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SAC-OCDMA IN FREE SPACE OPTICAL NETWORKS USING MULTI-WAVELENGTH LASER SOURCE

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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SAC-OCDMA IN FREE SPACE OPTICAL NETWORKS USING MULTI-WAVELENGTH LASER SOURCE

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Free space optical (FSO) networks offer high speed and secure communication system. To utilize the bandwidth of FSO networks efficiently, spectral amplitude coding optical code division multiple access (SAC-OCDMA) is proposed as a solution. The reason is that OCDMA in general and especially SAC have robustness against atmospheric effects. So far, few investigations have been done to evaluate the performance of the SAC-OCDMA in FSO. However, Most of them used broadband sources as transmitter which is not suitable for outdoor FSO networks due to their wide beam divergence (about 8 mrad) and low modulation bandwidth (about 200 MHz). On the other hand, multi-wavelength laser source are becoming more available with regards to cost and variety. The work in this thesis focuses on design, development and enhancement of the SAC system in FSO networks deploying multi-wavelength laser source. Three main contributions are presented which have been proved mathematically and using simulation software. The feasibility of the proposed system is also implemented using proof-of-concept hardware experiment.

As the first contribution, a mathematical model that represents the characteristics of SAC system in FSO networks is designed and developed. In addition to the impact of turbulence, influences of several system noises, such as, relative intensity noise (RIN), optical beat interference (OBI), shot noise and thermal noise have been studied. From the numerical results, it is found that the proposed system could achieve up to 2.7 km of transmission distance with 10 users.

As the second contribution, the performance of the aforementioned system is improved by proposing a new code namely double weight zero-cross correlation (DW-ZCC). It is shown that in comparison with modified double weight (MDW) and ZCC codes, DW-ZCC can improve the performance and transmission distance by at least 350 m and 200 m respectively.

As the third contribution, the study of the system is extended to quality of service (QoS) area. For this purpose, based on the promising results of DW-ZCC in theoretical analysis, a variable weight code is proposed namely multi-service ZCC (MS-ZCC) which can provide service differentiation capability. Moreover, in comparison with previous code namely variable weight ZCC, the results shows that MS-ZCC can improve the system performance in term of number of users with 10 and 22 users for weights $W = 4$ and $W = 8$ respectively.

For the next stage, the proposed system is implemented using Optisystem version 10 simulation software and hardware experimentation. Simulation results approve the mathematical approach and it is shown that DW-ZCC provides better performance compared to MDW and ZCC. In the experimental section, DW-ZCC is compared with MDW in back-to-back setting with broadband source deployment. With regards to required input power to attain threshold of 10^{-3} BER, MDW needs -2dBm, while this value is -13 dBm for DW-ZCC which shows 11 dBm improvement for DW-ZCC.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

TAJUK PENGGUNAAN PELBAGAI GELOMBANG LASER BAGI KEGUNAAN SAC-OCDMA DALAM RANGKAIAN BEBAS OPTIK

Oleh

MAJID MOGHADDASI

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Rangkaian ruang bebas optik (FSO) menawarkan kelajuan yang tinggi dan sistem komunikasi yang selamat. Untuk penggunaan jalur lebar FSO yang cekap, amplitud spektrum pengekodan pembahagian kod optik akses pelbagai (SAC-OCDMA) adalah alternatif yang sesuai. Ini kerana OCDMA secara amnya dan terutamanya SAC mempunyai daya tahan yang tinggi terhadap kesan atmosfera. Setakat ini, beberapa penyelidikan telah dilakukan untuk menilai prestasi SAC-OCDMA dalam FSO. Walau bagaimanapun kesemuanya menggunakan sumber jalur lebar sebagai penghantar dan tidak sesuai untuk rangkaian FSO luar disebabkan perbezaan pancaran lebar (kira-kira 8 mrad) dan jalur lebar modulasi rendah (kira-kira 200 MHz). Sebaliknya, laser yang mempunyai panjang gelombang pelbagai menjadi pilihan kerana lebih sesuai dengan kos dan isu pelbagai. Penyellidikan di dalam tesis ini memberi tumpuan kepada reka bentuk, pembangunan dan naik taraf sistem SAC dalam rangkaian FSO menggunakan sumber laser yang mempunyai pelbagai panjang gelombang dan menawarkan tiga sumbangan utama yang terbukti secara matematik dan menggunakan perisian simulasi analisis. Kemudian untuk membuktikan konsep yang dicadangkan, keputusan yang diperolehi disemak dan dinilai menggunakan analisis eksperimen.

Di peringkat awal, model matematik yang mewakili ciri-ciri sistem SAC dalam rangkaian FSO direka dan dibangunkan. Selain kesan pergolakan, kesan daripada gangguan dari sistem, seperti gangguan kekuatan bersama (RIN), rentak gangguan optik (OBI) bunyi ditembak dan bunyi haba telah dikaji. Daripada keputusan berangka, didapati bahawa pengaruh OBI boleh mencapai sehingga 2.7 km jarak penghantaran dengan jumlah pengguna 10 orang.

Sebagai sumbangan kedua, prestasi sistem yang dinyatakan di atas adalah lebih baik dengan mencadangkan satu kod baru iaitu dua berat sifar silang korelasi (DW-ZCC). Ia menunjukkan bahawa perbandingan dengan MDW dan ZCC, kod DW-ZCC boleh meningkatkan setiap prestasi dan jarak penghantaran sekurang-kurangnya 400m dan 200m.

Sebagai sumbangan ketiga, kajian sistem ini diperluaskan untuk kualiti perkhidmatan (QoS) kawasan. Bagi tujuan ini, berdasarkan keputusan memberangsanganakan DW-ZCC secara teori, kod berat boleh ubah dicadangkan iaitu pelbagai perkhidmatan ZCC (MS-ZCC) yang boleh menyediakan keupayaan perbezaan perkhidmatan. Selain itu, keputusan menunjukkan bahawa MS-ZCC boleh meningkatkan prestasi sistem dari segi bilangan pengguna dengan 10 dan 22 pengguna untuk berat $W = 4$ dan $W = 8$ masing-masing.

Untuk peringkat seterusnya, sistem yang dicadangkan dilaksanakan menggunakan perisian simulasi Optisystem versi 10 dan eksperimen. Keputusan simulasi setuju dengan teori matematik dan ia menunjukkan bahawa DW-ZCC memberikan prestasi yang lebih baik berbanding MDW dan ZCC. Dalam seksyen eksperimen, DW-ZCC dibandingkan dengan MDW. Disebabkan kekurangan peralatan, sistem ini dilaksanakan sebagai sistem “back-to-back” dan sumber jalur lebar, yang tidak berubah keunggulan kod dalam berbanding dengan kod lain. Berkaitan dengan kuasa input yang diperlukan untuk mencapai ambang log BER = -3, MDW perlu -2dBm manakala nilai ini memerlukan -13 dBm untuk DW-ZCC yang menunjukkan 11 dBm penambahbaikan untuk DW-ZCC.

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Lastly, this hard work was impossible to finish without the continuous love and infinite support from my family and I wouldn't be able to finish it without them. I dedicate this thesis to my beloved family.

I certify that a Thesis Examination Committee has met on 20 January 2017 to conduct the final examination of Majid Moghaddasi on his thesis entitled "SAC-OCDMA in Free Space Optical Networks using Multi-Wavelength Laser Source" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Brillion Scattering
CDRH	Center for Devices and Radiological Health
CS	Complementary Subtraction
CWH	Walsh-Hadamard
DCF	Dispersion Compensating Fiber
DD	Direct Decoding
DW-ZCC	Double Weight ZCC
EDFA	Erbium-Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FEC	Forward Error Correction
FFH	Fast Frequency Hopping
FSO	Free Space Optic
FWM	Four-Wave Mixing
GPSK	Quadrature Phase Shift Keying
GSFC	Goddard Space Flight Center
HDTV	High Quality Videos
IEC	International Electrotechnical Commission
KS	Khazani-Syed
LCRD	Laser Communication Relay Demonstration
LED	Light Emitting Diode

LOS	Line of Sight
MAI	Multiple Access Interference
MDW	Modified Double Weight
MQC	Modified Quadratic Congruence
MZM	Mach-Zehnder Modulator
NASA	National Aeronautics and Space Administration
OBI	Optical Beat Interference
OCDMA	Optical Code Division Multiple Access
OOC	Optical Orthogonal Code
OOK	On-Off Keying
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
OTDMA	Optical Time Division Multiple Access
OWDM	Optical Wavelength Division Multiplexing
PC	Prime Code
PDF	Probability Density Function
PIIN	Phase Induced Intensity Noise
PPM	Pulse Position Multiplexing
QoS	Quality of Service
RF	Radio Frequency
RIN	Relative Intensity Noise
ROC	Random Optical Code
ROP	Received Optical Power
RS	Reed-Solomon
RS	Raman Scattering

SAC	Spectral Amplitude Coding
SMF	Single Mode Fiber
SPE	Spectral Phase-Encoded
SRLED	Supper Radiant LED
TAPCB	Time-Averaging of a Partially Coherent Beam
TLS	Tunable Laser Source
TPE	Temporal Phase Encoding
VoIP	Voice over IP
VW-ZCC	Variable Weight ZCC
ZCC	Zero Cross-Correlation

CHAPTER 1

INTRODUCTION

1.1 Background

The demand for higher bandwidth and longer distance in metro and access level of communication networks has been continuously increasing. Increasing number of users and also new services such as high quality videos (HDTV), online games, voice and video over IP have increased the demand for ultra-high speed networks.

Optical communications provide many advantages compared to other types of communication systems. First of all, the transmission losses in optical fibers are much less than copper wires. This causes longer transmission distance and lesser number of intermediate repeaters which in turn decrease the system cost and complexity. In comparison with copper wires, optical fibers have wider bandwidth that means bigger amount of data can be sent over a single physical line. Other than that, the size and weight of optical fibers are much less than copper wires. This characteristic is even more important for places which weight and size of the cabling is critical. Since optical fibers consist of dielectric materials, they are immune to the electromagnetic interference influences observed in copper wires. Also, the security in optical fiber is high. Since the optical signal is confined inside the fiber, it is immune of being tapped, thus suitable for applications which security is an important issue for them [1].

Generally, in optical communication systems, optical fiber is more reliable transmission medium than free space optic (FSO). However optical fiber has its own issues and in some places, it is not possible or reasonable to be used. For example in areas which valleys or buildings prohibit the installation of fiber or inter satellite communications where space is the medium. Also in some situations the hosts/clients locations are not permanent and their places are changed. In all of the aforementioned situations, optical fiber installation is not possible. Moreover, if the system is required to be used temporarily, the costly fiber installation is not practical. It should be noted that although fiber is technologically superior to FSO, it is significantly more costly (at least five times) and the installation process time, is much longer compared to FSO installation (months versus hours) [2]. Another considerable aspect to take note is the environmental advantages of free-space optics. Fiber requires digging of trenches, which might cause cutting of trees, pollution, and destruction of historical places. FSO does not need these processes, therefore, it can be considered as green technology. On the other hand, as compared to radio frequency (RF) systems, FSO has many advantages. RF networks require immense investments to attain the spectrum license. Although RF-based networks are able to go longer distances, in comparison with FSO networks, they cannot provide high speed communications as FSO. Moreover, FSO networks (FSON) provide flexibility, security, and reduced time-to the market [2]. One of the applications of FSON is in “last mile” part of the optical networks. A study in U.S.A showed that more than 95% of business zones are located at less than one mile from an optical fiber node. It shows the importance of high data rate which FSON can provide it [3].

FSO networks can be utilized in military applications and also in inter-satellite communications to track and communicate with spacecraft in deep space to attain better performance with smaller size apertures and at lower power [4]. It can be divided into two categories: namely indoor and outdoor. In the indoor FSO networks, light emitting diode (LED) is preferred due to eye safety, high reliability and low cost as compared to laser. However, in the outdoor, beside channel loss, turbulence is the main source of impairment. Since an FSO network is mostly implemented in access network, it must be capable to interconnect with core network which includes single mode fiber and probably erbium-doped fiber amplifiers (EDFA) and wavelength division multiplexing (WDM) [5-6]. FSO networks are strongly dependent on the atmospheric conditions and without any doubt; this uncertainty is the biggest challenge in these systems. Also there is maximum allowable transmission power due to safety issue. Moreover, it requires strict alignment and line of sight (LOS) [7].

Lots of enhancements have been attained in FSO systems in the past few years. Recently, 100 Tb/s was achieved using orbital angular momentum mode-division-multiplexing in combination with wavelength-division-multiplexing and utilizing quadrature phase shift keying (QPSK) modulation format [8]. In inter satellite communication, the Laser Communication Relay Demonstration (LCRD) at 1.25 Gbps to geosynchronous satellites is currently under development at the National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC) with an anticipated launch date in 2016 [4].

On the other hand, in a communication system, the whole available bandwidth should be utilized to satisfy the demand for high bandwidth in future information networks. Optical networks are not exception and suitable multiplexing technologies must be used to deal with this issue hence increase the total system throughput. There are three common multiple access systems that will be discussed in this thesis which are capable of utilizing the shared bandwidth efficiently, which are Optical Time Division Multiple Access (OTDMA), Wavelength Division Multiple Access (WDMA) and Optical Code Division Multiple Access (OCDMA).

OTDMA is a technique where a pre-assigned time-slot is allocated for each channel. Although optical TDMA (OTDMA) systems can offer a large number of addresses, the performance of OTDMA systems is ultimately restricted by the time dependent nature of the technology. WDMA is a conventional method which allows different users to access the same channel. However, WDM requires multiplexers or individual tunable filters at the receiver which associates power loss [9]. OCDMA is a technology that provides multiple access ability in an optical communication system. In optical CDMA, each user is distinguished by an assigned optical signature code rather than a time slot in TDMA or wavelength in a WDMA. As a result, this system can provide asynchronous access to the network for multiple users. Here, the number of active transmitting users will determine the network performance [10]. OCDMA has many advantages compared to other multiple access techniques including security and quality of service (QoS) provision in physical layer, asynchronous access, compatibility with other multiplexing systems and network scalability which makes it feasible for bursty traffic [11-12]. Furthermore, OCDMA has robustness against atmospheric effects [13]. Therefore, this system is a strong candidate for the next generation high-speed access system which can be combined with FSON [14-15]. In this way, the benefits of both OCDMA and FSO technologies can be utilized. Many researchers investigated the idea of FSO-CDMA and most evaluated the effect of turbulence on OCDMA using either temporal or two-dimensional (2D) encoding schemes [16-18]. Considering that free space as a medium is much noisier than an optical fiber, OCDMA with spectral encoding scheme is better than the temporal schemes [10]. Spectral amplitude coding (SAC) is a type of OCDMA encoding which is popular in recent years due to its simplicity and asynchronous nature. Therefore, the implementation of SAC-OCDMA in an FSO system could be a promising solution for last mile bottleneck problem.

1.2 Problem Statement

SAC is a proper candidate to be used in current and future last mile optical networks. Several investigations have been done for SAC-OCDMA with optical fiber as transmission medium [19-20]. Nevertheless, only few studies have evaluated an SAC-OCDMA in FSO environments and none of them offered a comprehensive and reliable performance analysis for this system [21-23]. Moreover, the implemented researches used light emitting diode (LED) as source, while for high speed and robust outdoor communication, laser source is needed. The reason is that LED provides a wide optical spectral width (25 nm) and wide output beam divergence (8 mrad). Moreover, the speed is only limited to few hundreds megabits per second. Besides, maximum peak output power of LED which is launched into single mode fiber (SMF) is limited to -12.2 dBm. It should be noted that although super radiant LED (SRLED) can launch -6 dBm into the fiber, the output is unstable and not suitable for communication systems. Thus LED output power is considerably low for outdoor FSO applications. Meanwhile, semiconductor lasers are able to launch typically 0 dBm and up to 3dBm into fiber [24-25]. Furthermore, it can provide narrow optical spectral width (0.01 nm) and beam divergence up to (0.1 mrad). They also provide faster modulation and therefore higher transmission data rate [26]. This speed can reach to 10 Gbps for single channel that can be extended using WDM even to 120 Gbps [5, 27]. As a result, outdoor FSO networks with high speed and long range distance are implemented via laser source [28]. A vast and reliable investigation including mathematical approach is highly required. Furthermore, application of such a system is not well known. Thus, QoS provision with improvement of quality in FSO-CDMA could be very useful.

1.3 Objectives

Based on the problems discussed earlier, the objectives of this research are outlined as follows:

1. To design and develop an SAC-OCDMA system in FSON using multi-wavelength laser source.
2. To propose a new code to improve the performance of the SAC-OCDMA in FSON
3. To propose a variable weight OCDMA code for providing QoS suitable for FSON
4. To evaluate the performance of the developed SAC-OCDMA system in FSON

1.4 Scope of the Research

An OCDMA network can be implemented by guided channel (optical fiber) or unguided (wireless). Also OCDMA is generally divided into two different categories; incoherent and coherent, based on the method a particular user's code is applied to an optical signal. In the incoherent approaches intensity modulation and direct detection is utilized when in the coherent counterpart, phase encoding is applied into the optical signal and recovered by phase detection. A coherent OCDMA technique can address the system with high speed and long distance transmission, but it needs complex equipment for phase control, so it is mostly used in core level of the network [29]. On the other hand, incoherent system is much simpler and its components are low in cost which makes it more reasonable in access or even metro networks. Thus in this research, incoherent technology is used. Two approaches were implemented to develop and analyze the performance of SAC-OCDMA in FSO system, which are mathematical approximation and software simulation. In both approaches the effects of optical beat interference, relative intensity noise, shot noise and thermal noise are considered. Bit error rate (BER) in mathematical approach, and BER and eye diagram in simulation approach are used to analyze the system performance with the parameters such as number of users, transmission distance and received optical power per chip. The main focus of this research is to investigate the influence of turbulence beside OCDMA system noises including of thermal noise, shot noise, relative intensity noise (RIN) and optical beat interference (OBI) on the total performance. The scope of this thesis is illustrated in Figure 1.1.

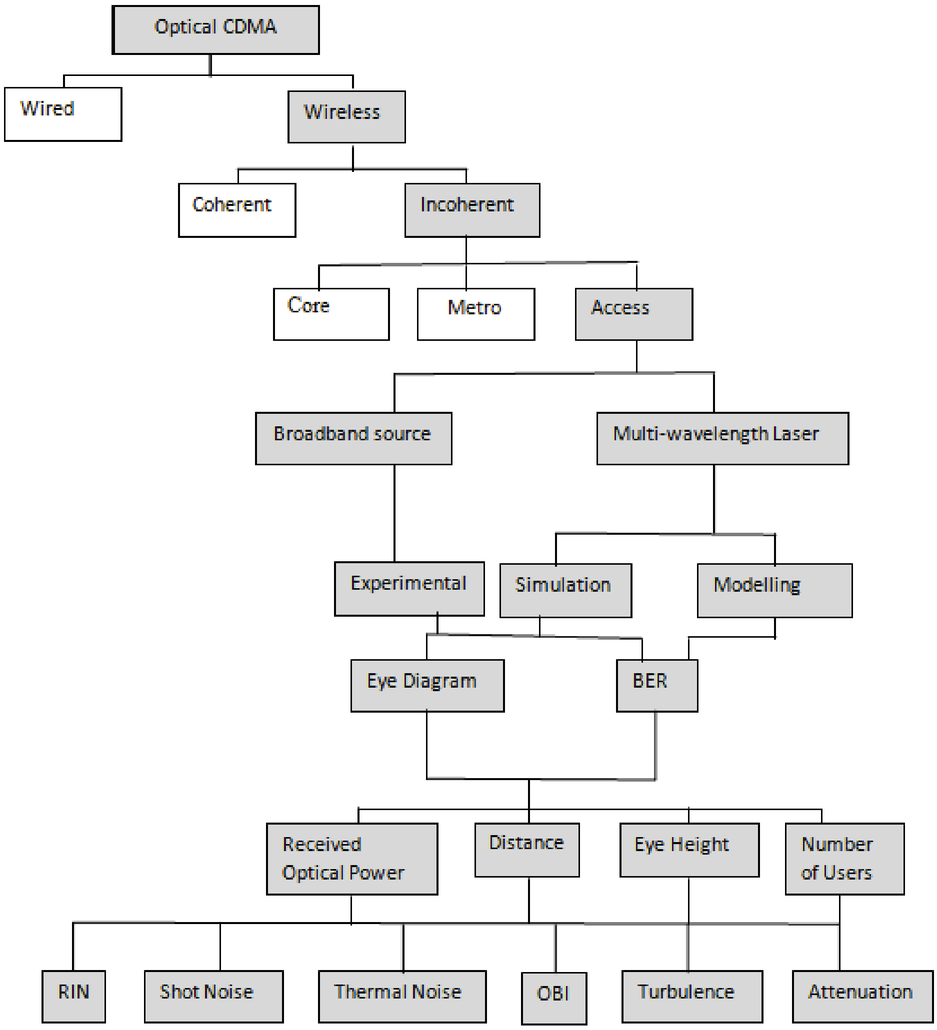

Figure 1.1 : Scope of the Thesis

A brief description of the methods implemented in achieving the outlined objectives is described below.In this thesis, first mathematical model is developed using the method proposed by [30-33]. The system based on spectral amplitude coding (SAC) is developed so that the behavior of the SAC-OCDMA in wireless environment can be investigated for point-to-point topology. The suitability of multi-wavelength source for this system has been mathematically proven using this model. The influence of optical beat interference (OBI), relative intensity noise (RIN), shot noise and thermal noise are investigated. Then a new code is proposed based on zero cross-correlation (ZCC) code which is called double weight ZCC (DW-ZCC). The performance of the code is studied and evaluated using mathematical approximation, simulation software and hardware approach. Then the proposed code is extended for Quality of Service (QoS) or service differentiation as one of the applications of OCDMA. Therefore, variable weight codes are proposed and developed to provide service differentiation capability. The proposed variable weight code is called MS-ZCC.

1.5 Outline of Research

This thesis is organized into 5 chapters. This chapter provides an introduction to FSO and OCDMA, presenting the motivation, problem statement and background of the research. Moreover the scope and objectives of the research are clearly defined and the research activities are presented to clarify the research methodology.

Chapter 2 continues with the overview of FSO networks and optical CDMA systems in term of the effect of system and channel impairments including OBI, RIN, shot noise and thermal noise. Also, different detection methods and influential factors in FSO channel is discussed. Moreover, the service differentiation by variable weight codes is explained. This chapter also gives a brief review of the investigations that have been done in FSO-CDMA area.

Chapter 3 includes theoretical analysis of the proposed system. The parameters and impairments of SAC-OCDMA and FSON are discussed and the performance of this system is presented. In the discussion, comparisons of different detection techniques are evaluated. Moreover, a coding technique for OCDMA is proposed to improve the system performance.

Chapter 4 comprises the performance analysis of the proposed system via simulation software and proof-of-concept hardware approach. All noises which were investigated in Chapter 3, are evaluated in this chapter as well. All associated impairments that have been described in Chapter 3 is discussed together with the different detection techniques deployed in the system. Besides the bit error rate (BER), eye diagram is used to assess the system behavior.

Chapter 5 concludes the whole thesis and major contributions of the whole research work. Future recommendation of this work is also suggested.

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