



**UNIVERSITI PUTRA MALAYSIA**

**IMPROVEMENT OF FREE SPACE OPTICAL COMMUNICATIONS  
USING DOUBLE CARRIER MODULATION/DIFFERENTIAL DETECTION**

**SALASIAH HITAM**

**FK 2006 37**



**IMPROVEMENT OF FREE SPACE OPTICAL  
COMMUNICATIONS USING DOUBLE CARRIER  
MODULATION/DIFFERENTIAL DETECTION**

**SALASIAH HITAM**

**DOCTOR OF PHILOSOPHY  
UNIVERSITI PUTRA MALAYSIA**

**2006**



**IMPROVEMENT OF FREE SPACE OPTICAL COMMUNICATIONS USING  
DOUBLE CARRIER MODULATION/DIFFERENTIAL DETECTION**

**By**

**SALASIAH HITAM**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in  
Fulfilment of Requirement for the Degree of Doctor of Philosophy**

**December 2006**



Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**IMPROVEMENT OF FREE SPACE OPTICAL COMMUNICATIONS USING  
DOUBLE CARRIER MODULATION/DIFFERENTIAL DETECTION**

By

**SALASIAH HITAM**

**December 2006**

**Chairman: Associate Professor Mohamad Khazani Abdullah, PhD**

**Faculty: Engineering**

Free Space Optical (FSO) communications receive growing attention for use in high data rates wireless link with recent commercialization successes. It is an interesting solution to achieve high bandwidth in the ‘last-mile’ problem with economical and fast deployment. However, in the poor weather such as the heavy rainfall and low visibility lead to degradation of the links performance, particularly over ranges of several hundred meters or longer.

Rare usage of FSO communications might be related to factors which are classified as scintillation, absorption, and scattering. In this purpose of studies, the heavy rainfall and low visibility data in Subang Airport, Malaysia were used for the analysis on conventional technique that is Intensity Modulation/Direct Detection (IM/DD) and a new technique namely Double Carrier Modulation/Differential Detection (DCM/Diff.D) as the worst case scenario.



Currently, most FSO communication systems are using the IM/DD which are still subjected to many problems. The main problems associated with FSO transmission systems are; atmospheric loss, geometric loss, mispointing loss, and the inability of the receiver circuit to regenerate the transmitted bits because of low signal power. Another prevalent problem is that of its masking noises. The recovery technique in the IM/DD technique uses an injected voltage level as a threshold into a decision circuit, which decides whether the incoming bit is a '0' or a '1'. This technique has two inherent problems; the instability of the injected threshold voltage, and the complexity of a dynamic threshold processing. Due to these problems, a new technique based on the automatic decision making known as DCM/Diff.D is provided to improve the transmissions.

The performance of IM/DD and DCM/Diff.D was simulated by using commercial simulation software, OptiSystem Version 3.1 and 4. From the simulation results, it appears clearly that the DCM/Diff.D technique improves for more than twice the distance supported by the IM/DD technique under the conditions of heavy rainfall and hazy days. The theoretical development on probability of error and digital signal-to-noise ratio for the worst case scenario also support these results. Another outcome in this thesis is the theoretical derivation on positioning a passive reflector with a time delay produced can be acceptable until 2.5 Gbps.



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

**PEMBAIKAN KOMUNIKASI OPTIK RUANG BEBAS MENGGUNAKAN  
PEMODULATAN PEMBAWA BERGANDA/PENGESAN BERBEZA**

Oleh

**SALASIAH HITAM**

**Disember 2006**

**Pengerusi:                   Profesor Madya Mohamad Khazani Abdullah, PhD**

**Faculti:                     Kejuruteraan**

Opik Ruang Bebas (ORB) mendapat sambutan yang menggalakkan untuk kegunaan talian wayarles kadar data tinggi dengan kejayaan pengkomersilan sejak kebelakangan ini. Ia adalah satu penyelesaian yang penting untuk mendapat lebar jalur besar dan masalah 'batu-terakhir' yang lebih ekonomi dan cepat dalam metropolitan. Walaubagaimanapun, dalam cuaca buruk seperti hujan lebat dan jarak penglihatan yang rendah mengakibatkan prestasi talian degradasi, selalunya terhadap jarak beberapa ratus meter atau lebih.

Penggunaan komunikasi ORB yang jarang mungkin berkaitan dengan faktor-faktor di mana ianya dikelaskan sebagai sintilasi, penyerapan dan penyerakan. Untuk tujuan penyiasatan ini, data hujan lebat dan jarak penglihatan rendah di Lapangan Terbang Subang, Malaysia digunakan untuk analisis teknik yang menjadi kebiasaan iaitu Pemodulatan Keamatan/Pengesanan Terus (PK/PT) dan satu teknik baru dinamakan



Pemodulatan Pembawa Berganda/Pengesan Berbeza (PPB/PB) sebagai senario kes terburuk.

Pada masa sekarang, semua sistem-sistem komunikasi ORB menggunakan PK/PT di mana masih tertakluk kepada beberapa masalah. Masalah utama yang berkaitan dengan sistem penghantaran ORB ialah; kehilangan atmosfera, kehilangan geometrik, kehilangan tidaktumpu dan ketidakbolehan litar penerima menjana semula bit penghantaran disebabkan kuasa isyarat yang lemah. Di antara masalah lain yang wujud ialah diakibatkan oleh hingar. Teknik pemerolehan semula dalam PK/PT menggunakan aras voltan suntikan sebagai satu ambang kepada satu litar keputusan, di mana memutuskan samada bit yang datang adalah 0 atau 1. Skim ini ada dua masalah semulajadi, ketidakstabilan voltan ambang suntikan, dan kerumitan pemrosesan ambang dinamik. Berikutan dari masalah-masalah ini, satu teknik baru berdasarkan pembuat keputusan automatik dikenali PPB/PB dihasilkan untuk membaiki penghantaran.

Prestasi PK/PT dan PPB/PB disimulasi dengan menggunakan perisian simulasi komersil, OptiSystem Versi 3.1 dan 4. Dari keputusan simulasi, ia dilihat dengan jelas bahawa teknik PPB/PB membaiki jarak yang disokong oleh PK/PT sebanyak lebih dari dua kali di bawah keadaan hujan lebat dan berjerebu. Pembangunan teori bagi kebarangkalian ralat dan nisbah isyarat-kepada-hingar digit untuk senario kes paling buruk juga menyokong keputusan ini. Hasil yang lain dari tesis ini ialah penerbitan teori untuk meletakkan satu pembalik pasif di mana masa tunda yang dihasilkan boleh diterima sehingga 2.5 Gbps.

## ACKNOWLEDGEMENTS

Praise is to ALLAH the almighty, for His help and support during the course of life and the moment of truth.

I would like to express my appreciation and sincere gratitude to my supervisor, Associate Professor Dr Mohamad Khazani Abdullah for his continuous support, encouragement and endless patience towards completing the research. These special thanks also dedicated to my supervisory committee member; Associate Professor Dr Mohd Adzir Mahdi and Associate Professor Dr Kaharudin Dimiyati for their invaluable guidance and constructive criticisms throughout the success of this project.

My special thanks to Mrs. Bibi Sarpinah Sheikh Naimullah and Mrs. Wan Azizun Wan Adnan for their help and solving of problems in this project. Special thanks to all my colleagues from, Photonics Lab for their support and encouragement. Working with all of you is a good experience that could never be forgotten. I would also like to express my appreciation to En. Azhar and all staff of Malaysian Meteorological Department, Climate Division, Petaling Jaya for their assistance in data collection.

A huge appreciation to my beloved husband, daughters and son for their continual support and patience made me strong in completing the thesis. Last but not least, I would like to thank my mother-in-law, and the rest of my family who keep encouraging and supporting me in whatever I do. Thank you very much.





I certify that an Examination Committee has met on 21<sup>st</sup> December 2006 to conduct the final examination of Salasiah Hitam on her Doctor of Philosophy thesis entitled “Improvement of Free Space Optical Communications Using Double Carrier Modulation/Differential Detection” in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

**Borhanuddin Mohd Ali, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Sudhanshu Shekar Jamuar, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Khairi Yusof, PhD**

Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Farid Ghani, PhD**

Professor  
School of Electrical and Electronic Engineering Studies  
Universiti Sains Malaysia  
(External Examiner)

---

**HASANAH MOHD. GHAZALI, PhD**

Professor/Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:



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

**Mohammad Khazani Abdullah, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Mohd Adzir Mahdi, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Kaharudin Dimiyati, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Malaya  
(Member)

---

**AINI IDERIS, PhD**

Professor/Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 12 APRIL 2007



## **DECLARATION**

I hereby declare that the thesis is based on my original work except for the quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

---

**SALASIAH HITAM**

Date: 9 FEBRUARY 2007



## LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
ASE	Amplifier Spontaneous Emission
ASIC	Advanced application-Specific Integrated Circuit
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BPFs	Band-Pass Filters
BS	Base Station
CATV	Cable Television
CCR	Corner-Cube Retroreflector
CD	Compact Disc
CD	Chromatic Dispersion
CDRH	Center for Devices and Radiological Health
CLEC	Competitive Local Exchange Carrier
CMRR	Common Mode Rejection Ratio
CNR	Carrier-to-Noise Ratio
CW	Continuous Wave
DPSK	Differential Phase-Shift Keying
DSNR	Digital Signal-to-Noise Ratio
DWDM	Dense Wavelength Division Multiplex
EDFA	Erbium Doped Fiber Amplifier
FDA	Food and Drug Administration



FDDI	Fiber Distributed Data Interface
FEC	Forward Error Correction
FOV	Field-of-View
FSK	Frequency Shift Keyed
FSO	Free Space Optical
FWM	Four Wave Mixing
GL	Geometric loss
HF	High Frequency
i.i.d	Identically Distributed
IEC	International Electrotechnical Commission
IM/DD	Intensity Modulation/Direct Detection
InGaAs	Indium Gallium Arsenide
IR	Infra-Red
ISI	Inter-Symbol Interference
ITU-R	International Telecommunication Union-Radio Communication
LANs	Local Area Networks
LD	Laser Diode
LED	Light Emitting Diode
LO	Local Oscillator
LOS	Line-of-Sight
LPFs	Low Pass Filters
MANs	Metropolitan Access Networks



MSL	Mode-Selective Loss
MST	Malaysian Standard Time
NDSF	Non-Dispersion Shifted Fiber
NRZ	Non Return-to-Zero
OC	Optical Carrier
OOK	On-Off Keying
OSI	Open Systems Interconnect
PC	Personal Computer
PRBS	Pseudo Random Binary Sequence
PSD	Power Spectral Density
RF	Radio Frequency
RIN	Relative Intensity Noise
RMS	Root-Mean-Square
Rx	Receiver
SDH	Synchronous Digital Hierarchy
Si	Silicon
SNR	Signal-to-Noise Ratio
SONET	Synchronous Optical Network
SPM	Self Phase Modulation
ST	Station Time
STM	Synchronous Transfer Mode
Terabps	Tera bit per second
THOR	TeraHertz Operational Reachback



Tx	Transmitter
VCSEL	Vertical-Cavity Surface-Emitting Laser
WDM	Wavelength-Division Multiplexing
XPM	Cross Phase Modulation



## LIST OF FIGURES

Figure		Page
1.1	Study Model Showing the Scope of Study in Propagation	11
1.2	Study Model Showing the Scope of Study in System Design	12
2.1	Point-to-Point Topology	16
2.2	Point-to-Multipoint Topology	17
2.3	Mesh Topology	18
2.4	Ring with Spurs Topology	19
2.5	A 1mrad Beam Divergence Produces a Spot Size of 1m in Diameter at a Range of 1km	23
2.6	Spread of the Central Maximum in the Far Field Diffraction Pattern	24
2.7	Metro Network Extensions	35
2.8	FSO Redundancy Link	36
2.9	Personal Cellular Service (PCS) Backhaul	37
3.1	An Outdoor Point-to-Point FSO System. The Propagation Path Schematically Depicts Free Space Loss	39
3.2	Schematic Showing the Smart Dust Mote [37]	42
3.3	Basic Optical Fiber System	43
3.4	Balanced Photodetector Scheme	46
4.1	The Assumptions of the Position and the Length of the Reflector	53
4.2	Wavelength $> 1400\text{nm}$ ; Light Absorbed in Cornea And Lens(Adapted from Fsona,2001)	62
4.3	(a) Original Bits, A1 (b) Inversion of original bits, A2 (c) The Resultant Subtracted Bits	69





4.4	DCM/Diff.D Model Setup	70
4.5	Distance $D1$ and $D2$	74
4.6	Distance $D3$ and $D4$	75
5.1	Atmospheric Transmittance Measured over a Sea Level 1820 m Horizontal Path [67]	81
5.2	Clear Sky Transmission as a Function of Wavelength for Water (a) and $\text{CO}_2$ (b) [67]	82
5.3	Patterns of Raleigh, Mie, and Non-Selective Scattering [7, 31]	84
5.4	Atmospheric Attenuation as a Function of Low Visibility	90
5.5	Atmospheric Attenuation as a Function of Link Distance	91
5.6	Formation of Small Droplets from a Large Droplet Collision and Coalescence [71]	92
5.7	Scattering Efficiency ( $Q(x)$ ) versus Ratio of Raindrop Radius to Wavelength ( $a/\lambda$ ) [68]	94
5.8	Atmospheric Attenuation as A Function of Rainfall Rate	97
5.9	Atmospheric Attenuation as A Function of Link Distance	98
5.10	Laser Beam Wander Due to Turbulence Cells that are Larger than the Beam Diameter	99
5.11	Scintillation or Fluctuations in Beam Intensity at The Receiver Due to Turbulence Cells that are Smaller than the Beam Diameter	101
5.12	Geometric Loss as a Function of Link Distance	103
5.13	Sunlight Through Raindrop [76]	106
5.14	Nondispersive	108
5.15	Dispersive media	108
5.16	Material Dispersion per Pulse Width as A Function of Link Distance	110
5.17	Material Dispersion as A Function of Wavelength	111



5.18	The Closest Distance Between the Two Channels (Fundamental Concept)	112
5.19	Illustration of the Diffraction-Limited Propagation of a Gaussian Beam	114
5.20	The Closest Distance between the Two Channels (Effective Area Concept)	116
5.21	The Closest Distance as a Function of Distance from Tx to Rx.	117
6.1	Receiver Noise Structure	122
6.2	Poisson Distribution	125
6.3	Photodetector Dark Current Noise Model	132
6.4	1/f Noise Modeling	137
6.5	(a) Fluctuating Signal Generated at the Receiver. (b) Gaussian Probability Densities of 1 and 0 bits	139
6.6	DCM/Diff.D Implementation	141
6.7	Voltage Difference, $V_d$ between $X$ and $V_T$	144
6.8	The Voltage Difference, $V_d$ in IM/DD and DCM/Diff.D	146
6.9	The Probability of Error in IM/DD and DCM/Diff.D	147
6.10	Effect of Distance in Heavy Rainfall	155
6.11	Effect of Distance during Hazy Days in Low Visibility (1550 nm)	156
6.12	Effect of Distance during Hazy Days in Low Visibility (850 nm)	157
6.13	Effect of Distance in Clear Weather	158
6.14	Effect of Distance in Heavy Rainfall Using Simulation Parameters	160
6.15	Effect of Distance in Heavy Rainfall (Noise Cancellation)	165



6.16	Effect of Distance during Hazy Days in Low Visibility (1550 nm) (Noise Cancellation)	166
7.1	Layout Of The Simulated System	169
7.2	BER in Relation to Increasing Distance for DCM/Diff.D and IMDD Techniques Operating at 2.5 Gbps under the Condition of Heavy Rainfall.	172
7.3	A Comparison of the BER Performance under Hazy Conditions at Conditions at Various Distances for both the DCM/Diff.D and IMDD Techniques Set at 2.5 Gbps.	173
7.4	Plotting BER in terms of Distance for both the DCM/Diff.D and IMDD Techniques Set at 2.5 Gbps under Clear Weather Conditions.	174
7.5	Comparing Signal and Noise Power in relation to Distance for both the IM/DD and DCM/Diff.D Techniques.	176
7.6	BER Measured Against Input Power for the IM/DD and DCM/Diff.D Techniques Set at 2.5 Gbps	178
7.7	Output Power and Noise Power as Measured Against Input Power for the IM/DD and DCM/Diff.D Systems Set at 2.5 Gbps	179
7.8	BER Measured against Bit Rate over a 1.5 km Distance under the Condition of Heavy Rainfall	181
7.9	BER Measured over Distance for both the RZ and NRZ Bit Formats	182
7.10	BER versus Electrical Filter Bandwidth	184
7.11	BER versus Distance for 850 nm and 1550 nm	186
7.12	The Time Delay at the 155 Mbps and 1.25 Gbps Bit Rates as a Function of Beam Divergence.	189
7.13	The Time Delay at Bit Rate of 155 Mbps and 1.25 Gbps as a Function of the Angle of Incidence.	191



7.14	The Distance from the Transmitter to the Reflector	192
7.15	The Time Delay for Bit Rate of 155 Mbps and 1.25 Gbps as a Function of Distance from Tx to the Reflector	193
7.16	The Time Delay for Bit Rate of 155 Mbps and 1.25 Gbps as a Function of Receiver Aperture.	195
7.17	Time Delay as a Function of the Bit Rate	196
7.18	The Attenuation as a Function of Distance	197



## LIST OF TABLES

Table		Page
2.1	Diameter of Transmitter and Receiver Aperture of FSO	26
2.2	Selected Detector Material System and Basic Physical Properties	27
4.1	Parameters for Nonlinear Dispersion Shifted Fiber G.652	54
5.1	International Visibility Code Weather Conditions and Precipitation along with Their Visibility, and dB/km Loss at 785 nm.	87
5.2	Data of Haze Visibility	88
5.3	Sample Data Records of Hourly Weather Conditions	95
5.4	Data of Rainfall	96
5.5	Diameter of Transmitter and Receiver Aperture of FSO	103
6.1	Parameters Used In the Calculation	144
6.2	Typical Parameters Used In the Calculation for The Signal Model and The Noise Model	154
6.3	Parameters Used In the Calculation and the Simulation for the Signal Model and the Noise Model	159
7.1	Design Parameters Used in The Calculation of the Time Delay when Beam Divergence is Varied.	188
7.2	Design Parameters Used in Calculating The Effect of Varying Angles of Incidence.	190
7.3	Design Parameters Used in Analyzing The Effect Of Varying The Distance Between The Transmitter And The Reflector	192
7.4	Design Parameters Used in The Analysis Of The Effect Of Varying Receiver Aperture	194
7.5	Design Parameters Used in Analyzing the Effect of Varying Bit Rate.	196





## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL</b>	viii
<b>DECLARATION</b>	x
<b>LIST OF TABLES</b>	xv
<b>LIST OF FIGURES</b>	xvi
<b>LIST OF ABBREVIATION</b>	xxi
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	
1.1 Background	1
1.2 Motivation and Problem Statement	5
1.3 Objectives	7
1.4 Scope of Works	8
1.4.1 Study Structure Description	8
1.5 Thesis Organization	13
<b>2 FREE SPACE OPTICAL COMMUNICATIONS</b>	
2.1 Introduction	15
2.2 FSO Architectures	15
2.3 FSO Performance Considerations	19
2.3.1 Transmission Characteristics (Internal Parameters)	20
2.3.2 External Parameters	28
2.4 FSO Advantages	31
2.4.1 Installation	31
2.4.2 Bandwidth	31
2.4.3 Security	32
2.4.4 Protocol Independence	33
2.5 FSO Applications	33
2.5.1 WI-FI Connectivity	33
2.5.2 Metro Network Extensions	34
2.5.3 Last Mile Access	35
2.5.4 Fiber Backup	35
2.5.5 Backhaul Applications	36
2.6 Conclusion	37



<b>3</b>	<b>IM/DD AND DCM/Diff.D TECHNIQUE</b>	
3.1	Introduction	38
3.2	Current FSO Systems	38
3.3	The Technique Improving Optical Transmission	42
3.4	DCM/Diff.D technique in FSO	48
3.5	Conclusion	49
<b>4</b>	<b>METHODOLOGY</b>	
4.1	Introduction	51
4.2	Methodology	51
4.2.1	Design Parameter	53
4.2.2	Performance Parameter	64
4.2.3	The Novel DCM/Diff.D Model	69
4.2.4	The Reflector Design	73
4.3	Conclusion	77
<b>5.</b>	<b>PROPAGATION STUDIES AND ANALYSIS</b>	
5.1	Introduction	79
5.2	Atmospheric Attenuation	79
5.2.1	Absorption	80
5.2.2	Scattering	83
5.3	Atmospheric Turbulence	98
5.3.1	Beam Wander	99
5.3.2	Scintillation	100
5.4	Alignment	101
5.4.1	Geometric Loss	102
5.4.2	Pointing Loss	104
5.5	Dispersion During Heavy Rainfall	105
5.6	Interference Between Two Channels	111
5.7	Conclusion	117
<b>6</b>	<b>RECEIVER NOISE MODELING, DETECTION AND PERFORMANCE CALCULATIONS</b>	
6.1	Introduction	119
6.2	Noise Analysis Fundamentals	119
6.3	Noise Sources in an Optical Receiver	122
6.3.1	Quantum-Shot Noise	124
6.3.2	Laser Intensity Noise	125
6.3.3	Modal Noise	127
6.3.4	Mode Partition Noise	128
6.3.5	Optical Background Noise	129
6.3.6	Photodetector Shot Noise	130





6.3.7	Photodetector Dark Current Noise	131
6.3.8	Avalanche Photodetector (APD) Excess-Noise	132
6.3.9	Electronic Thermal Noise	133
6.3.10	Electronic Shot Noise	135
6.3.11	1/f Noise	136
6.4	Probability Density Function (PDF)	138
6.4.1	Intensity Modulation/Direct Detection (IM/DD)	138
6.4.2	Double Carrier Modulation/Differential Detection (DCM/Diff.D)	141
6.4.3	Performance Comparison Between IM/DD and DCM/Diff.D	143
6.5	Digital Signal-to-Noise Ratio	147
6.5.1	Signal Model	149
6.5.2	Noise Model	152
6.5.3	Performance Comparison on DSNR	153
6.6	Noise Cancellation in DCM/Diff.D	160
6.6.1	SNR for IM/DD	162
6.6.2	SNR for DCM/Diff.D	162
6.7	Conclusion	166
<b>7</b>	<b>PERFORMANCE OF THE FSO (IM/DD AND DCM/Diff.D) AND THE REFLECTOR</b>	
7.1	Introduction	168
7.2	Simulation Setup for Point to Point Architecture	168
7.3	Simulation Results for Point to Point Architecture	170
7.3.1	The Effect of Distance on System Performance	170
7.3.2	The Effect of Input Power on System Performance	176
7.3.3	The Effect of Bit Rate on System Performance	180
7.3.4	The Effect of Bit Format on System Performance	182
7.3.5	The Effect of Electrical Filter Bandwidth on System Performance	183
7.3.6	The Effect of Wavelength on System Performance	186
7.4	Mathematical Results for The Reflector	187
7.4.1	The Effect of Beam Divergence	188
7.4.2	The Effect of the Angle of Incidence	189
7.4.3	The Effect of Distance Between The Transmitter and The Reflector	191
7.4.4	The Effect of Receiver Aperture	194
7.4.5	The Effect of Bit Rate	195
7.4.6	The Effect of Distance on Attenuation for LOS and Reflector in Clear Weather	197
7.5	Conclusion	198
<b>8</b>	<b>CONCLUSIONS AND FUTURE WORK</b>	
8.1	Conclusion	199
8.2	Future Works	202

