system is realized by S. Choi Chang-Soon's group in Germany [163]. The system can achieve 1-G bps data rate, SiGe BiCMOS technologies are utilized to make its 60-GHz super-heterodyne transceivers. Also in Germany, E. Grass etc. give details on how to implement a 60 GHz communication system which has ability to operate at 1 Gbps [164].

Use of EHF has the following two advantages: plenty of bandwidth, as well as EHF signals experience significantly stronger attenuation compared to those at the lower part of the spectrum, thus making development of short-link communication systems easier. However, there are significant technical hurdles to be passed, one of them been the unavailability of reliable integrated RF electronics for those frequencies. Its development and manufacturing of integrated circuitry at cost suitable for the consumer market is not expected in the foreseeable future. A different approach appeared during the ending years of last century; the use of wireless optical communication links. Wireless Optical Communications (WOC) have been used for several years to provide very high speed free space communication links. However the technology requires use of laser devices and should be ensured that the optics of the transmitting and receiving devices maintain optical line-of-sight connectivity, since even a few degrees of misalignment would break the communication link. Also optical signals experience significantly stronger attenuation when passing through fog, rain or snow, compared to RF signals. Photodiodes are considerably cheaper than laser diodes, however, their use on consumer products for communication purposes has been limited mostly to remote control and provision of low-bit-rate point-to-point communication links among computing devices and their peripherals (e.g. laptops, PDAs, printers). However, recent advancements in the field of the fabrication of integrated optical electronics opened the way for the development of inexpensive, medium to high speed & short range wireless optical communication systems that links in wireless medium to high speed short range wireless communication, triggering intensive research. Optical wireless is the combined use of "optical" (optical components) and "wireless" (physically not connected) communication links to provide telecommunication to clusters of end points that are geographically distant [2]. For example, there could be many electronic devices (end points) located within an office and equipped with wireless optical transceivers, communicating with each other by optical wireless transceivers. Traditionally, radio frequencies have been used for communicating through free space, while light waves sent through fibre provide ultra high speed wired links. In recent years, researchers have been trying to find methods of integrating these two technologies. Figure 1.2 illustrates this point.

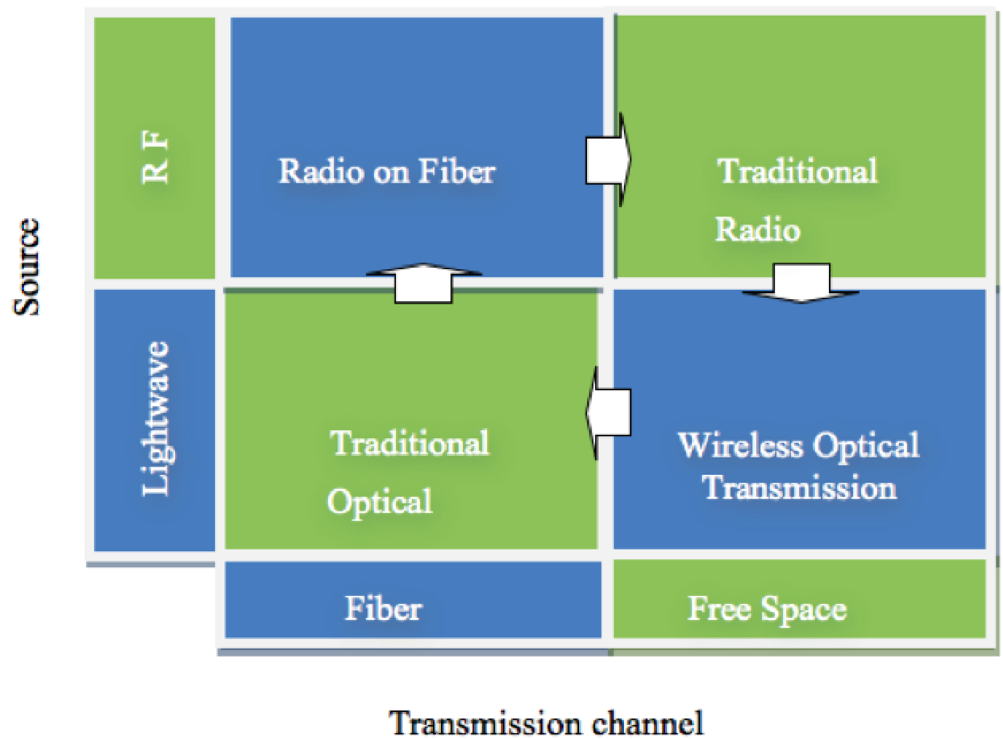


Figure 1.2 Integration of radio and optical communication

The integration of radio frequency (RF) and optical fibre is referred to as Radio over Fibre (RoF). In RoF technology, a RF (Radio Frequency) signal that carries data [82], [83] is sent through the light wave generated by a laser diode (LD) or a light-emitting diode (LED) [85] and transmitted in air, i.e. without the use of fibre. The ability to provide high-capacity wireless transmission (in the range of tens of KHz to tens of GHz [1]) makes optical wireless communication technology an important integration product of radio and optical technology.

1.2 Brief History of Optical Communication Systems

The use of optical emissions to transmit information has been practiced for thousands years. In *Iliad*, Homer discusses the use of optical signals to transmit messages regarding the Grecian siege of Troy in approximately 1200 BC [3]. By far, the fastest way to transmit important information was to light fire beacons at mountain tops to convey messages to people at other mountains. In the early 1790s, French engineer Claude Chappe invented the “optical telegraph”, an optical communications system that employed a series of semaphores mounted on towers. People could send messages by changing the orientation of the signalling “arms”. In order to convey messages over a long distance in short time (several minutes), a code book was invented. In this code book, inventors employed different orientations of the signalling arms to express messages including numbers, letters and common words. [3]. Photophone, patented in 1880 [95], was one of the earliest electronic detectors to use optical communication and was invented by A.G. Bell and C. S. Tainter. The operator’s voice was transmitted by modulating reflected light from the sun on a foil diaphragm [3]. The optical signal could be converted into an electrical signal by a selenium crystal at the receiver side. Figure 1.3 [3] shows an outline drawing of the system.

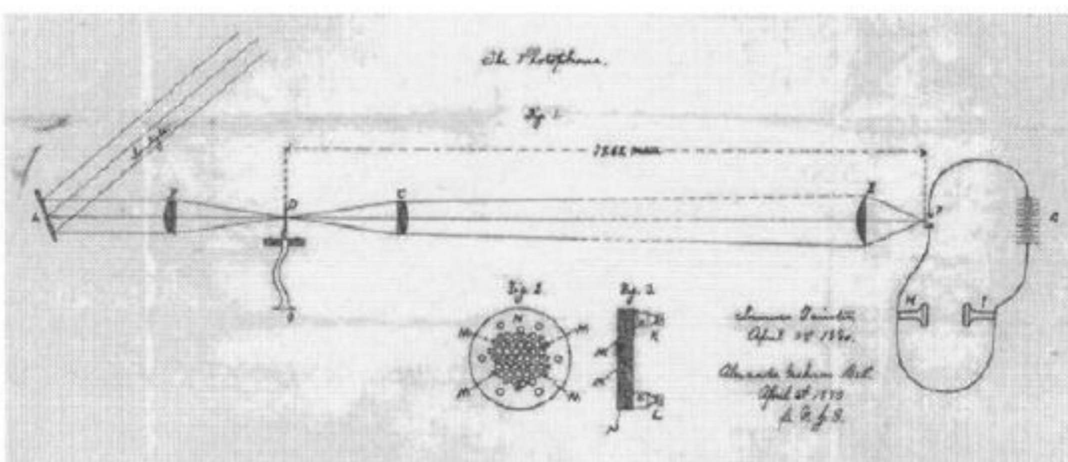


Figure 1.3 “Drawing of the photophone by Alexander Graham Bell and Charles Sumner Tainter,April 1880 [The Alexander Graham Bell Family Papers, Library of Congress]” [3, p. 25].

Optical fibre technology has been used widely in recent years. An optical fibre is a thin, flexible, and transparent fibre that acts as waveguide, or “light pipe”, to transport light between the two ends of the fibre [4]. Optical fibre technology is based on the physical phenomenon that light will be confined when it travels in one material that is surrounded by other materials with a relatively lower refractive index [85]. This principle was demonstrated for the first time in the early 1840 by Jacques Babinet and Daniel Colladon [4]. But after almost 120 years, when the laser was invented as a light source, the optical transmission finally became a mainstream technology in the telecommunications field. The ruby laser, a coherent light source, was invented by T. Mainman in 1960 and the helium-neon (HeNe) laser was developed by Bell Labs in 1961. Bell Labs invented the gallium arsenide (GaAs) semiconductor laser as well the following year. By 1970, many laboratories in the United States, Japan, and the Soviet Union successfully implemented GaAlAs laser devices generating continuous coherent oscillation of light wave, giving a significant push forward to the optical transmission technology.

The fundamental work that triggered serious R&D leading to the era of modern indoor wireless optical communication technology was the paper: “Wireless in-house data communication via diffuse infrared radiation” by F.R. Gfeller and U.H. Bapst published in 1979 [21]. In that system, diffused light signal with frequency near the infrared (IR) region was used to carry digital information from a controller to terminals located in the same room and vice versa. The Infrared Data Association (IrDA) was created in 1993 through the collaboration of major industrial organizations (around 50 companies, including NEC, Sony, and etc.) to establish an open standard for infrared data communication and to provide a simple, low-cost, and reliable method of IR communication between mobile devices [1][83]. Figure 1.4 shows an example of IrDA based short range wireless optical connectivity of devices.

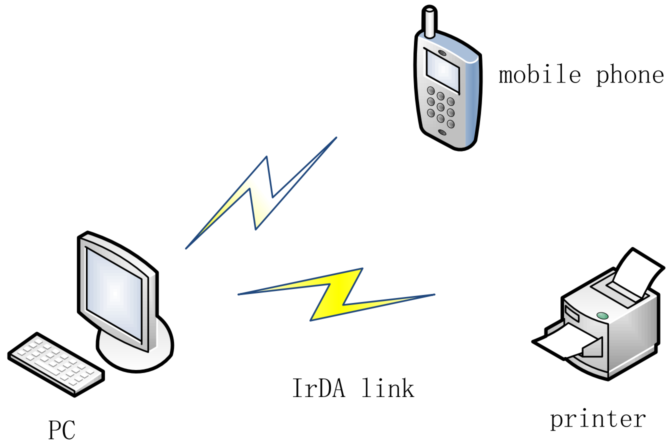


Figure 1.4 Establishing short distance communications among devices, using IrDA based systems.

1.3 Modern Optical Wireless Communication Systems

During the past two decades we have seen the development of some standards for wireless optical communications and the appearance of several related products in the consumer electronics market. In general, optical wireless communication systems can be classified into two categories, depending on the environment they are designed to operate: *indoor* and *outdoor* systems.

1.3.1 Indoor Systems

The increasing number of personal computers and mobile devices and the growing number of broadband applications pushed the need for coming up indoor wireless access networks of wider bandwidth. In terms of indoor applications, light waves are a strong candidate for wireless networks. The light wave frequency at infrared range (300G to 405T Hz [89]) is usually chosen due to the low cost to realize an IR communication system. However, in recent years, an increasing number of studies [5,6,7,8,9,10] show light waves in the visual range as the media for wireless networks because the visual light emitted by LEDs can be used to convey signals. This can be done with white LEDs used primarily to illuminate a room, with the head and tail lights of a car and goes on. This duplicate use of LEDs reduces cost and saves energy. Moreover, any "warm body" such as heating sources, warm walls & furniture, human bodies, even warm air generate radiation at the IR spectrum. It is the radiation at these frequencies that makes night vision goggles (extensively used in the military) possible. There are plenty of warm radiating sources in an indoor environment. In addition, incandescent and fluorescence light sources generate strong radiation in the IR part of the spectrum. All these sources act as disturbance to any communication system using the IR part of the spectrum. However most of them have none to minimal impact on systems operating to the higher part of the visible part of spectrum. [1].

1.3.2 Outdoor Applications

Fixed optical links, like those in communication systems with optical fibre, are not suitable for many situations such as temporary links, extremely costly and sensitive links. Currently, radio and microwave links are a popular solution [11] to some of these problems. However, these too come with their own drawbacks, including high cost and relatively limited bandwidth and interference problems. As such, the use of optical wireless systems is a promising candidate for these situations.

In parallel to the use of optical communications inside houses, use of optical communications outside, known as Free Space Optical (FSO) communications was developed as well. In outdoor applications [12,13,14,15], optical wireless solutions support long (1 to 5 km) as well as short (less than 500 m) communication links. Due to the extremely high bandwidth, long-distance solutions can easily provide 1 to 10 Gbps [1] with LOS channels. However, this flexibility is brought at the price of increased downtime due to occasionally unfavourable atmospheric conditions (e.g. fog, snow, rain, misalignment of transmitter-receiver due to blowing wind). Nonetheless, it is very useful when bandwidth is needed either very rapidly (e.g. for disaster recovery) or only temporarily (e.g. at a sporting event) [1]. Permanent systems with very high data rates could be designed for short-distance applications.

Recently, we saw use of LEDs for support of communication tasks in vehicular transportation. A system offering time sensitive information (e.g. a traffic jam, an accident, an emergency) and location related information to vehicular users is proposed in [16]. The information is transmitted to users by traffic lights comprising LEDs. Figure 1.5 gives a pictorial view of this system. In [78], visible light emitted by LEDs and received by using 2-dimensional image sensor is applied into a communication system. In [79], an intelligent transportation system is proposed by N. Kumar and his colleagues. This system, utilizes visible light as communication signal. A wireless monitoring system, which uses red LEDs and is based on GPRS is described in [80].

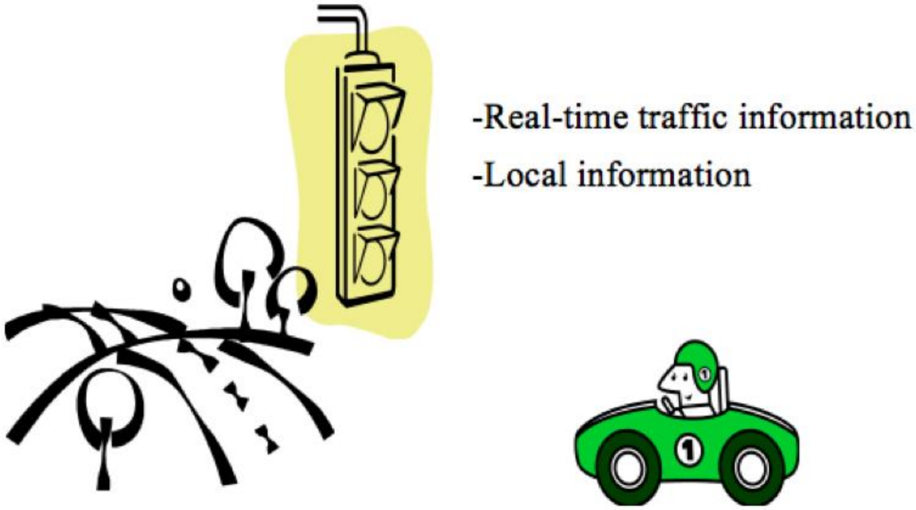


Figure 1.5 System image of a traffic information offering system using an LED traffic light.

1.4 Purpose of this Study

1.4.1 Challenges in Recent Studies

Many technical challenges remain in the area of optical wireless communications.

1.4.1.1 Cost

Cost is an important factor when considering implementation and commercialization of any technology. It impacts the competitiveness of product in the market and in many cases is the decisive factor that “makes-or-breaks” a certain product or technology. Thus, while developing more powerful communication systems is desirable, it comes to the point where we want to have something that meets the needs and is cheap rather than very powerful. As a simple example we can refer to the case of using a simple Gaussian or Butterworth filter instead of a relatively complex matched filter. Although a matched filter can provide the best bit error rate performance in an AWGN channel, it has higher cost. For example, a commercial matched filter costs about $10 in the market [17], while a Butterworth filter costs only about $3 [18].

1.4.1.2 Energy consumption and artificial light interference

Energy consumption is another decisive factor for choosing technology and its components. In traditional optical wireless infrared systems, users cannot see the infrared light—the optical power is used simply to convey data, to ensure there is a good ESNR can be achieved at receiver side, higher transmission power will be needed. On the other hand, visible light can be used both for illumination and as a medium for transmitting signals, users can easily align signal (light beam) with receiver, so transmission power is relatively less. Several studies have been conducted examining the use of visible lighting for communication purposes and have proposed visible lighting communication (VLC) systems [1,8,9,10,19], but research into which band is more suitable for indoor applications has not been investigated thoroughly. If we could identify the band that suffers the least from ambient noise, then we could achieve a good signal-to-noise ratio (SNR) while using less power.

1.4.1.3 Node relocation

Concerning the works associated with VLC, studies are available substantiating a system's bit error rate (BER) performance in terms of Optical SNR (OSNR), but there is not enough information available about the level of ESNR that we could achieve when the node is relocated.

1.4.1.4 Practical considerations

Last but not least, real operational conditions have not been studied thoroughly. For example, firstly, in some studies, the indoor environment is modelled after the following aspects: the transmitter's position, the communication distance, and the receiver's location. The receiver is often assumed as a point, and only the size of the photodiode (PD) is mentioned; but in reality, the receiver has its own size. The light has to pass through the receiver's surface (lens) before hitting the PD, if the difference in light energy between the receiver's two edges is too large, the assumption about the receiver is wrong. Secondly, the transmitter (LED or LD) is assumed working at linear part, but in fact, the output current of LED versus input voltage increases and decreases in exponentially [60]. Thirdly, the ambient light is usually the mix of nature light and artificial light. When researchers establish the noise model, many of them forget to discuss the ambient noise is isotropic or not, or many of them just assumed the noise is isotropic.

1.4.2 Research Motivation and Objectives

1.4.2.1 Motivation

We know that light waveforms provide large transmission bandwidth, that light-emitting devices and photo-detectors are cheap, and that cell planning becomes simple in indoor environments when using optical frequencies for communicating. In addition, when using visible frequencies, we have the opportunity to use the deployed LEDs for dual use: lighting the surrounding space and carry out the communication task. Other advantages of employing LEDs include the following:

1. LEDs are silicon based devices [60] and are environmentally friendly when disposed in opposition to incandescent or fluorescent light sources, which release in the environment poisoning metals and gasses.

2. They are more efficient from other light sources. In a well designed LED circuit, 80% efficiency could be achieved [77], thus they save energy. Their energy efficiency keeps increasing, making them more energy efficient. Luminous efficiency of 300 lumens per watt was realized in 2008 by using nano-crystals [60].

3. Life time of LEDs tends to be considerably longer as compared to incandescent and fluorescent light sources [78]. In table 1.1 we provide a comparison of LED, incandescent and fluorescent light sources in terms of efficiency, life time, and color temperature.

	Efficiency (lumens/watt)	Lifetime (hours)	Color temperature (Celsius degrees)
Incandescent	10 - 20	750-2,500	2700–2800 (warm)
Fluorescent	50 - 70	10,000	2700–6500 (warm to cold)
Light Emitting Diodes	150	25,000 – 100,000	5000 (cold)

Table 1.1 Comparison of incandescent fluorescent and LED-based lighting sources [78][60], All of these aspects make optical wireless a strong candidate for the next generation of wireless communications.

Although the cost and energy consumption of optical wireless systems are lower than those of RF communication systems, we still need to find methods to reduce them. Therefore, it is important to find a way of decreasing the cost while maintaining the system’s performance. Also, we need to investigate how the Electric SNR (ESNR) changes when the user is moving within the space of an indoor environment because factories need to know how much performance degradation occurs when increasing the communication distance.

1.4.2.2 Objectives

In this dissertation, we will attempt:

1. To decrease equipment costs by determining suitable modulation schemes and filtering strategies.
2. To identify a suitable transmission band for countermeasuring the noise from artificial lights.
3. To have the manufacturer understand what the characteristics of produced devices should be by determining the user's communication range and common practical problems For example, whether the actual dimension of receiver will affect our theoretical analysis or not? The details will be provided in chapter 5.

1.4.3 Research Contributions

To achieve the above-mentioned objectives, we have taken the following steps:

1. We designed an optical wireless communication system, which utilizes a Butterworth filter to replace the matched filter, for the purpose of reducing equipment costs. The reason of using Butterworth filter is discussed in section 4.3.3. In order to maintain or exceed the performance of the matched filter system, we added one and two layers FEC code to lower bit error rate.

2. We analyzed the energy spectrum of sunlight and some common indoor artificial lights to identify the suitable optical band for transmission of communication signals. We also considered the electric spectrum at the receiver side to determine the level of bit rate that should be used. Although we would like to employ the maximum bit rate, we should avoid strong electric noise introduced by surroundings optical noise sources. Our goal is to determine the maximum achievable bit rate that supports certain level of bit error rate performance. We conducted many simulations to figure out the user's mobility in an indoor environment with the goal of guiding the industrial production. We also solved the issue of practicality, which had not been considered in previous works. For example, in the theoretical analysis, the receiver is assumed as a point, but in the true environment, the receiver has a finite size, so we need to validate if this assumption is correct or not.
3. We developed a graphical user interface (GUI) product for research and industrial use. Users can input the parameters (e.g. incidence angle, irradiance angle, distance of transmitter and receiver), choose a certain modulation scheme and forward error correction (FEC) code, and the system outputs the BER results.

Figure 1.6 summarizes the challenges and proposed solutions for the indoor OWC system addressed in this research project.

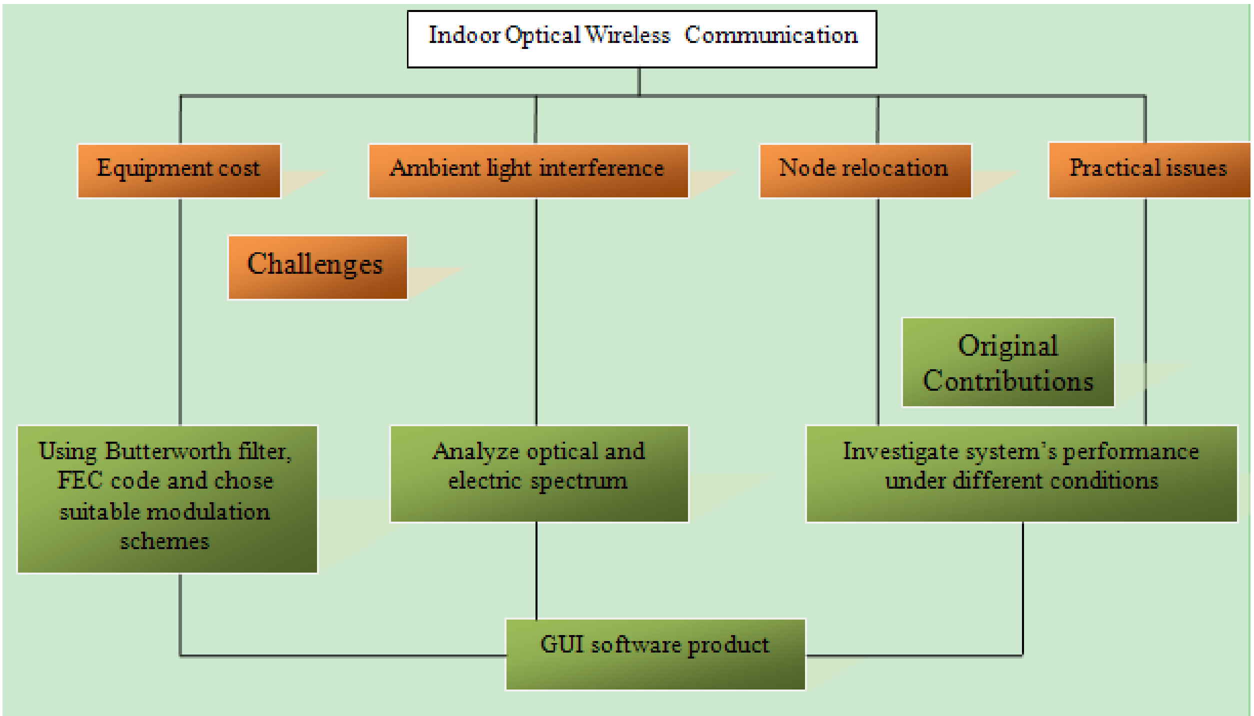


Figure 1.6 Summary of the challenges and original contributions

1.4.4 Thesis Structure

The thesis is structured as follows: Chapter 2 gives the overview of optical wireless communications; Chapter 3 introduces some studies that have used visible light-emitting diodes; Chapter 4 proposes the model of indoor visible light data transmission system utilizing blue LED lights; Chapter 5 discusses our simulation results and analysis; and finally, Chapter 6 provides our conclusion and identifies potential points for the future research.

Chapter 2

Overview of Optical Wireless Communications

2.1 Comparison of Light-Wave and Radio Media

Compared with Radio Frequency (RF) communication systems, optical wireless communication systems have several advantages:

1. *Bandwidth availability*. Optical carriers provide usually bandwidth in the range of GHz to THz per second, making optical communications ideal for ultra to extremely broadband communication systems. Wired communications have taken advantage of this nature of optical systems, having already materialized commercially available fiber optics systems supporting speeds as high as 8.8 Tbps [102]. Optical wireless communication systems are capable of communications at speeds similar to those we are used in fibre-optics based communications systems, however, they haven't reached the level of popularity and widely spread use of their fibre-optics based counterparts.
2. The cost of devices used in an optical wireless communication system is lower compared with RF systems (OWC systems using LEDs are cheaper from those using LDs. In general, OWC systems are cheaper than RF systems), making it an attractive candidate in a consumer communication system.

3. Unlike radio waves, light waves cannot go through opaque objects. This minimizes security issues such as eavesdropping, and makes cell planning in networks easy and simple.
4. The optical wireless frequency spectrum is different than radio frequency, making it convenient in places where electro-magnetic interference (EMI) is prohibited (e.g. in hospitals).
5. There is no law about the regulation of light wave frequencies by any government or organizations world wide.

Although the advantages of light waves over radio frequency are obvious, there are also some drawbacks. First, people have to install access points in every room for OWC systems, since light waves don't have the ability to pass through walls and other opaque objects.[1]. Second, in many environments, there is a ambient light noise resulting from nature and artificial light. This induces a strong noise current at the receiver side. Table 2.1 shows a comparison of radio and indoor optical wireless systems.

Property of medium	**Radio**	**Optical wireless**
Cost	$$	$
RF circuit design	Yes	No
Bandwidth regulated	Yes	No
Passes through walls?	Yes	No
Multipath fading	Yes	No
Multipath distortion	Yes	No

Path loss	High	High
Dominant noise	Other users	Background light
Input X(t) represents	Amplitude	Power
SNR proportional to	$\int \lvert X(t) \rvert^2 \, dt$	$\int \lvert X(t) \rvert^2 \, dt$
Average power proportional to	$\int \lvert X(t) \rvert^2 \, dt$	$\int X(t) \, dt$

Table 2.1 Comparison of optical wireless and radio systems

2.2 Link Configurations

An indoor wireless optical link can be classified in one of 4 different classes, identified by two characteristics. The first characteristic takes into consideration the degree of directionality of transmitter and receiver. These can be *directed*, *hybrid*, or *non-directed*, as shown in Figure 2.1 [20]. Power efficiency and transmission speeds are maximized in directed links and minimized in non-directed links. However, non-directed link is more suitable in many situations such as mobile terminals. Because in non-directed links, light rays are emitted by wide beam transmitters and received by wide field-of-view (FOV) receivers.

The second characteristic classifies links according to whether or not there is an uninterrupted line-of-sight (LOS) path between transmitter and receiver. LOS links maximize power efficiency and transmission speeds while NLOS are robust and convenient. From Figure 2.1, we can see that non-directed-NLOS, also named diffuse links, offer the greatest robustness and freedom of movement while maintaining connectivity.

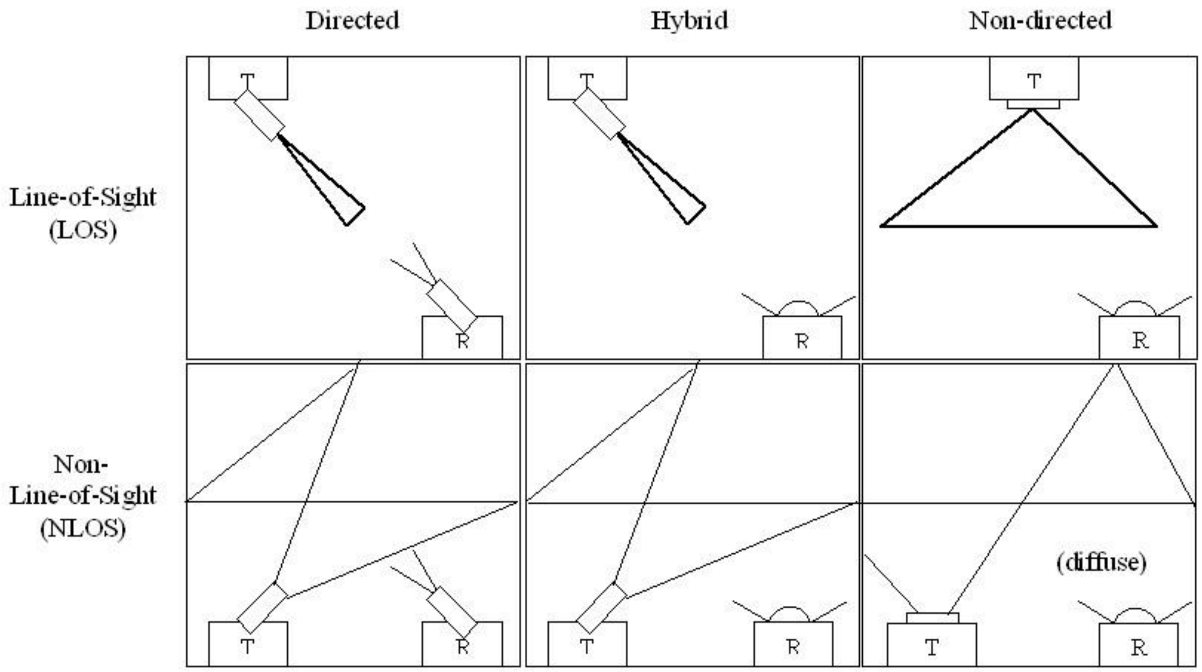


Figure 2.1 Classifications of simple indoor optical wireless links based on the degree of directionality of the transmitter and receiver and whether the link relies upon the existence of a LOS path between them [1]

In scenarios with directed links, the transmitter emits a narrow angle beam and the receiver has a narrow FOV regardless of LOS or NLOS. The advantage of this configuration is that it saves energy and minimizes multipath dispersion. However, the alignment is a significant problem because of the highly directional transmitter and receiver. To overcome the disadvantage of directed links, the hybrid system is designed with a wide angle transmitter and a narrow FOV receiver. This design reduces the requirement for alignment, while introducing stronger signal spreading due to multipath as compared to directed links.

NLOS links attract the most interest from researchers because they do not need to be aligned, which gives great flexibility to the user. The diffuse configuration consists of a wide beam transmitter and a wide FOV receiver, as shown in Figure 2.1. Light-wave is emitted by a wide beam transmitter pointed towards the ceiling, which has a surface with Lambertian properties[1] [105]. The light wave undergoes multiple reflections at the ceiling, after which it is received by a wide FOV receiver. With a diffuse link, a good mobility and link set up could be easily achieved, making it more suitable for portable terminal communication systems. Significant drawbacks, such as the high path loss and high intersymbol interference (ISI), resulting from the multipath propagation are unavoidable. The path loss could be in the range of 120-130 dB for the configuration at [21] [22], and the ultimate unequalized bit rate is limited to 260 Mbps due to the high ISI [19].

In order to improve the bandwidth availability of diffuse links while we maintain the freedom of location/movement offered by it, quasi-diffuse communication systems were designed [3, p. 34]. From Figure 2.2, we can see that, the transmitter in a quasi-diffuse system emits multiple narrow beams that are reflected by a ceiling and received by a receiver, which consists of a series of narrow FOV concentrators with the corresponding PDs.

[1] Lambertian surface: the brightness of an object's surface is the same to an observer, no matter where the observer stands. Lambertian surface could be assumed as a ideal diffuse emitter or reflector.

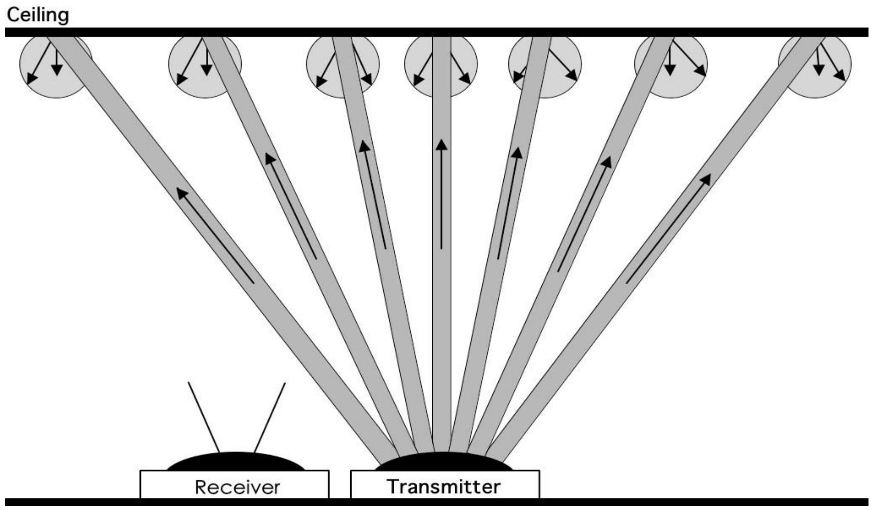


Figure 2.2 Quasi-diffuse wireless optical communication system [3, p 34]

2.3 Indoor Optical Wireless Channel

Many researchers believe that intensity modulation and direct detection (IM/DD) is a practical optical wireless communication system due to its low cost and simple implementation for short-range, indoor applications. [49]. Figure 2.3 (modified from [3]) provides a block diagram of the IM/DD communication system. The information is encoded in the power of the optical wave, which can be varied by appropriately changing the current's volume that acts as input to the light emitting source. A photodetector is employed at the receiver side to convert light waves to photocurrent. The generated photocurrent is proportional to the "instantaneous" optical power it receives. The n(t) in the figure corresponds to the ambient noise.

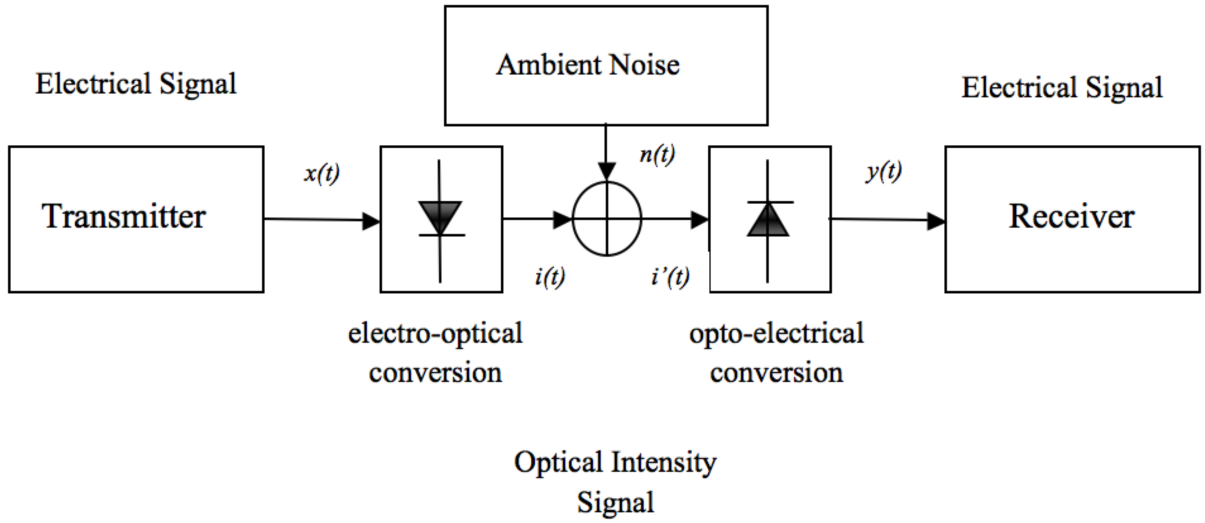


Figure 2.3 Block Diagram of Intensity Modulation-Direct Detection wireless optical communication system [3, p 10];

x(t) is the electrical signal*, i(t)* is the optical signal (the *X(t)* in Figure 2.4), *n(t)* is the ambient noise, *i'(t)* is the combined optical signal and ambient noise, and *y(t)* (*Y(t)* in Figure 2.4) is the electrical signal generated at the output of the photodiode.

Figure 2.4 shows the model of IM/DD in block diagram form.

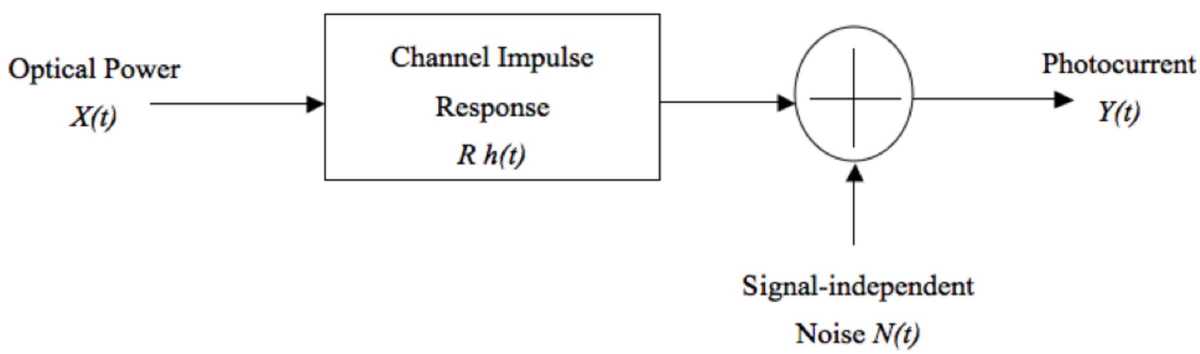


Figure 2.4 Equivalent IM/DD model

X(t) is the optical power, which is emitted by the LED. into the channel (will be changed in the channel) and then received at receiver. *Y(t)* is the photocurrent generated by photodetector, *R* is the responsivity of the photodetector, *N(t)* is the signal independent shot noise introduced by ambient light and self-noise produced by the information bearing optical signal itself. This model can be described with the following equation:

$$Y(t) = RX(t) \otimes h(t) + N(t) \tag{2.1}$$

where the symbol $\otimes$ represents convolution.

The most important difference between optical and RF links is the channel input *X(t)*. In an optical wireless channel, *X(t)* should be non-negative, because the instantaneous optical power is non-negative,

$$X(t) \geq 0 \quad \forall\, t \ \in Real\_num \tag{2.2}$$

where *Real_num represents the set of real numbers.* The average transmitted optical power $\mathrm{P_{avg}}$ is defined as [3, p. 41]:

$$P_{avg} = lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt \ \ \forall\, t \ \in Real\_num \tag{2.3}$$

while for an RF system, *X(t)* can be either positive or negative and the average transmitted power $\mathrm{P_{avgRF}}$ is given by:

$$P_{avgRF} = lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} |X(t)|^2 dt \tag{2.4}$$

and the ESNR in an optical wireless system is defined as [20]:

$$ESNR = \frac{R^2 P^2}{R_b N_o} = \frac{R^2 H^2(0) P_t^2}{R_b N_o} \quad (2.5)$$

where N_o is the single sided noise spectral density, R_b is the bit rate, and $H(0)$ is the channel DC gain, given by:

$$H(0) = \int_{-\infty}^{\infty} h(t)dt \quad (2.6)$$

The ambient light that comes from natural (sunlight) and artificial sources (incandescent lamps, fluorescent lamps, other LED based light sources) is the source of noise. Similarly with the optical signal, which includes self-noise. The ambient noise generates shot noise behaviour, which can be modelled as additive, white, Gaussian noise (AWGN), and is independent of *X(t)* [23]. In most environments where simple LED based optical wireless systems are employed, intense ambient light exists, so the dominant noise source is shot noise—especially in diffuse receivers. In the case of little to no presence of ambient light, and the optical signal's power is not strong enough, the main noise is not the shot noise any more, but the receiver's preamplifier noise, which is also information bearing signal independent, additive white Gaussian [20]. The single-sided power spectral density (PSD) N_0 of shot noise is given by [20]:

$$N_0 = 2qI_B \quad (2.7)$$

where I_B is the average DC photocurrent generated by the shot noise, and q is the charge of an electron.

Assuming all-time uninterrupted paths, the signal time variation due to multipath fading in the optical wireless channel is non-existent, because the dimensions of the photodetector's light sensitive area are orders of magnitude larger compared to the carrier's wavelength, while the received signal's temporal dispersion caused by multipath propagation remains a problem [24]. In indoor LOS links, the LOS channel is modelled as a linear attenuation and delay line [24], and is considered non-frequency selective. The signal power path loss in the case of LOS channels is proportional to the square of the distance between transmitter and receiver, and the radiant flux ($\varphi_e = Acos(\psi)$)detected by the receiver depends on the photodetector's photosensitive area and the irradiance angle ψ. The transfer function of the LOS link can be simplified to [25]:

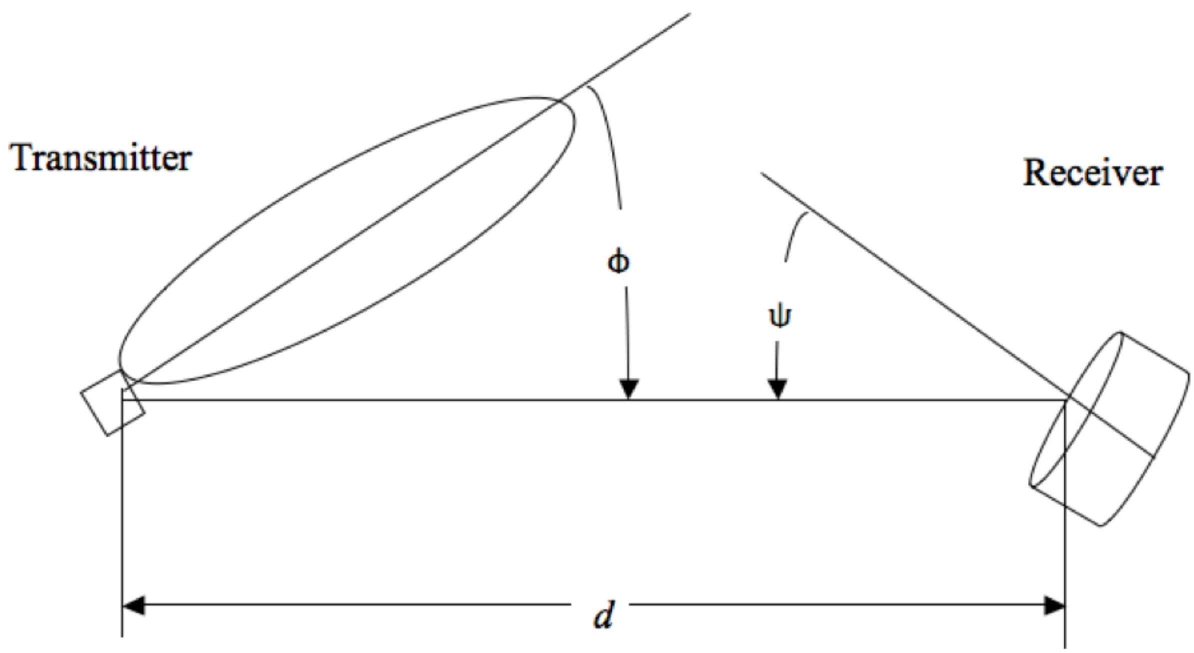


Figure 2.5 LOS channel model [20]

$$H(0) = \frac{Acos(\psi)}{d_{TR}^2} \quad (2.8)$$

The attenuation in diffuse channels is dependent on many factors, such as the transmitter's and receiver's distance and orientation, the reflectivity of the furniture, ceiling, and walls, and the presence of intense ambient light. Many researchers have been attempting to characterize the indoor optical channel [20, 26, 27, 28, 29, 30, 31, and 32]. Regardless of the method employed, the impulse response of an optical wireless channel is calculated by adding the optical power of all the components (directly, from one and multiple reflections) after the channels' multipath propagations [32].

In the case of LOS channel, a modified gamma distribution ($Y = K_{mg} - Z, \text{where } Z$ is gamma distribution) is followed for the LOS component, [105, p85,], and a modified Rayleigh distribution ($Y = K_{mg} - Z, \text{where } Z$ is Rayleigh distribution) should be followed, due to the reason of multiple reflections (LOS component with all reflections). In summary, the LOS term and the reflections separately, for the LOS term the statistical behaviour is described by modified gamma distribution, the multiple reflections component from modified Rayleigh

The first and a very popular optical channel model was proposed by Barry and his colleagues [34]. This model calculates the impulse response of the channel using a recursive algorithm. It is based on the finite elements method and calculates the multiple reflections of the optical waves propagating within a room. The disadvantage of this model is that it does not account for shadowing and the presence of objects (e.g. furniture) within the room. A more efficient model, which takes multiple reflections of the symbol into consideration, was proposed by Lomba for indoor channels and is described in [35, 36]. In this model, two advanced methods 'time-delay agglutination' and 'time and space indexed tables' are employed to improve efficiency. Another optical channel model, using the iterative method, was proposed by Carruthers et al. [37, 38]. In this model, the shadowing effect is taken into consideration. The author suggested that people should not employ the same model for channels with LOS paths and channels without

LOS paths (diffuse channel), because “the response of a LOS link is an impulse with delay due to the propagation path, while the received signal in case of the non-LOS links consists of various components arriving from different paths, with the path-length of these components differing in proportion to the room design, “hence there is broadening of the pulse” as was said by S. Rajbhandari. Compared with the traditional channel simulation methods, which separate the channel into a number of reflections, Lopez-Hernandez [39] suggested a new approach that would slice the channel into time steps to develop efficient simulation, because in the traditional method [49], only a few reflections can be simulated. Also in this new approach, database concept is used, which means that the main part of the calculations has been saved and could be used for different sets of receivers. Please note that the Monte-Carlo Ray tracing algorithm and Lambert’s model of reflection are used for most of the channel models described above.

2.4 Optical Transmitter and Receiver

The goals of designing appropriate transmitters and receivers for indoor optical wireless communication applications can be various. For example, some are require high data rate this requires direct-LOS channels), e.g. high definition television (HDTV). Others are aiming to provide a wider area coverage, in which use of diffuse channels is advised. Considering the users’ growing need for broadband access, mobility and device portability, new indoors wireless optical technology is required. Conventional diffuse transmitters and wide FOV receivers cannot satisfy the above-mentioned needs due to high path loss and low power efficiency. Under the LOS channel, a high data rate can be reached due to low path loss, but mobility is still limited due to the need for a high degree of alignment. To meet the needs of high data rate and mobility, various types of quasi-diffuse transmitters and quasi-diffuse receivers have been designed by researchers all over the world [21], [24], [26]. In this section, the principle behind the design of optical transmitters and receivers will be discussed in greater detail.

2.4.1 Optical Transmitter and Eye Safety

The function of an optical transmitter is to convert an electrical signal to an optical wave. Among many light sources, light-emitting diodes (LED) and semiconductor laser diodes (LD) are used widely in optical communications. In certain operation areas, the optical intensity of their output seems approximately linearly proportional to the drive current. Direct band gap semiconductors [60] are integrated into LEDs, and the central wavelength λ of the emitted photons is given by [40]:

$$\lambda = \frac{hc}{E_g} \tag{2.9}$$

where h is Planck's constant, c is the speed of light in vacuum, and E_g is the band gap energy.

The operation principles of LEDs and LDs are different: LEDs operate by spontaneous emission while LDs, which operate by stimulation emission, need to create a population inversion[2]. The following are advantages of LDs over LEDs: (1) LDs are highly coherent, and (2) the spectral width of LDs is smaller than that of LEDs. However, the disadvantage of LDs is the high

---

[2] "A population inversion occurs when a system (such as a group of atoms or molecules) exists in a state with more members in an excited state than in lower energy state" [108].

manufacturing and operating cost. A comparison of the two light sources is provided in Table 2.2.

Characteristics	LED	LD
Optical spectral width	25-100 nm	0.1 to 5 nm
Modulation bandwidth	Tens of KHz to hundreds of MHz	Tens of kHz to tens of GHz
Special circuitry required	None	Threshold and temperature compensation circuitry.
Eye safety	Considered Eye safe	Must be rendered eye safe
Reliability	High	Moderate
Cost	Low	Moderate high

Table 2.2 Comparison of LEDs and LDs [3]

Many factors—such as cost, data rate, and eye safety—have to be taken into consideration when choosing which light source will be used as the optical transmitter. Compared to LEDs, LDs can provide high-speed operation because of the stimulated emission. In fact, LEDs can only work in a megahertz range while LDs operates in gigahertz range [3]. However, LDs may not be a good choice for indoor optical applications due to their high intensity, which might hurt human eyes. In contrast, LEDs are considered to be safe for the eyes because the generated light has a wide angle and is more suitable for diffuse links [41].

The human eye is a very sensitive tissue that can be permanently damaged under certain conditions. High-intensity light in the range of visible and near-IR could permanently damage the eye if focussed on the retina. This is because the retina has no pain sensor [19, p.3]. Due to the physical characteristics of the human eye, light in the IR range is invisible, so lasers operating at near-IR wavelengths are much more dangerous to humans. Eye-safety regulations limit the average power to less than 1 mW [42]. However, the energy of laser beams at the 1550-nm wavelength is absorbed by the cornea and lens and does not concentrate onto the retina, making them potentially safe [43]. The permitted average optical radiation power varies with the wavelength. Some information is given in Table 2.3.

	Wavelength			
Category	**650 nm (Visible)**	**880nm (Infrared)**	**1310nm (Infrared)**	**1550nm (Infrared)**
Class 1	≤ 0.2mW	≤ 0.5mW	≤ 8.8mW	≤ 10mW
Class 2	0.2-1mW	N/A	N/A	N/A
Class 3A	1-5mW	0.5-2.5mW	8.8-45mW	10-50mW
Class 3B	5-500mW	2.5-500mW	45-500mW	50-500mW

Table 2.3 Laser classifications [3,41].

Class 1: totally safe to the human eye. Class 2: Harms the human eye when staring directly for a long time. Class 3A: May cause serious damage to the human eye when exposed to, with direct contact for longer than 2 minutes. Class 3B: May cause serious damage if the beam enters the eye directly [103].

2.5 Optical Receiver

The light that conveys information is collected and converted into electrical current by optical receivers. A model of a basic optical receiver has three parts, which are shown in Figure 2.6.

The structure of the optical receiver can be classified into two types: *direct detection receiver* and *heterodyne detection receiver*. Direct detection[3], is a non-coherent detection scheme. It measures and processes the received optical signal power for information recovery. Heterodyne detection receivers, in many cases referred to as coherent detection receivers, involve the optical mixing of a locally generated light wave field with the received field through a front-end mirror, and then the combined wave is photodetected [44]. The implementation of a heterodyne receiver is therefore more difficult because it requires close tolerances in terms of spatial coherence between the two optical fields being mixed [44, p. 5]. Figure 2.7 shows the structures of direct detection and heterodyne detection receivers.

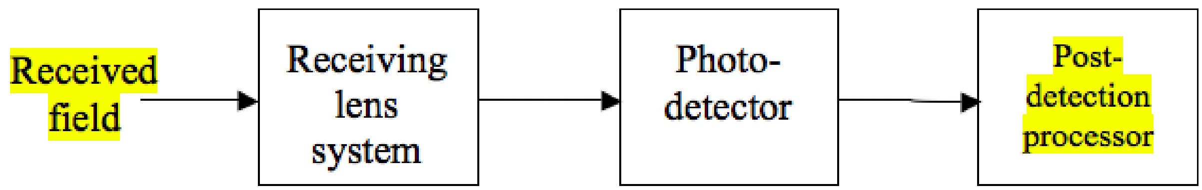
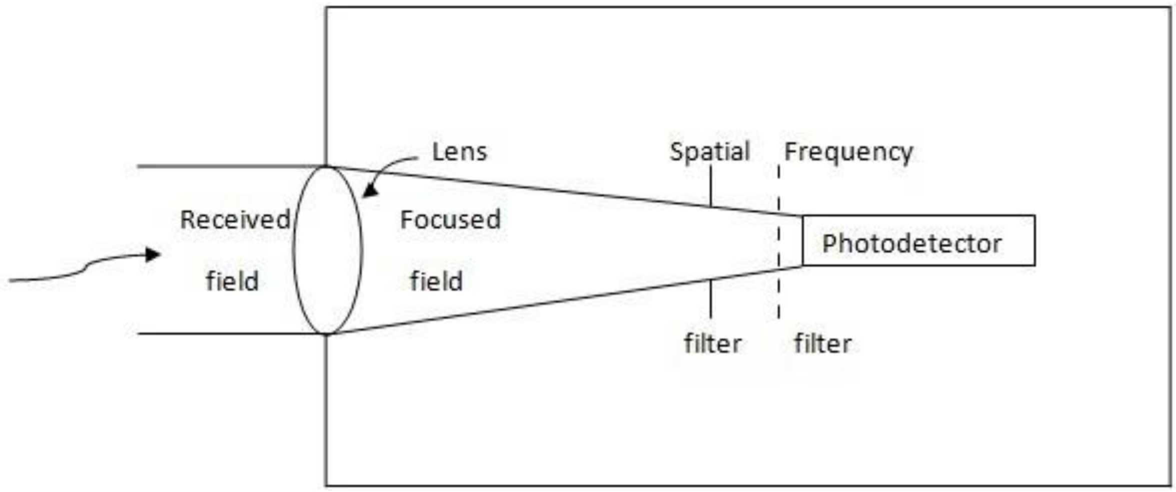
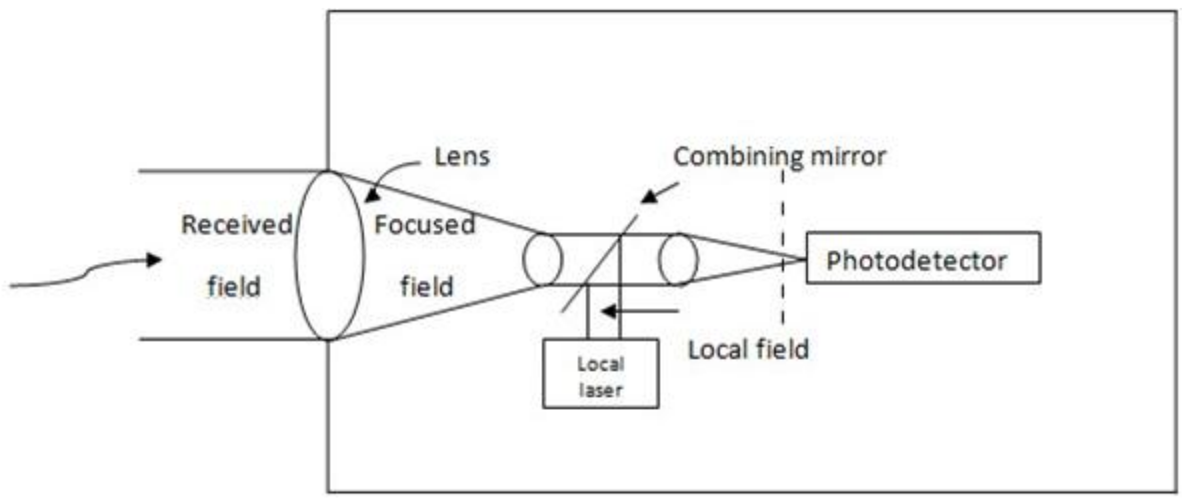


Figure 2.6 The optical receiver model

[3] Because it is practically the only non-coherent technique used in optical communications, the term non-coherent detection, when used in optical communications, points to direct detection.



(a)



(b)

Figure 2.7 (a) Direct detection receiver,
(b) Heterodyne detection receiver

Some of the photons falling on the photosensitive area of a photodiode generate free electron-hole pairs, which generate photocurrent. The expression of the average value of photocurrent generated by a solid-state photodiode operating at steady-state can be modelled as follows [3]:

$$I_p = q\eta_i \frac{P_p}{h\nu} \tag{2.10}$$

where I_p is the average photocurrent, η_i is the quantum efficiency of the device, P_p is the incident optical power, v is the (optical) carrier's frequency, and hv is photon's energy. The conversion efficiency of optical power to photocurrent, , of the device is known as responsivity, and is expressed as follows [3, p. 23]:

$$R = \frac{I_p}{P_p} = \frac{q\eta_i}{hv} \tag{2.11}$$

Avalanche photodiodes (APDs) [3, p. 23] and positive-intrinsic-negative (PIN) [3, p. 23] photodiodes are two widely used types of silicon photodiodes. Junction capacitance is an important limiting factor of their use in wireless communications, as it can limit the frequency of operation. From the transfer function of LOS links (see Eq. 2.8), we know that a photodiode with a larger area can collect more light to improve the received optical power and the corresponding photocurrent. However, a photodiode with a large area will lead to high capacitance and reduce the speed of operation, the trade-off of these factors should be considered in the design of optical wireless receivers [44].

The working schemes of APDs and PIN photodiodes are different. The operation mechanism of APDs is based on avalanche multiplication: more carriers (electrons) are produced when free carriers collide with other electrons [45], [3, p. 25]. However, a PIN diode needs to absorb enough light to generate adequate photocurrent. Various operation schemes result in different unit gain for APDs and PIN diodes. "APDs have a photocurrent gain greater than unity, while PIN photodiodes are fixed at unit gain," [20].

In the design of direct detection receiver for OWC systems, APDs are employed widely when there is no or little ambient noise, since their internal gain has the advantage in overcoming thermal noise introduced by the preamplifier [20]. But there are some factors that limit the use of APD, for example, due to the non-linear behaviour of the APD, a redundant circuit, which increases the cost and decreases the reliability of the system, is needed to improve the receiver's performance [20]. As such, in indoor optical wireless communication, PIN photodiodes are used widely due to their characteristics of linear response in wide ranges, their tolerance of great temperature fluctuations, and their operation with low power [20]. Table 2.4 provides a comparison between PIN diodes and APDs [3, p. 26].

Characteristic	**PIN photodiode**	**APD**
Modulation bandwidth	Tens of MHz to tens of GHz	Hundreds of MHz to tens of GHz
Photocurrent gain[4]	1	$10^2 - 10^4$
Special circuitry required	None	High Bias voltage and temperature compensation circuitry
Linearity	High($$$)	Low($)
Cost	Low($)	Moderate to high($$ to $$$)

Table 2.4 Comparison of PIN diodes and APDs [3, p. 26]

[4] "The photocurrent may be enhanced by internal gain caused by interaction among ions and photons under the influence of applied fields" [109]

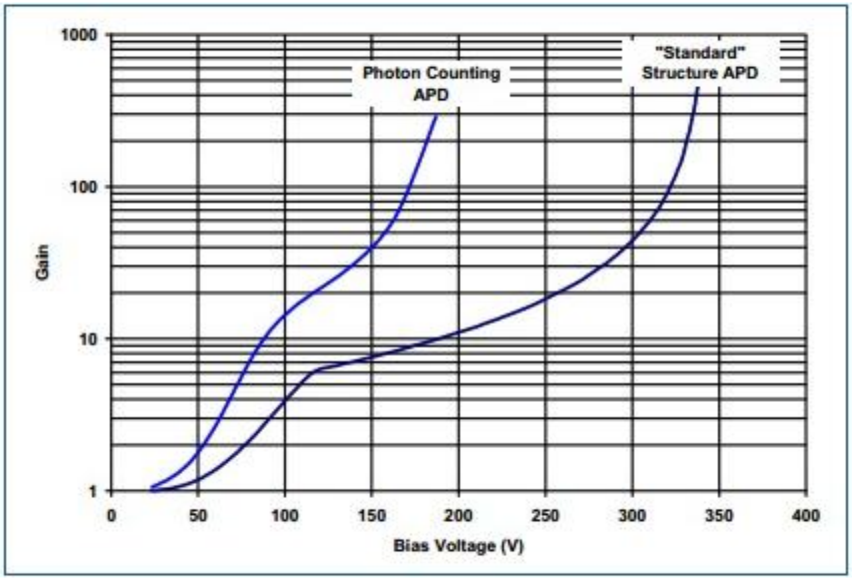


Figure 2.8 Bias Voltage vs. Gain for Standard Structure APD and Photon Counting APD [107]

2.6 Noise

There are mainly three types of noise that can affect the performance of an indoor optical wireless system: background noise, shot noise, and thermal noise. Unlike shot noise, background noise and thermal noise (introduced by the pre-amplifier and post-amplifier, and all the other elements of the receiver side) are not affected dramatically by the environment. So, shot noise, which is introduced by ambient and artificial light (in many cases, the shot noise introduced by the signal itself is not considered significant compared the shot noise introduced by the ambient and artificial light [1]) , is the main problem we need to consider in optical wireless communication using visible light. At present, most sources of artficial light used indoors are incandescent or fluorescent bulbs. In the future, WLED-based (white LED-based) lighting sources are expected to dominate the market. This change, however, will be gradual and will take several years before it becomes widespread.

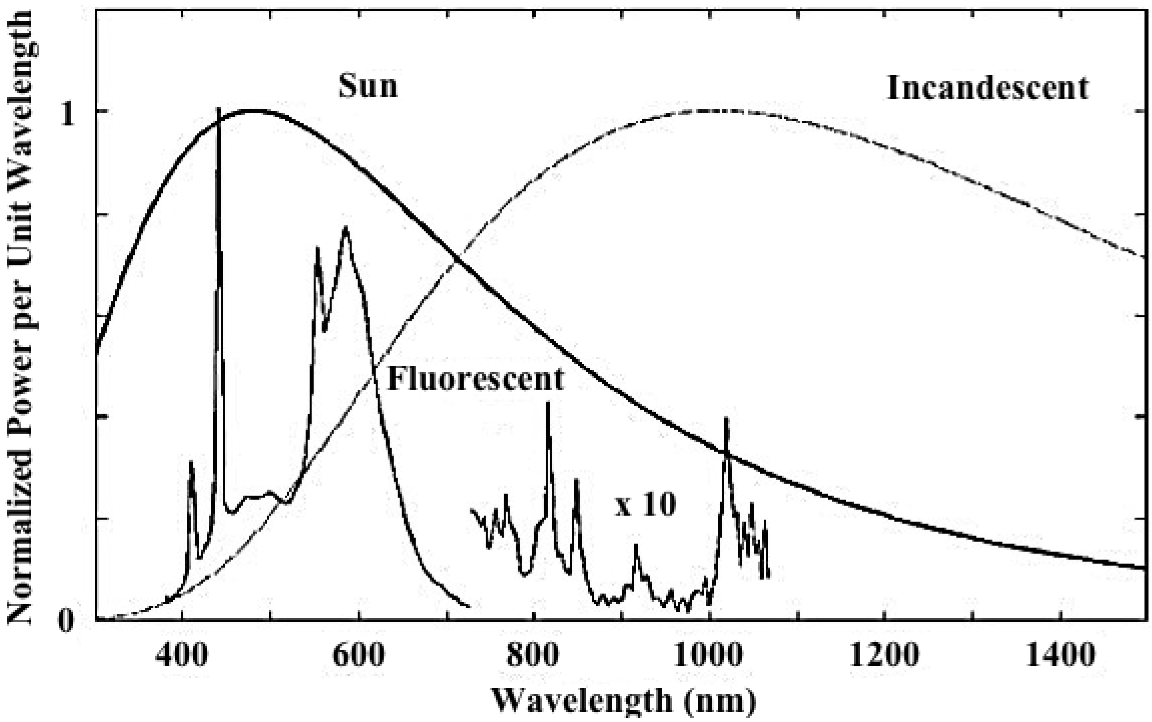
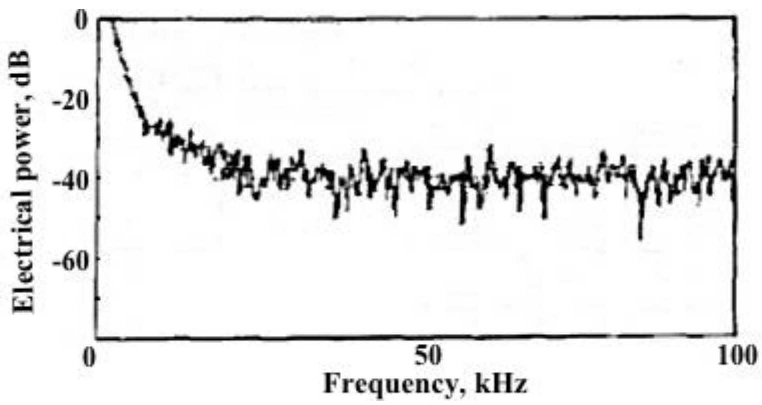


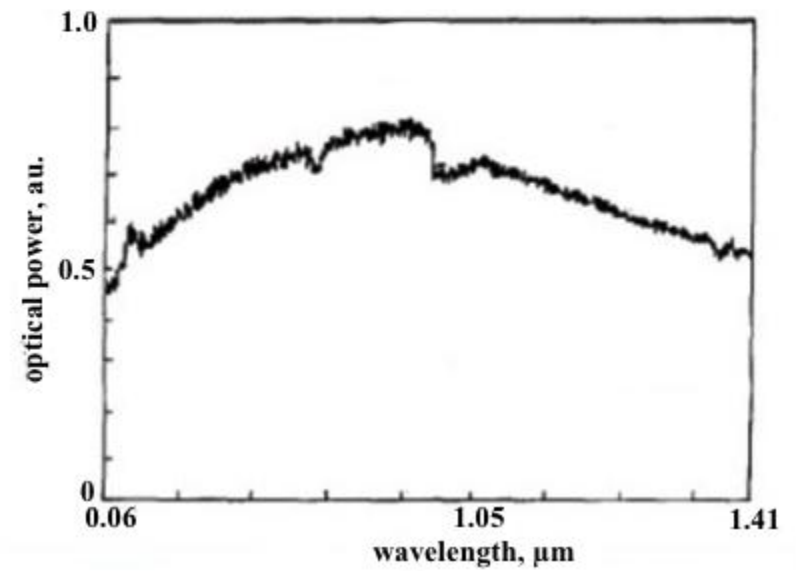
Figure 2.9 Spectral behaviour of: (a) Sunlight;
(b) Incandescent (tungsten) lamp;
(c) Fluorescent bulb. [46]

Figure 2.9 shows the spectral power density content of sunlight, of an incandescent lamp and of a fluorescent bulb. Reflective windows found in modern buildings tend to block a considerable amount of sunlight from passing through, leaving the artificial light sources as the main source of ambient noise.

While understanding the spectral behaviour of ambient light sources at optical frequencies is important, it should not escape our attention that what will determine the impact of ambient light on the performance is the electric noise it generates at the output of the photodetector-based receiver.



(a)

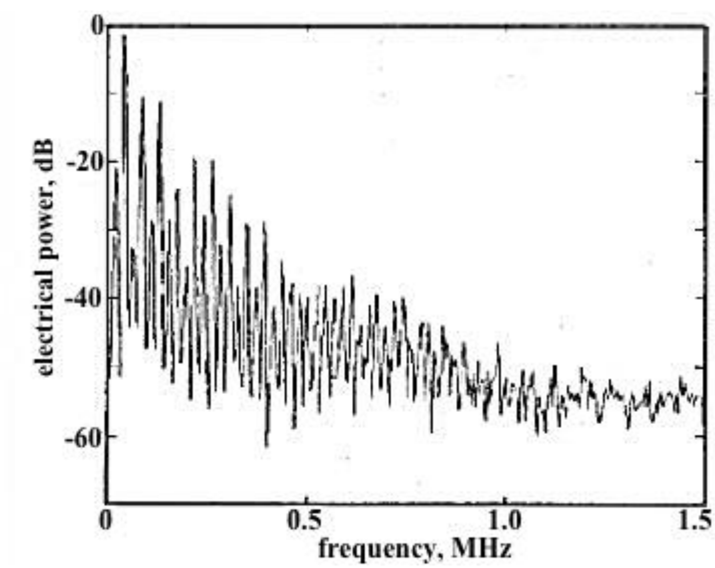


(b)

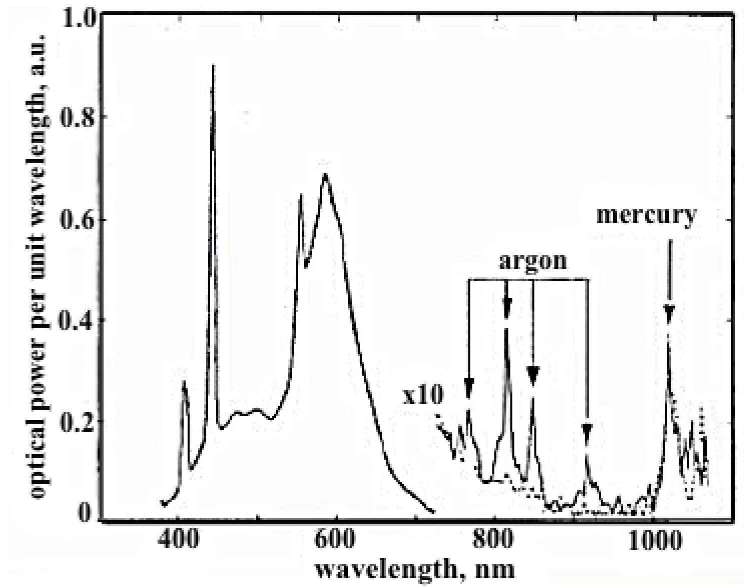
Figure 2.10 (a) Normalized spectral behaviour of an electric signal at the output of a photodetector illuminated by a tungsten filament lamp;
(b) Corresponding optical spectrum. [46]

Figure 2.10 (a) displays the spectral behaviour of the electric signal at the output of a silicon PD illuminated by a tungsten light bulb, while Figure 2.10 (b) provides the corresponding optical spectrum in the 600- to 1500-nm range. As Figure 2.10 (a) shows, it is evident that while there is a strong power content at DC and low frequencies, the spectrum flattens for frequencies 20 KHz and higher, showing attenuation at the range of 40 dB compared to its strength at low frequencies. It is evident that the electric noise generated by tungsten filament lamps behaves as white noise for frequencies in the range of 20 KHz and above.

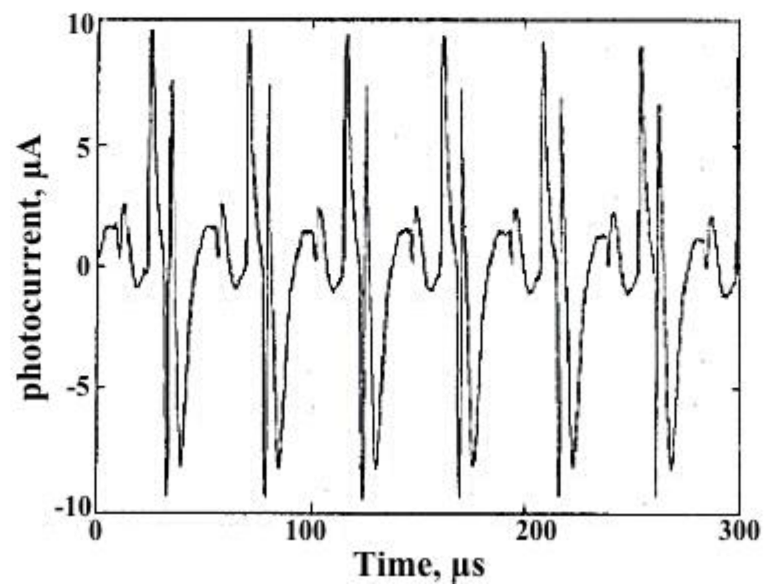
Figures 2.11 (a) and (b) show the electric and optical signal spectrums respectively, when the PD is illuminated by a fluorescent lamp that uses a 22-KHz ballast. We see the presence of strong harmonics. The harmonics are integer multiples of the ballast's frequency of operation (in this case, 22 KHz). They stay above the receiver's noise level for frequencies up to 1 MHz.



(a)



(b)



(c)

Figure 2.11 (a) Normalized spectral behaviour of an electric signal at the output of a photodetector illuminated by a fluorescent lamp driven by 22-KHz electronic ballast;
(b) Corresponding optical spectrum;
(c) Photocurrent at the output of the photodetector. [46]

Figure 2.11(c) shows the photocurrent at the output of the PD. It is periodic with frequency of repetition 22 KHz. This explains the mentioned strong spikes at multiples of the ballast's frequency.

2.7 Modulation Schemes

The IM/DD systems comprise two steps of modulation. In the first step, the baseband data-containing signal is modulated by carrier frequency,. In the second step, the electric modulated signal is transformed to light using a LED or PD. The following three aspects are used to qualify communication systems: *transmission reliability*, *bandwidth efficiency,* and *power efficiency*. As power efficiency we define the number of lumen the light source produces per watt. Light sources need to be regulated in terms of eye safety, There are several international standards bodies that provide guidelines on LED and laser diode emissions, namely: the International Electrotechnical Commission (IEC) (IEC60825-1), the American National Standards Institute (ANSI Z136.1), and the European Committee for Electrotechnical Standardization (CENELEC) among others [3, p. 11]. -.

1) *Transmission reliability.* Bit error rate is critical to the performance of a communication system and impacts the behaviour of overlaying protocols and applications. Almost all parts of a communication system should be designed with mutual consideration, targeting to provide a complete communication system that is providing an acceptable BER. A long series of “zeros” and “ones” should be avoided, so as not to make clock recovery difficult [48]. Moreover, other factors such as phase jitter, pulse extensions, and pulse distortions [47] should be taken into consideration.
2) *Power efficiency.* The transmitted optical power must be large enough to provide adequate amount of received optical power at the receiver’s location, so as to sustain reliable operation of the communication system that is operating under the optical

channel impairments and ambient noise. However, the allowed maximum transmitted power is limited by eye-safety and power consumption requirements (see section 2.4.1, table 2.3). As such, an important issue in designing an indoor wireless optical communication system is how to efficiently use power. In general, to achieve a certain BER, the requirement of received power, channel behaviour, and OSNR for different modulation schemes varies. The power efficiency, η_p, of a modulation scheme is given by the average received optical signal power required to achieve a given BER at a given data rate [49]. Mathematically, η_p is defined as follows [50]:

$$\eta_p = \frac{E_{pulse}}{\bar{E}_{bit}} \tag{2.12}$$

where E_{pulse} is the energy per pulse and $\bar{E}_{bit}$ is the average energy per bit.

3) *Bandwidth efficiency.* Although there is plenty of spectrum available at optical frequencies, several constituents of the communication system (e.g. the capacitance introduced by the photocurrent sensitive area, which increases with the size of the area, occurrence of multipath in the channel) limit the usable bandwidth that can support distortion-free communication [3],[51]. Also, the ensuing multipath propagation in diffuse link/non-directed LOS limits the available channel bandwidth [50]. The bandwidth efficiency, η_B, is defined as follows [50] :

$$\eta_B = \frac{R_{bit}}{B} \tag{2.13}$$

where R_{bit} is the bit rate and B is the signal's bandwidth. The relationship between bandwidth and power efficiencies depends on the average duty cycle γ[5] given by [50]:

$$\eta_p = \frac{\eta_B}{\gamma} \quad (2.14)$$

A comparison of different basic modulation techniques in terms of optical power requirements and bandwidth requirements is shown as Table 2.5, and has been taken by [47]. The first three, on-off keying (OOK), two-pulse-position modulation (2-PPM), and binary phase-shift keying (BPSK), are binary modulation techniques. The other three are related to multilevel modulation techniques and are the: L-level baseband pulse-amplitude modulation (L-PAM), L-level quadrature-amplitude modulation (L-QAM), and L-level PPM (L-PPM).

As Table 2.5 shows, OOK has the advantage of achieving the same BER performance with the least bandwidth and optical power. This aspect, along with its simplicity, makes it widely used in optical wireless communication systems.

Due to the characteristics of multiple-subcarrier systems, the power required is much greater than that in a binary modulation system. This situation could be observed from the table below:

Modulation scheme	**Optical power requirement**	**Bandwidth requirement**
OOK	$\sqrt{N_0 R_B} Q^{-1}(BER)$	R_B
2-PPM	$\sqrt{N_0 R_B} Q^{-1}(BER)$	R_B
BPSK	$\sqrt{2 N_0 R_B} Q^{-1}(BER)$	$2R_B$

[5] In [104], duty cycle is defined as " the time that an entity spends in an active state as a fraction of the total time under consideration", in our case, duty cycle is *T*.

L-PAM	$(L-1/\sqrt{log_2 L})\sqrt{N_0 R_B}Q^{-1}(BER)$	$(R_B/log_2 L)$
N-L-QAM	$\sqrt{4N}(L-1/\sqrt{log_2 L})\sqrt{N_0 R_B}Q^{-1}(BER)$	$(2R_B/log_2 L)$
L-PPM	$(1/\sqrt{0.5L\ log_2 L})\sqrt{N_0 R_B}Q^{-1}(BER)$	$(LR_B/log_2 L)$

Table 2.5 Comparison of various modulation schemes in terms of optical power requirement and bandwidth requirement, adapted from [47]

Chapter 3

Earlier Works on Visible Light Communications

Wireless visible light communication (VLC) constitutes a new research in the wireless communications field. It uses LEDs operating in the range of 380nm and 700nm; the visible range of the spectrum. Communication using visible light has many advantages over other types of communication, including the minimization of the eye safety issue because human eyes can see the source and instinctively close and/or the human turns his/her head away. Visible light communication has a promising future for the following reasons:

- As is the case for all wireless communication systems, those making use of optical light for communication purpose is not regulated in terms of spectrum, and the available bandwidth is extremely large. As such, the introduction of new products is easier.
- Visible LED based lighting sources made their entrance in commercial markets lighting market for office and residential space, started appearing in public (e.g. offices, malls), and residential spaces, in the public transportation system (e.g. traffic lights, lighting sources of roads, underground stations), and as lighting sources on vehicles. Considering the dual purpose capabilities of those devices (act as lighting and/or communication sources) and the expectation of them becoming widespread, makes them ideal for use in ubiquitous communications [54]. Figure 3.1 [114] shows actual

data and a prediction trend of the global LED market. From the figure, we can see that the growth rate is expected to increase fast between 2012 and 2015.

- Image sensors[6] can be utilized as receivers. The use of image sensors makes it possible to detect incoming vectors[7] from a transceiver correctly [53]. The image sensor technology opens the use of visible light communication to various new applications (e.g. indoor navigation, augmented reality, accurate control of robots or vehicles, highly accurate position measurement ("each LED in a lighting apparatus sends its differential three dimensional space coordinate, which is received by the image sensor can processed accordingly" [116]) [54], [58], [59]) that cannot be achieved by radio wave technology. By using image sensors, "the receiver (camera) can continuously take images of a scene with a LED light and the receiver detect the optical intensity at a pixel where the LED light is focused on, even if multiple sources send data simultaneously, an image sensor has the ability to receive and demodulate all the data at the same time with no interference" [53]. Figure 3.2 [53] demonstrates this scenario.

[6] Image sensor is "a 2D array of light-sensitive elements that convert photons to electrons" [added 6 p.43].

[7] "A vector image or geometric image represents an image mathematically through the use of geometrical primitives such as points, lines, curves and polygons" [added 6 p.43]

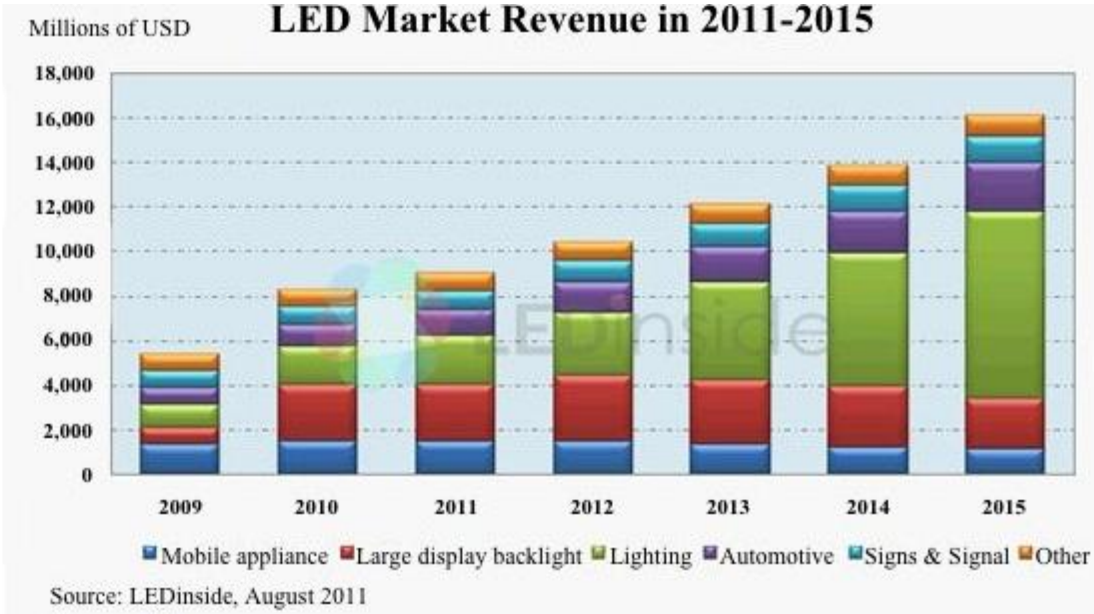


Figure 3.1 Prediction of LED lighting in the global market [114]

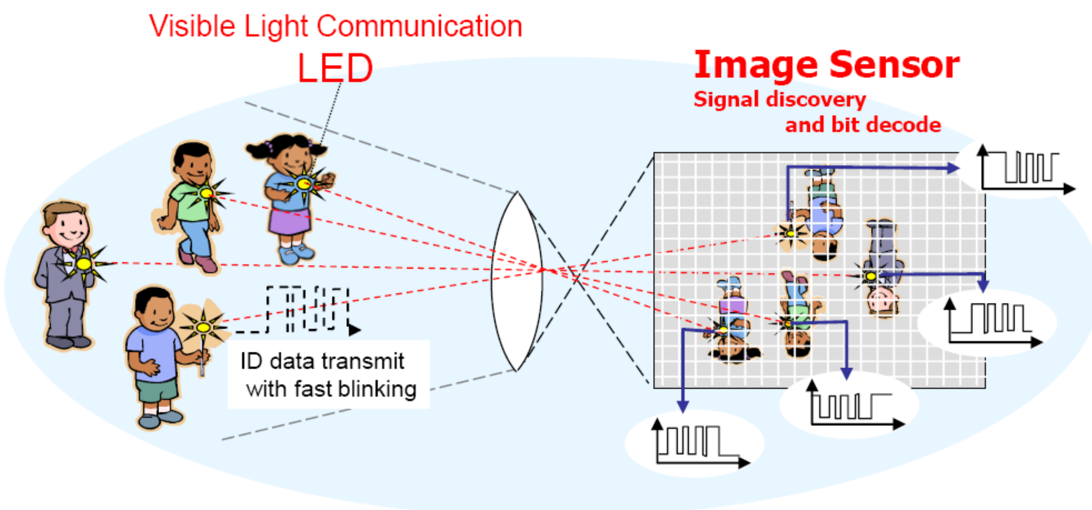


Figure 3.2 Scenario of multiple users sending data simultaneously [53]

In general, research into visible light communication focuses on four areas.

Several research centers have been formed in recent years. In Keio University (Japan), Nakagawa Laboratory started to work at 2003. It focuses on using LEDs to transmit data by using visible light [111]. In US, there have been established several research centers on VLC also. Smart Lighting Engineering Center at Boston University, is working on using visible light for both indoor and outdoor applications [112]. UC-Light center, located at University of California Riverside, whose mission is “to enable wireless communications by embedding signals into the light emitted by next-generation LEDs in systems for illumination, traffic control, advertising, and other purposes,” [110]. In Europe, the OMEGA project is aiming to develop a “user-friendly home access network capable of developing high-bandwidth services and content at a transmission speed of one Gigabit per second,” [113]. Also a group at Cambridge University will be mentioned later.

3.1 Indoor Visible Light Communication Applications

The Infrared Data Association (located in California, USA) and the Visible Light Communications Consortium (VLCC) (located in Tokyo, Japan. Chairman: Prof. Haruyama of Keio University) have been working together since September 2008 towards visible light communication using IrDA protocol stacks [54]. In one of these research programs, users can download needed information from a digital signage board, which sends data using its backlight [53].

A 100-Mbps duplex multi-access visible light communication system was designed by the Nakagawa Laboratory in Keio University, Yokohama, Japan. It is based on a 100-Mbps infrared LAN standard proposed by the Infrared Communication Systems Association (ICSA) [118] member of The Association of Radio Industries and Businesses (ARIB) [119]. It makes use of optical CSMA/CD (carrier sense multiple access with collision detection) and covers communication distance of up to three metres.

A high-speed parallel wireless visible light communications system using 2D image sensors and LED transmitters [56] was designed by Keio University and Sony Kihara Laboratory. The transmitter is composed of 64 LEDs, and different data streams are transmitted by each of these 64 LEDs. The light emitted by a specific LED of the transmitter's apparatus is projected onto a different pixel of a high-speed image sensor, which has a 50 times faster data rate compared to the data rate provided by a single LED (due to overhead, an increase of 64 times could not be achieved). Figure 3.3 shows a picture of the transmitter's and receiver's hardware.

(a)

(b)

Figure 3.3 (a) Transmitter;
(b) Image sensor based receiver [56]

OFDM (Orthogonal frequency division multiplexing) could be used in VLC system. In [129], a VLC system using OFDM is proposed. In RF transmission systems, because of the non-linarites of the power amplifier, the high PAR (peak-to-average ratio) is considered as a disadvantage. But as indicated in [129], “it is demonstrated theoretically and by means of an experimental system that the high PAR in OFDM can be exploited constructively in visible light communication to intensity modulate LEDs”.

Since LEDs (especially white LEDs) are usually installed at the ceiling for illumination and are connected to the electric power network, the use of ubiquitous power line cables as a communication medium between other fixed network and LED lights becomes possible [130]. In [130], a good review is made by S. E. Alavi and his colleagues for integrating VLC and PLC systems. In [131], an application of OFDM on integrated system of visible free space optical communication system with PLC is proposed by S.E. Alavi and H. Rezzaie.

The use of equalizer in indoor VLC system is discussed in [132]. In [133], we read that “Typically, white illumination is achieved by blue-emitting LEDs coated with a phosphor layer. The bandwidth of the commercial phosphor-based LEDs is thus limited to a few megahertz (typically 2–3 MHz), because of the slow response of the phosphor. In order to overcome this limitation, a blue filter should be placed at the receiver to suppress the slow phosphorescent components; this increases the bandwidth up to 20 MHz. A data rate of more than 100 Mbps was demonstrated using OOK modulation with PIN or APD receivers and blue filter [147].” Patens on VLC indoor applications could be found in [134][135], and [136].

3.2 VLC in Location Identification Applications

A global location service that uses a visible light ID system has been developed by NEC and Matsushita Electric Works [53]. “It accesses the Internet by first obtaining a codeword from a visible light source such as LED lights. It then accesses the location server from the cellular phone in order to obtain location-related information” [53]. The system’s accuracy could achieve several meters. Figure 3.4 shows this situation.

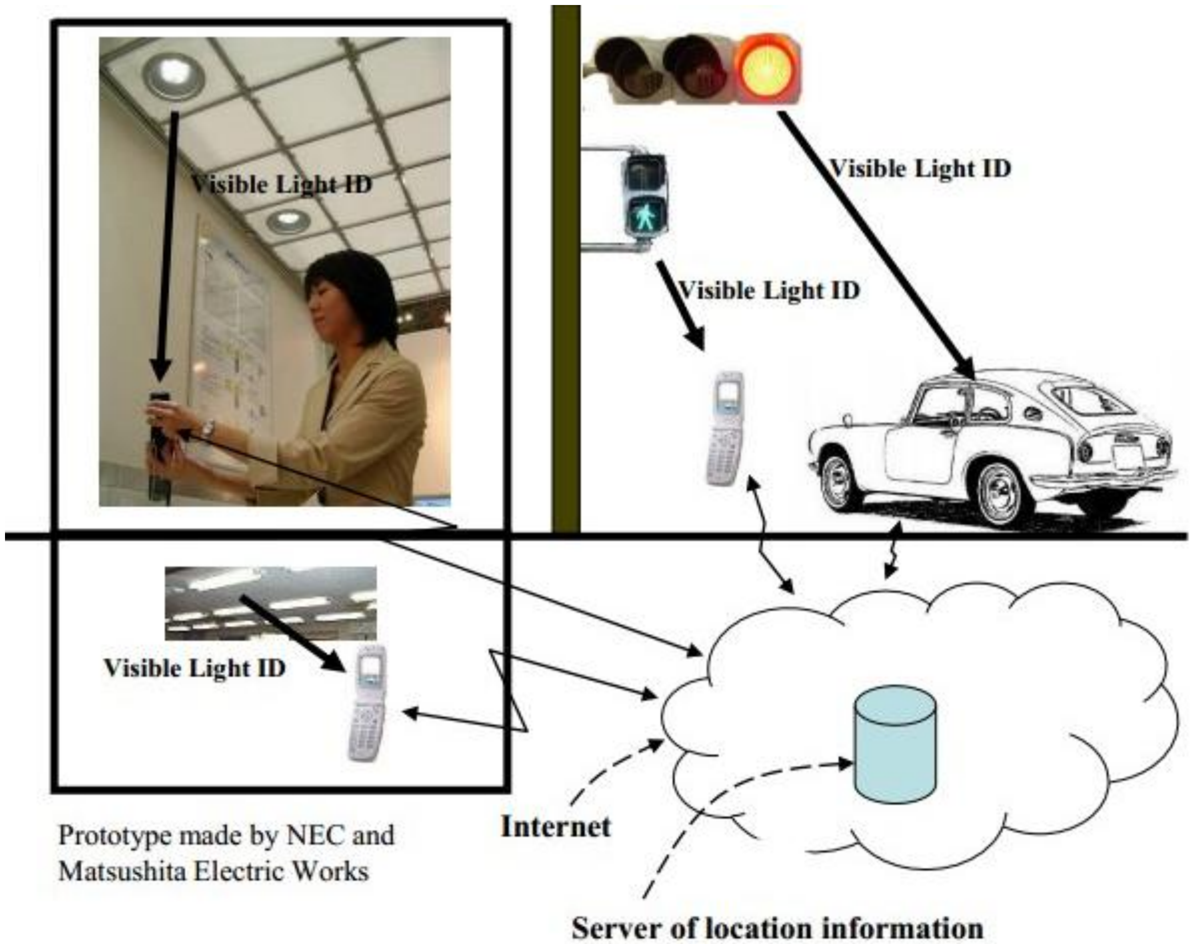


Figure 3.4 Global Location Service that uses visible light ID system [53].

Since 2010, seventeen companies and institutions, including Keio University, have been collaborating on research with the Geospatial Information Authority (GSI) [53] in an joint effort to standardize the format of location information [53]. This research is planned to be completed by 2012.

In this research project, the whole area of Japan is divided into 3-m by 3-m squares, with each square being assigned a unique code. When this unique number is used in IC tag, the possibility of acquiring location services universally could be achieved. However, currently this application only works well for outdoor locations with GPS or other GNSS satellites. The detection of a user's indoor accurate position is very difficult. Figure 3.5 shows the location code format proposed by GSI.

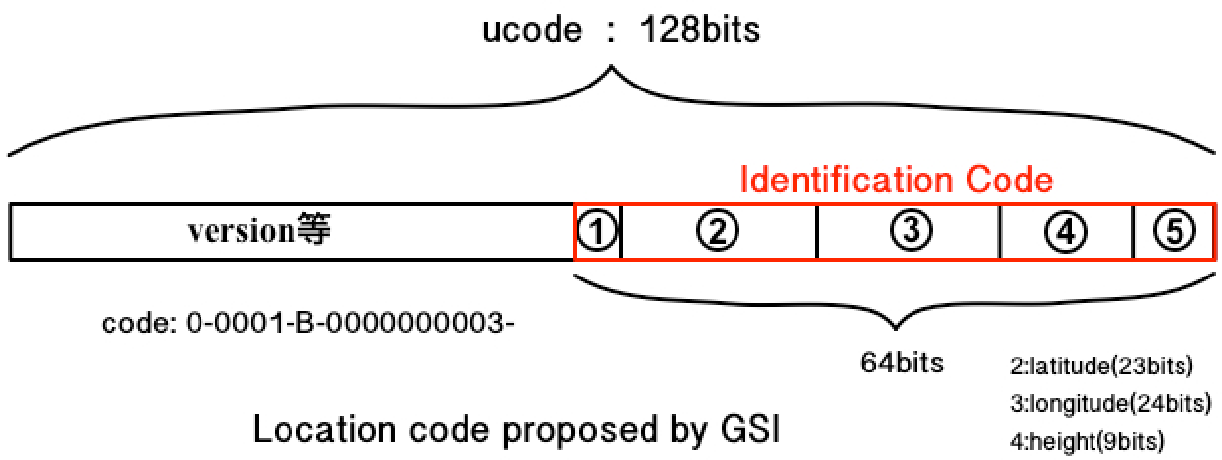


Figure 3.5 Location code proposed by GSI [54]

The three-dimensional position measurement system [57], a more precise location detection system that uses visible light communication, was introduced by Nakagawa Laboratory of Keio University, and Sumitomo Mitsui Construction Co., Ltd. The system is an automated photogrammetric system [57] that can measure a variety of distances using light as reference point [57]. Moreover, by utilizing unique blinking patterns, it easily identifies a specific light source even when observed from different viewpoints. There is no need for a pre-determined threshold to extract a light area based on the working scheme of the lighting patterns (Because it is using unique blinking patterns, since we can observe the blinking patterns, of course we don't need to set the range we can extract) [57]. The experimental result shows that the margin of error for a 100-metre object is about 5 mm.

There have been some patents on this subject. For example, a navigation system and a navigation method inside a building using Visible Light Communications (VLC) are provided in [121]. “The navigation system includes a map server, in which map information required to provide a navigation function is stored, for transferring the map information to each lamp, a plurality of lamps, installed in each zone inside the building and having their respective identifiable and unique IDentifications (IDs), for receiving the map information required to provide the navigation function from the map server, and for generating a visible light signal in response to the received map information by using a VLC module, and a mobile terminal, equipped with a visible light Rx module, for being provided with the map information upon receiving the visible light signal generated from the lamp, and for displaying a map image in response to the provided map information” [121].

3.3 VLC in Underwater Applications

Technologies that use radio waves as a wireless communication medium have matured. However, in some situations, radio-wave technology is not suitable for use due to the nature of radio waves themselves or the cost and durability of the communication devices.

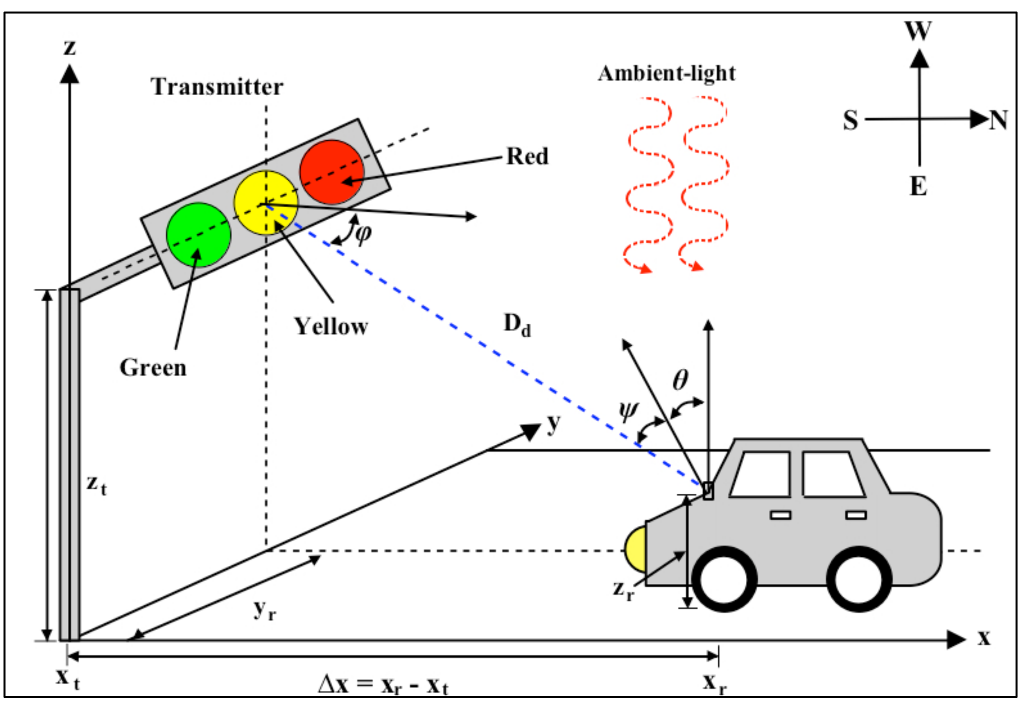
When distance radio waves can travel in water is limited. Researchers in Rise [117] and Nakagawa Laboratories of Keio University have demonstrated that a flashlight visible light transmitter has the ability to transmit signals over a 30-metre distance [58]. Researchers first analyzed the communication performance under absorption of energy by water and scattering (making use of scattering theory) and evaluated the wavelength dependent channel. They then proposed a wavelength selection/multiplexing scheme combined with rate-adaptive transmission to combat the change in turbidity and particle distribution underwater (sea) [58]. 9 pseudo-white LEDs are used in this system, and each LED is 3W. The battery can maintain 4 hour’s communication, and the channel could be LOS or non-LOS. Two or more people can talk together when using non-LOS channel, but the communication range is narrow [126]. By using this VLC-based device, a diver could talk with his or her partner. First, the sound of the voice is converted into an electric signal and then is emitted by the LED. The light that conveys the signal is received by a photodiode, which is placed besides the LEDs. Figure 3.6 shows a scenario using this product. Other VLC systems for underwater applications are talked in [127][128]. Since we are focusing on VLC indoor application, there is no need to describe them.

Figure 3.6 A diver communicate with other people by using the underwater VLC system [58]

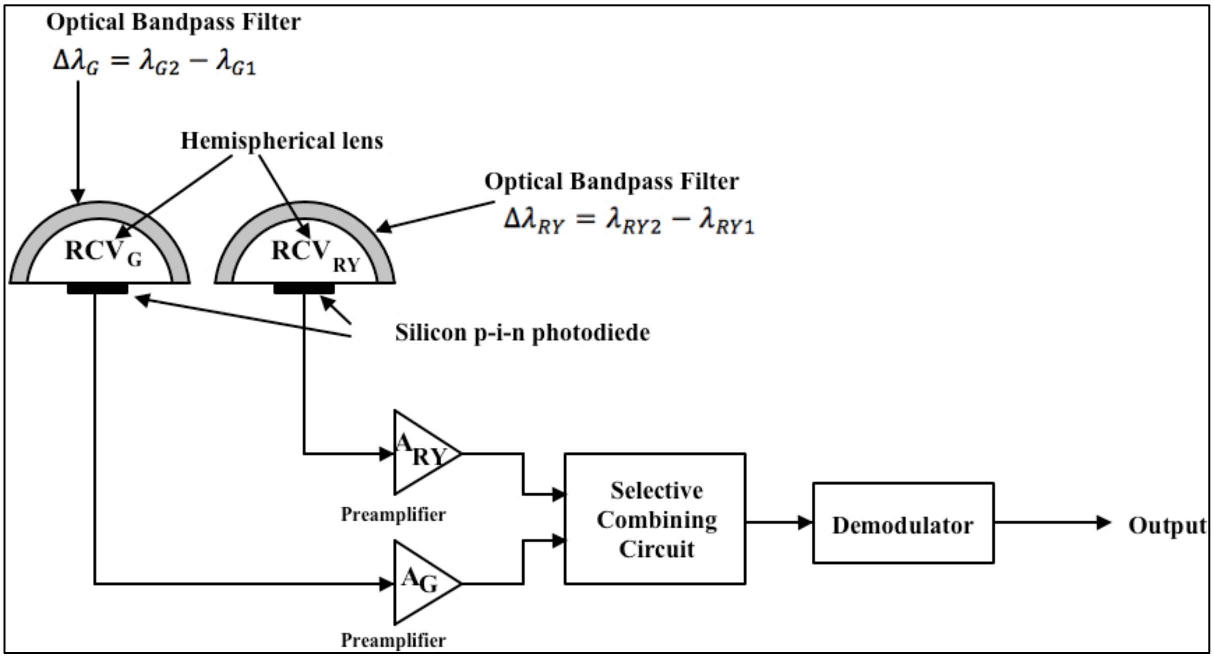
There are many patents [120][125] about VLC for underwater applications, for example, in [120], Don Gunasekara and Tom Wilson invented an underwater VLC system which “includes a master control station that determines the amount of impairment introduced by the water medium and selects between a wired and a wireless communication transceiver for communicating with a device located in the water" [120].

3.4 VLC in Transportation Applications

VLC could also be applied in transportation applications [59] [124]. An Intelligent Transportation System (ITS) using VLC was presented by It Ee Lee and his colleagues at Multimedia University [59]. In this study, the researchers first identified the major limitations of implementing VLC in an outdoor environment. They then introduced a new and innovative receiver design with dual receptions and effective ambient-light rejection capabilities [59]. Figure 3.7 shows the receiver structure and the proposed system model [59], D_d is the distance from transmitter to receiver, φ is the angle of irradiance, ψ is the angle of incidence to the signal, and ϑ is the incidence angle to the noise.



(a)



(b)

Figure 3.7 (a) The proposed ITS model;
(b) The newly proposed selective combining receiver structure [59]

In the receiver structure, the bandwidth ranges of the optical filters (one for receiving the signal from green LEDs, and the other is for receiving signal from red and yellow LEDs are between 500 nm and 540 nm, and between 600 nm and 640 nm (In this system, the peak spectral wavelength of LEDs are: 625nm for Red LEDs, 610nm for Yellow LEDs, and 525nm for Green LEDs). The signal with the bigger ESNR will be sent to the demodulator. A 20-metre improved communication distance is achieved as compared with the conventional receiver (bandwidth range: 500 nm to 650 nm) and the average data rate can reach 29.98 Mbps during the daytime. Patents [122] [123] exist on this subject. For example, the invention [122] “provides a visible light communication apparatus for in-flight entertainment system in an aircraft cabin in which a visible light communication (VLC) system is used for wireless communication of various contents data for in-flight entertainment” [122].

Based on the discussions above, it is clear that VLC is a promising technology in the future of wireless communications, with some products already being introduced to the market. The VLC system has its own advantages over IR and RF systems, which have been discussed in chapter 2. Many new applications have been introduced based on the characters of VLC systems, including indoor applications, VLC in transportations, VLC in underwater communications, etc.). Several labs focusing on VLC have been established all around the world.

From chapter 3, we can learn that VLC is developing fast. Many researchers from all around the world are focusing on this subject. A through survey is made in this chapter, we go through each aspect of applications to give readers a clear concept of how can VLC be employed in them, and what is the advantage of using VLC in them.

In this thesis, a wireless VLC system is proposed for indoor applications. To design this system, we first considered a suitable optical band that would suffer less noise from the ambient environment. Then, with cost and power consumption in mind, we selected modulation/demodulation schemes and defined the communication range. This system will be discussed in greater detail in Chapter 4.

Chapter 4

Research on Indoor Visible Light Data Transmission System Utilizing Blue LED Lights

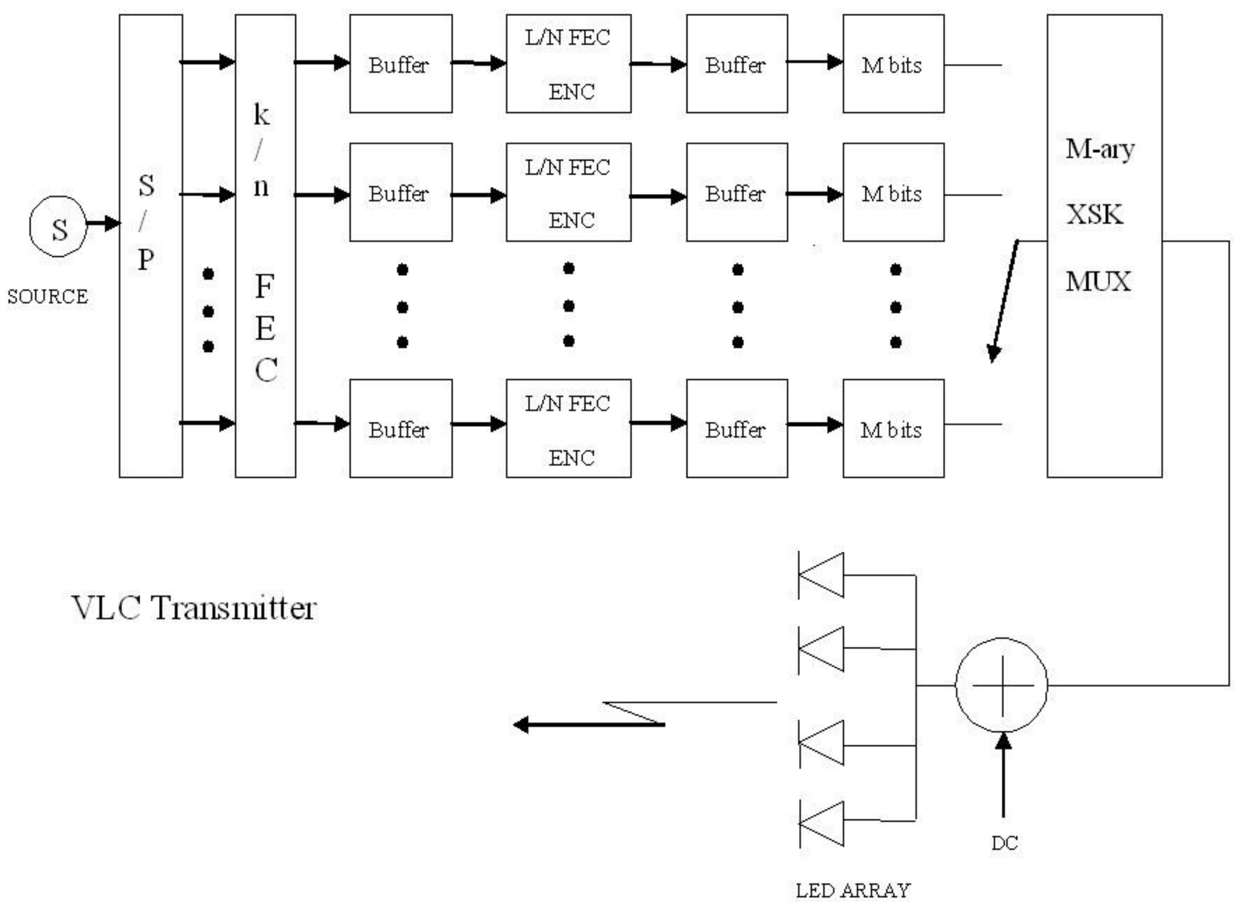
From previous chapters, it can be seen that VLC is a promising technology and can find use in several applications and operational environments requiring use of wireless communications. In the future of wireless communications, with some products already being introduced to the market.

In this chapter, a wireless VLC system is proposed for indoor applications. To design this system, we first looked for a suitable optical band; one that would suffer less ambient noise in the indoors environment. Then, taking into consideration system cost and power consumption, we selected modulation/demodulation schemes and defined the communication range. Figure 4.1 shows this system.

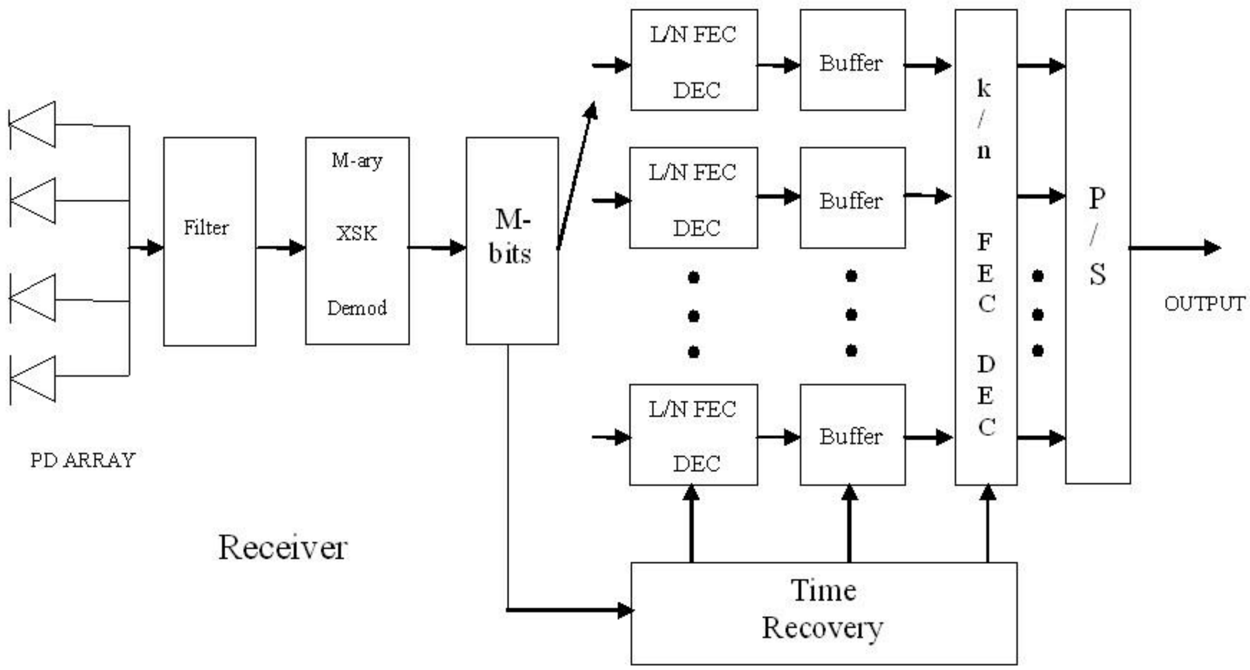
4.1 Proposed System Model

The block diagram of the transceiver is shown below. As the diagram shows, there are two stages of forward error correction (FEC) encoding. The first stage generates a sequence of n-parallel streams, which get encoded once more by a second FEC process. The output of each FEC encoder is passed to a buffer. Each time, M bits are retrieved and their combination defines one of the possible $2^M = X$ frequencies used by the modulator. The resulting electric signal is optically modulated by means of intensity modulation (IM).

At the receiver, the PD unit transforms the optical signal back to electric. It then passes through a filter that rejects the broad noise and the signal is passed through an array of X band-pass filters, each centred at one of the frequencies used by the modulator. At this point, the two stages of the decoding process begin. The L/N FEC coding process helps to correct random errors. The k/n FEC does the same; however, it also deals with error bursts. Such behaviour is due to blocking of the line of sight between transmitter and receiver.



(a)



(b)

Figure 4.1 Proposed optical wireless communication system: (a) Transmitter; (b) Receiver

In the following sections, we will discuss each part of the proposed system. To clearly introduce the system, we will separate it into two parts, optical components and electrical components. In the optical part, we will firstly introduce how we choose the suitable optical band for transmission, and then, the reason of using LOS optical channel model and noise model will be explained in sections 4.2.2 and 4.2.3. In the electrical part, we will firstly introduce the reason of employing OOK and FSK modulation scheme, and then we will talk about why we use Golay code (23,12,7) as our FEC code and why we employ interleaving code to cope with the problem of burst errors. Finally, we will talk about the reason of employing Butterworth filter to replace matched filter in section 4.3.3.

4.2 Optical Components

We classify the optical transmission band, optical wireless channel, and the noise as the optical components. The term noise means combined shot noise and thermal noise. The thermal noise is introduced mainly by the amplifier at the receiver side, but compared with the shot noise, the thermal noise could be neglect. The reason will be discussed in section 4.2.3.

4.2.1 Suitable Optical Band for Transmission

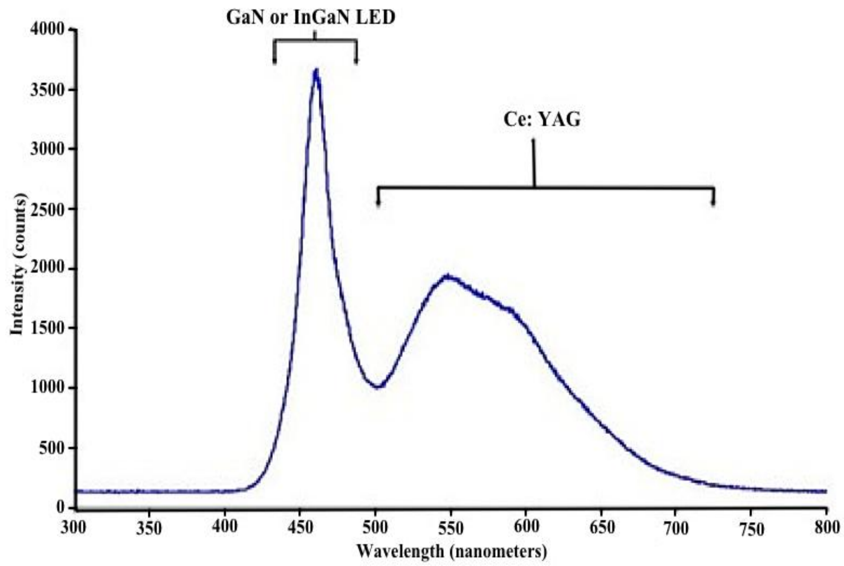
First, a suitable optical band for the transmission of the optically modulated signal needs to be determined. A suitable band should experience relatively small interference by ambient light (natural and artificial light). Based on figures 2.9 to 2.11, we can conclude the following:

a) Sunlight has very strong content between 440 nm and 550 nm; however, this should not be of major concern in indoor operations.

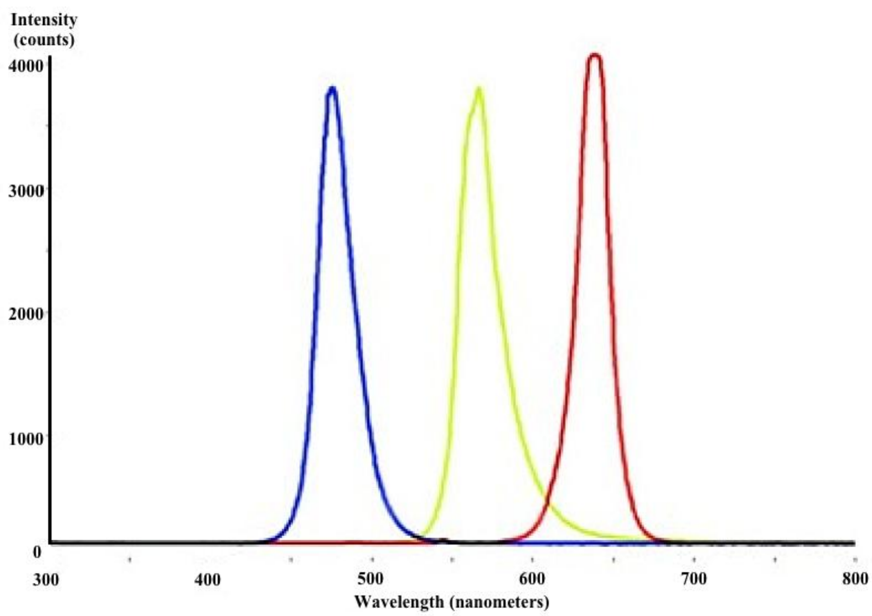
b) The radiation generated by a Tungsten light source is almost at its lowest level within this band.

c) Incandescent sources show energy spikes at or close to 440 nm and 550nm; however, there is very smooth (almost flat) spectral behaviour between the bandwidth of 460 nm and 520 nm. The energy spectral content is quite low. In Figure 4.3 we use blue and red lines to show our selection idea.

Also, Figure 2.11(a) indicates that the power content at frequencies of the electric spectrum (meaning the spectrum of the signal at the output of the PD) around 0.5 MHz has an attenuation around 40 dB, compared to the power content at low frequencies. This attenuation increases and, at 1 MHz, becomes too weak to have an impact on the communication system.

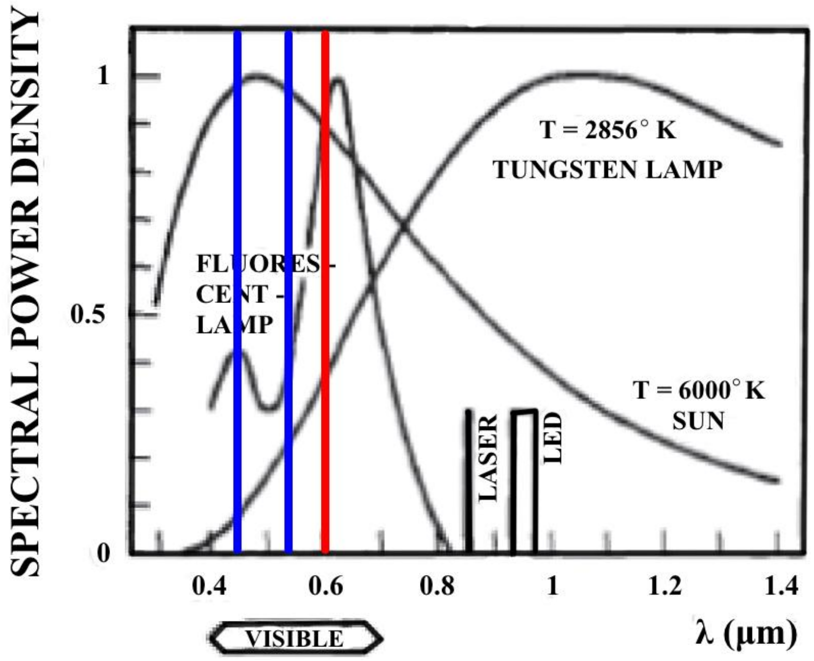


(a)

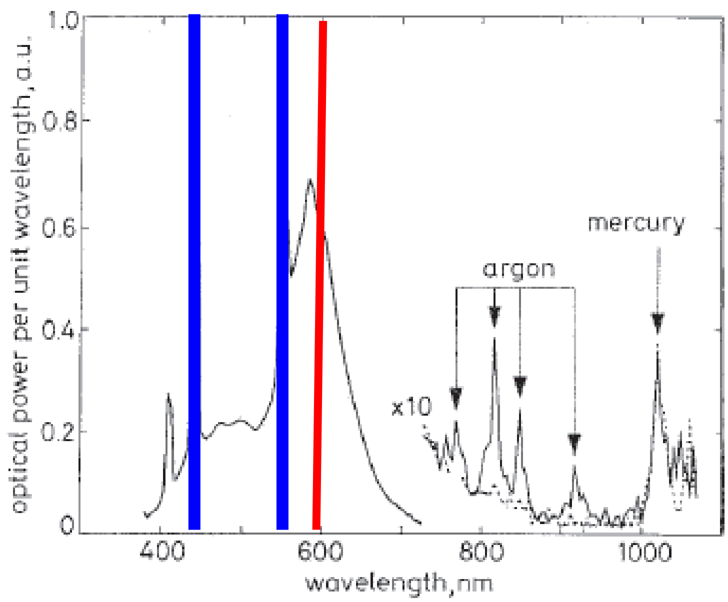


(b)

Figure 4.2 Spectrum of white light emitted by: (a) a yellow phosphorous-based WLED device; (b) combination of blue, yellow-green, and high-brightness red solid-state LEDs [60] (other WLED spectrum pictures could be found in [137] and [138]).



(a)



(b)

Figure 4.3 Blue lines at 440 nm and 550 nm and red line at 600 nm included, modified from [46]

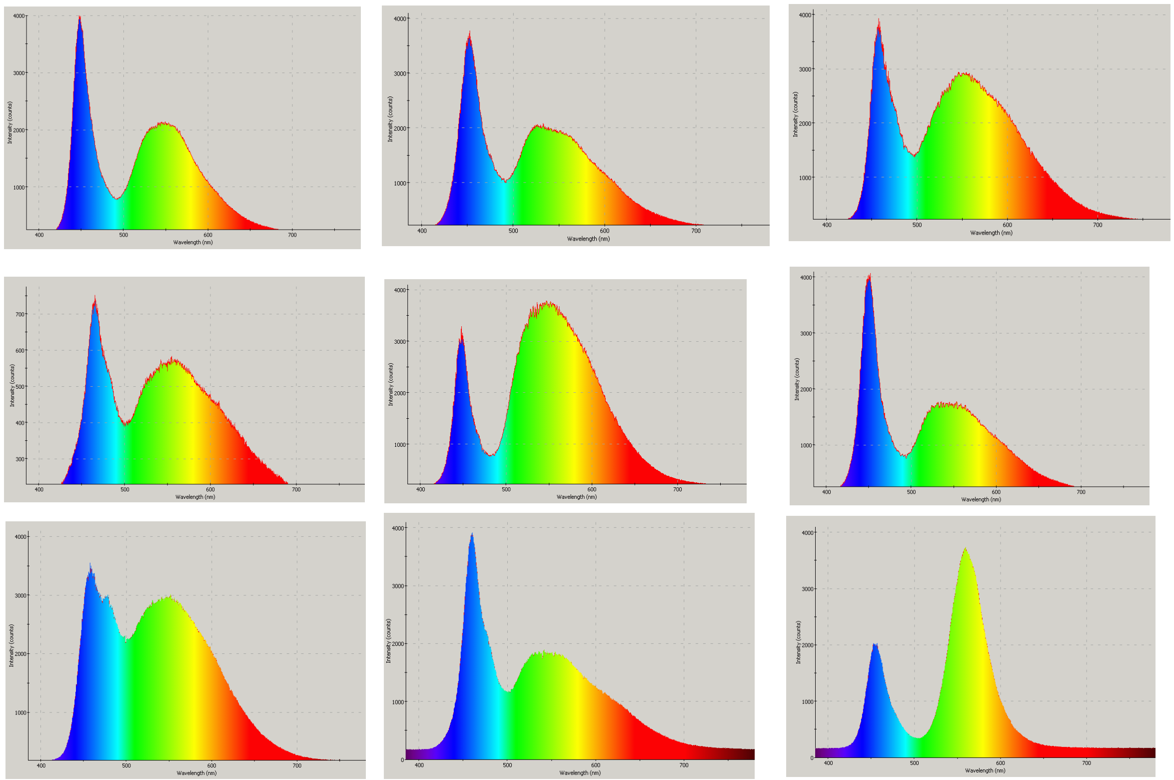


Figure 4.4 Spectral behaviour of several commercial WLEDs manufactured by using a blue LED whose light emitting surface is covered by yellow phosphor.

Figure 4.4 provides the spectral behaviour of several commercially available WLEDs [61]. The following observations can be made:

a) There is noticeable variability in the spectral behaviour of different models of commercially available WLEDs. This variability is due to the characteristics (e.g. width) of the yellow phosphor covering the light-emitting surface of the blue LED, and the characteristics of blue LED itself [60].

b) There is a strong and relatively narrow blue light component (corresponding to the blue light emitted by the blue LED) and a wider spectrum at lower frequencies.

The yellow phosphor (the existing commercial WLED products employ "YAG" phosphor coating to mix yellow light with blue to produce "white" light [60]), increases the capacitance of the LED, increasing its response time to changes at the input current, consequently reducing the bandwidth of the optically modulated signal to MHz [146]. Should the manufacturer use a (blue LED with its photons emitting surface coated with) yellow phosphor (to produce a) WLED instead of a pure blue LED at the transmitter, the PD with the blue optical band pass filter used at the receiver will allow the blue light component to pass through, filtering out the optical energy content at lower frequencies. This approach increases the bandwidth of the optically modulated signal considerably, placing it in the range of 20-25 Mbps [146]. Although a 100 Mbps NRZ VLC system using White LED has been realized at the University of Oxford [147]. However, in [147] the researchers are using a simple first-order analogue equalizer, and the communication distance is only 10cm. On the contrary, in [146], there no equalizer is employed, and the communication range is several meters for indoor application (the room is 12 x 3 x 3 m^3). Of course, there is a reduction of the energy coming through the system; however, the tenfold increase of electric of bandwidth allows higher transmission speed, part of which can be used in conjunction with error correction coding to improve the power efficiency of the communication system. This would fully compensate the loss of energy resulting from the use of the blue optical band pass filter and would increase the energy efficiency of the device.

Taking into consideration all above-mentioned observations, we decided that: (a) the blue light part of the optical spectrum should be used for transmission; (b) a blue optical band pass filter should be used at the PD to reduce or at least, considerably attenuate, the electric noise power generated by the optical power of ambient noise generated by fluorescent or incandescent lamps, located outside the optical signal transmission band.

4.2.2 Optical Wireless Channel

Among many LOS/NLOS channel models proposed by researchers [20, 25, 26, 28-39], we chose the LOS channel model proposed by Kahn and Barry [20], shown in Figure 4.4. We made this decision for the following reasons:

Firstly, the environment in which our system operates is assumed to be indoors, with no obstacles between the transmitter and receiver. In the NLOS channel, strong power is required at the transmitter side to maintain a good bit error rate. This is against the aim of the present study.

Secondly, in LOS channels (especially direct LOS channels), the amount of power of the diffused light (i.e. reflection on the ceiling or walls) reaching the receiver tends to be weaker compared to the power coming through the LOS path. As such, the channel models proposed by [5, 12, 25-39] were not suitable for this study, and Kahn and Barry's model was utilized.

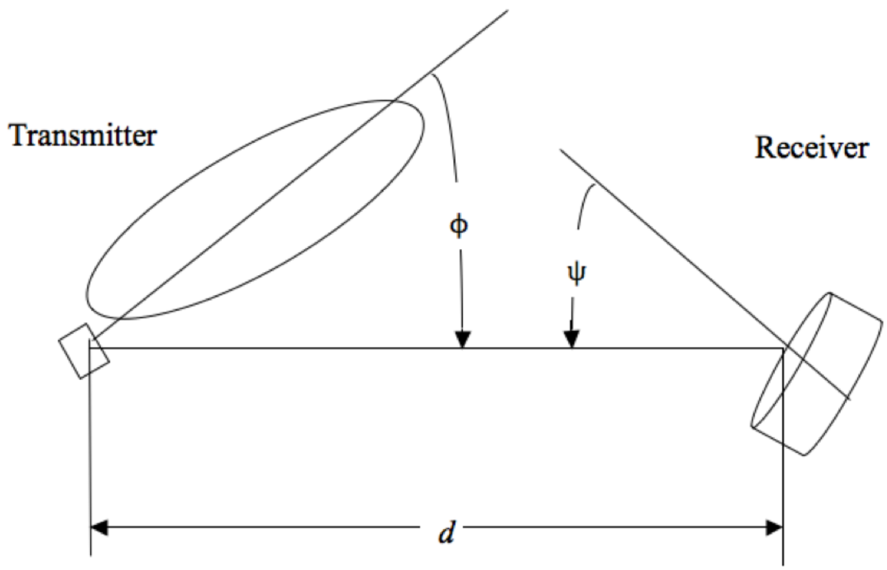


Figure 4.5 The LOS channel model

The channel DC gain is given by [20]:

$$H(0)_{LOS,Gen,Lamb}=\begin{cases}\frac{(m+1)A}{2\pi d^2}cos^m\phi T_{s(\psi)}g(\psi)cos\psi & 0\le\psi\le\psi_c\\ 0, & \psi>\psi_c\end{cases} \quad (4.1)$$

with

$$m=-ln2/ln(cos\phi_{1/2}) \quad (4.2)$$

$$g(\psi)=\begin{cases}\frac{n^2}{sin^2\psi_c}, & 0\le\psi\le\psi_c\\ 0, & \psi>\psi_c\end{cases} \quad (4.3)$$

m is the order of Lambertian emission, *d* is the distance from transmitter to receiver in metres, *A* is the size of the light-sensitive area of the PD in m^2 , ϕ is angel of incidence, ψ is the angle of irradiance, $T_{s(\psi)}$ is the signal transmission of the filter, $g(\psi)$ is the gain of the concentrator,

ψ_c is the FOV at the receiver, *n* is the refractive index and $\Phi_{1/2}$ is the semi-angle at half luminance of the LED.

As we all know, an increase in the communication distance worsens the system's performance, which is also affected by the system's other parameters. While most researchers are only concerned about using varying modulation schemes to get different performances, we conducted a thorough study, using various parameters, on how channel DC gain affects the signal power. The simulation results will be discussed in greater detail in Chapter 5.

4.2.3 Noise Model

Shot noise (introduced by the photodiode and the signal itself) and thermal noise (introduced by the pre-amplifier and post-amplifier at the receiver side) are the two most significant noise that affect the performance of our optical communication system. So, the total noise can be expressed simply as:

$$N_{total} = N_{shot} + N_{thermal};$$

where N_{total} is the total noise, N_{shot} is the shot noise, and $N_{thermal}$ is the thermal noise, which are introduced mainly by the amplifier at the receiver side. Because the shot noise is introduced by the signal light and ambient light, it can be expressed as:

$$N_{shot} = N_{signal\ shot} + N_{ambient\ shot};$$

and the thermal noise can be modelled as [20]:

$$N_{thermal} = \frac{4kT}{R_F} + \frac{16\pi^2 kT}{g_m}\left(\Gamma + \frac{1}{g_m R_D}\right) C_T^2 f^2 + \frac{4\pi^2 K I_D^a C_T^2 f}{g_m^2} \quad (4.4)$$

where k is the Boltzmann's constant, T is the absolute temperature, Γ is the FET (field-effect transistor) [8]channel noise factor, K and a are the FET 1/f noise coefficients, $I_D$is the FET drain current, R_D and R_F are the resistances of the preamplifier, its model shown in Figure 4.6.

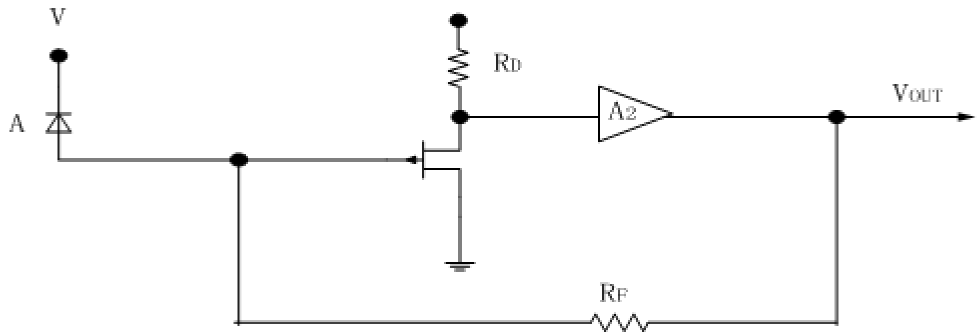


Figure 4.6 Simplified schematic of the FET-based transimpedance pre-amplifier [20]

The presence of intense ambient light is assumed in our model. The shot noise introduced by the background light dominates over all the other sources of noise, and can be modelled as an Additive White Gaussian process [1]. The ESNR at the receiver could be given by [1]:

$$ESNR = \frac{RP_S^2}{2qR_bP_n} \tag{4.5}$$

where R is the conversion efficiency of the PD in A/W, P_S is the signal's optical power in watts, q is the elementary electric charge (charge of a proton =1.6x10^{-19} coulombs), R_b is the data rate, and P_n is the ambient shot noise power in watts. The channel model is described as [1]:

$$y(t) = x(t) \otimes H(t) + n(t) \tag{4.6}$$

[8] "The field-effect transistor (FET) is a transistor that uses an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material" in [145].

Here, *y(t)* is the received optical signal, *x(t)* is the transmitted optical pulse, *n(t)* is the optical AWGN noise, symbol $\otimes$ represents convolution, and $H(t)$ is the optical channel impulse response.

Moreover, in our channel model, multipath fading can be neglected because the signal carrier we are using is light, whose frequency is around 10^{14} Hz. This makes the Doppler frequency of fading far higher than the data rate. Furthermore, the dimensions of PDs are in the order of thousands of wavelengths, leading to efficient spatial diversity that prevents multipath fading [1, p. 13]. The multipath distortion could be neglected in Direct-LOS and hybrid-LOS links [20, p. 268].

4.3 Electronic Components

In the electronic components, we will firstly introduce the modulation schemes we employed in the proposed system, and then the FEC code and electronic filter will be discussed in detail.

4.3.1 Modulation Schemes

From Figures 2.7 and 2.8, it is evident that electronic noise generated by tungsten or fluorescent lamps has strong power content at low frequencies, and gradually reduces. The spectrum of noise generated by a tungsten lamp flattens at 30 KHz and higher, the level of its power density being in the range of 40 dB below the pick density of the noise. The spectrum of electric noise generated by fluorescent ambient noise has also very strong components at the lower part of the spectrum. As discussed in section 4.2, the power density of the electric noise contains strong discrete components that are introducing periodic behaviour to the noise pattern. Such behaviour reduces the randomness of the noise and has impact when conventional FEC codes (most designed to better operate under random error patterns) are used. However, for frequencies higher than 0.5 MHz, such components have been attenuated considerably (40 dB plus), and become extremely weak for frequencies at the 1 MHz range and higher. Based on this information, we consider that the electric information signal should be located at a frequency range above 0.5 MHz (preferably at 1 MHz and higher).

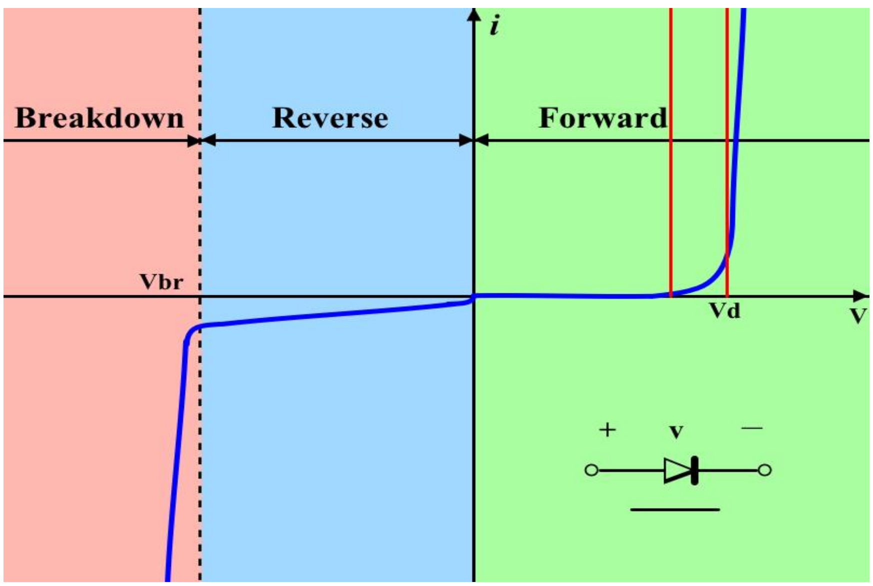


Figure 4.7 Output current vs. input voltage behaviour of a diode [150, p. 23] [60]

LEDs are by nature solid state diodes and as such, the relation between input voltage and output current is as follows [63], [150, p. 23]:

$$I_D = I_s\left(e^{\frac{qV_D}{KT}} - 1\right) \quad (4.7)$$

where I_D is the current passing through the diode when positive voltage is placed across its input terminals, I_s is the reverse current, q is the charge of a proton (=1.6x10^{-19} coulombs), T is the temperature in Kelvin, K is the Boltzmann's constant (=1.3807x10^{-23} joules per Kelvin), V_D is the forward voltage applied across the diode's input terminals. The generated light intensity is proportional to I_D. Since V_D carries the information, it is important that the relationship between these two elements is linear. If not, intermodulation will occur, distorting the signal and generating intermodulation noise. This postulates that if we were to use a linear modulation scheme, we would be forced to keep the diode operating at low levels of radiating power (between red lines in Figure 4.7) in order to avoid generating serious intermodulation distortion.

However, in this case, we don't take full advantage of the radiating power of the LED, reducing the operational length of the communication system and the power efficiency (a critical factor for handheld devices).

An additional issue that requires attention is the impact of signal multiplexing at the electrical domain, i.e. prior to applying optical intensity modulation (IM). Because the electric signal applied at the output of the photodiode must always be non-negative (single polarity), for a a given maximum amplitude and certain M-ary alphabet, the distance between neighboring signal amplitude levels (corresponding to different symbols of the M-ray alphabet) is reduced when compared to the use of bipolar signals, which inevitably reduces the power efficiency of the system.

The following modulation schemes were considered: OOK (On-Off keying), single and multicarrier M-PSK (Multiple phase-shift keying), single and multicarrier M-QAM (Multiple quadrature-amplitude modulation), OFDM (Orthogonal frequency-division multiplexing), M-FSK (Multiple frequency-shift keying). Taking the above-mentioned factors into consideration and the disadvantages associated with the need to use carrier recovery circuitry, we decided that OOK and M-FSK should be used as the uplink modulation scheme. Some of the main factors leading us to this decision are the following:

(i) OOK is the simplest modulation scheme and is widely used in optical wireless communication, although its ability to bear noise is limited.

(ii) M-FSK can be implemented as a constant envelope scheme, making it possible to drive the LED at high illumination levels without generating intermodulation distortion.

(iii) The modulation and demodulation processes are far simpler compared to other schemes, e.g. OFDM (OFDM can cope with severe channel conditions without complex equalization filters, and channel equalization is simplified because OFDM may be viewed as using many slowly modulated narrowband signals rather than one rapidly modulated wideband signal, but it requires very strict synchronization of subcarrier and also running FFT and I-FFT algorithms), M-QAM (has the advantage of using a combination of both PSK, and ASK) & M-PSK (can provide lower BER than MFSK when M is equal or less than 4) require reliable carrier recovery, which increases cost and limits the SNR level at which the system can operate, even if coding is used). Regarding optical M-FSK, the optical signal can be generated by switching the LED on-off at the desired frequency and also it can use a simple, non-coherent demodulator/receiver, which is important for developing low cost receivers.

a) OOK Modulation

As discussed above, On-off Keying (OOK) and Frequency Shift Keying (FSK) have been selected as most suitable. In this section, these models are described in greater detail.

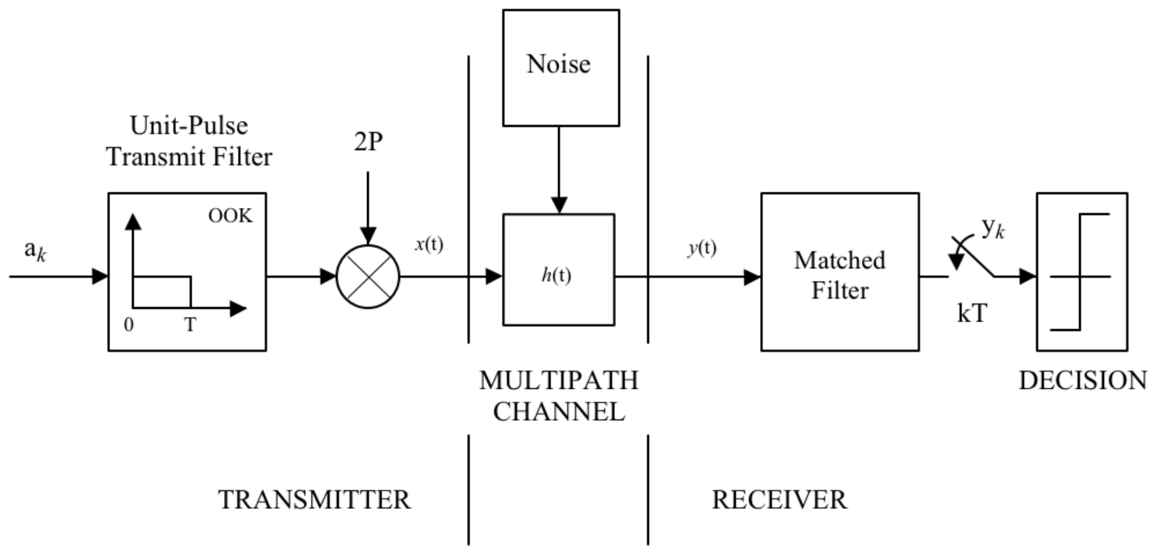


Figure 4.8 OOK modulation model [1]

Figure 4.8 shows the baseband OOK modulation model. In the figure, a_k bits, generated by the source, are entering a unit-maximum transmit filter, converting them to OOK pulses (we have electric signal now). Ones and zeros contained in the a_k bit sequence are assumed equally likely (the bit sequence is uncoded here, we don't consider to show the FEC coding and decoding part in this model), and then the electric signal is send to the transmitter (LED) to be converted to optical signal, The optical pulses generated by the LED have power level 2*P,* thus, the average transmitted optical power is *P.* And *T* is the symbols' transmission period, and the duration of each generated optical pulse. The optical OOK pulses can be expressed as:

$$x(t) = 2P \sum_k a_k p(t - kT) \quad (4.8)$$

where *p(t)* is the unit-maximum transmit filter, given by:

$$p(t) = \begin{cases} 1 & for\ t \in [0, T) \\ 0 & elsewhere \end{cases} \quad (4.9)$$

Transmitted optical pulses then pass through the surrounding space that acts as multipath channel having impulse response *h(t)*, and become subjected to channel loss and noise. As indicated in [20], multipath distortion could be neglected in Direct LOS and Hybrid LOS links, and even with a very simple design, it is possible to achieve a bit rates above 100Mbps. The distorted optical pulses captured by the receiver, by passing through PD (responsivity is *R*), optical pulses are converted to electric current, *y(t)*, and then the electric current will be sent to a matched filter, after which the received pulses will be compared with the threshold to decide if the transmitted pulses are ones or zeros (the block diagram is shown as Figure 4.9). So, *y(t)* is expressed as:

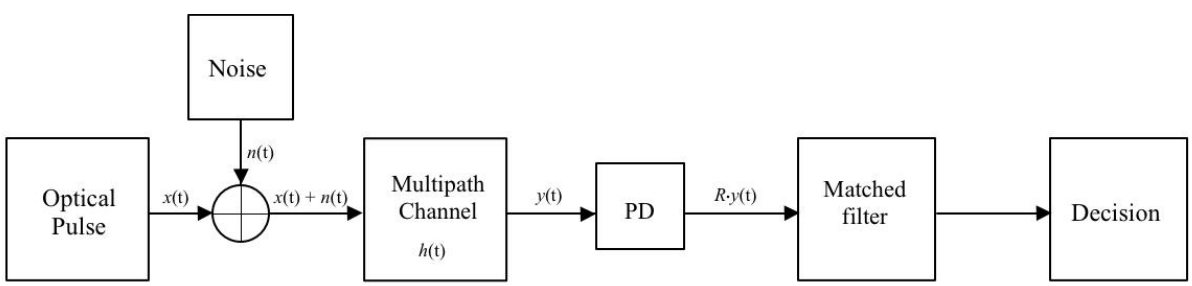


Figure 4.9 Block diagram of “receive procedure” of optical OOK system.

$$y(t) = R(x(t) \otimes h(t) + n(t)) \quad (4.10)$$

The bit error rate for an optical wireless system with baseband OOK modulation scheme and optimal receiver is given by [64, p. 241] ($SNR= \ Eb/No$):

$$BER = Q(\sqrt{\frac{SNR}{2}}) \tag{4.11}$$

b) FSK Modulation

Figure 4.10 (put in a separate page due to its large size) represents the Binary FSK (we utilize BFSK because it is the simplest M-FSK scheme, can be realized easily and provides a good BER performance for our need) model assumed in this chapter. The signal bits ones and zeros are presented by sinusoidal signals $s_1(t)$ and $s_2(t)$, which have frequencies f_1 and f_2, respectively. So, the signal after BFSK modulation can be expressed as:

$$s_i(t) = \sqrt{\frac{2E_b}{T}} cos(2\pi f_i t + \phi); t \in \{0, T\} \tag{4.12}$$

where E_b is the bit energy, T is the symbol duration and ϕ is an arbitrary phase. To achieve the best possible performance, the two frequencies should be chosen orthogonally, i.e.

$$\int_0^T \sqrt{\frac{2E_b}{T}} cos(2\pi f_i t + \phi) \sqrt{\frac{2E_b}{T}} cos(2\pi f_i t + \phi)\, dt = E_b, i \in \{1,2\} \tag{4.13}$$

$$\int_0^T \sqrt{\frac{2E_b}{T}} cos(2\pi f_1 t + \phi) \sqrt{\frac{2E_b}{T}} cos(2\pi f_2 t + \phi)\, dt = 0 \tag{4.14}$$

Similar to the OOK optical pulses, BFSK optical pulses also suffer from channel loss when passing through the multipath channel. At the receiver side, the optical signal with noise (AWGN) is converted into electric signal *s(t)* by passing PD, and the electric signal is sent to two band pass matched filters with frequencies f_1 and f_2, respectively. The filtered signals then pass through two envelop detectors to get values r_1 and r_2. These two values will be sent into a comparison device to decide if the output bit is one or zero. If $r_1 > r_2$, the output is 1; otherwise, the result is 0. The value of optical signal that after being modulated is positive, which is a significant difference compared with RF signals. The bit error rate for an optical wireless system with a FSK modulation scheme and optimal receiver is given by [151, p. 489][64 p. 245]. Note, this is an approximation for high Eb/No, but it is good enough in this thesis, since with low Eb/No, the system's performance is very bad, so we don't need to consider the scenario for low Eb/No.

The error probability of $s_1(t)$ is expressed as (4.15) [151 p. 489]:

$$P\left(E\middle|s_1(t)\right) = \int_0^\infty f_{R_1(r_1)}\left[\int_{r_1}^\infty f_{R_2(r_2)} dr_2\right] dr_1, \tag{4.15}$$

where $f_{R_1(r_1)}$ is the Rician pdf of $r_1(t)$, and $f_{R_2(r_2)}$ is the pdf of $r_2(t)$. By symmetry, it follows $P\left(E\middle|s_1(t)\right) = P\left(E\middle|s_2(t)\right)$. An approximate BER equation could be expressed as (4.16)

$$BER \cong \frac{1}{2}\exp(-\frac{E_b}{2N_o}), \tag{4.16}$$

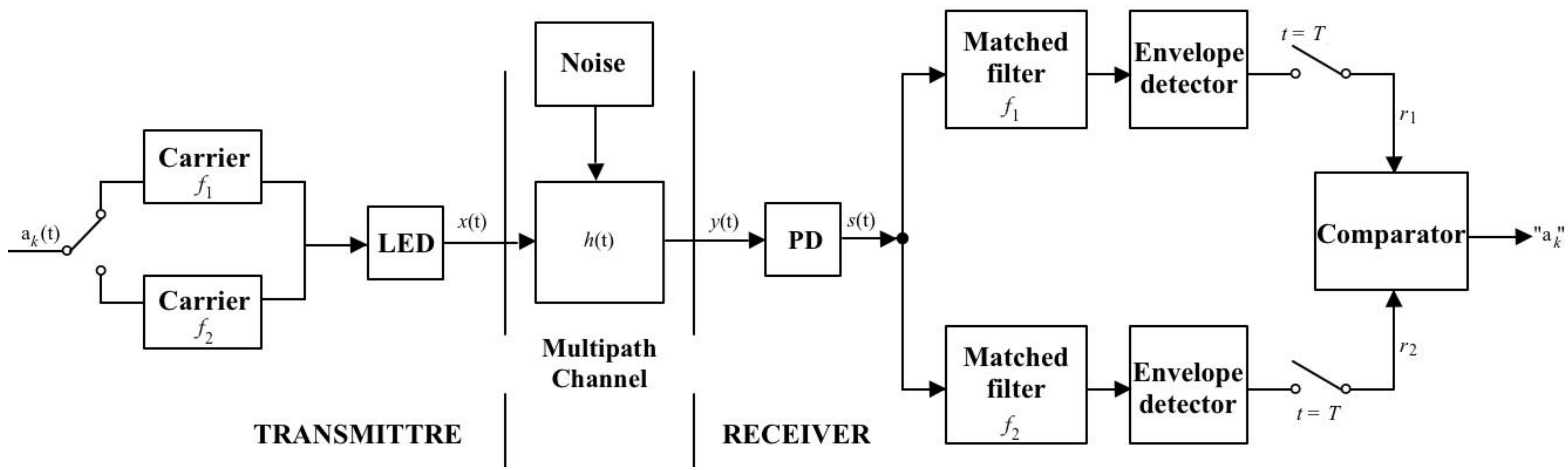


Figure 4.10 BFSK modulation model

4.3.2 FEC Coding

For wireless communication systems, the operational distance between transmitter and receiver is very important. A big issue for wireless systems is that increasing distance decreases the power of the received signal, thus, the SNR becomes lower. One way to increase the operational distance is to make use of coding, which would not only allow increased communication distance in a limited range, but also save the transmitted energy. For the above reasons, we incorporated FEC coding into our system.

We took the following FEC codes into consideration: Reed-Solomon, Golay, BCH, and Hamming codes. The Golay code was chosen after comparing its relative merits with those of other codes. While the Reed-Solomon code is very powerful and is capable of correcting error bursts, its alphabet size is too large, which will introduce delay [144]. Meanwhile, Hamming codes tend not powerful enough for our system. The family of Golay codes forms a special type of BCH codes [65, p. 179][149, p. 98]. As such, we decided to use the Golay (23,12,7). Please note that there are two types of binary Golay (23,12,7) code; extended binary Golay code (24,12,8) , and perfect binary Golay code (23,12,7). They both have the ability to correct 3-bits error patterns. However, since the perfect binary Golay code deletes one coordinate position than its counterpart, we decided to use this code. Convolutional codes are not utilized due to their decode chips are much more expensive than Golay decode chips [165][166]. Because errors typically occur in bursts rather than independently, when there is an object blocking the LOS link. In some situations, there are too many errors within a codeword, which exceed the code's error-correction ability, or the code cannot deal with error burst and the code will is unable to recover the original word [148]. Interleaving could alleviate this problem by shuffling source symbols across several code words, in order to strengthen the randomization of errors appearing in the received codeword [148][149 p. 114]. Thus, the possibility of appearance of error clusters will be reduced.

- Example:

  Transmission without interleaving:

Original message: 0000111100001111000011110000
Error-free message: 0000111100001111000011110000
Transmission with a burst error: 00001**000**0000111100001111 0000

There is a bluster errors , so it cannot be decoded correctly.

Transmission with interleaving:

Original message: 0000111100001111000011110000
Interleaved: 0101010010101001010100101010
Transmission with a burst error: 0101010**101**101001010100101010
Received code words after de-interleaving: 0**1**001**0**110000**10**11000011110000

After de-interleaving, a cluster of errors is turned into 3 random errors, our golay code (23,12,7) is sufficient to decode everything correctly.

Interleaving also has some disadvantages including increased latency. This is because the entire interleaved block must be received before the packets can be decoded [68][148][149 p. 114]. Also, interleavers hide the structure of errors. In [69] we can learn that, “without an interleaver, more advanced decoding algorithms can take advantage of the error structure and achieve more reliable communication than a simpler decoder combined with an interleaver”. Nonetheless, for our system, the merits of interleaving outweigh its faults.

4.3.3 Filter

In order to decrease the cost, we try to use another type of filter to replace the matched filter. We take the following four types of filters into consideration: Gaussian filter, Butterworth filter, Chebyshev filter (type I and type II), Bessel filter and Elliptic filter.

The Butterworth filter has a flat frequency response in passband, so it is normally related to maximally flat magnitude filter[70][140, p. 150]. “Chebyshev filters are having a steeper roll-off and more passband ripple (type I) or stopband ripple (type II) than Butterworth filters, and they have the property that they minimize the error between the idealized and the actual filter characteristic over the range of the filter, but with ripples in the passband” [71][140, p. 160]. A Bessel filter is a type of linear filter with a maximally flat group delay, often used in audio crossover systems [72][141]. And an elliptic filter has equalized ripple behaviour in both the passband and the stopband [73][140, p. 164]. The Gaussian filter’s characteristics are similar to Bessel’s, but its group delay is not as flat as Bessel’s. Gaussian filter’s curve starts to change in the passband, and it has a slow speed to close to 0. The cut-off characteristic of Gaussian filter is not very good [142][143].

By analyzing their characteristics, we decided to employ Butterworth filters to replace matched filters. Firstly, it has simple architecture, secondly it has a flat frequency response in passband, and it can provide the most linear response. This characteristic is very important in our system, since we are using non-coherent modulation schemes, we don't care about the phase distortion, but do want to have a flat gain in passband (we don't want ripples, so Chebyshev and Elliptic filter are not suitable). Also, the cut-off characteristic is also good, this is a reason of not employing Gaussian filter and Bessel filter.

4.3.4 Conclusions

In this chapter, we start with proposing a VLC system model, and then describe its optical and electrical components respectively. In the optical part, we first discuss how we select the suitable optical band for transmission. Secondly, we describe the optical wireless channel used in our system, and thirdly the noise model we utilized is discussed. In the electrical part, we discussed and define the modulation schemes, the FEC coding and the post detection baseband electrical filter selection we made.

In the following chapter, our simulation results will be shown, and the analysis will be made based on the results.

Chapter 5

System Performance Evaluation

In the previous chapter, we proposed, described in detail and justified the choices we made. In this chapter, we introduce an optical wireless communication system simulation tool, which is a GUI application based on Matlab. By using this simulation tool, we can set the parameters, choose different modulation schemes, add or remove use of FEC coding from the proposed system. Most of our simulation results are generated by employing this simulation tool. We evaluate the performance of the proposed system and analyse the results in section 5.2. Finally in section 5.3, we discuss research related to the behaviour of the proposed system when mobile within the indoor environment, and address practicality issues related to the implementation of the proposed system.

5.1 OWC systems simulation tool

An optical wireless communication system simulation tool has been developed by us. It is based on Matlab, with the parameters easily set and the simulation executed through an easy to use GUI, shown in Figure 5.1 (a). By employing this simulation tool, users can set the parameters (communication distance, incidence angle, FOV, etc.), choose modulation scheme (OOK/BFSK), filter's type (Matched/Butterworth), and add one or two layers' FEC coding, according to the actual need.

There are two parts in the Operation Panel. The left part is used to calculate the LOS channel gain, while the right part is used to input parameters for the OOK and FSK Optical Systems. The units of parameters for calculating the channel gain are as below:

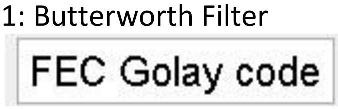
Area	Square meter
Distance	Meter
Incidence angle	degree
Irradiance angle	degree
FOV	degree
Phi1/2	degree
Power	Watt

Table 5.1 Units of the parameters.

For the simulation part, we use 0 and 1 to represent different schemes.

- 

:
  0: OOK
  1: FSK
- 

:
  0: Matched Filter
  1: Butterworth Filter
- 

:
  0: No FEC code
  1: One layer Golay code (12,23,7)
  2: Two layers Golay code (12,23,7)

After the simulation, the LOS gain, OSNR, ESNR, BER, and the number of errors will be returned to the users. Usually, the number of errors is required to be larger than 200 to make sure the reliability. And if two layers' FEC code is employed, we suggest the simulation should be ran at least 5 times to decrease the results' variance. Because in the code, the data length is fixed, when using two layers FEC coding, the number of errors will be decreased, so the result may be not accurate.

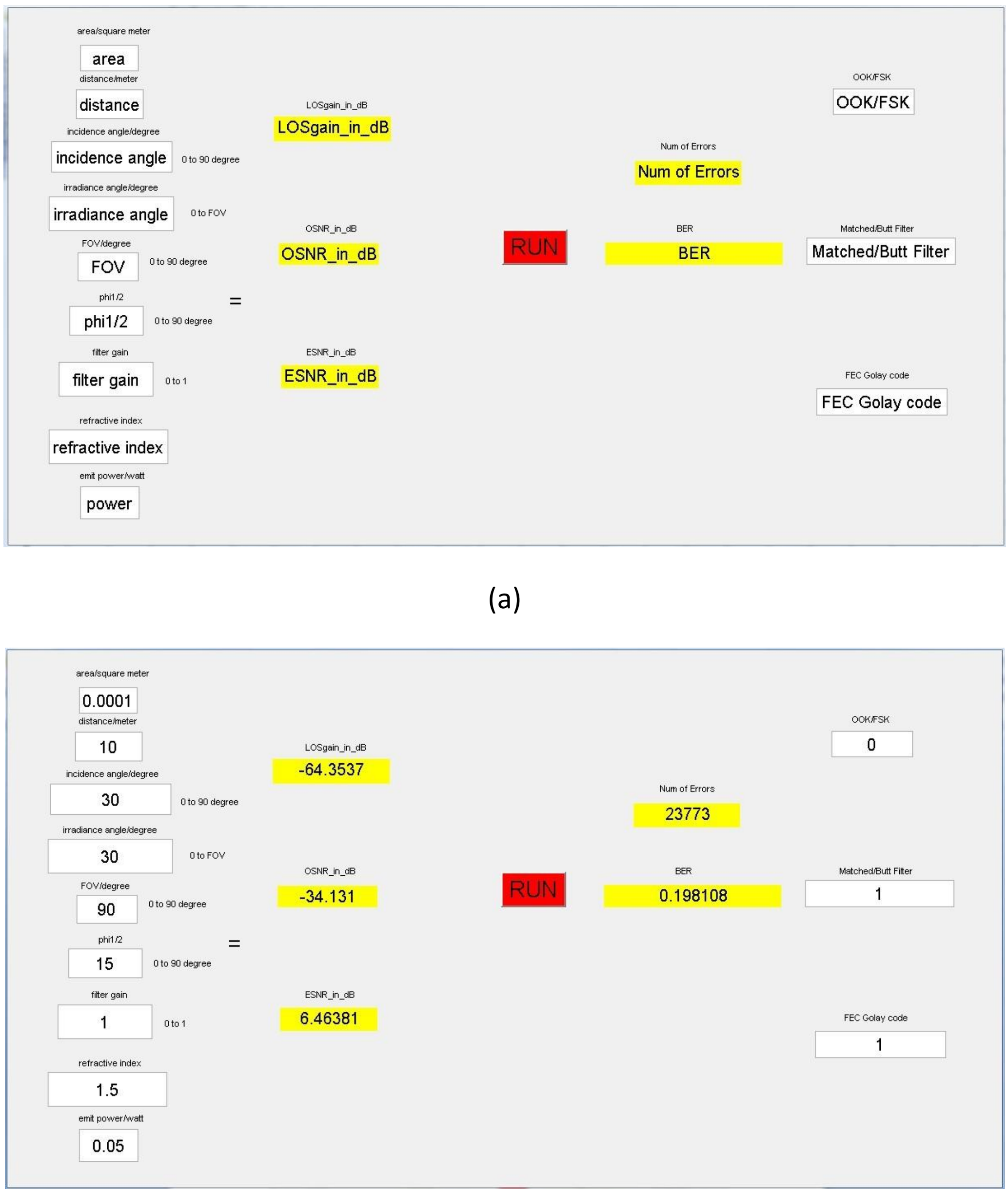


Figure 5.1 Optical wireless simulation tool: (a) user interface;
(b) simulation result.

5.2 Performance evaluation of the optical communication systems

5.2.1 Optical OOK System

As we discussed previously in chapter 4, the optimal receiver for a communication system operating under AWGN and channel distortion (determined by the impulse/frequency response of the channel) requires use of a matched (to the concatenated transmit filer & channel response) filter. However in many cases the impulse response of the matched filter is complex and costly to implement in addition to the fact that the in many cases the channel response of the channel tends to be time-variant, requiring the use of some form of adaptive mechanism in the implementation of the matched filter. These raise serious concerns in terms of its suitability for implementation in the low cost, small size, energy limited systems we consider. To address this issue, we make use a Butterworth filter for post detection filtering purpose of the electric signal generated by the PD. The transmitter and receiver models have shown in Chapter 4. Note that we use Electrical SNR in Figure 5.3, not Optical SNR, since the final processing involved in deciding the information sequence is performed on the electric signal. At the transmitter side, the digital bits, 0 and 1 for example, are mapped to symbols (e.g. 2-level or 4-level), acquire a certain pulse shape through direct shaping or filtering (e.g. for OOK the pulse shape is an orthogonal pulse) and the resulting electric signal is modulated using a certain modulation scheme, such as PPM, FSK and BPSK. The resulting electric signal is driving the LED, and the generated optical signal is transmitted sent through the air. At the receiver side, the optical signal is firstly filtered by a blue optical filter, and then received by the photo diode, which transforms it to electrical signal. Then the electrical signal is demodulated, sampled, and passed to the decision making device that outputs a 0 or 1 decision. Since the decision process is occurring using the electric signal, the SNR that determines the performance is the ESNR. The expression of the ESNR is given by Kahn and Barry [20] as (we have provided these equations in chapter 4, we state them again for the reader's convenience) :

$$ESNR = \frac{R^2P^2}{R_bN_o} = \frac{R^2H^2(0)P_t^2}{R_bN_o} \quad (5.1)$$

$$P = H(0)P_t \quad (5.2)$$

where *R* is the responsivity of photodiode in *A/W*, *P* is the received optical power of the signal in watts, P_t is the average power of transmitted signal, R_b is the bit rate, N_o is the Gaussian noise double-sided power-spectrum density, and $H(0)$ is the channel gain. The N_o could be given as:

$$N_o = 2qI_b \quad (5.3)$$

where q is the elementary charge, I_b is the average DC photocurrent generated by shot noise. So ESNR could be expressed as follows:

$$ESNR = \frac{R^2P^2}{2qI_bR_b} \quad (5.4)$$

$$I_b = RP_n \quad (5.5)$$

P_n is the optical background noise power, so ESNR could be expressed as :

$$ESNR = \frac{R^2P^2}{2qRP_nR_b} = \left(\frac{R}{2q}\right)\left(\frac{P}{R_b}\right)\left(\frac{P}{P_n}\right) \quad (5.6)$$

If we assume the optical SNR as the ratio between the average power of the received signal power, divided by the average power of the background noise power at the receiver side in an optical channel (in Figure 5.2, we can see that, our optical signal exists in a certain range of the spectrum, but the noise appears over a wide frequency range. To calculate OSNR, we only take the noise power in the range of the used optical filter), which means $\mathrm{OSNR} = \frac{\mathrm{P}}{\mathrm{P_n}}$ [152, p. 11], [70], the ESNR in dB format could be expressed as:

$$ESNR_{dB} = OSNR_{dB} + 10\, log_{10}(\frac{RP}{2qR_b}) \quad (5.7)$$

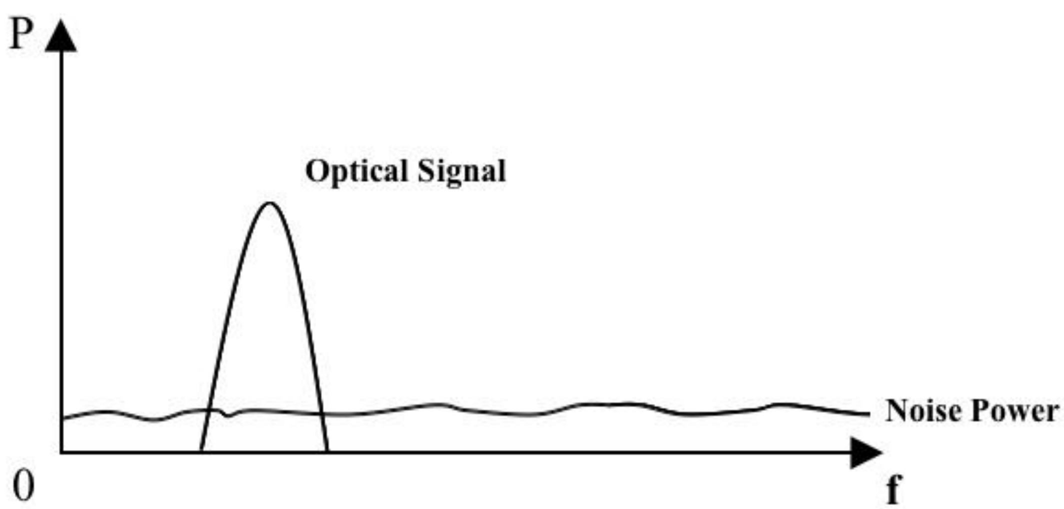


Figure 5.2 Optical power density of information signal and ambient power.

Firstly, we examine the performance of optical OOK system with the optimal filter (matched filter). The system specifications used in the simulation are shown in table 5.2:

Optical Modulation/Demodulation	IM/DD
Electrical Modulation/Demodulation	OOK
Bit Rate	1 Mbps

Filter Type	Matched Filter

Table 5.2 Parameters of Optical OOK system

The simulation (CI: 95%) and theoretical results [20] are shown as Figure 5.3. We provide simulation results and theoretically derived curve compare and confirm our simulation software works properly.

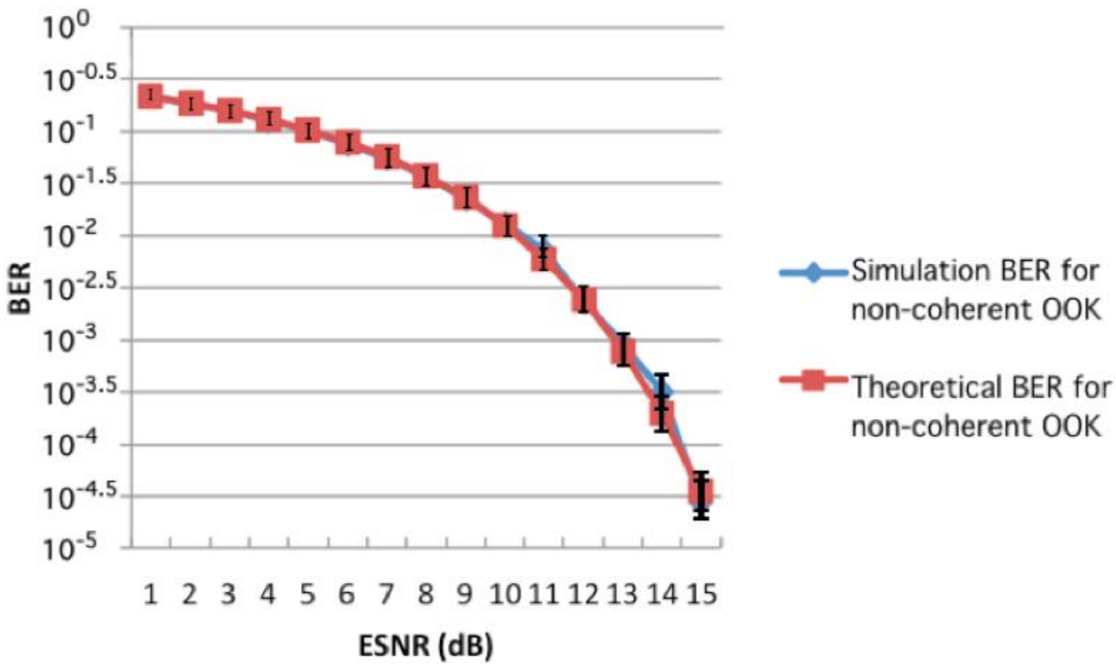


Figure 5.3 Theoretical and simulation based results for the optical OOK system (non-coherent detection: envelope detection)

From the Figure 5.3, we can see there is a good agreement between simulation and theoretical results with a 95% confidence interval, for case of matched filter receiver. We now replace the matched filter with a Butterworth filter. Such approach makes sense for the reasons mentioned in both of Chapter 4 and Chapter 5, which is because the Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the pass-band so that it is also termed a maximally flat magnitude filter [150, p. 150] [70].

The BER in terms of OSNR (Confidence Interval (CI): 95%) is shown as Figure 5.4, the configuration is listed below (Table: 5.3):

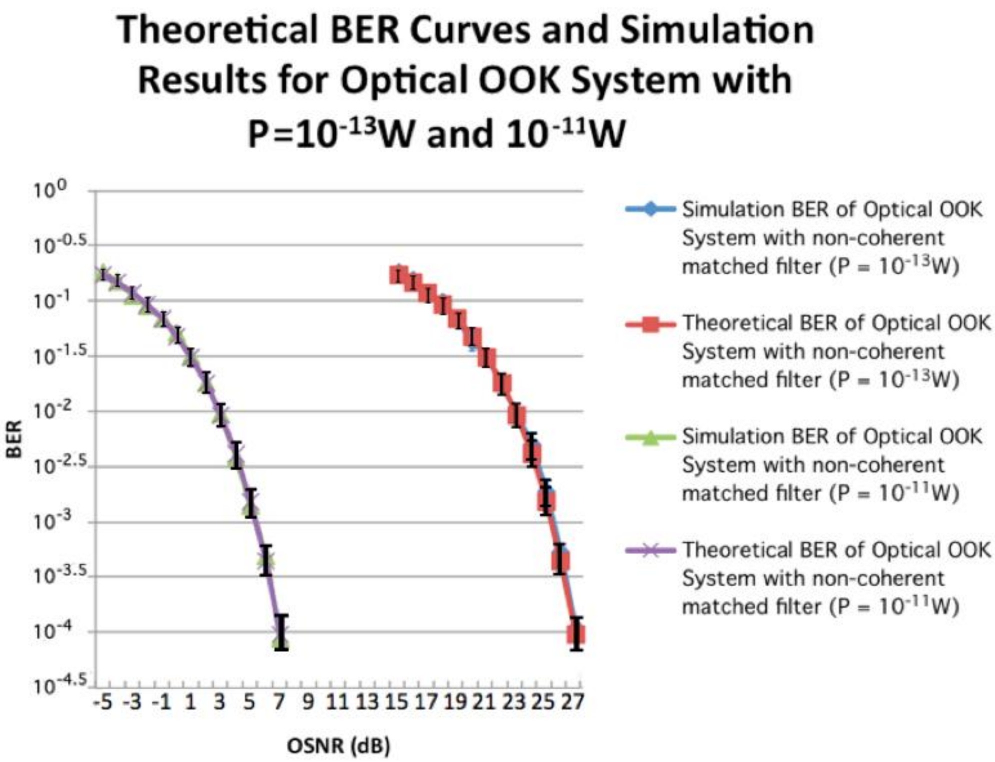


Figure 5.4 Theoretical BER curves and simulation results for optical OOK system with different transmit powers (CI: 95%).

Bit rate	1M bps
Filter type	Matched filter
FEC code	None
Modulation scheme	OOK

Table 5.3 Configuration of Figure 5.4.

From Figure 5.4 we can conclude that the stronger the received optical power P is, the better the performance of the communication system becomes. It can be seen that under the same

OSNR, the system with higher P is doing considerably better. Evidently, by increasing P, the receiver becomes more robust to the presence of optical noise.

To choose an appropriate Butterworth filter, we need to consider the system's performance and cost/complexity of the filter. The Butterworth's transfer function is:

$$|H(\omega)|^2 = \frac{1}{1+(\frac{\omega}{\omega_c})^{2n}}; \quad (5.8)$$

where *n* is the order of the filter, ω_c is the cut-off frequency, ω is the angular frequency, and $|H(\omega)|$ is the transfer function. Butterworth filter with different orders could be seen in Figure 5.5 [70]:

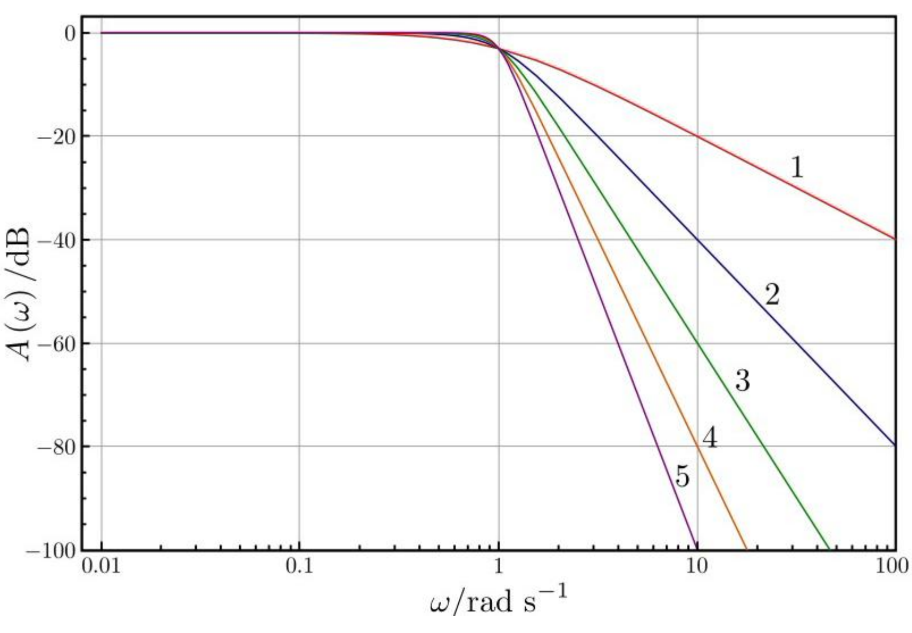


Figure 5.5The gain of Butterworth low-pass filter of orders 1 through 5, with cut-off frequency is equal to 1 [70].

These are opposing factors. Specifically, a Butterworth filter of higher order has the potential to provide better performance due to having steeper stop-bands it has, which filters out more noise from the system, however, it has higher implementation complexity that could lead to higher development cost in some cases. The best compromise between these two factors needs to be made. In order to make our selection, we performed simulations using different orders of Butterworth filters. The passband is fixed at 1MHz. By changing the bandwidth of stopband, we get different orders (from 2 to 4, since orders higher than 4 require complex implementation) of the filter, and their performances in terms of BER. We provide the results in Table 5.4

Pass band(Hz)	Stop band(Hz)	Order N	BER	ESNR dB
1M	5M	2	0.000572	13
1M	4M	3	0.000393	13
1M	3.5M	3	0.000316	13
1M	3M	4	0.000527	13
1M	2.5M	4	0.00109	13

Table 5.4 The simulation results collected for the selection of an appropriate Butterworth filter (CI: 95%)

From the simulation results, the third order Butterworth filter with 1M passband and 3.5M stopband is chosen to replace the matched filter, because the narrow stopband of a forth order filter cuts too much signal power, which makes the performance bad, and other third order filters allow too much noise into the system, which also decreases the ESNR (there may be other combinations of passband and stopband Butterworth filters to reach better performance, however, we are confident we have made a good choice). The simulation result (CI: 95%) of the optical wireless OOK system using Butterworth filter is shown in Figure 5.6.

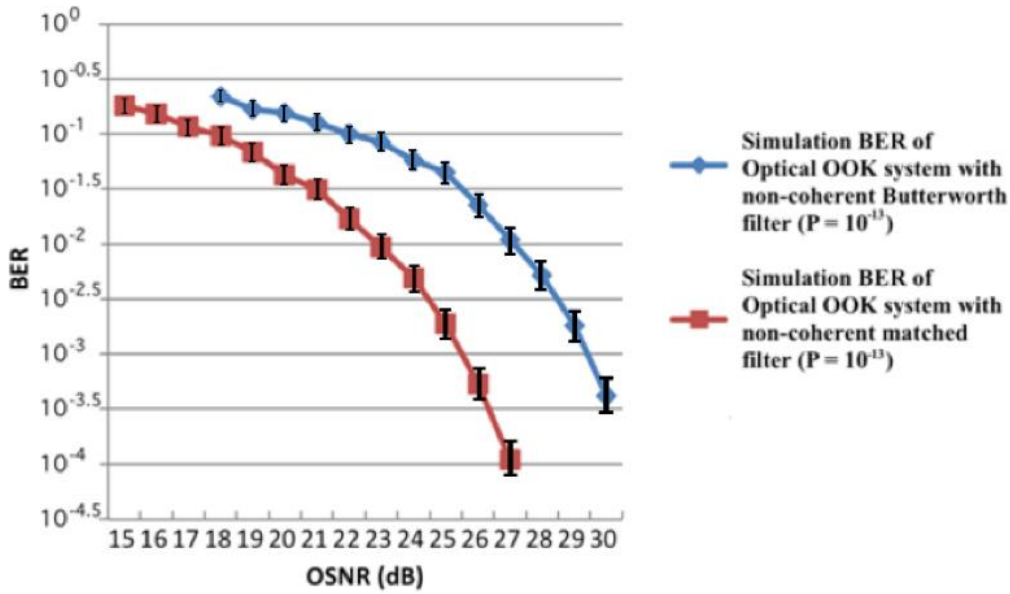


Figure 5.6 Simulation results of optical OOK system with matched filter and Butterworth filter (CI: 95%).

Bit Rate	1M bps
Filter type	Butterworth 3rd order low pass filter
Pass Band	1MHz
Stop Band	3.5 MHz
P	10^{-13}W
Responsivity of PD	0.2A/W

Table 5.5 Parameters of communication system used to acquire the BER results shown in Figure 5.6.

From the presented simulation results, a phenomenon could be observed is that when using a Butterworth filter the performance is 3 to 4 dB worse compared to the matched filter case. To countermeasure this weakness, we make use of FEC coding and specifically employ the Golay code (23,12,7) to improve the performance. One and two layers Golay code is used and the simulation results are shown in Figure 5.7. The system parameters used to acquire the results shown in Figure 5.7 are given in Table 5.6:

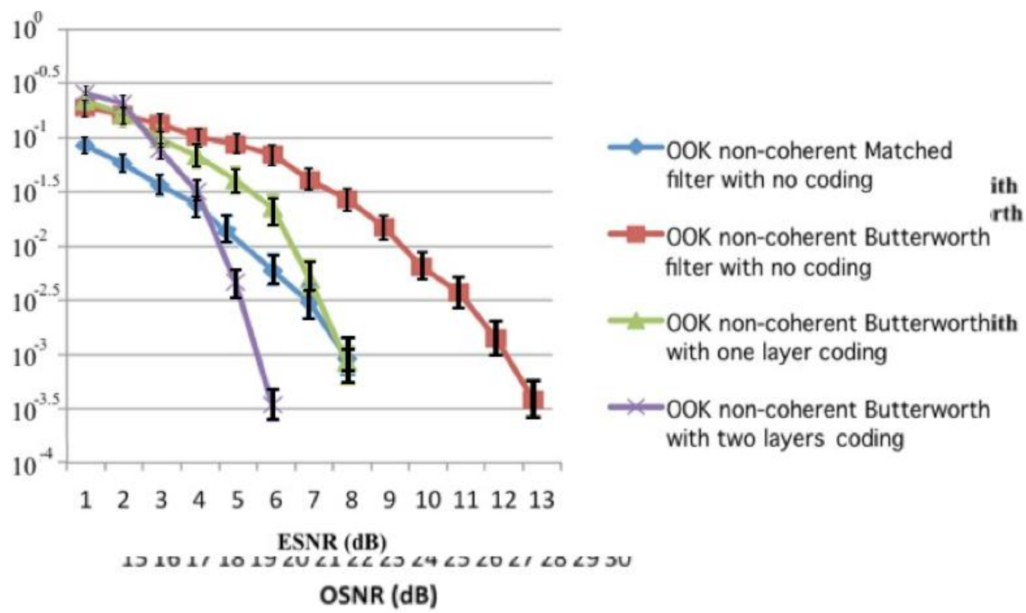


Figure 5.7 BER performance for optical OOK system with Butterworth filter, with one layer and two layers FEC code (CI: 95%).

The system parameters used to acquire the results shown in Figure 5.7 are given in Table 5.6:

Bit Rate	1M bps
Filter type	Butterworth 3rd order lowpass filter
Passband	1MHz
Stopband	3.5 MHz
Pavg	10^{-13}W
Responsivity of PD	0.2A/W
Used FEC code	(12,23,7) Golay code

Table 5.6 Parameters of Figure 5.7.

From the curves of Figure 5.7, we can conclude that the performance of optical OOK system with Butterworth filter is improved considerably when making use of the mentioned coding scheme. The BER curve of the system using Butterworth filter and one layer FEC code is close to the BER curve of the system using matched filter and no FEC code. To improve the performance further, we use a second layer coding (interleaving method), and it shows that the performance with two layers Golay codes is considerably better from the performance of using matched filter with no FEC coding when ESNR is above 6 dB. We could also see that, when ESNR is below 4 dB, the uncoded matched filter system has superior performance compared to all evaluated schemes that are using Butterworth filter, however, the BER at that range is very is higher than 0.032; a BER unsuitable for operation of most telecommunication systems. It is also evident there is crossover between the uncoded and encoded schemes, occurring at ESNR less that 3 dB. This performance is known behaviour of coded schemes and was expected.

5.2.2 Optical BFSK System

In the previous section, we discussed the optical OOK system for indoor environment with LOS channel. In this section, the optical FSK system will be investigated in detail.

A typical optical FSK system could be modeled as in Figure 4.10. At the transmitter, the bits '0' and '1' will be represented by electric signals $s_1(t)$ and $s_2(t)$ (Eq. 4.13) with the frequencies f_1 and f_2 respectively. Then the signals will be emitted by the optical transmitter, a LD or a LED into the space. After suffering a LOS channel gain, the optical signals hit the surface of photo-detector, and being transmitted to electric signal, which will be send into two detection channel to determine the bit is '0' or '1'.

As we discussed previously, the optimal filter for AWGN channel is the matched filter and the theoretical BER expression for the optical IM/DD BFSK system in this case is given by (Eq. 4.16):

Our simulation results for the optical IM/DD BFSK system is shown in Figure 5.8, and the parameters for the simulation are listed in Table 5.7.

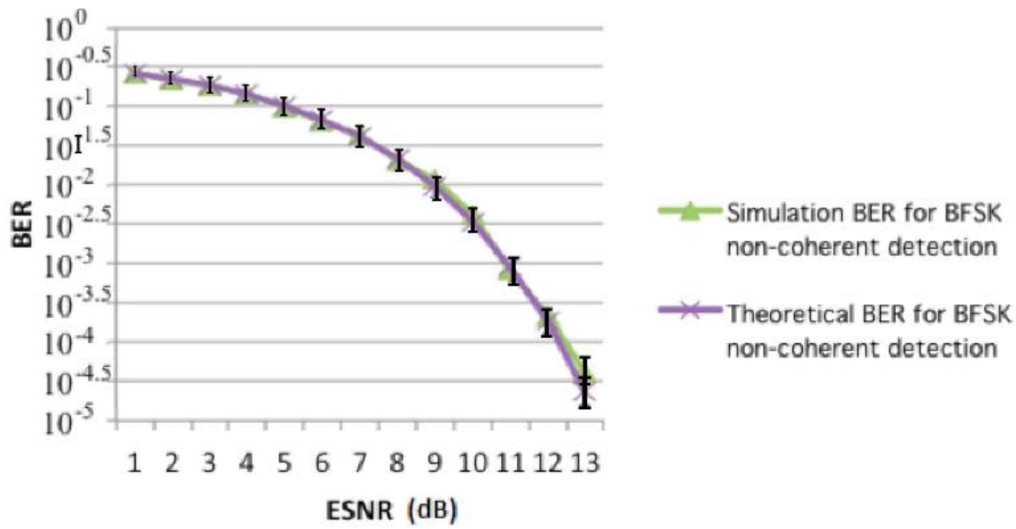


Figure 5.8 Simulation based and analytical result describing the performance of the electric part of the optical IM/DD Binary FSK system

Bit rate	1Mbps
Optical modulation/demodulation	IM/DD
Electrical Signals modulation/demodulation	FSK
Receiver's filter type	Matched filter
f_1	10 MHz
f_2	20 MHz

Table 5.7 Parameters of the system used to acquire the simulation results displayed in Figure 5.8

The BER in terms of OSNR is shown in Figure 5.9, and the parameters are given in the Table 5.8:

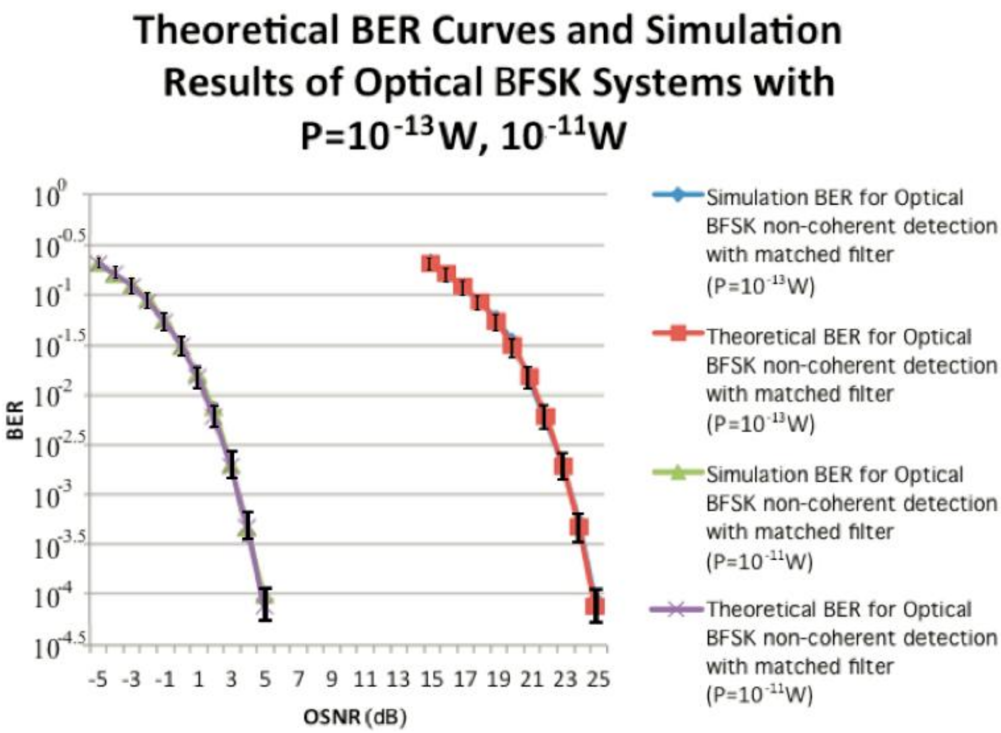


Figure 5.9 Theoretical and simulation based BER curves (CI: 95%) of an optical BFSK system using matched filter receiver.

Similar conclusion could be made by observing Figure 5.9. By improving the power of P_{avg}, the system can work smoothly at the low OSNR condition.

Bit Rate	1 Mbps
Optical Modulation/Demodulation	IM/DD
Electrical Modulation	FSK
Filter Type	Matched Filter
f_1	10 MHz
f_2	20 MHz
P_{avg}	$10^{-11}/10^{-13}$W
R	0.2A/W

Table 5.8 Parameters of the simulated BFSK system used to derive the results shown in Fig.5.9.

Running simulations, we selected appropriate band pass Butterworth filters to replace matched filters. Firstly, the data rate has been placed at 1Mbps in order to avoid degradations due to aliasing of spectrum. The used carrier frequencies are 10MHz and 20MHz (if we chose two frequencies close to each other, e.g. 11MHz and 12MHz for example, aliasing will occur). The order of Butterworth filters should be no higher than 3, in order to keep actual implementation simple (since we chose a 3rd order Butterworth filter in our optical OOK system). To select a good combination of passband and stopband, we set the passband to a fixed values and test different stopbands, then we alternate, we set the stopband at fixed values and test various passbands. Note there might be a better combination of passband and stopband for a 2nd order Butterworth filter, but our selection is good enough for our system and design purpose (we are aiming to sending control data, not picture or videos for indoor application). Three cases of the simulation results (CI: 95%) are shown as Table 5.9:

Filter 1: Passband:[9.5,10.5]MHz Stopband:[0-7.5,12.5-Fs/2]MHz Order:2 Filter 2: Passband:[19.5,20.5]MHz Stopband:[0-17.5,22.5-Fs/2]MHz Order:2(chosen)	BER=0.00092 when ESNR=10dB, bit rate=1Mbps, f1=10MHz, f2=20MHz
Filter 1: Passband:[8.75,11.25]MHz Stopband:[0-7.5,12.5-Fs/2]MHz Order:3	BER=0.00085 when ESNR=10dB, bit rate=1Mbps, f1=10MHz, f2=20MHz

Filter 2: Passband:[18.75,21.25]MHz Stopband:[0-17.5,22.5-Fs/2]Hz Order:3	
Filter 1: Passband:[9.5,10.5]MHz Stopband:[0-7,13-Fs/2]MHz Order:2 Filter 2: Passband:[19.5,20.5]MHz Stopband:[0-17,23-Fs/2]MHz Order:2	BER=0.00128 when ESNR=10dB, bit rate=1Mbps, f1=10MHz, f2=20MHz

Table 5.9 BER performances by using passband Butterworth filters with various parameters.

From the simulation results, it can be observed that use of second order Butterworth passband filters is a good choice. Two second order Butterworth filters are employed to replace the matched filters, and the simulation results are shown as Figure 5.10:

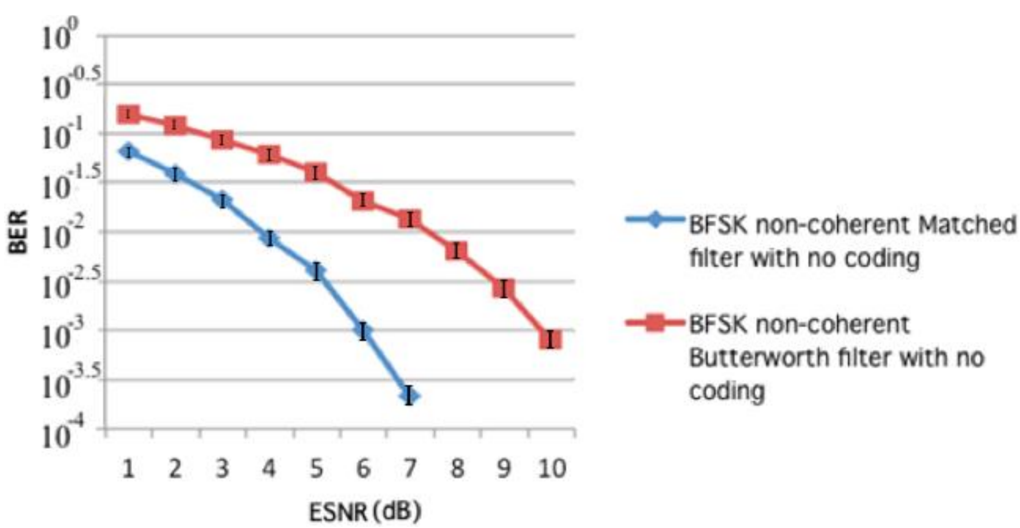


Figure 5.10 BER performance of Optical Binary FSK using at the receiver (a) matched and (b) 2nd order Butterworth filters (CI: 95%).

Obviously, there is a deficiency in the range of 4 dB at BER=10^{-3} when using the bandpass Butterworth filters instead of matched filters. One and two layers of Golay code are used to improve the BER performance. The simulation results are in Figure 5.11, while the used system parameters are listed in Table 5.10.

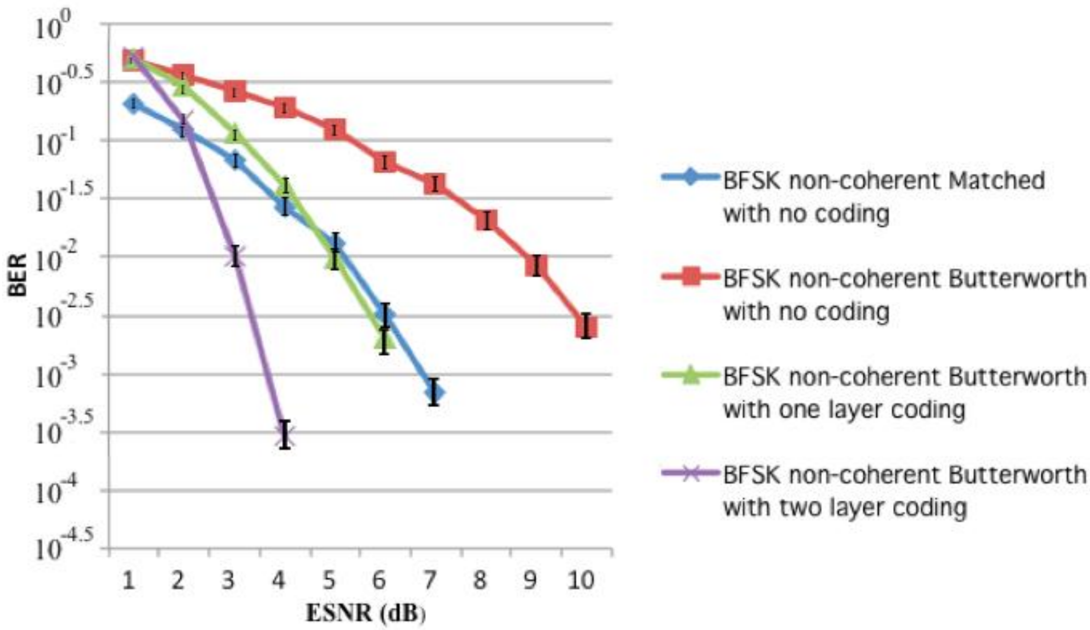


Figure 5.11 BER performance of Optical FSK system with one and two layers FEC code (CI: 95%).

Bit Rate	1M bps
F1:	10MHz
F2:	20MHz
Filter	Two Butterworth 2nd order bandpass filters
Filter 1: Pass band	[9.5 10.5] MHz
Filter 1: Stop band	[0-7.5],[12.5-Fs/2]MHz
Filter 2: Pass band	[19.5 20.5]MHz

Filter 2: Stop band	[0-17.5],[22.5-Fs/2]MHz
P	10^{-13}W
Responsivity of PD	0.2A/W
FEC code	(12,23,7) Golay code

Table 5.10 The parameters for Figure 5.11

By observing Figure 5.11, the following conclusions can be made: 1) the performance of the optical FSK system with Butterworth filters and one layer Golay code is close to the system with matched filters, and even better when the ESNR is above 5 dB. 2) The system with Butterworth filters and two layers Golay code can work smoothly in low SNR conditions; it can achieve a BER of 10^{-4} at 4 dB. 3) The performance of the system with Butterworth filters and two layers Golay code is better from that of the system that is using matched filters for ESNR higher than 2 dB, and the higher the value of ESNR is, the larger the gain of the 2 layers Goley code system becomes. Thus the matched filter could be replaced without problems.

By compare the simulation results of optical OOK and optical FSK systems, the following differences have been identified:

1. To reach the same BER, the optical FSK system needs less ESNR than the optical OOK system. This is due to the nature the two systems (Orthogonal BFSK and OOK) function.
2. With one layer Golay code, the performance of optical BFSK system with Butterworth filters is more close to the performance of optical BFSK using matched filter (with no Goaly code) as compared to the distance between the equivalent optical OOK systems.

With two layers Golay code, the optical BFSK with Butterworth filters system provide better performance compared to the optical BFSK with matched filters (with no Golay code) for ESNR values of 2 dB and above. For the case of optical OOK, this happens at 4 dB and higher. From the above simulation results, we could choose the suitable operation scheme for the projects from the view of performance, cost, and power assumption. In the following sections, we will focus on the user mobility for indoor optical wireless communication systems.

5.3 Research on the Indoor Mobility of the Proposed Systems

In this section, the optical OOK/FSK systems for indoor application will be introduced and described in detail. In an indoor environment, the main noise is ambient noise, which consists of natural and artificial noise, the nature noise comes from sunlight, and the electric incandescent lamp and fluorescent are the main source for artificial noise. In [1], it has been determined that even when a narrow band optical filter is utilized, a steady shot noise having a photon arrival rate in the order of 10^7 to 10^8 photons/bit for a 100Mbps system is generated, due to the reason of the intense ambient light that strikes the detector. So we can neglect the self-noise of the information bearing optical signal. The strength of the ambient noise allows us to model the ambient shot noise as a Gaussian process [44, p. 203].

Should we use the ambient noise intensity used in [1], and considering we are working at a data rate of 1 Mbps, we would have to scale the number of photons per bit 100 times higher, i.e. in the range of 10^9 to 10^{10} photons/bit. However, taking into consideration that many office spaces use reflective windows as well as working space within most cubicles receives artificial light, we maintain the 10^7 to 10^8 photons/bit figure. Thus the ambient noise energy per bit is

$$E = h\nu N_{noise} = \frac{hcN_{noise}}{\lambda} \quad (5.9)$$

where $h = 6.626 * 10^{-34}$J is the Plank' s constant, ν and λ are the frequency and wavelength of the carrier respectively, N_{noise} is the number of noise photons, and c is the speed of light.

For blue light that is selected as the operational optical frequency range for communication, the wavelength is in the range of 420nm, thus, E=6.626*10^{-34}*(3*10^{8})*(10^{8}) / (420*10^{-9})) =0.0473* 10^{-9} J. When the data rate $R_b = 1Mbps$, the power of ambient noise is E*R_b0.0473*10^{-9}*10^{6}=4.73*10^{-5}W.

We assume the distance from the LED to photodiode is 10 meters, which is long distance for an indoor environment, and the power of LED is 50mW. Below we determine how the incident angle and irradiance angle affect the BER performance of the optical OOK/FSK systems.

5.3.1 Incidence Angle vs. BER

In this simulation, all other parameters are fixed, having the values listed in Table 5.11 a communication distance for 10m is enough for indoor application, and 10^{-4} mm^2 is assumed the size of light sensitive area of PD [1]. Since we are using visible light, people can adjust the incidence angle and irradiance angle easily, so 30 degree is set as the up limit of the incidence angle and irradiance angle. Since we want to investigate the effect of incidence angle on the BER performance, so we fix all other parameters in this part; only the change of incidence angle is changed so that we can assess its impact on the BER.

d (distance from transmitter to receiver)/m	10

A (the size of the light sensitive area of the PD)/m^2	0.0001
ϕ (the angles of incidence)/deg	10,20,30
ψ (the angle of irradiance)/deg	30
$T_{s(\psi)}$ (the signal transmission of the filter)	1
ψ_c (the FOV at the receiver)/deg	90
$\phi_{1/2}$ (the semi-angle at half luminance of the LED)/deg	30
N (refractive index)	1
Power	50mw
Filter Type	Matched filter

Table 5.11 Parameters used for the simulation of incidence vs. BER

The simulation results are shown as Table 5.12.

Incidence Angle (degree)	**ESNR (dB)**	**BER (OOK)**	**BER (FSK)**
10	12.3821	0.0013	0.000092
20	10.6515	0.0069	0.0014
30	7.23441	0.0521	0.03395

Table 5.12 The simulation results for incidence angle vs. BER performance (CI: 95%).

From the simulation results, we can conclude that when incidence angle is 10 degree, the BER performance is excellent, but with the increase of the incidence angle, the ESNR of the system is decreasing rapidly. In terms of performance, assuming an acceptance performance is for BER higher than 10^{-3} (a threshold set for cellular systems) we see that optical FSK can support reliable communication even for 20 degree of incidence angle. Since a 10 degree incidence angle is reasonable and could be achieved easily by using visible blue light (people can adjust the angle easily since they can see the light), in the following simulations, we assume the incidence angle is fixed at 10 degree.

Another element, which limits the mobility of the optical wireless system is the angle of irradiance. Below we examine how the angle of irradiance affects the system's performance.

5.3.2 Irradiance angle vs. BER

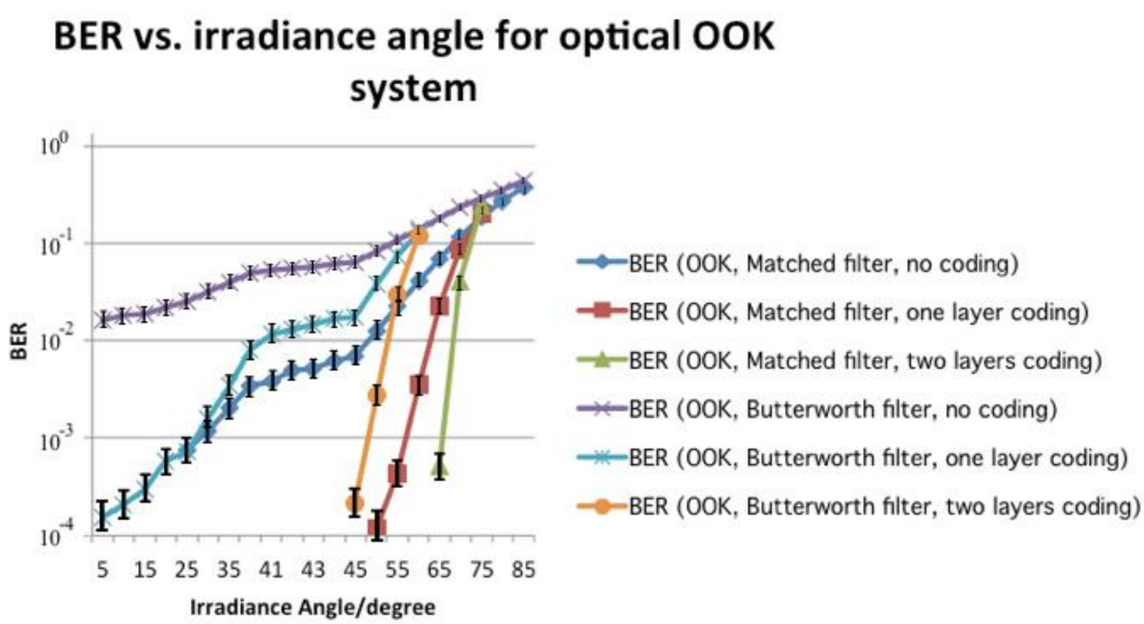
To investigate the influence of irradiance angle on BER performance, we fix all the other parameters as Table 5.13.

d (distance from transmitter to receiver)/m	10
A (the size of the light sensitive area of the PD)/m^2	0.0001
ϕ (the angles of incidence)/deg	10
ψ (the angle of irradiance)/deg	5 to 85
$T_{s(\psi)}$ (the signal transmission of the filter)	1
ψ_c (the FOV at the receiver)/deg	90
$\phi_{1/2}$ (the semi-angle at half luminance of the LED)/deg	30
N (refractive index)	1
Power	50mw
Filter Type	Matched/Butterworth filter
FEC code	Golay code (12,23,7)

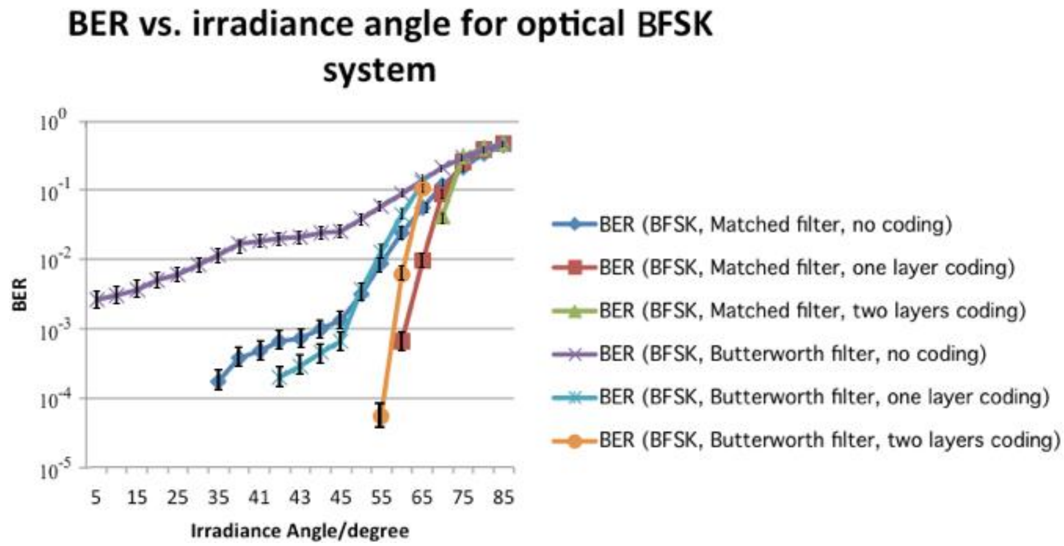
Table 5.13 Parameters for the simulation of irradiance angle vs. BER

The simulation results are shown as Figure 5.13 (a) and (b). Based in them we can conclude that, with two layers Golay coding, even an optical OOK system with Butterworth filter could achieve good performance even with angle of irradiance as large as 45 degrees, which means, a hemisphere non-imaging optical concentrator [20] is good enough for use with the system.

We think the range of 40 to 45 degree could provide convenience to users. Taking this as starting point we increase by 1 degree at each step. For the cases of using Butterworth filter with one or two layers coding, we see that their BER is below 0.001 at 45 degree, so we don't need to investigate their performance in the range of 40 to 45 degree.



(a)



(b)

Figure 5.12 BER vs. irradiance angel for various (a) optical OOK system; (b) optical FSK system (CI: 95%).

From Figure 5.12, we can further learn that, the best performance is achieved by matched filter with two layers Golay code, and this applies to both optical OOK and optical FSK. They can provide good communication quality when irradiance angle is smaller or equal to 60 degrees. Butterworth filters with two layers Golay codes cannot work as well as their matched filter(s) counterparts. In optical OOK system, it can only work well when the irradiance angle is smaller or equal to 50 degree, and in the optical FSK system, it can provide good performance when the irradiance angle is smaller or equal to 55 degree. The above results and analysis give a clear guide when we need to consider the trade-off between the performance and cost.

5.3.3 Communication Distance vs. SNR

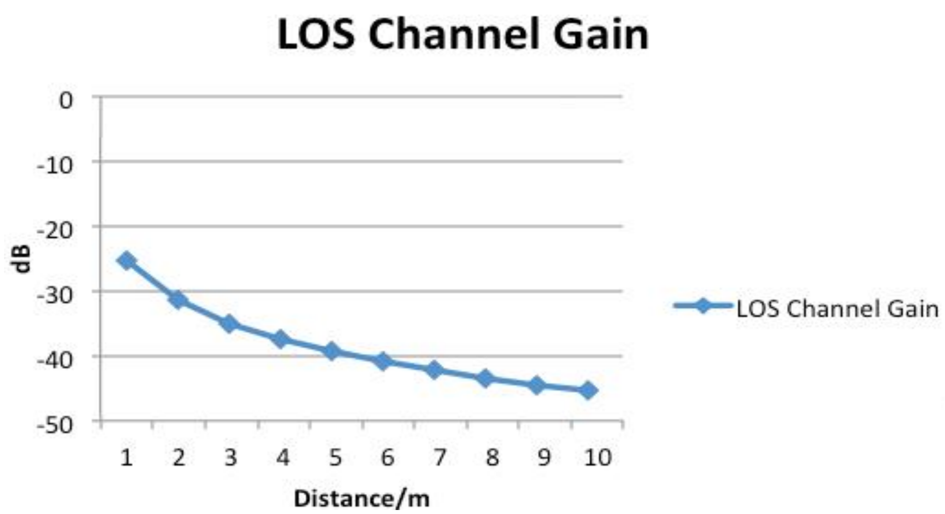
Communication distance is an important factor in optical wireless communication systems. To get a thoroughly understanding about how the communication distance affects the signal power, we investigate the change level of channel DC gain by setting different values for parameters. In this simulation, we fixed all the other parameters, in order to eliminate the impact of their change. The results of this simulation could be applied for all the indoor LOS OWC systems, not only the OOK and FSK mentioned in this thesis.

Firstly, we study how the change of distance between the transmitter and receiver affects the channel's DC gain (refer to Eq. 4.1). The parameters are set as Table 5.14.

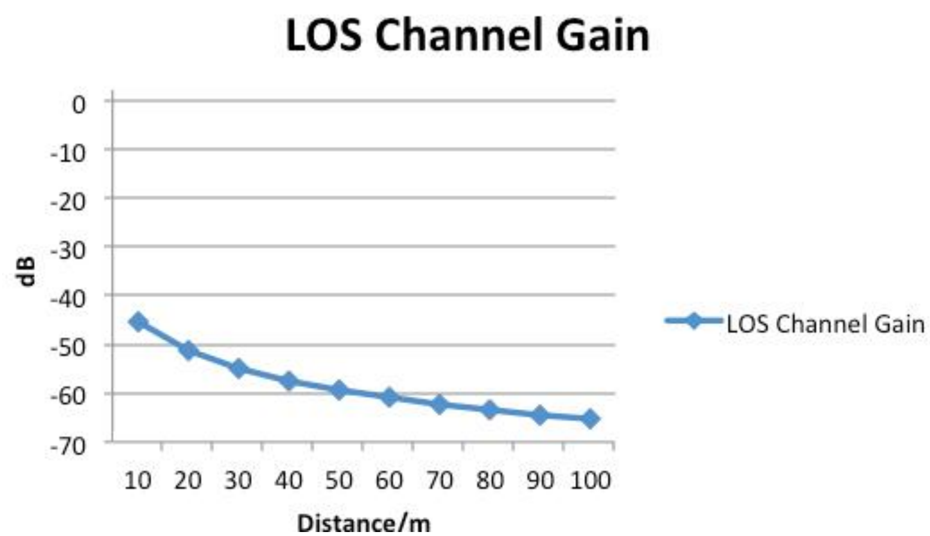
d (distance from transmitter to receiver)/m	1 :1: 10; 1 :10: 100
A (the size of the light sensitive area of the PD)/m^2	0.0001
m (the order of Lambertian emission)	45.2776
ϕ (the angles of incidence)/deg	20
ψ (the angle of irradiance)/deg	30
$T_{s(\psi)}$ (the signal transmission of the filter)	1
$g(\psi)$ (gain of the concentrator)	4
ψ_c (the FOV at the receiver)/deg	30
$\phi_{1/2}$ (the semi-angle at half luminance of the LED)/deg	10
N (refractive index)	1

Table 5.14 The Parameters for LOS channel gain vs. Distance

The results are shown as Figure 5.13 (a) and (b)



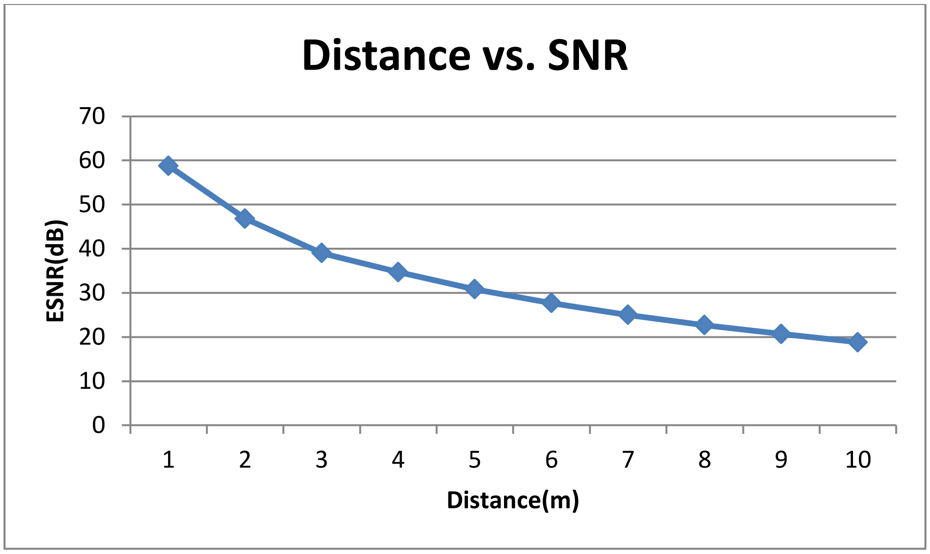
(a)



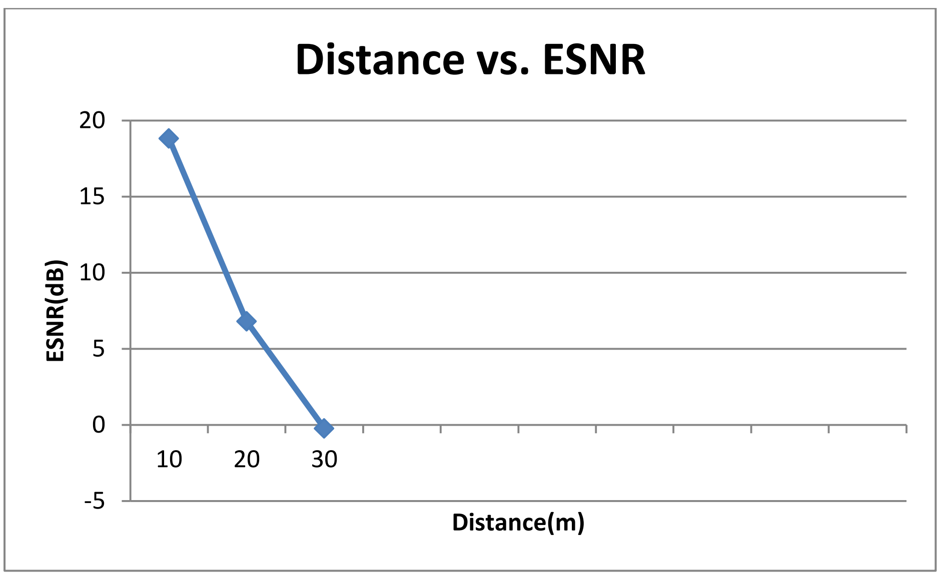
(b)

Figure 5.13 LOS Channel Gain vs. Distance from (a) 1m to 10m and (b) 10m to 100m

Channel gain is a little vague; we thus plot ESNR vs. Distance (Figure 5.14) for the system specified in table 5.14 to make it more specific. In this calculation, we assume the emitting power from the transmitter is 50mW, and the shot noise is 10^8 photons/bit.



(a)



(b)

Figure 5.14 ESNR vs. Distance from 1m to 10m & 10m to 30m

From the above calculation results, a simple conclusion could be made, with a short distance and narrow beam transmitter, a good performance could be achieved. The ESNR is above 15 dB when the communication distance is shorter than 10m, even when the distance is 20m, the SNR still could reach 6.8 dB, which means by using our optical BFSK system, with matched filters or

Butterworth filters jointly with 1 or 2 layers coding, we can get BER below 0.001. For our optical OOK system, only using Butterworth filter with 2 layers coding can reach the similar performance. But the results presented above, used for the made conclusions, correspond to a system with small incidence and irradiance angle. We became aware from sections 5.3.2 and 5.3.3 that increase of the incidence angle and irradiance angle lead to a significant increase of BER. Thus, there is a trade-off between distance, incidence angle and irradiance angle.

5.3.4 Energy Difference between the Edges of Receiver

Another issue of the practical importance consideration of implementing an optical system is the dimension of the receiver. Usually, in the theoretical analysis, the receiver is assumed as a point, but in the true environment, the receiver has its dimension, we need to consider the power difference between two edges of the receiver, in order to check if the light intensity distribution in the receiver is isotropic or not, since equations [20] for calculating received ambient noise power are different for isotropic case and localized case. Also, if the ambient noise light is not isotropic in the receiver, we need to take it into consideration when we want to use an array of PDs. We assume the transmitter and receiver are placed as Figure 5.15.

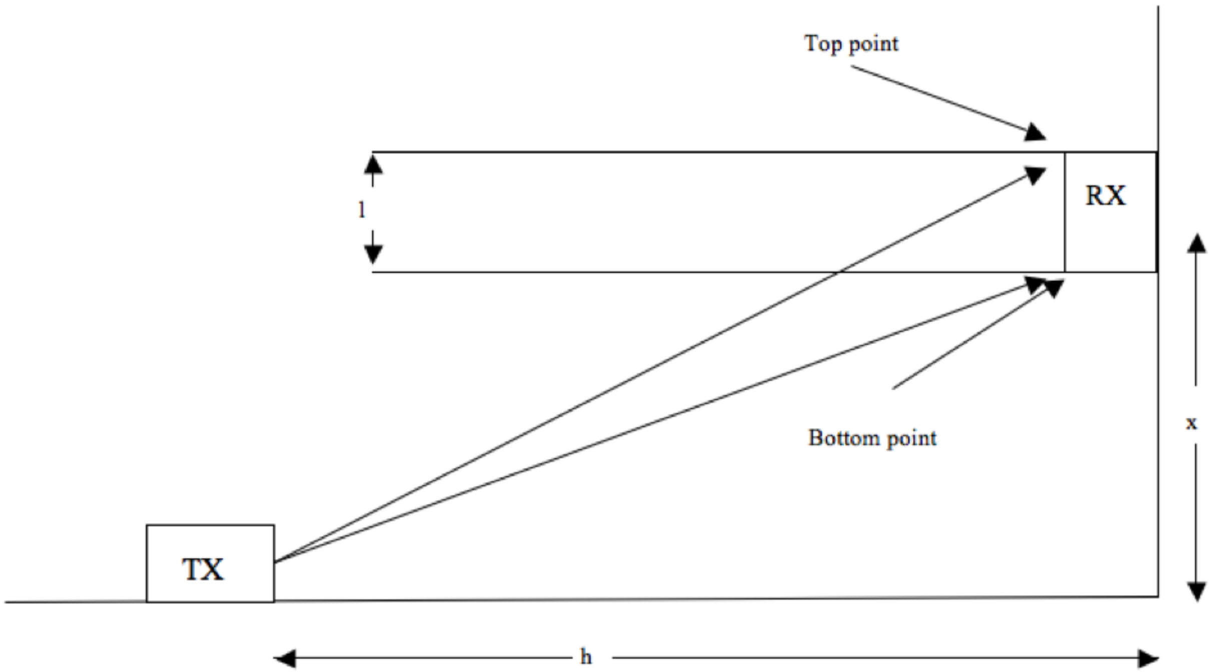


Figure 5.15 The assumed locations of transmitter and receiver

The distance between the transmitter (LED) to the vertical line of receiver is *h*, the length of the receiver is *l*, the vertical distance between the center of the receiver to the horizontal line of transmitter is *x*.

Consider *h* is taking values between 2 and 10 meters, *l* is 0.2 m, *x* is 1.5m, the ratio between two points are shown as the following picture in dB. We calculate the power difference between the top point and the bottom point of the receiver by using different h, and get a result as Figure 5.16:

$$Ratio = 10log_{10}^{(\frac{P_{bottom}}{P_{top}})} \quad 5.10$$

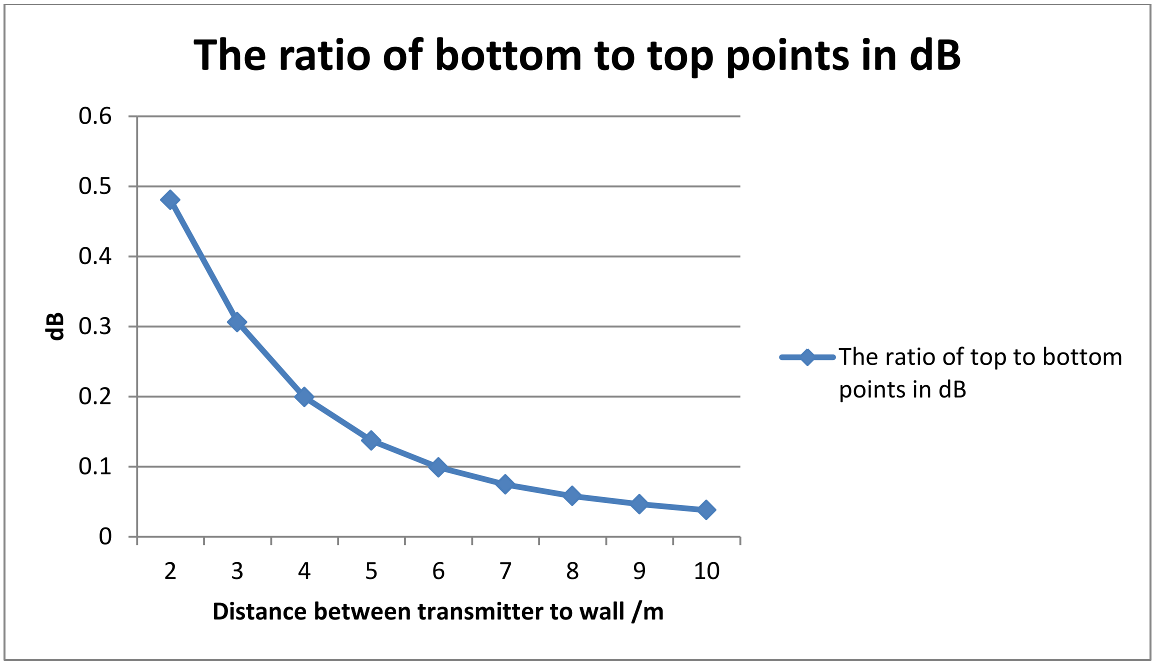


Figure 5.16 The ratio of the bottom point to the top point of the receiver in dB

From the calculation result, we can see that, with the increase of distance between transmitter and wall, the difference is getting smaller. Even when the distance is 2 meters, the ratio of the bottom point to the top point is only 0.48 dB, which could be neglected.

5.4 Conclusion

In this chapter, we firstly introduced the developed GUI tool based on MATLAB. And then, by using this tool, we evaluated the proposed system in chapter 4, and analyzed the simulation results in section 5.2. In section 5.3, we focused on the mobility of the proposed optical wireless system in the indoor environment, and we also solved a problem about energy difference between the edges of receiver from the view of reality.

Chapter 6

Conclusions and Future Work

In this thesis, a visible light communication system for indoor application is designed and evaluated by taking the following steps:

1. The designed VLC system employs Butterworth filters to replace the matched filters, in order to decrease the cost of equipment. The reason of using Butterworth filter is explained in chapter 4. In chapter 4, we also make a thorough analysis on selecting proper FEC code in order to maintain or exceed the performance of the matched filter system.
2. The energy spectrums of sunlight and some common indoor artificial lights is analyzed by us, for the purpose of identifying the suitable optical band for transmission of communication signals. The electric spectrum at the receiver side also needs to be taken into consideration, in order to determine the level of bit rate that should be used. We should avoid strong electric noise introduced by surroundings optical noise sources. To determine the maximum achievable bit rate that could support a certain level of BER performance is our final goal.
3. By acquiring many simulation results, we determine how the ESNR changes when the node's location or incidence/irradiance angle is changing.

4. We determined the validity of the “point source” and “point receiver” assumption broadly maid, when using large structures, e.g. an array of photodetectors. Specific results are provided.
5. Finally, a software package using a user friendly GUI to input parameters and output results was implemented. After inputting the parameters, and choosing a certain modulation scheme with FEC code, a BER result is shown on the screen as an output. This product could be a very convenient tool to manufacturers as well as to those deploying visual lights within some space.

From our work, following things can be concluded:

First, VLC is a promising candidate for next generation’s indoor wireless communication system. The advantages of VLC systems includes low cost equipment, avoid eavesdropping, unlicensed communication bandwidth, low energy consumption. But due to the current technology, the communication data rate is limited to several M bps.

Second, the designed optical OOK/BFSK communication systems can provide good performance for indoor use within a certain communication range. This communication range is decided by combining a number of parameters, such as incident angle, irradiant angle, and communication distance. We provide several circumstances in this thesis to show systems’ performance with different parameters. ESNR is utilized to represent the communication range in our work.

Third, to reduce the overall cost, we make the following decisions based on analysis. Butterworth filter, Golay codes and OOK/BFSK schemes are selected in our design. Although they cannot provide the best performance for our systems, there is always a trade-off between cost and performance. Based on our analysis and simulation results, our choices are perfectly matched our project goal.

In the future work, we would like to continue our research with experiments. If we can measure the spectrum of ambient light, we will have sufficient data to make our analysis more reasonable, and our simulation software more accurate. Other modulation schemes will be employed in next step. For example, to utilize bandwidth more efficiently, optical OFDM scheme is considered to be investigated later.

Appendix I

Indoor Artificial Light Spectrum Analysis

To select suitable spectrum curves for indoor artificial lights (fluorescent and incandescent), results from different independent experiments are compared:

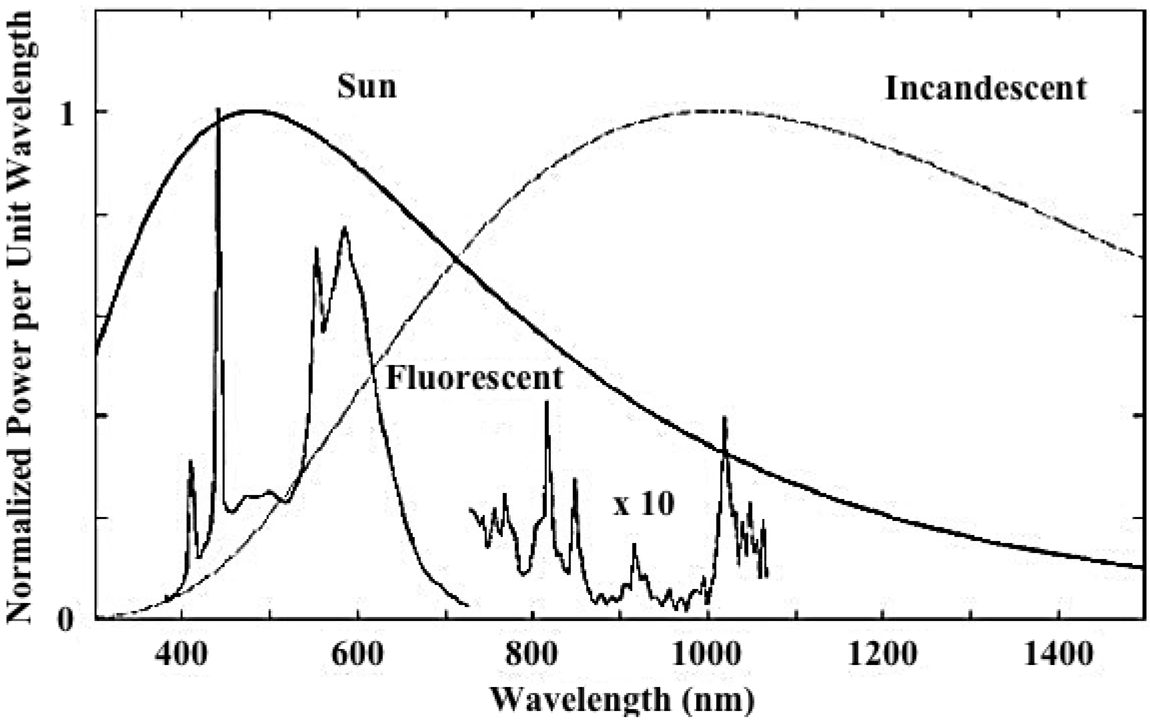


Figure 1 Spectral behaviour of: (a) Sunlight;
(b) Incandescent (tungsten) lamp;
(c) Fluorescent bulb. [20]

This is the figure utilized in this thesis. In [20], Magnatek Tread model B240R120 fluorescent and Phillips model SLS15 incandescent were employed as indoor artificial lights to make these curves. Similar figures from other sources can be obtained as bellow:

Figure 2 [153] and Figure 3 [154] show experience results of using General Electric "warm white" code number "f30t12wwrs" fluorescent and a typical incandescent respectively. We can learn that, fluorescent and incandescent spectrum curves in Figure 2 and Figure 3 are very similar to their counterpart in Figure 1.

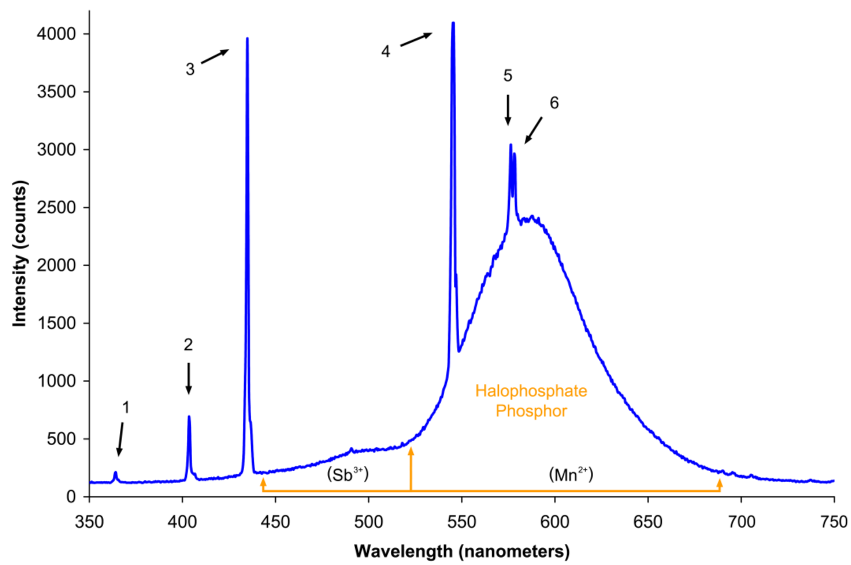


Figure 2 Spectrum of a typical fluorescent light [153]

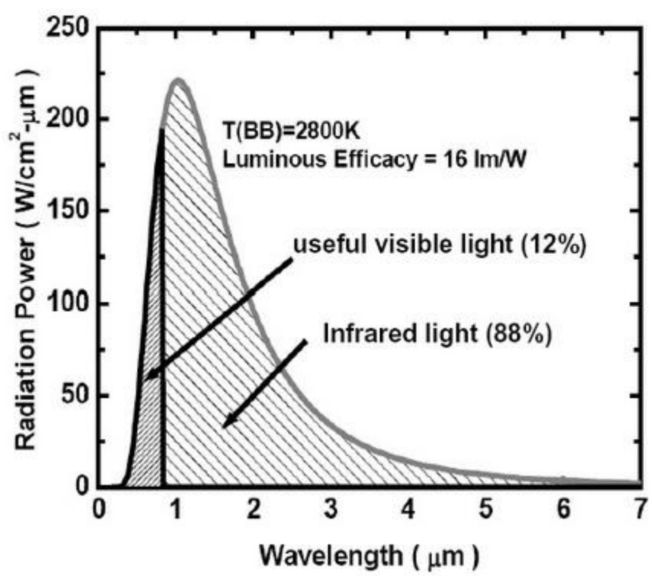


Figure 3 Spectrum of a typical incandescent [154]

Appendix II

Optical Communication System Simulation Software User Guide

This product (Optical Wireless Communication Systems Simulation Tool) is created based on MATLAB, please follow the under steps to use this product.

Step 1:

Open MATLAB product and input "guide" at the command window.

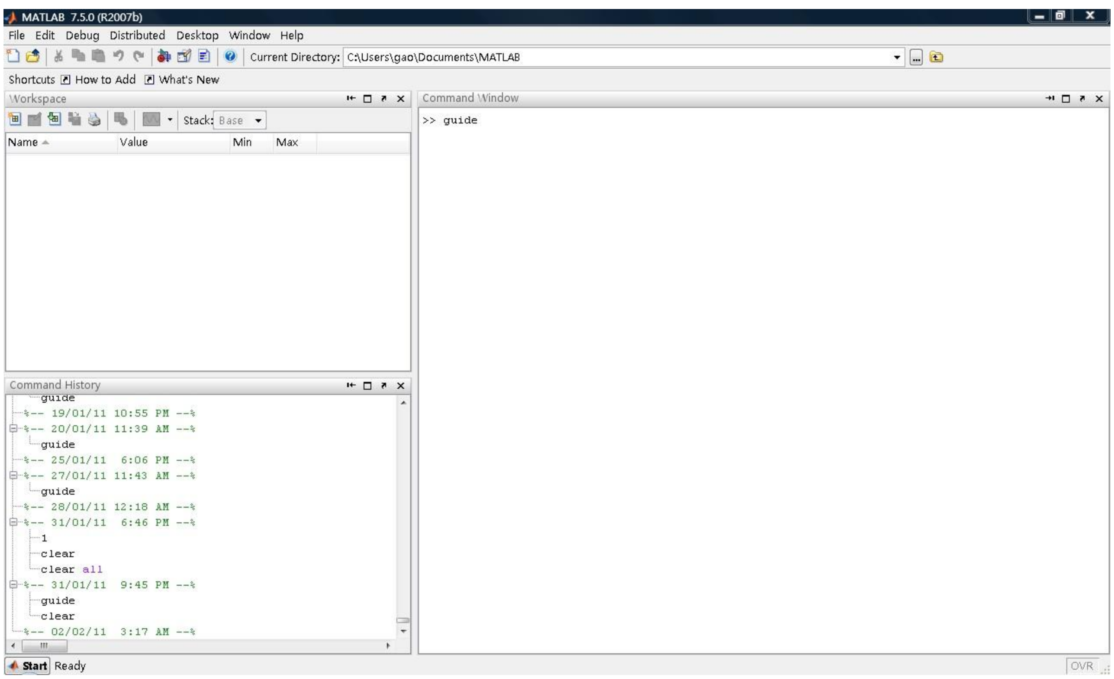


Figure 1 User interface of MATLAB (R200b).

Step 2:

Choose "Open Existing GUI", and then click "Browse" to find and open the product file. File's name:

<OpticalSystem.fig>

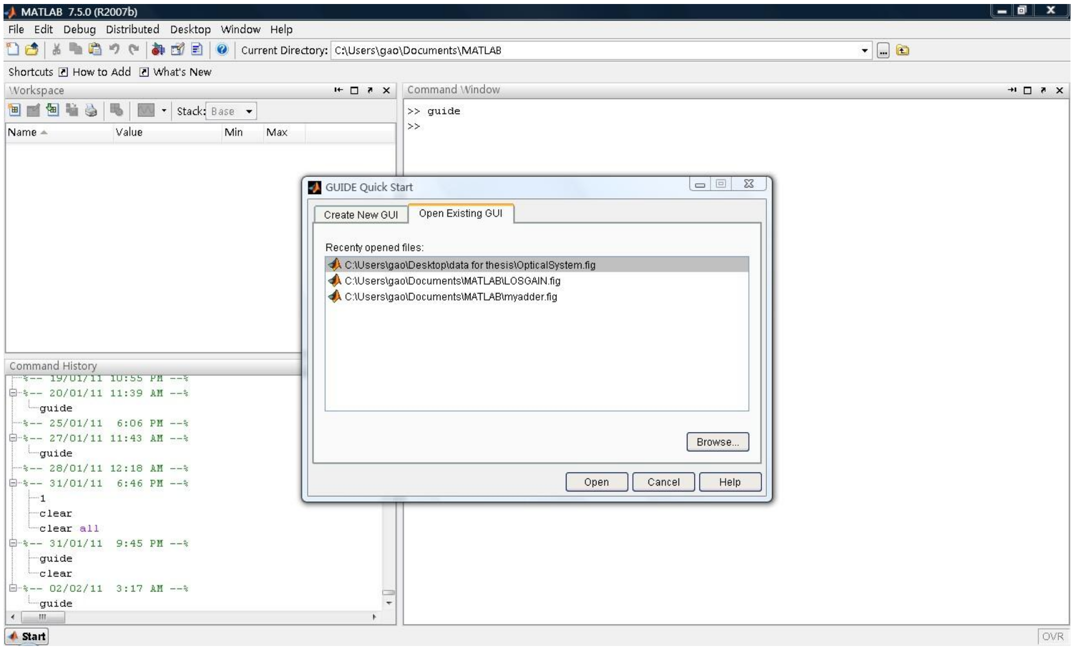


Figure 2 Software installation procedure.

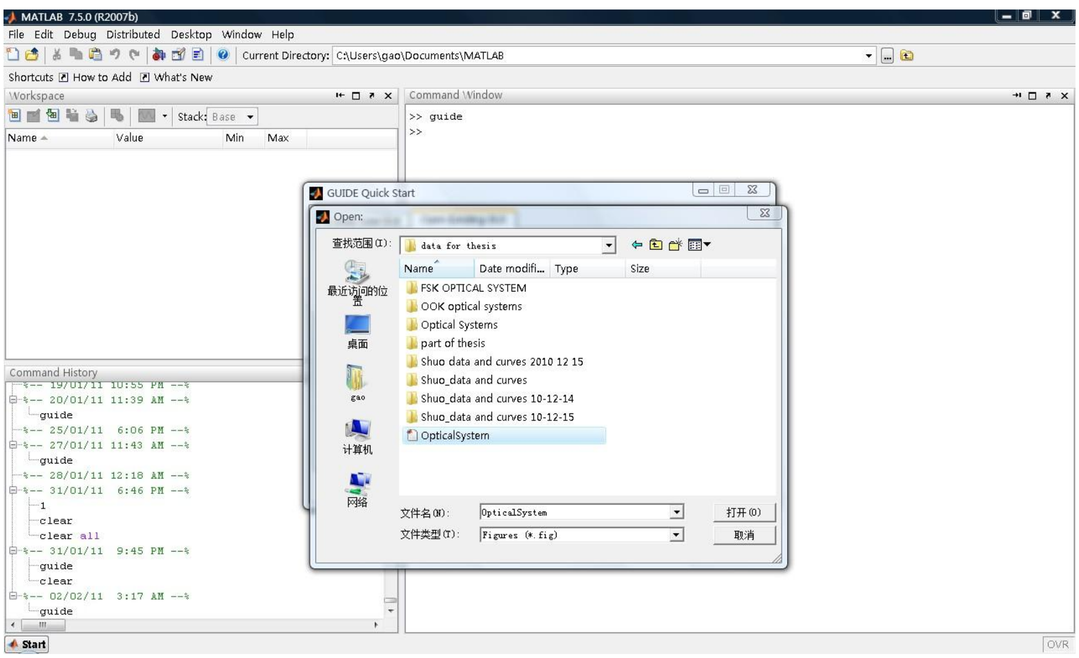
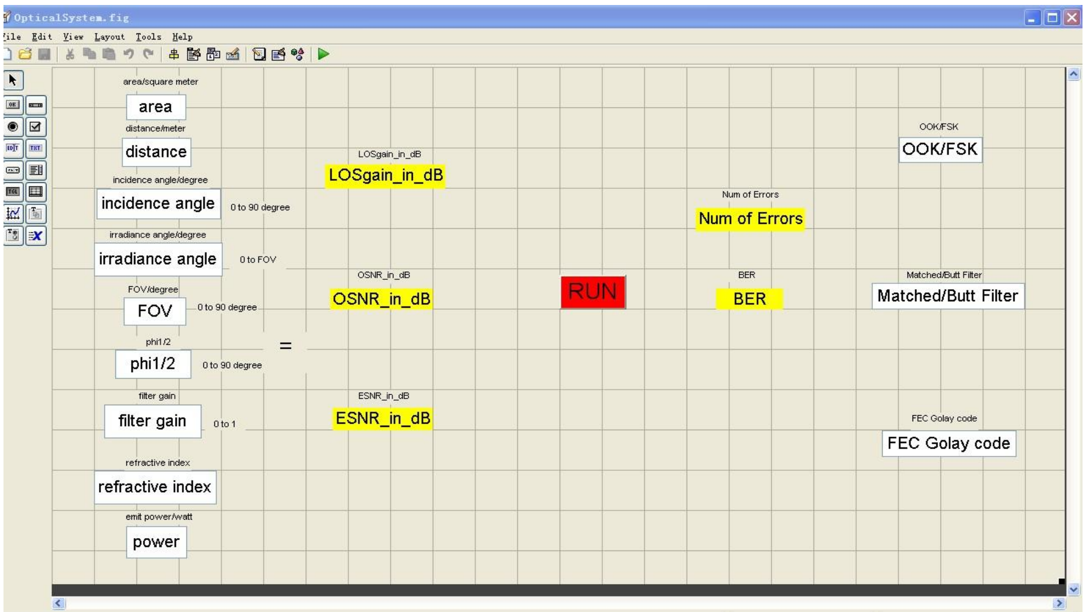


Figure 3 Software installation procedure.

Step 3:

Click the button "RUN"  of the first picture, then the operation panel (the second picture) will be shown.



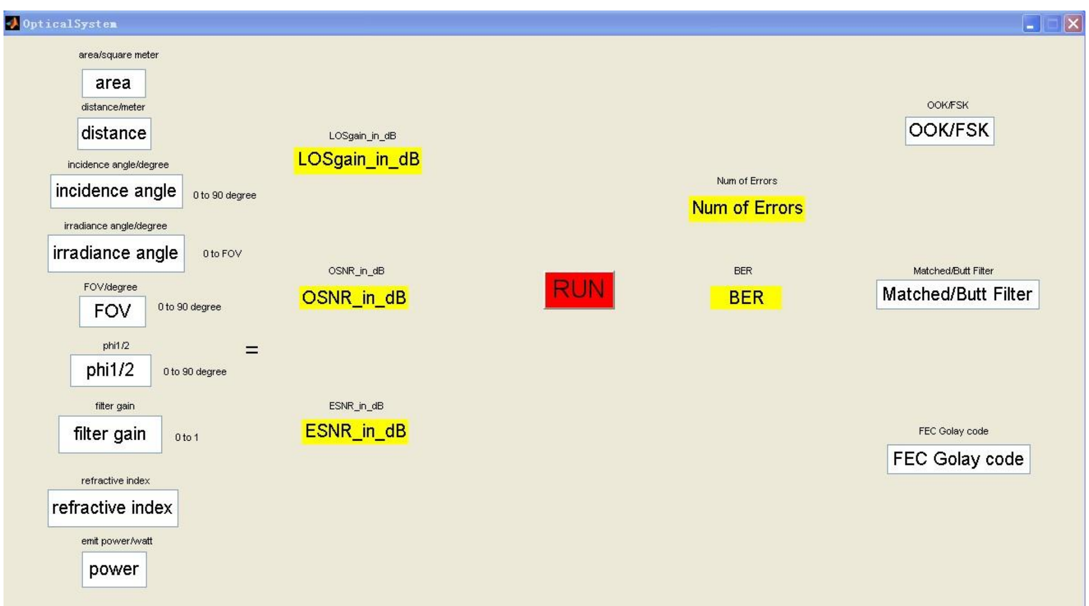


Figure 4 Optical communication system software interface.

There are two parts of the Operation Panel, the left part is used to calculate the LOS channel gain, and the right part is used to simulate the OOK and FSK Optical Systems. The units of parameters for calculating the channel gain are as below:

Area	Square meter
Distance	Meter
Incidence angle	degree
Irradiance angle	degree
FOV	degree
Phi1/2	degree
Power	Watt

Table 1 Parameters of optical communication system software interface.

Filter gain: the signal transmission of the filter.

Represent an average over the filter transmission at different wavelengths (if the source spectrum is not narrow) and/or angles of incidence upon the filter (if different rays strike the filter at different angles of incidence). All losses arising from reflections, e.g., at the concentrator detector interface) are included in it.

For the simulation part, we use 0 and 1 to represent different schemes.

:

0: OOK

1: FSK

:

0: Matched Filter

1: Butterworth Filter

FEC Golay code:

0: No FEC code

1: One layer Golay code (12,23,7)

2: Two layers Golay code (12,23,7)

Example

An OOK optical system, Butterworth filter and no Golay code should be set as follow:

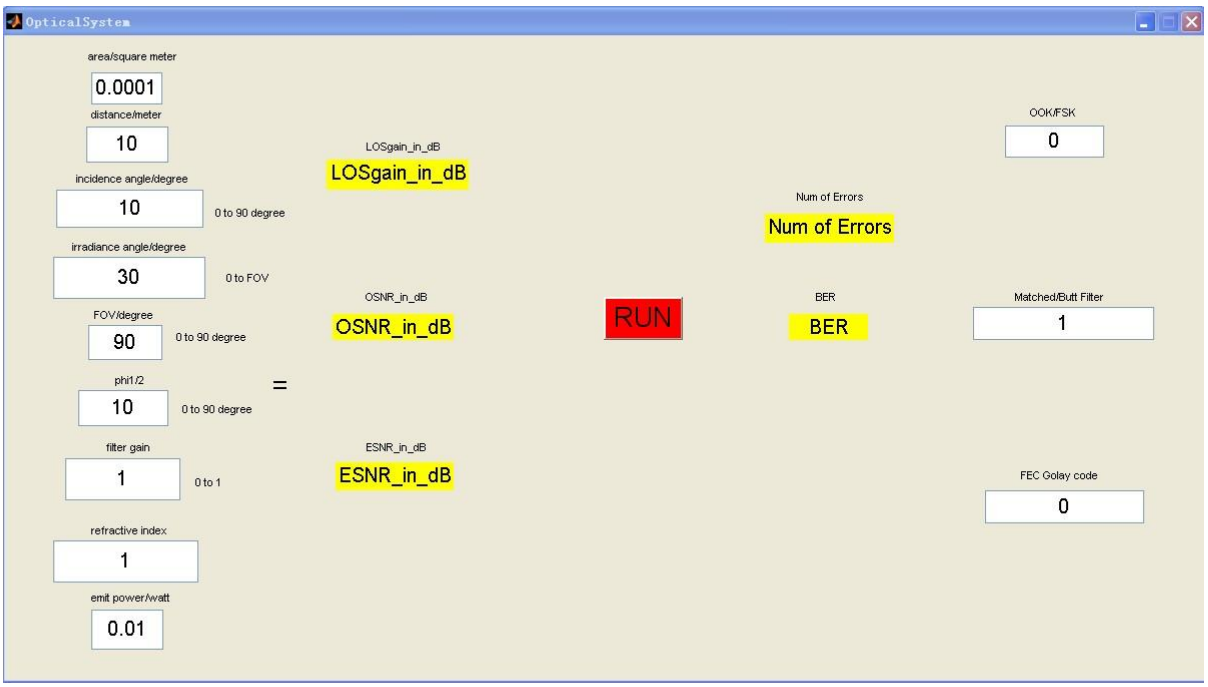


Figure 5 An example of software input.

And the result will be shown as:

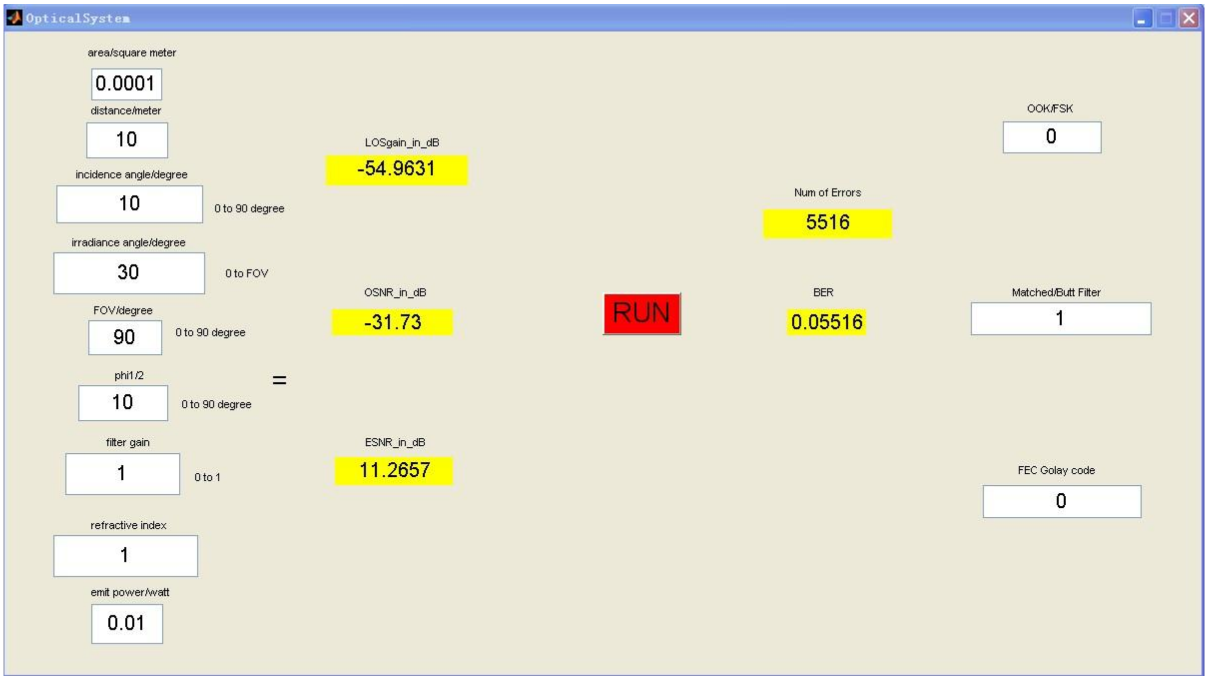


Figure 6 An example of software output.

Due to the limitation of the operation time, this product can only work for the bit error rate larger than 10^{-4} .

If you want to make another simulation, just need to modify the parameters in the background with white color, and then click "run" button.

For FSK optical systems, there are 6 scenarios:

1: FSK with non-coherent detection and matched filter (1 0 0);

2: FSK with non-coherent detection matched filter and one layer Golay code (1 0 1);

3: FSK with non-coherent detection matched filter and twolayer Golay code (1 0 2);

4: FSK with non-coherent detection and Butterworth filter (1 1 0);

5: FSK with non-coherent detection Butterworth filter and one layer Golay code (1 1 1);

6: FSK with non-coherent detection Butterworth filter and one layer Golay code (1 1 2).

For OOK optical systems, there are 6 scenarios:

1: OOK with non-coherent detection and matched filter (0 0 0);

2: OOK with non-coherent detection matched filter and one layer Golay code (0 0 1);

3: OOK with non-coherent detection matched filter and two layer Golay code (0 0 2);

4: OOK with non-coherent detection and Butterworth filter (0 1 0);

5: OOK with non-coherent detection Butterworth filter and one layer Golay code (0 1 1);

6: OOK with non-coherent detection Butterworth filter and one layer Golay code (0 1 2).

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