



Extended Free-space Optical Communications

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Abstract

This thesis investigates the performance of free-space optical (FSO) communication systems in a turbulent atmosphere employing optical amplifiers (OAs) to extend transmission reach and wavelength-division multiplexing (WDM) to improve capacity. This system performance is considered in the presence of amplified spontaneous emission (ASE) noise, scintillation, beam spreading, atmospheric attenuation and interchannel crosstalk. In this work, the modulation scheme used is the on-off keying non-return-to-zero and the main performance metric employed is the average bit error rate (BER). Various performance evaluation methods are used to estimate system performance.

Analysis of single link, cascaded OA and WDM FSO communication systems are given and the implications of using both adaptive (to channel state) and non-adaptive decision threshold schemes are analysed. The benefits of amplifier saturation, for example in the form of effective scintillation reduction when a non-adaptive decision threshold scheme is utilised at the receiver for different atmospheric turbulence regimes, are presented. Monte Carlo simulation techniques are used to model the probability distributions of system parameters such as the optical signal power, amplified spontaneous emission noise, optical signal to noise ratio and the average bit error rate due to scintillation.

It is found that the performance of an adaptive decision threshold is superior to a non-adaptive decision threshold for both saturated and fixed gain preamplified receivers and the ability of a saturated gain OA to suppress scintillation is only meaningful for system performance when a non-adaptive

decision threshold is used at the receiver. In a saturated gain preamplified system, the optimum non-adaptive decision threshold is investigated.

An OA cascade can be successfully used to extend reach in FSO communication systems and specific system implementations are presented. The optimal cascade scheme with a non-adaptive receiver would use frequent low gain saturated amplification although this has a cost implication. Furthermore, a saturated gain amplified WDM FSO system with a non-adaptive decision threshold is superior to a non-amplified WDM FSO system with an adaptive decision threshold.

Dedication

This thesis is dedicated to my parents, Professor and Mrs S. O. Bandele, for their unfathomable love and prayers.

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Thank you God, for enriching me in many ways with knowledge and wisdom and for giving me all the strength I needed to complete this thesis.

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Glossary of Abbreviations

AF	Amplify-and-forward
ANSI	American national standards institute
APD	Avalanche photodiode
AR	Antireflective
ASE	Amplified spontaneous emission
ASK	Amplitude shift keying
AWG	Arrayed waveguide grating
BER	Bit error rate
CB	Chernoff Bound
CDF	Cumulative distribution function
CDMA	Code division multiple access
CDRH	Center for devices and radiological health
CENELEC	European committee for electrotechnical standardization
CGM	Cross-gain modulation
CSI	Channel state information
DBR	Distributed Bragg reflector
DD	Direct detection
DF	Decode-and-forward
DFB	Distributed-feedback
DPSK	Differential phase-shift-keying
DWDM	Dense wavelength division multiplexing
EC	External cavity
EDFA	Erbium-doped fibre amplifier
EDFFA	Erbium-doped fluoride fibre amplifier
FEC	Forward error correction
FOAADT	Fixed gain amplified systems with an adaptive decision threshold

FOANADT	Fixed gain amplified systems with a non-adaptive decision threshold
FP	Fabry-Perot
FSO	Free-space optical
FTTB	Fibre-to-the-building
FTTC	Fibre-to-the-curb
FTTH	Fibre-to-the-home
GA	Gaussian Approximation
GaAs	Gallium arsenide
Ge	Germanium
IEC	International electrotechnical commission
IET	Institution of Engineering and Technology
IM	Intensity modulation
InGaAs	Indium gallium arsenide
InGaAsP	Indium gallium arsenide phosphide
InP	Indium phosphide
IR	Infrared
IrDA	Infrared Data Association
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
LASER	Light amplification by stimulated emission of radiation
LED	Light-emitting diode
LIA	Laser Institute of America
LOS	Line-of-sight
MC	Monte Carlo
MCB	Modified Chernoff Bound
MGF	Moment generating function
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MLM	Multiple-longitudinal mode

MLSD	Maximum likelihood sequence detection
MPE	Maximum permissible exposure
NOAADT	Non-amplified systems with an adaptive decision threshold
NOANADT	Non-amplified systems with a non-adaptive decision threshold
NRZ	Non-return-to-zero
OA	Optical amplifier
OBPF	Optical band pass filter
OEO	Optical-electrical-optical
OLT	Optical line termination
ONU	Optical network units
OOK	On-off keying
OSNR	Optical signal-to-noise ratio
PCA	Power control algorithm
PD	Photodiode
PDF	Probability density function
PIN	positive-intrinsic-negative
PON	Passive optical network
PPM	Pulse position modulation
RF	Radio frequency
RZ	Return to zero
Si	Silicon
SL	Semiconductor laser
SLM	Single-longitudinal mode
SOA	Semiconductor optical amplifier
SOANADT	Saturated gain amplified systems with a non-adaptive decision threshold
SPA	Saddle Point Approximation
UV	Ultraviolet
WDM	Wavelength-division multiplexing

Glossary of Symbols

c	Speed of light
h	Planck's constant
q	Electronic charge
η	Quantum efficiency
ν	Frequency of the optical carrier
B_e	Electrical filter noise equivalent bandwidth
κ	Boltzmann's constant respectively. T
R_b	Bit rate
E_g	Energy gap
P	Optical power
P_{ase}	Optical noise power
P_{sat}	OA internal saturation power
G_{ss}	OA small signal (fixed) gain
G	OA operational gain
N_0	ASE power spectral density (PSD)
F_n	Noise figure
σ_{th}^2	Thermal noise variance
σ_{sh}^2	Shot noise variance
σ_{sig-sp}^2	Signal-spontaneous beat noise
σ_{sp-sp}^2	Spontaneous -spontaneous beat noise variance
R_L	Load resistor
i_d	Dark current
R	Responsivity

i	Photocurrent
G_m	Avalanche multiplicative gain
F_A	APD's excess noise factor
E	Optical field
B_{opt}	OBPF bandwidth
m_t	Number of polarisation states parameter
NF	Noise figure
SNR	Signal-to-noise ratio
ω_{sig}	Signal angular frequency
ϕ_{sig}	Signal phase
n	Refractive index
σ_l^2	Scintillation index
p_{atm}	Atmospheric pressure
C_n^2	Refractive index structure parameter
I	Irradiance
$\langle I \rangle$	Average irradiance
σ_R^2	Rytov variance
k	Optical wave number where
λ	Optical wavelength
L_{bs}	Beam spreading loss
d_{rx}	Receiver diameter
ϕ	Beam divergence angle
D	Link length
α	Atmospheric attenuation factor
Q	Q factor

Chapter 1

Introduction

1.1 Background

The use of light for information transmission through the air between different points is known as optical wireless (or free-space optical (FSO)) communication. This form of communication began with the use of fire beacons and smoke signalling techniques around 800 BC and 150 BC respectively. Since then, there have been various advancements in optical wireless communication technology such as the use of signalling lamps in the 2nd century and the use of a semaphore in the 1790s. The photophone (showcased in 1880) can be described as the first optical communication device used for transmission through an unguided medium. Since the discovery of lasers in the 1960s, FSO communication systems have been used for various applications such as television signal transmission, commercial traffic and military operations [1].

Recently, the FSO communication technology has attracted further interest due to the advantages it offers such as being easily deployable, having low

power requirements and a small beam size, having a wide bandwidth and the ability to support more users due to its high data capacity [2-5]. The employment of a FSO communication system has various benefits such as eliminating the cost of purchasing and laying the optical fibre which would be needed in optical fibre communication systems [6-8]. FSO communication systems can also be used as backup for optical fibre communication links, backhaul for cellular communication, disaster recovery, multiple communication networks and ad hoc networks [9-12].

The practical implementation of an FSO link is highly prone to unpredictable severe atmospheric conditions. For instance, beam attenuation can occur as a result of scattering and photon absorption which is caused by rain, fog, snow, aerosol and atmospheric gases. Also, thermal expansion, earth tremors and wind loads can result in high-rise building sway [13, 14]. Due to inhomogeneities in pressure and temperature changes in the atmosphere (even in clear weather conditions), the refractive index varies leading to atmospheric turbulence. The effect of atmospheric turbulence is highly significant because it results in scintillation i.e. fluctuations of the power of the optical signal propagated through the atmosphere. These fluctuations in the received signal power lead to a reduction in system performance. [1, 9, 12, 14]. Various distributions can be used to describe the atmospheric-induced scintillation. The lognormal, K and negative exponential distributions are commonly used to describe the fluctuations in the weak, strong and saturated turbulence regimes respectively while the gamma-gamma distribution is used to describe the fluctuations in the weak to strong turbulence regimes [1]. Different methods that have been proposed in the literature to mitigate the effects of atmospheric

turbulence include aperture averaging [13, 15], the use of a saturated optical amplifier (OA) [16-18], multi-hop transmission and cooperative diversity [19], forward error correction (FEC) with interleaving [20] and spatial diversity [12, 21-23].

OAs may be used to extend reach or improve receiver sensitivity in optical fibre and FSO based communication systems [9, 24]. However, the OA produces noise in the form of amplified spontaneous emission (ASE) which limits system performance [9, 22]. The on-off keying (OOK) modulation format is widely used in optical communication systems due to its simplicity but it requires an adaptive decision threshold to perform optimally in a turbulent atmosphere. Since the practical implementation of an adaptive decision threshold is not easy, it is desirable to obtain acceptable performances with a non-adaptive decision threshold [12]. The need to simultaneously connect multiple users to network services has brought about the development of systems such as wavelength-division multiplexing (WDM) passive optical networks (PONs). However, crosstalk (which causes a reduction in system performance) can occur in WDM systems due to factors such as imperfections in the optical components (e.g. demultiplexer) used [25, 26].

The purpose of this work is to investigate schemes for improving performance, extending communication reach and improving the capacity of FSO communication systems affected by atmospheric turbulence, beam spreading, atmospheric attenuation, ASE noise and interchannel crosstalk.

1.2 Thesis organisation

This thesis is made up of eight Chapters. The present Chapter contains an overall introduction to the thesis. Chapters 2-4 contains relevant background and literature reviews of FSO communication systems and Chapters 5-7 contains the novel contributions made to knowledge. Conclusions and recommendations for further work are provided in Chapter 8.

Chapter 2 contains more elaborate details about the basics of FSO communication systems and the components required for their successful implementation. The features and applications of FSO communication systems are presented and details about how information is transmitted between different points are discussed. The attributes and modes of operation of the optical components used for the transmission and reception of optical signals are highlighted. In addition, different types of transmitters and photodetectors are reviewed. Various means of improving the optical signal quality (i.e. optical amplification) and reach (i.e. use of multiple communication links) as it traverses the propagation channel are examined. Details about the effects of various impairments (such as noise and linear crosstalk) on the performance of FSO communication system are also reviewed.

Chapter 3 contains details about the atmospheric channel (the FSO channel considered in this work). The effects of atmospheric turbulence on the propagated signal (described with various probabilistic scintillation models) and how the effects limit system performance are reviewed. Other impairments such as pointing and coupling loss, beam spreading and atmospheric attenuation are also discussed. The use of Monte Carlo (MC) simulation

techniques for the modelling of system parameters affected by atmospheric turbulence is highlighted and some of the scintillation mitigation methods already proposed in literature are examined. A review of various modulation techniques used in FSO communication systems is presented in Chapter 4 with particular emphasis on the OOK method. Various performance analysis methods such as the Gaussian Approximation (GA), Chernoff Bound (CB), Modified Chernoff Bound (MCB), and the Saddle Point Approximation (SPA) are also reviewed and compared.

The performance of single link (and single wavelength) FSO communication systems in a turbulent atmosphere are presented in Chapter 5. Non-amplified and amplified FSO communication systems are analysed and the effect of OA gain saturation on system performance (especially its ability to mitigate scintillation even when channel state information (CSI) is not available) is shown. Bit error rate (BER) results (including the effect of ASE noise) are shown for different atmospheric turbulence regimes and various decision thresholding schemes are analysed. Chapter 6 shows the performance of a cascaded OA (with single wavelength) FSO communication system. Fixed and saturated gain OAs are considered and the mitigation of scintillation by employing multiple saturated OAs are shown. The probability distributions (with which system performance can be analysed) of the optical signal power, ASE noise, optical signal-to-noise ratio (OSNR) and BER in various turbulence regimes are obtained by using MC simulation methods. Chapter 7 shows the performance of non-amplified and amplified WDM PON FSO communication systems. Different WDM PON FSO system configurations are analysed (using MC simulation techniques) and compared by determining (for

each system) the obtainable average BER and achievable link length in the presence of ASE noise, interchannel crosstalk and atmospheric turbulence. The thesis concludes with Chapter 8; which contains a general summary, conclusions and suggestions for further work.

1.3 Novel contributions

In Chapter 5, the following novel contributions (part of which led to publication [27]) are made.

- Formulation of a general expression for a non-adaptive decision threshold.
- Investigation and performance modelling (using the GA), in the presence of atmospheric turbulence and ASE noise, of a saturated gain preamplified single link FSO communication system using a non-adaptive decision threshold.
- Investigation of an optimum non-adaptive decision threshold in a saturated gain preamplified single link FSO communication system.
- Investigation and performance modelling (using the CB, MCB and SPA), in the presence of atmospheric turbulence and ASE noise, of a fixed gain preamplified single link FSO communication system using a non-adaptive decision threshold.

In Chapter 6, the following novel contributions (part of which led to publication [27]) are made.

- Investigation and performance modelling (using MC simulation techniques and the GA) of a cascaded OA (with fixed and/or saturated gain) FSO communication system in the presence of atmospheric turbulence and ASE noise using adaptive and non-adaptive decision thresholds.
- Determination of the achievable propagation distances (with adaptive or non-adaptive decision thresholds) for various target BERs in a cascaded OA (with fixed and/or saturated gain) FSO communication system.

In Chapter 7, the following novel contributions are made.

- Investigation and the use of MC simulation techniques for the performance modelling of amplified and non-amplified WDM PON FSO communication systems (with and without a power control algorithm (PCA)) impaired by atmospheric turbulence and interchannel crosstalk. In amplified systems, the effect of ASE noise is incorporated for both fixed and saturated gain OAs.
- Investigation and performance modelling of WDM PON FSO communication systems using adaptive and non-adaptive decision thresholding schemes.
- Determination of the achievable propagation distances (for various target BERs) in various WDM PON FSO communication systems.

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Chapter 2

FSO Communication System: Basics and Components

2.1 Introduction

This Chapter reviews the main components used in free-space optical (FSO) communication systems. The Chapter begins with an introduction to the FSO communication technology; where some features and applications of the technology are presented. The various components involved in the transmission, amplification and reception of information over optical channels are discussed and issues affecting system performance such as noise and crosstalk are highlighted. An overview of laser safety and standards is also given in this Chapter.

2.2 Overview of the FSO communication technology

FSO communication is a form of optical wireless technology where information is transmitted optically at wavelengths ranging from near infrared

(IR) to ultraviolet (UV). It naturally also covers the visible light spectrum [1, 2]. Although, FSO communication systems are predominantly configured as line-of-sight (LOS) (i.e. an arrangement where the transmitting telescope is pointed directly at the receiving telescope without any physical obstruction), non-LOS outdoor and indoor configurations has also been successfully demonstrated [3]. Typical implementations of the FSO technology incorporate the ability to have duplex communication where messages can be concurrently sent and received at both ends of the link [4].

FSO communication systems have features such as:

- A narrow beam which makes alignment with other communication components easier [4]
- Immunity from electromagnetic interference [5, 6]
- A large bandwidth due to its wide wavelength range on the electromagnetic spectrum [4]
- Large capacity: Since the bandwidth is directly related to system capacity, FSO communication systems have the potential to transmit considerably more information than systems based on radio frequency (RF) [5, 7]
- Easily deployable compared to fibre communication systems and consumes low power [4]
- Highly susceptible to unpredictable and sometimes severe atmospheric conditions due to its unguided transmission [4, 8]
- Having an unregulated spectrum unlike RF based communication systems [5, 7]

- Easily integrated with other communication technologies such as fibre and RF based communication systems [4]

FSO communication systems have applications such as:

- Being able to enhance communication from an optical fibre to end users (i.e. last mile access) [6, 9]
- Backhaul for cellular communication and information transmission of code division multiple access (CDMA) signals between the base stations and cell sites [4]
- A back-up link at fast Ethernet speeds for optical fibre networks and for connections between networks of different campuses [4, 9]
- Suitable as a temporary communication solution in case of disaster [4]
- Useful in terrains where it is either impossible or too costly to install fibre optic cables [4, 8]

Note that while the term ‘free space’ refers to unguided channels such as underwater, space and the atmosphere, the focus of this work will be on the atmospheric channel. A FSO communication system is primarily made up of a transmitter, a carrier channel (i.e. the atmosphere) and a receiver [10, 11]. A diagram showing the basic configuration of a FSO communication system is shown in Fig. 2.1. The transmitter converts the information to be sent (i.e. in form of electrical signals) into optical signals and then sends the optical signals through the atmosphere [4, 12]. At the receiver, the optical signal is first converted to an electrical signal and then the sent information is recovered by applying methods such as amplification and signal processing [1, 2, 13].

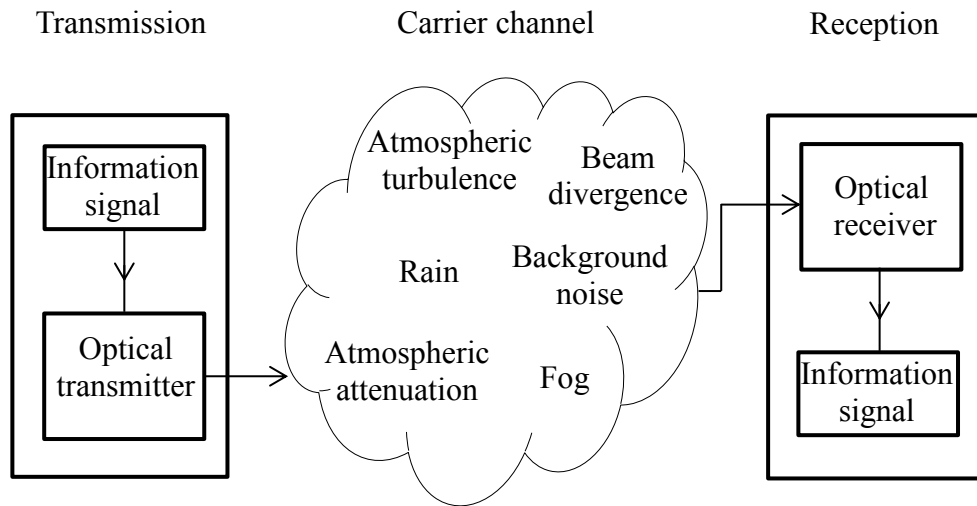


Fig. 2.1: Basic configuration of a FSO communication system.

2.3 The transmitter

At the transmitter, the electrical (information) signal to be transmitted is first converted to an optical signal by modulation (either directly or externally) [2]. In FSO communication systems, the modulated optical signal is transmitted through the atmosphere (where it is prone to impairments such as atmospheric attenuation, geometric spread attenuation, atmospheric turbulence, rain and fog [11]) to an optical receiver [2]. The atmospheric channel is discussed in Chapter 3. Note that a transmitting telescope is used to collimate and direct the optical signal towards the optical receiver [4]. For an optical transmitter to be useful, it is essential that its output power has attributes such as [2, 4, 14]

- High radiance
- Ability to have a steady operation over a long period of time
- Ability to emit radiation at specific wavelengths

- Reliability
- Ability to modulate the information signal easily

Semiconductor lasers (SLs) and light-emitting diodes (LEDs) are the main optical components used as light sources in optical fibre and FSO communication systems [4, 12, 14]. SLs and LEDs can both be used interchangeably for a variety of applications due to their similar attributes such as a forward-bias mode operation, high efficiency, compatibility with optical fibre communication systems, allowance for direct modulation and sufficient output power. However, SLs produce a coherent and monochromatic optical output, making them more suited for LOS applications while LEDs produce an incoherent and wide spectrum optical output [2, 12, 13, 15]. Compared to SLs, LEDs provides a less costly option especially for applications requiring low data rates across short distances [2]. Note that both the SLs and LEDs can be designed to emit radiation at various wavelengths within the optical wavelength range (i.e. IR to UV) of the electromagnetic spectrum [2, 4]. The achievable peak wavelength or wavelength range of an optical source largely depends on the type of configuration and/or materials used in the design process [4]. Note that a SL transmitter is assumed in all the analysis performed in this work.

2.3.1 Semiconductor lasers (SLs)

The most common type of lasers used for communication are SLs. SLs have features such as being compact, easily manufactured in large quantities, not requiring optical pumping, high efficiency and being able to produce high output powers. A laser (originally LASER; acronym for Light Amplification

by Stimulated Emission of Radiation) is made when an optical gain medium is confined inside a reflective cavity; resulting in the emission of light. To design a simple laser (e.g. Fabry-Perot (FP) laser), the gain medium is placed in a FP cavity (i.e. two parallel planes) [2, 16]. Lasers that emit light concurrently on different wavelengths are known as multiple-longitudinal mode (MLM) lasers. Since MLM lasers are more prone to crosstalk especially in wavelength-division multiplexing (WDM) systems, it is important to design lasers that emit light on a single wavelength (i.e. single-longitudinal mode (SLM)) [2, 4, 16].

A SLM laser can be actualised by introducing a filtering system to a FP laser. The filtering system chooses the desired wavelength and ignores the remaining wavelengths. FP lasers last long, have a lower eye safety requirement and can produce output powers of about 28 mW. Another SLM laser is known as a distributed-feedback (DFB) laser. In a DFB laser, SLM operation is achieved as a result of reflections caused by corrugations along the width of the reflective cavity. Note that the term DFB lasers refer to lasers where the corrugations are located within the gain medium. A variant to this are distributed Bragg reflector (DBR) lasers (also performs SLM operation) where the corrugations are located outside the gain medium. FP lasers are easy to manufacture and less costly but they are only useful for communication over shorter distances unlike DFB and DBR lasers which are both useful for high-speed communication and, with the right configuration, can produce output powers up to 2 W [2, 4, 12, 16]. External cavity (EC) lasers (i.e. SLM lasers fabricated by including an external cavity in addition to the cavity where the gain medium is situated) have more temperature stability compared to DFB lasers but their cavity length makes direct modulation impossible in high speed

applications [2, 14]. Vertical cavity surface-emitting lasers (VCSELs) (i.e. SLM lasers fabricated by significantly reducing the reflective cavity length) offers increased switching speed and the ability to adopt an array configuration (which makes them preferable for WDM networks). VCSELs can produce output powers of about 6 mW and are very efficient but their need for added thermal cooling due to excessive heat makes them less desirable [2, 4, 12]

2.3.2 Light emitting diodes (LEDs)

An LED is a forward-biased pn-junction that emits light spontaneously [2, 4]. The light emitted from an LED has a broad spectrum because spontaneous emission takes place across the entire gain medium bandwidth. Note that there is a limit to the amount of output power that an LED can produce (due to spontaneous emissions) [2]. LEDs easily modulate light for wireless communication due to their extremely high switching time (i.e. a rapid on-and-off response time operating with speeds up to millions of cycles per second). For instance, LEDs that can be modulated for signalling by up to 100 MHz are commercially available [17]. Even though an LED has limited inherent modulation bandwidth, its modulation bandwidth can be increased by decreasing its carrier lifetime. This can be achieved by either increasing the LED's carrier density or the recombination region's doping level. Note that increasing the doping level of an LED significantly will result in the reduction of its quantum efficiency [4]. For a point-to-point communication where directed light is required, an LED needs to be collimated to have a reasonable signal reception at the receiver. A collimator collects all the light from the LED

and redirects it to the receiving area. Collimation results in reflection and absorption losses but efficiencies of more than 90% can be obtained [2, 18].

2.4 Optical amplification

The optical signals that are sent from a transmitter experience loss as a result of impairments such as absorption, scattering and beam spreading along the propagation path [4, 11]. Due to the signal loss, the transmitted signal can effectively lose all its power before it gets to the receiver or arrive at the receiver with a power that is weak and undetectable. A way of ensuring that the optical signal reaches the receiver with sufficient power is to always ensure that the propagation distance is short. For long distance communication, an optical amplifier (OA) ensures that the signal strength is restored or amplified either immediately after the transmitter (power OA), at some point along the propagation path (line OA) as investigated in Chapters 5 and 7 or just before the receiver (preamplifier) as investigated in Chapter 6 [2, 12, 19-21]. Due to the fact that optical amplification is normally independent of the modulation format or the bit rate (this does not apply to saturated semiconductor OAs (SOAs)), they can be used in numerous applications and are easily upgradable [22, 23]. Also, since OAs have a wide bandwidth, they are useful in WDM applications where a single OA can be used to concurrently amplify signals at different wavelength [24].

The principle behind optical amplification is stimulated emission of radiation. When an optical signal is incident on the OA, absorption and emission of photons can take place. The emitted photon and the incident

photon have the same energy, phase, direction and polarisation. For optical amplification to occur, the amount of stimulated emission must be more than absorption. Naturally at thermal equilibrium, the degree of absorption is always more than stimulated emission due to the higher number of electrons present in the lower energy level. In order to ensure that stimulated emission is greater than absorption and for amplification to continuously occur, a process called population inversion (i.e. pumping or pushing photons to a higher energy level) is required. In addition to stimulated emission of radiation, another phenomenon particular to OAs is spontaneous emission; where the emitted photon has the same energy as the incident photon but has irregular phase, direction and polarisation. These spontaneously emitted photons are also amplified; resulting in an amplified spontaneous emission (ASE) which shows up as noise at the OA output [2, 12].

2.4.1 Erbium-doped fibre amplifier (EDFA)

An erbium-doped fibre amplifier (EDFA) is an OA typically made with silica fibre with an erbium (Er^{3+} ions)-doped core. To achieve population inversion, an EDFA incorporates a laser pump at either or both ends. A wavelength-selective coupler at the EDFA input combines the pump light with the incident optical signal and an isolator is inserted on both ends of the EDFA to prevent reflections and backward ASE from propagating. Fig. 2.2 shows a basic EDFA configuration. An EDFA is generally preferred in optical communication systems due to the advantages it offers over other types of OAs such as a more straightforward light coupling process, polarisation insensitivity, ease of operation and reliability. Also, EDFAs do not introduce crosstalk when used to

amplify signals concurrently on different wavelengths in WDM systems [2, 12].

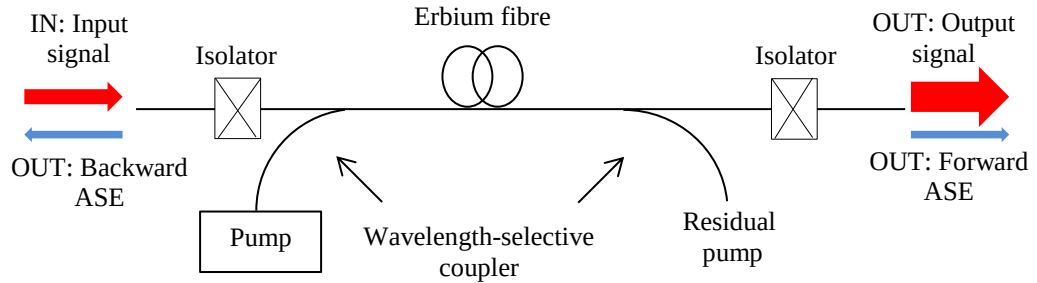


Fig. 2.2: Basic EDFA configuration (Modified and redrawn from [2]).

2.4.2 Semiconductor optical amplifier (SOA)

A SOA is made up of a forward-biased pn-junction having a depletion layer at the junction. This depletion layer is referred to as the active region because it is where stimulated emission of radiation takes place. Antireflective (AR) coatings are applied to both ends of the active region to avoid ripples in the OA gain. Fig. 2.3 shows a basic SOA configuration. SOAs typically have a large bandwidth (i.e. about 100 nm achievable compared to less than 50 nm in EDFAs). In comparison to EDFAs, SOAs have limitations such as higher coupling and polarisation loss, lower achievable gain and difficulty in producing the quality of AR coatings required at both ends of the active region [2, 12]. Other comparisons with EDFAs are shown in Table 2.1. Even though SOAs are known not to be very useful in WDM systems because they experience crosstalk (and cross-gain modulation (CGM)) when used to concurrently amplify signals at different wavelengths, the use of differential

phase-shift-keying (DPSK) modulation with a steady signal power has been shown to reduce the CGM effect [22]. Crosstalk in SOAs can also be reduced by measures such as ensuring that the OA operates in the small signal gain regime where it is not dependent on the incident optical signal power [2].

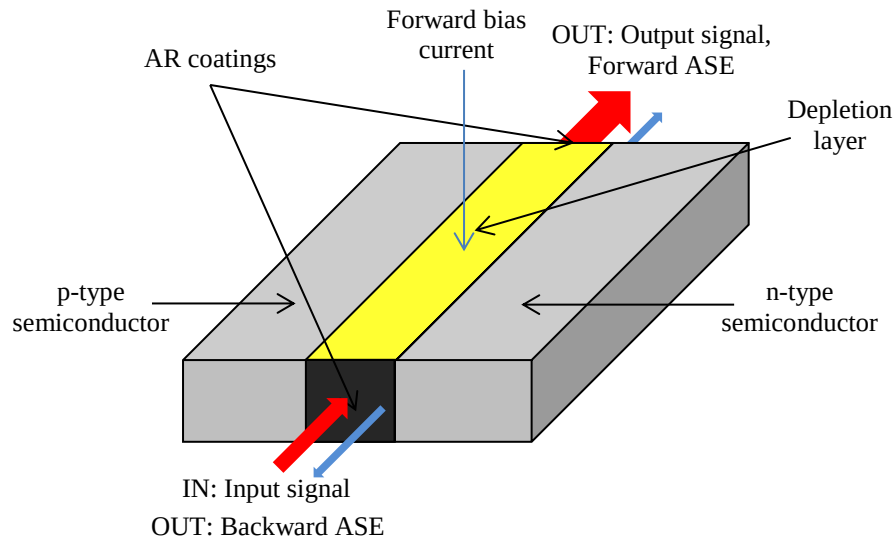


Fig. 2.3: Basic SOA configuration (Modified and redrawn from [2]).

Table 2.1 shows the comparisons between EDFAs and SOAs.

Table 2.1: Comparison between EDFAs and SOAs [2, 12, 25, 26]

Property	EDFA	SOA
Cost	Cheaper for comparable performances	Requires accurate design
Gain	Up to 51 dB	Up to 35 dB
Gain recovery speed	~5 GHz	~10 GHz
Noise figure	Better noise figure	
Wavelength range	Limited	Wide range
Signal distortions	No distortions	Distorts signals when in saturation
Power	Higher	Lower
Polarisation	Largely polarisation insensitive due to geometry	Requires accurate design
Weight	Heavier	Lighter
Gain ripples	Travelling wave amplifier so no gain ripples	Requires AR coatings
Insertion	Low insertion loss	Higher insertion loss
Spontaneous emission lifetime	Large	Not large enough; prone to crosstalk
Planar waveguide optics	Unsuitable	More suitable

2.4.3 Gain non-flatness and saturation

When OAs are used for amplification in WDM systems, there is a tendency for different signals (at different wavelengths) to be amplified with different gain values because the OA gain is not flat across its wavelength range. It is however desirable that the same gain is experienced by signals in different WDM channels [27, 28]. A flatter gain spectrum is obtained with erbium-doped fluoride fibre amplifiers (EDFFAs) because they are made with fluoride glass fibre (i.e. the fluoride is responsible for the flatter gain) unlike EDFAs which are made with silica fibre. However, the fluoride glass in EDFFAs gives a poorer noise performance compared to EDFAs due to the additional upper energy level involved in the emission of radiation process [2].

Gain saturation (shown in Fig. 2.4) occurs in an OA when the input signal power becomes very high. Naturally, the OA is expected to provide gain regardless of the value of the input signal power but due to factors such as the OA's pump power and design, there is a limit to how much signal power the OA can give out. The relationship between the OA gain and the input signal power is given as [2, 29]

$$G = 1 + \frac{P_{sat}}{P_{in}} \ln \left(\frac{G_{ss}}{G} \right) \quad (2.1)$$

where P_{in} , P_{sat} , G_{ss} , G represents the incident optical signal power, internal saturation power, small signal (fixed) gain and operational gain of the OA respectively. Note that G cannot be made the subject of equation (2.1); which makes it slightly problematic to work with. EDFAs are preferable in WDM systems because the different wavelengths saturate separately (inhomogeneous gain), unlike the SOA, where different wavelengths saturate collectively (homogeneous gain). In an experiment by Yoon-Suk *et al.*, power and line gain saturated OAs were used in a 8×10 Gb/s WDM channel over a propagating distance of 2.4 km. The experiment showed that operating the OAs in the gain saturation regime reduced the effect of weather conditions on the FSO link [20]. Other findings by Abtahi *et al.* [30], Ciaramella *et al.* [31], Boucouvalas *et al.* [32], Wei *et al.* [33] and Yiannopoulos *et al.* [34] have also shown that operating an OA in the saturation regime can be beneficial in FSO links.

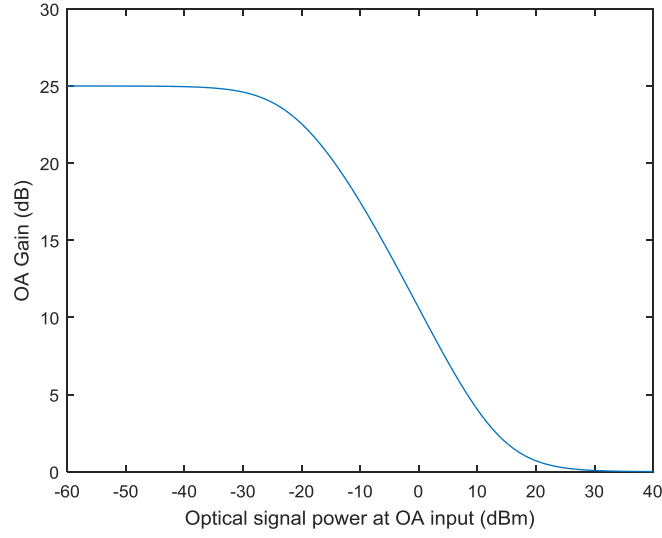


Fig. 2.4: OA gain against input signal power at OA input ($G_{ss} = 25$ dB and $P_{sat} = 5$ dBm).

2.4.4 Optical signal-to-noise ratio (OSNR)

The optical signal-to-noise ratio (OSNR) refers to the ratio of the optical signal power to the noise power and it is given as

$$OSNR = \frac{P_{sig}}{P_{ASE}} \quad (2.2)$$

where P_{sig} represents the optical signal power, $P_{ASE} = 2N_0B_{OSNR}$ represents the optical noise power and B_{OSNR} represents a standard bandwidth over which the single polarization ASE power spectral density (PSD), N_0 is assumed constant. The OSNR is particularly useful in cascaded OA links where the ASE noise accumulates along the link and the receiver sensitivity cannot be used to effectively predict system performance. The OSNR is solely dependent on the optical signal and noise powers and independent of the bandwidth of the optical filter, pulse shape and data format. Thus, while the OSNR is an

important contributor to determining the bit error rate (BER), it is important to have other pieces of information to completely understand system performance. Various techniques such as linearly interpolating the ASE noise level and the use of a spectrum analyser with narrow filters can be used to monitor the OSNR of an optical signal [35-37].

2.4.5 OA cascade and ASE noise

OA cascades are common in fibre based communication systems but only recently proposed for FSO based communication systems. In FSO links, line OAs can be introduced at intervals along the propagation path to ensure that the signal strength does not fall below acceptable levels and to increase the achievable information propagation distance [38]. Three different scenarios can occur in a cascaded OA link. Firstly, the configuration can be such that the loss in each interamplifier section is more than the gain of the OAs placed after each interamplifier section. In such a situation, the OAs will not fully compensate for the loss in each interamplifier section and the optical signal power (and OSNR) will eventually fall below acceptable levels. Secondly, the configuration can be such that OAs placed after each interamplifier section just fully compensate for the loss in each interamplifier section thereby ensuring that the power at the output of each OA is the same as the original transmitted signal power. Thirdly, the configuration can be such that OAs overcompensates for the loss in each interamplifier section. When this occurs, the OAs further down the link will eventually experience gain saturation (assuming they are not gain controlled as they can be in fibre based communication systems) due to high input signal powers. Naturally, mixed cases can also occur within any

cascade. The generation of ASE noise by OAs becomes even more detrimental to system performance in cascaded OA links because the ASE noise generated by each OA accumulates along the propagation path and the total accumulated ASE noise is incident on the receiver [39].

2.5 The optical receiver

In optical communication systems, at the receiving end, the transmitted information is retrieved from the optical signal by an optical receiver. As shown in Fig. 2.5, in FSO communication systems, a receiving lens is used to amass and direct the incident optical signal towards the photodetector. Note that a larger proportion of signals (and more background noise) can be collected by increasing the receiver aperture diameter [4]. The means of detection by the optical receiver can either be coherent or non-coherent (direct detection (DD)). With DD optical receivers, a photodetector directly detects the instantaneous power of the received optical signal and produces a proportional output photocurrent. However, DD optical receivers are only implementable for intensity modulated signals where the information signal is used to vary the amplitude of the optical source. For coherent receivers, a local oscillator signal is combined with the received optical signal before photodetection takes place. Coherent detection can either be homodyne or heterodyne. In homodyne detection, the difference in frequency between the combined signals is set to zero while it is set to a particular frequency in heterodyne detection [12, 40]. Coherent optical receivers are more efficient but DD optical receivers are

commonly used in FSO systems due to their easy implementation and lower cost [41].

Note that a preamplifier can be optionally used to boost the optical signal strength before photodetection takes place. After photodetection takes place, the electrical signal is amplified with a front-end amplifier. A filtering operation then takes place to perform tasks such as noise reduction, pulse shaping and in some cases, equalization on the amplified electrical signal. The signal is then sent to a decision circuit where the transmitted information is recovered. In order to recover the transmitted information, a periodic waveform (or clock) having the same period as the bit interval is required for timing recovery and the determination of the bit boundaries. Usually, the clock is extracted from the information signal. Sampling takes place at the decision circuit; which makes decisions based on the type of modulation format used at the transmitter [2]. A diagram showing the information recovery process in a DD optical receiver is shown in Fig. 2.5.

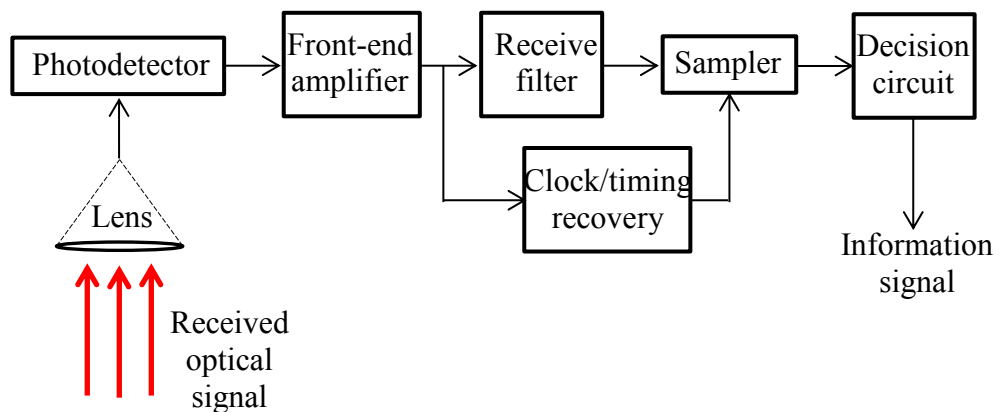


Fig. 2.5: Information recovery process in a DD optical receiver (Modified and redrawn from [2]).

2.5.1 Photodetection

At the receiver, the optical signals are first converted into electrical signals with the help of a photodetector. The role of the photodetector is to produce an electrical signal (i.e. photocurrent) corresponding to the received optical signal. In photodetectors, the bandgap energy must not be higher than the incident photon energy for photodetection to take place. This condition is shown in the equation below [2, 12]

$$E_g (J) \leq hf_c = \frac{hc}{\lambda(\mu m)} \quad (2.3)$$

where c , h , q , E_g and f_c (related to the wavelength λ) represents the velocity of light, Planck's constant, electronic charge, bandgap and frequency at which the semiconductor material can be used for photodetection respectively. The condition in (2.3) therefore restricts semiconductors to being only useful for photodetection at certain wavelengths and a cutoff wavelength λ_{co} , represents the largest wavelength value for which (2.3) is true. Table 2.2 shows different photodetector materials with their corresponding cut-off wavelengths and bandgap energies.

Table 2.2: Photodetector materials with their corresponding cut-off wavelength and bandgap energies [2]

Semiconductor material	Cutoff wavelength (nm)	Bandgap (eV)
Si	1060	1.17
Ge	1600	0.775
GaAs	870	1.424
InP	920	1.35
InGaAs	1650	0.75
InGaAsP	1650-920	0.75-1.35

In a photodetector, an efficiency value of close to unity (this is achievable by increasing the thickness of the semiconductor material to an appropriate level) is highly desirable especially for long distance communication [2, 12].

2.5.1.1 PIN photodiode

Practically designing a photodetector with a semiconductor material only is not very efficient because recombination of electrons and holes take place thereby limiting system performance. In order to achieve better performances, a photodiode (PD) is used. A typical PD is a reverse-biased semiconductor pn-junction. This design format ensures better performances because the electrons in the conduction band are able to leave the semiconductor quicker thereby reducing recombination of electrons and holes. Another means of increasing the responsivity and efficiency of the PD is by putting an intrinsic semiconductor material in-between the pn-junction resulting in a PD known as a PIN (i.e. positive-intrinsic-negative) PD. The PIN PD is fabricated such that the widths of the p-type and n-type semiconductor materials are intentionally made much smaller than that of the intrinsic semiconductor material. This ensures that photodetection takes place mostly in the intrinsic region. Another way of further improving the performance of a PIN PD is to ensure that the p-type and n-type semiconductors surrounding the intrinsic semiconductor are made with materials that are not suitable for the wavelength of interest (i.e. introducing an InGaAs doped semiconductor material in-between p-type and n-type semiconductors (both doped with InP)) such that absorption only takes place in the intrinsic semiconductor region. These types of PIN PDs are referred to as heterostructures.

2.5.1.2 Avalanche photodiode

The achievable responsivity in photodetectors (applicable to all the photodetectors discussed earlier) is restricted by the fact that the transition of electrons from the valence band to the conduction band only requires the absorption of a single incident photon (i.e. an electron-hole pair). However, photodetector responsivity can be improved by ensuring that more electrons are transmitted from the valence band to the conduction band. By applying a sufficiently high electric field to the electron that was produced through the absorption process, the electron will in turn trigger the transition of other electrons from the valence band to the conduction band leading to more electron-hole pairs. If a sufficiently high electric field is further applied to the new electron-hole pairs, other electron-hole pairs can be produced. PDs designed to operate this way are referred to as avalanche PD (APD) due to the avalanche multiplication involved. While this multiplication effect provides gain, it has a disadvantage of introducing noise in the APD. In applications where APDs are used, even though the multiplicative effect boosts system performance, a decision has to be made about the acceptable noise level [2, 12]. Essentially, the APD is beneficial (compared to a PIN PD) until its signal dependent shot noise becomes significant relative to the thermal noise.

2.5.2 Receiver circuitry noise

During the photodetection process, some other currents known as noise currents usually accompany the photocurrent. These noise currents can be broadly classed as thermal and shot noise currents but other noise currents can also be present [42]. For instance, when a preamplifier is present, the

spontaneous emission of radiation in the OA produces an ASE noise which can also have significant effect on system performance due to the beat noises produced. Similarly, noise currents due to background radiation (which can be particularly detrimental in some optical wireless systems [43]) can also be present at the receiver [44].

2.5.2.1 Thermal noise

Thermal noise is generated at the receiver as a result of thermal fluctuations (random movements at finite temperatures) of electrons in the photodiode resistor. For a load resistor R_L operating at a temperature T , the thermal noise current can be represented by a Gaussian distribution having a mean of zero. Thermal noise current is not dependent on frequency; hence it is referred to as white. The variance of the thermal noise current is given as [2, 12, 45]

$$\sigma_{th}^2 = \frac{4\kappa T}{R_L} B_e \quad (2.4)$$

where B_e and κ represent the noise equivalent bandwidth of the receiver's electrical filter and the Boltzmann's constant respectively. The receiver's electrical bandwidth is dependent on the bit rate (R_b) of the optical signal and to prevent signal distortions, its value should not be less than half the bit rate value (i.e. $B_e \geq R_b/2$). By including the noise contributions of the front-end amplifier (which is represented by its noise figure F_n with values ranging from 3 to 5 dB), the variance of the thermal noise contribution of the receiver is given as [2, 46, 47]

$$\sigma_{th}^2 = \frac{4kT}{R_L} F_n B_e \quad (2.5)$$

2.5.2.2 Shot noise and dark current

Shot noise occurs due to the random nature of photons arriving at the receiver. Also, in the absence of an incident optical signal, a current known as dark current can be generated. Since it is more difficult for electrons to move between energy levels without an incident optical signal hitting the photodetector, dark current is not prominent in semiconductor materials with large energy gaps. By including the contribution from dark current, the total shot noise current has a variance given as [2, 12]

$$\sigma_{sh}^2 = 2q(I + I_d)B_e \quad (2.6)$$

where I_d represents the dark current and $I = RP_{in}$ represents the photocurrent produced in a PIN PD. For an APD, $I = G_m RP_{in}$ where G_m represents the avalanche multiplicative gain. In APDs, the noise currents are classified as shot noise currents with the variance given as [2, 39]

$$\sigma_{sh}^2 = 2qG_m^2 F_A(G_m) RP_{in} B_e \quad (2.7)$$

where R represents the responsivity of the photodiode and the APD's excess noise factor ($F_A(G_m)$) is given as

$$F_A(G_m) = k_A G_m + (1 - k_A)(2 - 1/G_m) \quad (2.8)$$

where k_A represents the ionisation coefficient ratio. When $G_m = 1$, the APD behaves like a PIN PD. In most cases, the shot noise current can be neglected as its variance is much lower than that of the thermal noise current [39]. Note

that an increase in the receiver's electrical bandwidth improves the signal waveform quality but it also lets more noise through, hence, a trade-off has to be made between the acceptable noise level and the receiver's electrical bandwidth.

2.5.2.3 ASE beat noises

The photodetection operation can be described as square law detection where the input optical signal interacts with the ASE noise such that the signal beats with itself (no noise), the signal beats with the ASE noise (signal-spontaneous beat noise) and the ASE noise beats with itself (spontaneous-spontaneous beat noise) [2]. The resultant photocurrent after beating takes place is given as

$$i(t) = R \overline{(E_{sig}(t) + E_{sp}(t))^2} = R \left(\overline{[E_{sig}(t)]^2} + 2E_{sig}(t)E_{sp}(t) + \overline{[E_{sp}(t)]^2} \right) \quad (2.9)$$

where $E_{sig}(t)$ and $E_{sp}(t)$ represents the optical fields of the signal and ASE respectively. Also, the bar implies time averaging over optical frequencies. Usually, an optical band pass filter (OBPF) is used to reduce the ASE noise before it gets to the receiver. The variance of the signal-spontaneous beat noise is given as [48]

$$\sigma_{sig-sp}^2 = 4R^2 P_{in} N_0 B_e \quad (2.10)$$

and the variance of the spontaneous -spontaneous beat noise is given as [48]

$$\sigma_{sp-sp}^2 = 2m_t R^2 N_0^2 B_{opt} B_e \left(1 - \frac{B_e}{2B_{opt}} \right) \quad (2.11)$$

where B_{opt} and m_t represents the OBPF bandwidth and number of polarisation states parameter (1 or 2). The ASE noise, described by its PSD is given as [48]

$$N_0 = \frac{1}{2}(NFG - 1)h\nu \quad (2.12)$$

where ν represents the frequency of the optical carrier. $NF = SNR_{in}/SNR_{out}$ represents the noise figure where SNR_{in} and SNR_{out} represents the signal-to-noise ratio at the input and output of the OA respectively. Note that when a preamplifier is present, $P_{in} = GP_{OAin}$ where P_{OAin} represents the preamplifier input power.

2.6 Crosstalk

Crosstalk occurs in a communication system when an undesired signal interferes with the desired signal. It is particularly prevalent in WDM systems and it adversely affects system performance [2]. The effect of crosstalk on various FSO links has been investigated by various researchers. Ren *et al.* [49] investigated the impact of atmospheric turbulence on crosstalk and power penalty using orbital angular momentum (OAM) multiplexing while Mbah *et al.* [50, 51] and Aladeloba *et al.* [52] investigated the impact of turbulence-accentuated interchannel crosstalk on WDM systems by using pulse position modulation (PPM) and on-off keying (OOK) modulation formats respectively.

Crosstalk can either be linear (due to imperfections in optical components such as demultiplexer) or non-linear (due to non-linear effects leading to power

transmission between different channels) [39]. Unless otherwise stated, linear crosstalk is assumed in this work.

A desired signal arriving at a receiver can be assumed to have an optical field (with unit $W^{1/2}$) given as

$$E_{sig}(t) = \sqrt{2P_{sig}(t)} \cos(\omega_{sig}t + \phi_{sig}t) \quad (2.13)$$

where P_{sig} , ω_{sig} and ϕ_{sig} are the power, angular frequency and phase of the desired signal respectively. Also, a crosstalk signal arriving at a receiver (presumably at the same time) can be assumed to have an optical field (with unit $W^{1/2}$) given as

$$E_{xt}(t) = \sqrt{2P_{xt}(t)} \cos(\omega_{xt}t + \phi_{xt}t) \quad (2.14)$$

where P_{xt} , ω_{xt} and ϕ_{xt} are the power, angular frequency and phase of the crosstalk signal respectively. In an uncommon scenario where the signal and crosstalk are polarized, no beating exists between the desired signal and the crosstalk signal and the resultant photocurrent is given as

$$i(t) = R(\overline{(E_{sig}(t))^2} + \overline{(E_{xt}(t))^2}) = R(P_{sig} + P_{xt}) \quad (2.15)$$

If the desired signal fully interacts with the crosstalk signal, the resultant photocurrent after beating takes place is given as

$$i(t) = R(\overline{(E_{sig}(t) + E_{xt}(t))^2}) = R(\overline{[E_{sig}(t)]^2} + 2E_{sig}(t)E_{xt}(t) + \overline{[E_{xt}(t)]^2}) \quad (2.16)$$

which can be simplified (after ‘time averaging’ terms at double optical frequencies to zero) as

$$i(t) = R(P_{sig}(t) + P_{xt}(t) + 2\sqrt{P_{sig}(t)P_{xt}(t)}\cos((\omega_{sig} - \omega_{xt})t + \phi_{sig} - \phi_{xt})) \quad (2.17)$$

2.6.1 Interchannel crosstalk

When the wavelengths of the desired and crosstalk signals are sufficiently distanced from each other on the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) frequency grid such that their wavelength difference is bigger than the receiver's electrical bandwidth, the crosstalk is referred to as interchannel crosstalk. After filtering out the $\cos$ term in (2.17), at the decision circuit, the photocurrent is given as [2, 39]

$$i(t) = R(P_{sig}(t) + P_{xt}(t)) \quad (2.18)$$

The photocurrent is similar to when there is orthogonal polarization between the desired and crosstalk signals since the decision is not influenced by beating. Interchannel crosstalk can occur due to many reasons such as the inability of a demultiplexer to perfectly reject unwanted wavelengths [39].

2.7 Laser safety and standards

The emissions from optical sources could be potentially hazardous (especially from a laser as most LEDs are considered safe) to the eyes (and skin) if the level of radiation exceeds an acceptable limit. In order to ensure safety, various organisations such as the American National Standards Institute (ANSI), Laser Institute of America (LIA), International Electrotechnical Commission (IEC), Center for Devices and Radiological Health (CDRH) and the European Committee for Electrotechnical Standardization (CENELEC)

[53] have adopted eye safety regulations. Details about the response of the eye at different wavelengths and the maximum permissible exposure (MPE) of the human eye to radiation are given in [53] and [54] respectively.

Lasers are broadly grouped into four different Classes (shown in Table 2.3) based on their output power, wavelength and type. As shown in Table 2.3, Class 1 laser radiations are safe in all circumstances; making them the Class of choice for applications where human contact is more likely such as FSO communication. Class 1M lasers (which are largely safe to use as long as they are not viewed with optical aids such as eye loupes and binoculars) are commonly used for most commercial FSO applications with data rates up to 1.5 Gb/s. Lasers of higher Classes can also be used for FSO communication as long as there is no human contact with the propagated beam (i.e. equipment situated on top of tall buildings). Note that safety should also be ensured by installing warning signs and safety labels in places where laser Classes higher than Class 1 are used [4, 55].

Table 2.3: Classification of lasers by the IEC EN 60825-1 standard [4, 55]

Type	Details
Class 1	• Largely safe when used in predictable operating conditions. • No need for precise safety controls since it cannot exceed the lowest MPE values. • If a higher Class laser is embedded, it has to be fully enclosed. • Can be safely viewed with optical aids such as eye loupes and binoculars.
Class 1M	• The beam has a large diameter or is widely divergent (i.e. 302.5 - 4000nm). • Seen as a Class 1 laser but viewing with optical aids such as eye loupes and binoculars is regarded as unsafe.
Class 2	• Has operating wavelength ranging from 400 to 700nm. • Only applies to visible lasers where it takes at least 0.25 seconds to exceed the MPE. • Aversion responses such as head movements and blinking reflexes protect the eye. • Can be safely viewed with optical aids such as eye loupes and binoculars
Class 2M	• The beam has a large diameter or is widely divergent. • Seen as a Class 2 laser but viewing with optical aids such as eye loupes and binoculars is regarded as unsafe.
Class 3R	• Has a lower risk compared to Class 3B but it is potentially dangerous to view its beam directly. • Applies to visible and invisible lasers that have limits as high as five times the limits of Classes 2 and 1 lasers respectively.
Class 3B	• Viewing the beam directly is unsafe for the eyes. • Viewing a specular reflection of the beam is potentially harmful for the eyes. • Viewing a diffuse reflection of the beam is potentially safe for the eyes and skin.
Class 4	• Applies to all lasers with limits exceeding that of Class 3B • Viewing the beam directly is always unsafe for the eyes and skin. • Viewing a diffuse reflection of the beam is potentially unsafe for the eyes and skin unless there is proof of safety. • Both reflected and scattered beams from this laser Class could cause a fire.

2.8 Summary

This Chapter reviewed the basic components used in FSO communication systems. An overview of the FSO technology which includes its features and applications was presented. Various optoelectronic devices involved with the transmission, amplification and reception of information with optical signals were discussed in detail and their impact on the FSO technology were highlighted. The limitations imposed by impairments such as noise and crosstalk were shown and an overview of laser safety and standards was presented.

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Chapter 3

The atmospheric channel

3.1 Introduction

This Chapter reviews the atmospheric channel and begins by providing a general description of the atmospheric channel with particular emphasis on the various impairments that adversely affect the transmitted optical signal. The attenuation due to beam spreading, absorption, scattering, pointing and coupling loss are discussed in this Chapter. An overview of atmospheric turbulence (and how it leads to scintillation) is provided and various probabilistic scintillation models used in describing the turbulent channel are reviewed. The use of Monte Carlo (MC) simulation methods for atmospheric turbulence modelling is discussed. Some of the turbulence mitigation methods already proposed in literature such as aperture averaging, maximum likelihood sequence detector (MLSD) and spatial diversity were also reviewed in this Chapter.

3.2 Overview of the atmospheric channel

The optical signal propagated through the atmospheric channel is usually attenuated due to its susceptibility to various impairments [1]. Line-of-sight (LOS) impairments such as physical obstructions along the propagation path can be reduced (or eliminated) by correctly positioning the transmitter and receiver. However, impairments dependent on the geographic location and time such as fog, rain, snow, haze and atmospheric suspended particles (mainly concentrated near the earth surface) such as aerosols and gases presents a greater challenge [2-4]. These impairments result in scattering (i.e. directional change in the transmitted signal due to suspended particles) and absorption (i.e. conversion of photon to heat after colliding with atmospheric molecules such as nitrogen, oxygen, argon and carbon dioxide). Absorption is mainly wavelength dependent and its effect can be mitigated by choosing an appropriate wavelength for the transmitted signal. Also, scattering (which makes the most contribution to the atmospheric attenuation factor) can be classified (based on the suspended particles radius and wavelength) into three different types namely Rayleigh, Mie and non-selective (described with geometric optics) scattering [2, 3, 5].

A major impairment to seamless signal transmission through the atmosphere is thermal inhomogeneity. These thermal inhomogenities cause random temporal and spatial refractive index changes which results in large-scale and small-scale eddies (i.e. atmospheric turbulence) that haphazardly interacts with the transmitted optical signal [1, 6]. Atmospheric turbulence causes scintillation (i.e. optical signal power fluctuation) and it significantly affects

system performance [1, 7]. The effect of atmospheric turbulence becomes even more severe in long distance communication [5, 8]. It is essential that system designers understand the various impairments in the atmospheric channel so that adequate penalties can be incorporated where required.

3.3 Atmospheric turbulence

The earth surface consists of various packets of air varying in size and temperature [1]. This inhomogeneity in the thermal state of the atmosphere causes refractive index changes (mainly due to temperature fluctuations [6]) referred to as optical turbulence [9-11]. An approximation of the refractive index can be given as [6]

$$n = 1 + 77.6 \times 10^{-6} \left(1 + 7.52 \times 10^{-3} \lambda (nm)^{-2} \right) \frac{p_{atm} (mbar)}{T(K)} \quad (3.1)$$

where p_{atm} and T represents the atmospheric pressure and temperature respectively. The packets of air in the atmosphere are then further split by optical turbulence into turbulence eddies; which can be classified into inner scales l_0 and outer scales L_0 depending on their sizes (shown in Fig. 3.1) [3, 6, 12]. Typically sizes of l_0 and L_0 are 1 to 10 mm (near the earth surface) and 1 to 100 m respectively [6]. According to Kolmogorov, the power spectral density of the refractive index random fluctuations in the inertia subrange (eddies with sizes between the outer and inner scale [3]) is given as [3, 6]

$$\phi_n(\kappa) = 0.033 C_n^2 \kappa^{-1/3}; \quad 2\pi/L_0 \ll \kappa \ll 2\pi/l_0 \quad (3.2)$$

where C_n^2 represents the refractive index structure parameter and $\kappa = 2\pi/\iota$ where ι represents the size of the turbulent eddy. Since the Kolmogorov spectrum model is only limited to the inertia subrange, other models have been derived to cover the outer and inner scales. For instance, the spectrum model originally developed by Novikov [6] for velocity fluctuations but later adapted by Tatarskii [6] for refractive index random fluctuations in both the inertia and dissipation ranges (eddies with sizes smaller than the inner scale) is given as [3, 6]

$$\phi_n(\kappa) = 0.033C_n^2\kappa^{-11/3}\exp\left(-\frac{\kappa^2}{\kappa_m^2}\right); \quad \kappa \gg 1/l_0; \quad \kappa_m = 5.92/l_0 \quad (3.3)$$

While another spectrum model (that incorporates the outer scale) was developed by Andrew as shown in [6], it is noteworthy that free-space optical (FSO) links are mainly affected by the energy of eddies in the inertia subrange [6]. The atmospheric turbulence strength (i.e. scintillation magnitude) can be described by a scintillation index given as [12]

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \quad (3.4)$$

where I and $\langle I \rangle$ represents the optical signal irradiance and average irradiance respectively. The effect of atmospheric turbulence is more significant when a point receiver is used due to the varying degree of beam intensity [6].

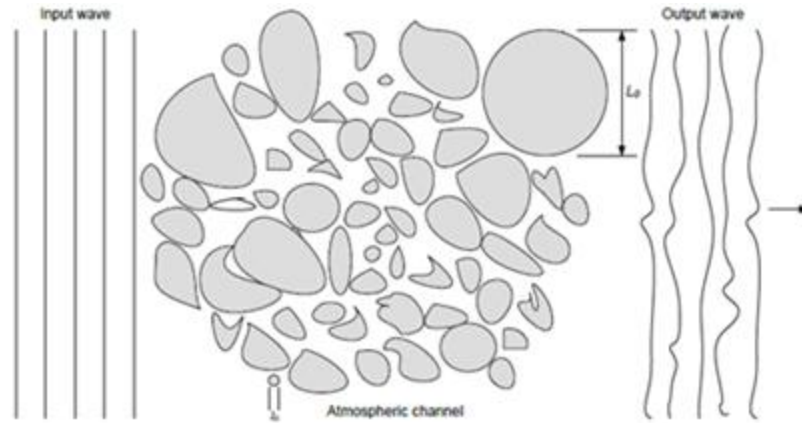


Fig. 3.1: Diagrammatic representation of a fluctuating signal due to the atmospheric turbulence [1].

3.3.1 Probabilistic scintillation models

Various statistical models (representing the randomly varying signal intensity) have been used to describe atmospheric-induced turbulence fading [12]. The lognormal distribution is commonly used to characterise the weak turbulence regime [9, 13] and the K distribution (which is consistent with experimental results [14]) is used to characterise the strong turbulence regime [15, 16]. Compared to the lognormal distribution, the gamma-gamma distribution used to characterise the weak to strong turbulence regimes [17, 18] shows better agreement between experimental and theoretical data [6, 14]. In a saturated turbulence regime, the negative exponential distribution has proved to give a better fit when compared with theoretical data [19]. Note that a plane wave assumption is made for the received optical waves.

3.3.1.1 Lognormal Turbulence Model

When light propagates through the atmosphere, it experiences phase delay and scattering [11]. By applying the central limit theorem, the light's log-amplitude has a Gaussian marginal distribution from which the lognormal probability density function (PDF) can be obtained as [7, 9, 13]

$$f_{LN_I}(I, \langle I \rangle) = \frac{1}{I\sqrt{2\pi\sigma_I^2}} \exp \left\{ -\frac{\left[\ln(I/\langle I \rangle) + \frac{1}{2}\sigma_I^2 \right]^2}{2\sigma_I^2} \right\}; \quad I > 0 \quad (3.5)$$

It is computationally convenient to define a parameter h , which can be used to describe the varying channel loss or gain due to atmospheric turbulence. h has a mean value of 1, and in the turbulent free limit, this mean value is attained at all times. With $h = I/\langle I \rangle$ and by transforming random variables (i.e. $f_{LN_I}(I)dI = f_{LN_h}(h)dh$), the lognormal PDF is given with respect to h as

$$f_{LN_h}(h) = \frac{1}{h\sqrt{2\pi\sigma_I^2}} \exp \left\{ -\frac{\left[\ln(h) + \frac{1}{2}\sigma_I^2 \right]^2}{2\sigma_I^2} \right\}; \quad h > 0 \quad (3.6)$$

where the variance of the natural logarithm of the irradiance (i.e. the scintillation index given in (3.4)) can be obtained as [1]

$$\sigma_I^2 = \exp \left[\frac{0.49\sigma_R^2}{\left(1 + (1.11\sigma_R^{12/5})\right)^{7/6}} + \frac{0.51\sigma_R^2}{\left(1 + (0.69\sigma_R^{12/5})\right)^{5/6}} \right] - 1 \quad (3.7)$$

where σ_R^2 , the Rytov variance used to characterise the different turbulence regimes is given as [12]

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} D^{11/6} \quad (3.8)$$

where $k = 2\pi/\lambda$ represents the optical wave number where λ represents the optical wavelength. Note that the weak, moderate, strong and saturated turbulence regimes can be described by $\sigma_R^2 < 1$, $\sigma_R^2 \sim 1$, $\sigma_R^2 > 1$ and $\sigma_R^2 \rightarrow \infty$ respectively [7]. Even though the Rytov variance can be used to describe the different turbulence levels for the lognormal distribution, experimental results have shown that the lognormal approximation is only valid for the weak turbulence regime because at higher turbulence levels, the multiple scattering experienced is not accounted for in the Rytov approximation [1]. The lognormal PDF is shown in Fig. 3.2 for different Rytov variance values. In Fig. 3.2, it is observed that as the turbulence level increases, the PDF becomes more skewed to the left with longer tails to the right. This shows how much the channel inhomogeneity has adversely affected the irradiance fluctuation.

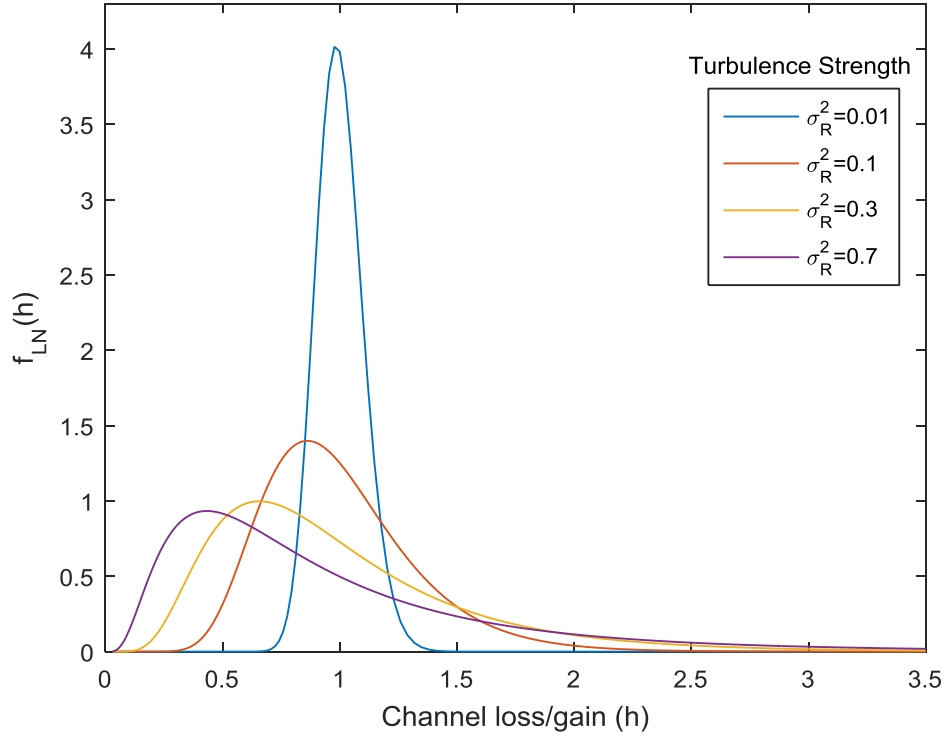


Fig. 3.2: Lognormal PDFs against h for different Rytov variance values.

3.3.1.2 Gamma-Gamma Turbulence Model

The fluctuations experienced by an optical signal propagating through a turbulent atmosphere consists of small-scale and large-scale effects. The small-scale effects (scattering) are caused by eddies smaller than either the first Fresnel zone $\sqrt{D/k}$ or the coherence radius ρ_0 while the large-scale effects (refraction) are caused by eddies larger than the Fresnel zone or the scattering disk $D/k p_0$ [20]. Thus, the unconditional gamma-gamma PDF (which is obtained from the contributions of the small-scale and large-scale effects) can be given as [14, 17, 18, 20]

$$f_{GG_I}(I, \langle I \rangle) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{I}{\langle I \rangle} \right)^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta \left(\frac{I}{\langle I \rangle} \right)} \right); \quad I > 0; \quad (3.9)$$

where α and β are the number of large and small scale eddies due to the scattering process respectively, $\Gamma(\cdot)$ is the Gamma function and $K_u(\cdot)$ is the modified Bessel function of the second kind with order, u . The unconditional gamma-gamma PDF is obtained with respect to h as

$$f_{GG_h}(h) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} h^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta h} \right); \quad h > 0; \quad (3.10)$$

where the parameters α and β are defined as [7, 20]

$$\alpha = \left\{ \exp \left[\frac{0.49\sigma_R^2}{\left(1 + \left(1.11\sigma_R^{12/5}\right)\right)^{7/6}} \right] - 1 \right\}^{-1} \quad (3.11)$$

$$\beta = \left\{ \exp \left[\frac{0.51\sigma_R^2}{\left(1 + \left(0.69\sigma_R^{12/5}\right)\right)^{5/6}} \right] - 1 \right\}^{-1} \quad (3.12)$$

The gamma-gamma PDF is shown in Fig. 3.3 for the weak, moderate and strong turbulence regimes. Fig. 3.3 shows that as the turbulence strength increases, the PDF spreads out more. As earlier stated, the gamma-gamma distribution, which shows excellent agreement between experimental and theoretical data when used to characterise the weak to strong turbulence regimes is preferred for turbulence modelling in many applications [6, 14]. Also, it can be observed in Fig. 3.3 that as $\beta \rightarrow 1$ (stronger turbulence), the gamma-gamma distribution tends towards a K distribution.

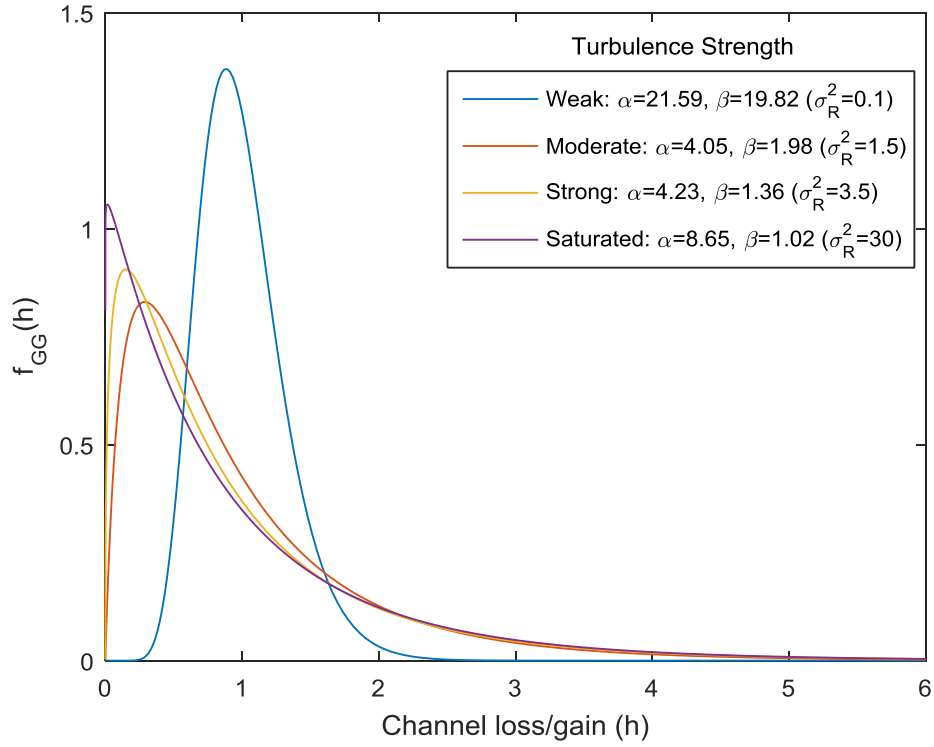


Fig. 3.3: Gamma-gamma PDFs against h for different turbulence strengths.

3.3.1.3 K Turbulence Model

The K distribution (arising from two independent distributions; the negative exponential and gamma distributions) is widely accepted for modelling the strong atmospheric turbulence regime because it gives a good agreement with experimental data [14, 15]. The unconditional PDF of the K distribution is given as [14-16]

$$f_{K_I}(I, \langle I \rangle) = \frac{2\alpha}{\Gamma(\alpha)} \left(\alpha \left(\frac{I}{\langle I \rangle} \right) \right)^{\left(\frac{\alpha-1}{2} \right)} K_{\alpha-1} \left(2 \sqrt{\alpha \left(\frac{I}{\langle I \rangle} \right)} \right); \quad I > 0; \quad (3.13)$$

which is written with respect to h as

$$f_{K_h}(h) = \frac{2\alpha}{\Gamma(\alpha)} (\alpha h)^{\left(\frac{\alpha-1}{2}\right)} K_{\alpha-1}(2\sqrt{\alpha h}); \quad h > 0; \quad (3.14)$$

The K PDF is shown in Fig. 3.4 where the PDF right hand tail spreads out more and the peak decreases as the turbulence strength increases. Note that as $\sigma_R^2 \rightarrow \infty$, the K distribution tends towards a negative exponential distribution.

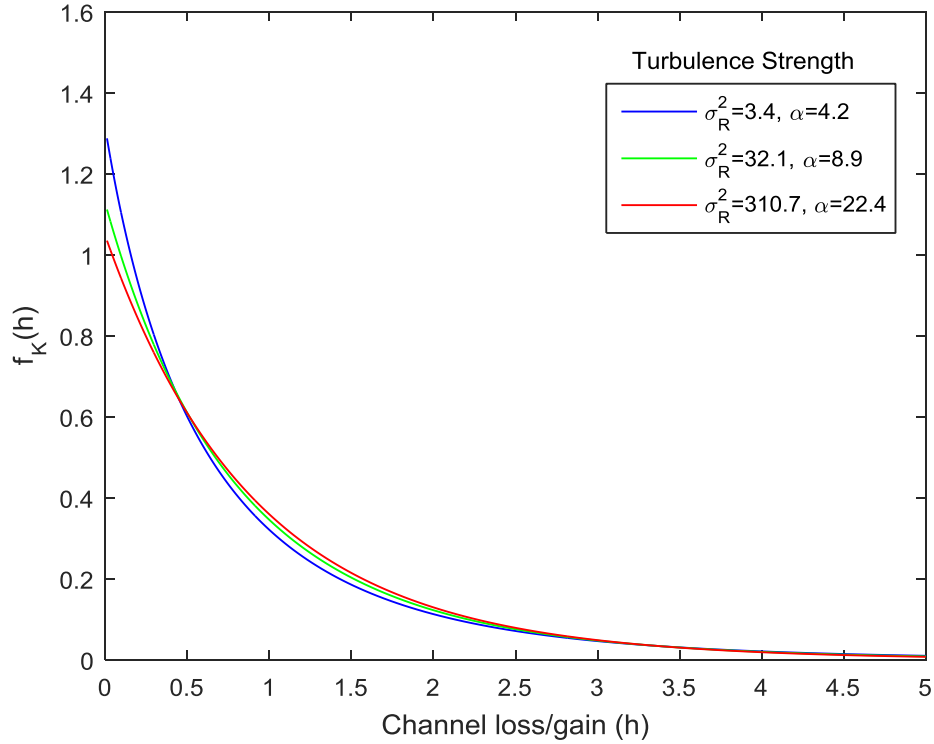


Fig. 3.4: K PDFs against h for different strong turbulence values.

3.3.1.4 Negative Exponential Turbulence Model

For a large number of independent scattering and propagation paths spanning several kilometres, the optical signal experiences very strong irradiance fluctuation and the turbulence regime is known as the saturated (i.e. fully developed speckle [19]) regime [7, 21]. Theoretical and experimental verifications have proved that negative exponential statistics are suitable for

modelling the saturated turbulence regime [19]. The PDF of the negative exponential is given by [6, 19]

$$f_{NE_I}(I, \langle I \rangle) = \frac{1}{\langle I \rangle} \exp\left(-\frac{I}{\langle I \rangle}\right); \quad I > 0; \quad (3.15)$$

Also, the negative exponential PDF is obtained with respect to h as

$$f_{NE_h}(h) = \exp(-h); \quad h > 0; \quad (3.16)$$

The negative exponential PDF is shown in Fig. 3.5. As expected, the PDF is similar to those obtained with the gamma-gamma and K distributions at very strong turbulence regimes.

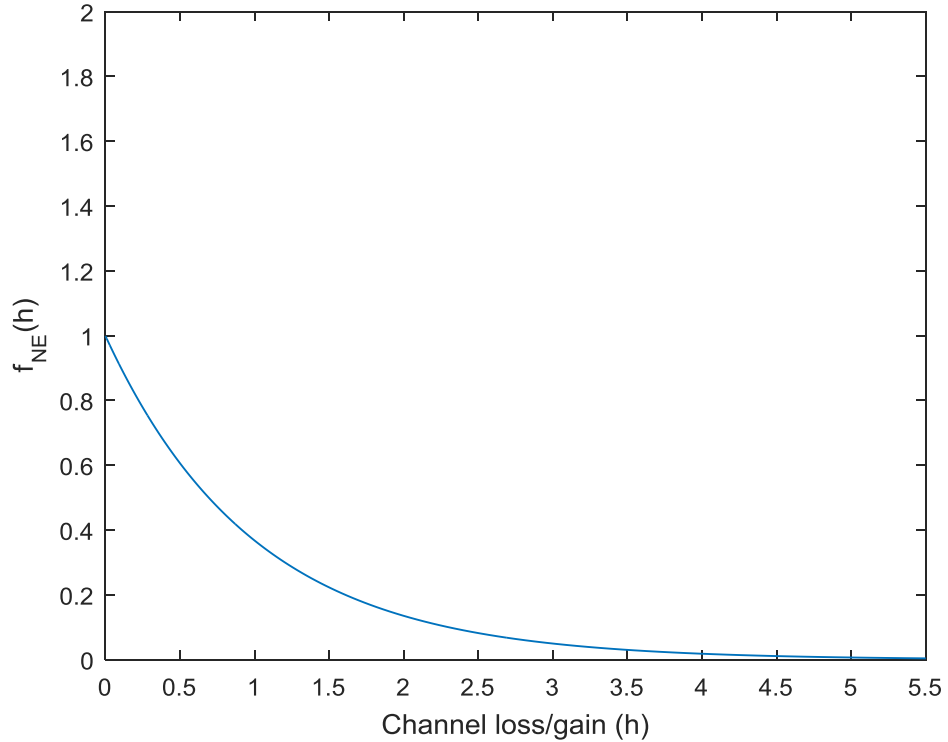


Fig. 3.5: Negative exponential PDFs against h for different average irradiance values.

In addition to the turbulence models mentioned above, the weak to strong turbulence regime can be modelled with the I-K and lognormal-Rician distributions. Note that the K, lognormal-Rician, I-K and gamma-gamma turbulence models all tends towards the negative exponential turbulence model in very strong to saturated turbulent regimes [19].

3.4 Attenuation due to beam spread and the atmospheric channel

Beam spreading is a distance dependent impairment which refers to an increment in the transmitted beam divergence angle as it propagates the atmosphere thereby reducing the amount of radiation captured by the receiver (shown in Fig. 3.6) [2, 22]. With assumptions that no obstructions exist between the transmitter and the receiver, that the transmitted power has a uniform distribution and that the transmitter diameter is very small, the loss due to beam spread in an FSO link can be given as [22-24]

$$L_{bs} = \left(\frac{d_{rx}}{d_{bD}} \right)^2 \quad (3.17)$$

where d_{rx} represents the receiver diameter and $d_{bD} = \phi D$ represents the beam diameter due to diffraction alone where ϕ and D represents the beam divergence angle and propagation distance respectively.

The attenuation experienced by the optical signal as it propagates through the atmosphere is dependent on the channel visibility and varies with time. The atmospheric attenuation is given by the Beer-Lambert law as [2, 25]

$$L_{atm} = \exp(-\alpha D) \quad (3.18)$$

where α (a function of scattering and absorption) represents the atmospheric attenuation factor. With the impact of absorption largely negligible, α (assuming the Mie scattering model) is given as [2]

$$\alpha = \frac{3.91}{V} \left(\frac{\lambda}{550nm} \right)^{-\delta} \quad (3.19)$$

where V , λ and δ represent the atmospheric visibility (the longest horizontal atmospheric distance through which an object is visible), operating wavelength of the laser source and a parameter (values given by the Kim [26] and Kruse [27] models) related to visibility and distribution of particle size in the propagation path respectively.

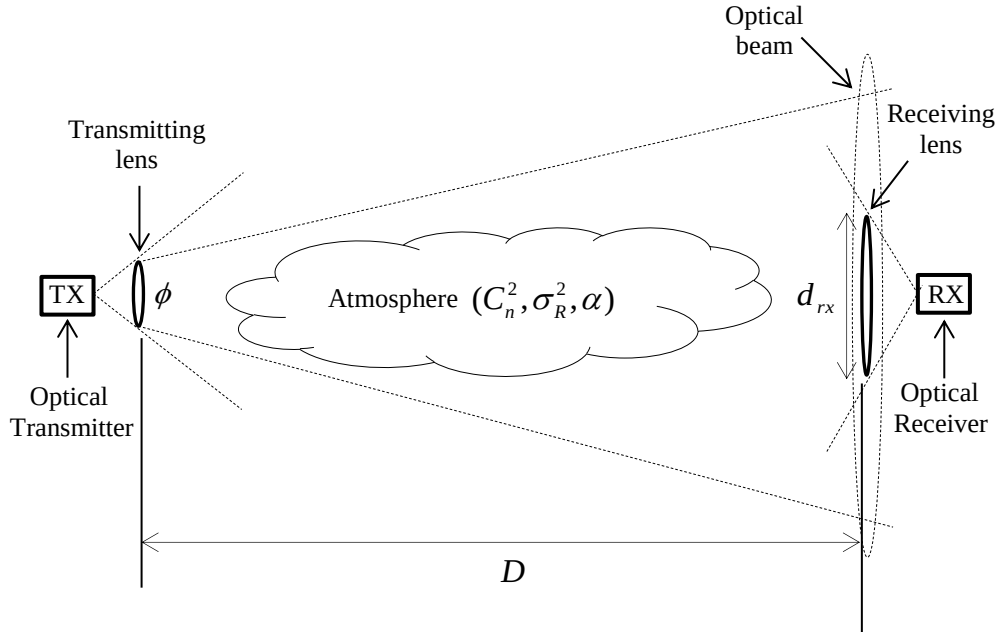


Fig. 3.6: Diagrammatic representation of an FSO link.

3.5 Attenuation due to pointing and coupling losses

Pointing loss occurs due to inability to perfectly align the transmitter and receiver. Misalignments can be caused by strong winds and building sway. While alignment issues can be overlooked in links over short distances, they are more significant in long distance transmission where the transmitted signal can be misdirected such that it essentially misses the receiver completely. Pointing loss has a detrimental effect on system performance. However, with increased implementation cost, responsive tracking systems can be used to automatically align the transmitter with the receiver thereby mitigating the effect of pointing error [2, 28-30].

Under the assumptions that the received beam is Gaussian, the receiver aperture is circular and the radial displacement from the beam centre axis r follows a Raleigh distribution model, the probability density distribution of the attenuation due to pointing error and beam spreading is given as [28, 30, 31]

$$f_{h_p}(h_p) = \frac{\varsigma^2}{a_0^{\varsigma^2}} h_p^{\varsigma^2-1}; \quad 0 \leq h_p \leq a_0 \quad (3.20)$$

where $\varsigma = w_{\varsigma_{eq}} / 2\sigma_s$, σ_s represents the standard deviation of the pointing loss displacement at the receiver, $w_{\varsigma_{eq}}$ represents the equivalent beam width, a_0 represents the fraction of the power collected by the receiving lens and h_p represents attenuation due to pointing error and beam spreading.

When fibre components are integrated into FSO links (i.e. systems with optical amplifiers (OAs) and wavelength-division multiplexing (WDM) networks), loss occurs as the optical signal is coupled into the fibre. The

coupling loss is largely due to a turbulence-induced reduction in the atmospheric coherence length and while adaptive optics can be used to mitigate its effect, it is customary to include a coupling loss penalty in the link budget [7, 23, 24, 32].

3.6 Modelling of system parameters under atmospheric turbulence conditions with Monte Carlo simulation methods

MC simulation (also known as statistical sampling) is a computational technique used to obtain numerical results by repetitive random sampling. It is particularly useful in applications where it is either too complicated or impossible to use other mathematical methods [33]. Due to the random effect of atmospheric turbulence which, in some cases, overstretches analytical methods when used, MC simulation methods are used in several aspects of this work. The MC simulation technique used in this work (flowchart shown in Fig. 3.7) involves the generation of random numbers that follows pre-defined turbulence distributions. To generate a sample random variable of a particular turbulence distribution, a uniform random variable (i.e. $U(0,1)$) can be used to give a value for the cumulative distribution function (CDF) of the turbulence distribution, which is mapped to the appropriate argument and thus directly samples the desired input PDF. By performing repetitive sampling, a histogram approximating to the PDF corresponding to the particular turbulence distribution and more particularly, functions of its samples can be obtained for different system parameters. The system parameters are then used to analyse

system performance. This approach is particularly computationally convenient and useful in cascaded FSO links.

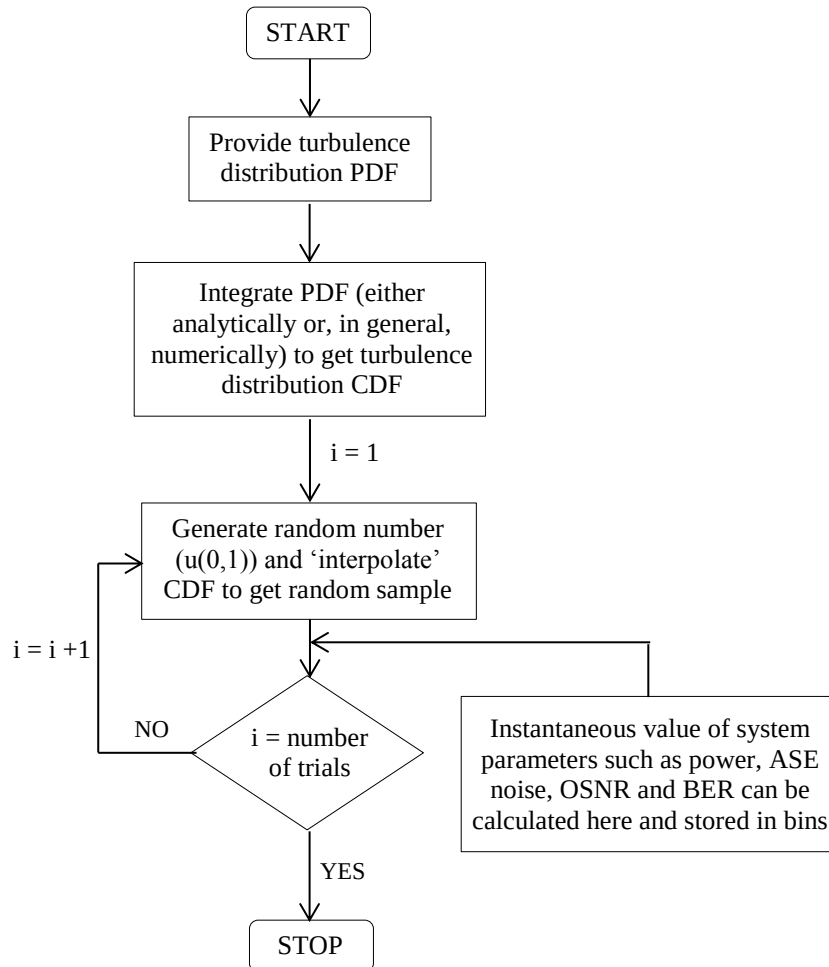


Fig. 3.7: Flowchart showing a MC simulation technique for modelling system parameters affected by atmospheric turbulence.

3.7 Scintillation mitigation techniques

Some of the methods already proposed in literature for scintillation mitigation are summarised below.

- a) Aperture averaging: This technique involves making the receiver aperture size bigger than the correlation length of the intensity fluctuation such that the signal fluctuations are averaged over the receiver aperture size [1, 12]. While aperture averaging has been shown to be effective (even in strong turbulence [34]), it is sometimes expensive or impractical to make the aperture size bigger than the correlation length of the intensity fluctuation [35, 36].
- b) Spatial diversity: This technique ensures that multiple faded versions of the same signal are collected at the receiving end. In order to prevent correlated fading (and ensure improved system performance [36]), the spatial separation between the transmitting and/or receiving lenses should be made bigger than the coherence length of the intensity fluctuation [37]. Spatial diversity can be realised either as multiple transmitters sending signals to multiple receivers (MIMO), multiple transmitters sending signals to a single receiver (MISO) or a single transmitter sending signals to multiple receivers (SIMO) [9, 15]. The practical realization of a spatially diverse system is costly due to the multiple transmitters/receivers required and difficult to implement because of the transmitter and receiver alignment requirements [36].
- c) Maximum likelihood sequence detector (MLSD): This technique jointly detects multiple symbols depending on the statistical and temporal

characteristics of the channel [38]. MLSD has been analysed for instances where channel state information (CSI) is known and when it's not known [38, 39]. Even though MLSD has been shown to efficiently mitigate scintillation, its complicated operation (i.e. performing multidimensional integration) makes it less attractive [35].

- d) Forward error correction (FEC) with interleaving: The FEC technique involves the addition of error correcting codes to the transmitted information. If the errors in the received signal are minimal, FEC can easily be used to recover the original transmitted information. However, for burst errors (possible in FSO communication systems due to atmospheric turbulence), FEC becomes less efficient for information recovery. Using interleaving with FEC is beneficial in a turbulent atmosphere. Interleaving involves a reshuffling process (which reduces the effect of burst errors) at the transmitting and receiving ends such that the recovery performance of FEC is improved even when burst errors occur [40, 41].
- e) Cooperative diversity and multi-hop transmission: This technique involves the introduction of relay nodes in-between the transmitter and receiver. The configuration of the relay nodes could be serial (i.e. multi-hop) or parallel (i.e. cooperative diversity) [42]. The relaying methods can be further characterised based on their mode of operation as shown below.
 - 1. Amplify-and-forward (AF): At each relay node, the received optical signal is first normalized to unity after which the relay modulates the signal with the transmitter power. The signal is

then retransmitted to another relay or the receiver. This method ensures that, at each relay point, the optical signal is transmitted with the same power as the transmitter power [25, 42, 43].

2. Decode-and-forward (DF): At each relay node, the received optical signal is decoded and directly modulated with the transmitter power. The signal is then retransmitted to another relay or the receiver. This process only takes place if the received signal-to-noise ratio exceeds a pre-determined decoding threshold [42, 44, 45].

- f) Use of a saturated OA: This technique exploits the saturation characteristics of the OA gain (i.e. the ability of the OA to adapt its gain to new power levels by providing lower gains to higher input powers and higher gains to lower input powers) with the assumption that the gain dynamics is faster relative to atmospheric turbulence [46-48]. This method will form part of the focus of the present work.

3.8 Summary

This Chapter reviewed the atmospheric channel through which the transmitted optical signal propagates. Impairments such as obstacles along the propagation path, absorption, scattering and atmospheric turbulence were discussed. Various models used to characterise the turbulent channel were reviewed. The lognormal turbulence model is known to be valid in the weak turbulence regime and the gamma-gamma turbulence model (which covers the weak to strong turbulence regime) gives results that are similar to experimental results. The K and negative exponential turbulence model are suitable for the

strong and saturated turbulence regimes respectively. The impact of the attenuation due to beam spreading, atmospheric channel, pointing and coupling losses on the transmitted optical signal were discussed in this Chapter. The use of MC simulation techniques for modelling atmospheric turbulence was discussed and some turbulence mitigation methods were examined.

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Chapter 4

Modulation and Performance Analysis Methods

4.1 Introduction

This Chapter reviews some of the modulation techniques and performance evaluation methods used for free-space optical (FSO) communication systems. The Chapter compares various modulation techniques and discusses the on-off keying (OOK) modulation format in greater details. Methods used to evaluate the performance of FSO communication systems are also examined in this Chapter and the suitability of each method for performance estimation is discussed.

4.2 Modulation

Modulation refers to the process of changing some property (or properties) of a carrier wave in order to encode data (i.e. the information to be sent) on (in this work) an optical signal at the transmitter before onward transmission

through the channel (i.e. atmosphere) [1]. Since the receiver is responsible for decoding the sent information, it is essential that it understands the modulation method used at the transmitter. Various modulation methods exist but methods involving intensity modulation (IM) at the transmitter and direct detection (DD) at the receiver (known as IM/DD) are commonly used in FSO links because they are easily implementable and also sufficient for many of the data rates presently used [2]. Table 4.1 shows a broad comparison of various modulation formats.

Table 4.1: Comparison of various modulation formats [3].

Modulation Format	Cost	Power Efficiency	Signal to Noise Ratio	Bandwidth Efficiency
OOK-NRZ	Low	Lower than PPM and RZ	Moderate	Higher than PPM and RZ
OOK-RZ	Low	Higher than NRZ	Moderate	Lower than NRZ
PPM	Moderate	Higher than OOK	Low	Lower the OOK
Amplitude Modulation	Low	Low-moderate	Low-moderate	High
Frequency/Phase Modulation	Moderate	Moderate	Moderate	Moderate
Digital	High	High	High	Low

The choice of modulation scheme to adopt depends on factors such as bandwidth capacity, ease of operation and power requirements [3]. Unlike OOK modulation which requires an adaptive decision threshold to perform optimally in a turbulent atmosphere, pulse position modulation (PPM), as commonly used, has no decision threshold [3-5].

4.2.1 On-off keying (OOK)

On-off keying (a special case of amplitude shift keying (ASK)) is the most popular modulation format used in optical communication systems due to its simple implementation [3]. This simplicity also extends to performance calculations. In OOK, a 1 bit is encoded when the transmitter is turned on and a 0 bit is encoded when the transmitter is turned off. OOK modulation can be achieved by directly adjusting the transmitter (i.e. turning it on and off to represent the 1 and 0 encoded bits respectively) or by making use of an external modulator to achieve the same purpose. The use of an external modulator is preferred in long-distance high-speed fibre communication systems because it reduces dispersion penalty from chirp (not a problem in FSO communication systems) [1, 2] and facilitates a better extinction ratio.

When the optical signal reaches the receiver, a decision is made to determine the transmitted bit. A 1 bit is determined to have been sent if the received signal level is above a decision threshold (i.e. presence of light) and a 0 bit is determined to have been sent if the received signal level is below the decision threshold (i.e. absence of light) [1]. While this method is very acceptable for optical fibre communication systems (at least until reaching $\approx 40\text{Gb/s}$), it is known to be particularly vulnerable (compared to other methods such as PPM) in FSO communication systems due to the power fluctuations caused by atmosphere turbulence when a non-adaptive threshold is used at the receiver. In order to obtain an optimal performance when the OOK modulation format is used in FSO communication systems, an adaptive decision threshold (which can be practically realised with a Kalman filter [6]) that can constantly track

the power fluctuations is required at the receiver [3, 7]. The OOK modulation format is being used in commercial FSO applications designed by organisations such as the Infrared Data Association (IrDA) [3].

The OOK modulation method can be actualised either as return-to-zero (RZ) or non-return-to-zero (NRZ). In NRZ-OOK, a 0 bit is described by ‘no pulse’ across the bit interval and for a 1 bit; the pulse duration is equal to the bit duration [1, 3]. In a work by Ijaz *et al.*; where they experimentally compared the performances of the OOK-RZ and the OOK-NRZ modulation formats in a turbulent channel, the OOK-RZ was shown to perform better (at the expense of increased bandwidth demands) than the OOK-NRZ. In a work by Elganimi, it was shown that the OOK-RZ requires less power and signal-to-noise ratio (SNR) than the OOK-NRZ to achieve the same bit error rate (BER) performance [8]. Also, since the OOK-RZ has a higher peak-to-average power ratio, it provides a better Q-factor and BER performance than the OOK-NRZ [9]. However, OOK-RZ pulses would naturally have higher filtering requirements. Note that unless otherwise stated, the IM/DD with OOK-NRZ modulation scheme is assumed in this work.

4.3 Performance analysis of FSO communication systems

The goal of a system designer is to have a receiver that correctly demodulates and retrieves the transmitted information with minimal errors [1]. The optical signal arriving at the receiver is usually impaired due to reasons such as intersymbol interference, background radiations, signal distortions and power loss. It can also be affected by amplified spontaneous emission (ASE) noise in

systems with optical amplifiers (OAs). The optical receiver itself also introduces noise currents such as thermal noise. These impairments affect how the receiver decodes the transmitted information. The performance of FSO communication systems can be evaluated with methods such as determining the outage probability for a target instantaneous BER [10] and the average BER [11]. For instance, if an optical receiver demodulating OOK signals detects a 1 bit for a transmitted 0 bit, an error is detected. The BER; which gives a ratio of the incorrectly detected bits to the total number of bits is the key performance attribute commonly used for digital communication system analysis [1]. While various methods are used to model the BER, the Gaussian Approximation (GA) is widely used due to its speed of operation and simplicity [1]. Other methods that can be used to estimate the BER include moment generating functions (MGF) methods such as the Chernoff Bound (CB), Modified Chernoff Bound (MCB), and the Saddle Point Approximation (SPA) [12, 13].

4.3.1 BER evaluation with the Gaussian Approximation

By making a GA assumption for the noise signals and assuming that the transmitted 1 and 0 bits have equal probability of occurrence (i.e. $P(1) = P(0) = 1/2$), the BER can be given as [13, 14]

$$BER_{GA} = \frac{1}{2} [P(0|1) + P(1|0)] \quad (4.1)$$

where the conditional probabilities, $P(0|1)$ and $P(1|0)$ are the probabilities of receiving a 0 bit when a 1 bit is transmitted and the probability of receiving a 1 bit when a 0 bit is transmitted respectively. By making an assumption that the

noise present in the 1 and 0 bits are zero mean Gaussian with variances σ_1^2 and σ_0^2 respectively when sampling takes place in the receiver, the conditional probabilities in (4.1) can be re-written in terms of the Gaussian distribution probability density function (PDF) with continuous random variable y_x as [14, 15]

$$BER_{GA} = \frac{1}{2} \left[\frac{1}{\sqrt{2\pi\sigma_1^2}} \int_{-\infty}^{i_D} \exp\left(-\frac{(i_1 - y_1)^2}{2\sigma_1^2}\right) dy_1 + \frac{1}{\sqrt{2\pi\sigma_0^2}} \int_{i_D}^{\infty} \exp\left(-\frac{(y_0 - i_0)^2}{2\sigma_0^2}\right) dy_0 \right] \quad (4.2)$$

where i_x represents the noise-free signal current level (and thus the mean of the signal and noise combination) at the sampling instant for transmitted data bits, $x \in \{0,1\}$. By applying the $\text{erfc}(\cdot)$ function (used in Gaussian statistics to calculate the area in the tails of the PDFs), the BER is given as [15]

$$BER_{GA} = \frac{1}{2} \left[\frac{1}{2} \text{erfc}\left(\frac{i_1 - i_D}{\sqrt{2\sigma_1^2}}\right) + \frac{1}{2} \text{erfc}\left(\frac{i_D - i_0}{\sqrt{2\sigma_0^2}}\right) \right] \quad (4.3)$$

where $i_x = RP_x$, P_x represents the input power and i_D represents the decision threshold. Note that for a preamplified receiver, $P_x = GP_{OAin_x}$ where P_{OAin_x} represents the OA input power and G is the OA gain. For a binary symmetric channel (BSC), $P(0|1) = P(1|0)$, an ‘optimal’ decision threshold can be obtained as [16]

$$i_D = \frac{i_1\sigma_0 + i_0\sigma_1}{\sigma_1 + \sigma_0} \quad (4.4)$$

It is known that the decision threshold value obtained from (4.4) is not exactly optimal (especially when ASE noise is present) but it leads to a valid Q factor and BER value [1]. With this ‘optimal’ decision threshold, the BER can be re-written as [13]

$$BER_{GA} = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \right] \quad (4.5)$$

where the Q factor, Q is given as

$$Q = \frac{i_1 - i_0}{\sigma_1 + \sigma_0} \quad (4.6)$$

4.3.1.1 Limitations of the Gaussian Approximation

Even though the total photocurrent PDFs for the 1 and 0 bits in the earlier section were treated as Gaussian, it is well known that the GA is not always completely accurate and further suffers from an inability to accurately give an optimum decision threshold when there is significant ASE. Firstly, the photocurrent PDFs are not strictly Gaussian in optically preamplified receivers due to the presence of ASE beat noises. Also, in a non-amplified optical receiver where the dominant thermal noise is Gaussian, the shot noise (which also makes a contribution to the PDF) is not strictly Gaussian. Hence, a PDF containing both noises is not strictly entirely Gaussian [17, 18]. Also, experimental evidence has shown that when ASE beat noises are present, the PDFs for the 1 and 0 bits are non-Gaussian [19]. While some other BER estimation methods will be used in this work, the main focus is on the GA due to its ease of use.

4.3.2 BER evaluation with moment generating function methods

The use of MGF methods to approximate the BER has been shown to give more accurate estimates compared to the GA because they give better representations of the signal and noise components [13, 16]. The MGF methods considered in this section include the CB, MCB and SPA. While the actual BER is not known, the CB provides an upper bound on the BER and can be regarded as being more accurate than the GA because there is uncertainty about when the GA values are higher or lower than the actual BER. The MCB, which is similar to the CB but regarded as more reliable in predicting the performance of FSO communication systems, also provides an upper bound on the BER [13, 16]. The SPA is similar to the MCB but more complicated and slower because it involves taking the second derivatives of the MGF [12, 16]. Now, an MGF of an optical signal (which takes the ASE noise into consideration) is given as [12, 13]

$$M_{Y_x}(s) = \frac{\exp\left(\frac{RGsP_{in_x}}{1 - (RN_0 s/T)}\right)}{(1 - (RN_0 s/T))^L} \quad (4.7)$$

where s represents a standard parameter in the MGF transform domain, $L = B_{opt}m_tT$ and T represents the bit period. A more elaborate definition of the MGF, that includes the effect of receiver thermal noise, is given as [12, 13]

$$M_{Z_x}(s) = M_{th}(s)M_{Y_x}(s) \quad (4.8)$$

where the thermal noise MGF, $M_{th}(s) = \exp(\sigma_{th}^2 s^2 / 2)$. By assuming that the transmitted 1 and 0 bits have equal probability of occurrence, the BER can be given as [13, 14]

$$BER_{em} = \frac{1}{2} [P(0|1) + P(1|0)] \quad (4.9)$$

for $em \in \{CB, MCB, SPA\}$. The CB on the BER is then given as [12, 13, 16]

$$BER_{CB} \leq \frac{1}{2} [\exp(s_0 i_D) M_{Z_0}(-s_0) + \exp(s_1 i_D) M_{Z_1}(-s_1)] \quad s_0 < 0, s_1 > 0 \quad (4.10)$$

The MCB on the BER is given as [12, 13, 16]

$$BER_{MCB} \leq \frac{1}{2} \left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0 \sqrt{2\pi\sigma_{th}^2}} + \frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1 \sqrt{2\pi\sigma_{th}^2}} \right] \quad s_0 < 0, s_1 > 0 \quad (4.11)$$

The SPA of the BER is given as [12, 16]

$$BER_{SPA} = \frac{1}{2} \left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0 \sqrt{2\pi\psi_0''(s_0)}} + \frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1 \sqrt{2\pi\psi_1''(s_1)}} \right] \quad s_0 < 0, s_1 > 0 \quad (4.12)$$

where functions ψ_0 and ψ_1 are given as

$$\psi_0 = \ln \left[\frac{\exp(s_0 i_D) M_{Z_0}(-s_0)}{s_0} \right] \quad s_0 < 0 \quad (4.13)$$

$$\psi_1 = \ln \left[\frac{\exp(s_1 i_D) M_{Z_1}(-s_1)}{s_1} \right] \quad s_1 > 0 \quad (4.14)$$

The decision threshold i_D can be obtained by differentiating the CB BER with respect to the threshold and equating the result to zero as follows [13, 16]

$$\frac{\partial(BER_{CB})}{\partial i_D} = 0 \quad (4.15)$$

Even though the separate optimisation of s_0 and s_1 gives the tightest bounds, it is acceptable to set $s = -s_0 = s_1$ for easier computation [13, 16]. The CB optimum threshold (which can be applied to the MCB and SPA) is obtained as

$$i_D = \frac{\ln(M_{Y_0}(s)/M_{Y_1}(-s))}{2s} \quad (4.16)$$

With this optimum decision threshold, (4.10), (4.11) and (4.12) can be re-written as [12, 13, 16]

$$BER_{CB} = M_{th}(s) \sqrt{M_{Y_0}(s)M_{Y_1}(-s)} \quad s > 0 \quad (4.17)$$

$$BER_{MCB} = \frac{M_{th}(s) \sqrt{M_{Y_0}(s)M_{Y_1}(-s)}}{s \sqrt{2\pi\sigma_{th}^2}} \quad s > 0 \quad (4.18)$$

$$BER_{SPA} = \frac{M_{th}(s) \sqrt{M_{Y_0}(s)M_{Y_1}(-s)}}{2s \sqrt{2\pi}} \left[\frac{1}{\sqrt{\psi_0''(-s)}} + \frac{1}{\sqrt{\psi_1''(s)}} \right] \quad s > 0 \quad (4.19)$$

4.4 Summary

This Chapter reviewed some of the modulation techniques used in FSO communication systems. The OOK is widely used in FSO links due to its simplicity and bandwidth efficiency but it requires an adaptive decision threshold to perform optimally in a turbulent atmosphere. The methods used to

evaluate the performance of FSO links were also discussed in this Chapter. Even though the GA is computationally convenient and gives an acceptable measure of performance, some MGF based methods gives upper bounds on the BER and can be used to confidently describe the performance of FSO communication systems.

4.5 References

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Chapter 5

Single Link Optically Preamplified FSO Communication Systems

5.1 Introduction

This Chapter discusses the performance of single link free-space optical (FSO) communication systems in a turbulent atmosphere. In this Chapter, some references are made to systems with non-amplified receivers but the main focus is on systems with preamplified receivers. The effects of operating a preamplifier in the saturated and unsaturated gain regimes in a non-return-to-zero (NRZ) on-off keying (OOK) single link FSO communication system are discussed and the suppression of scintillation (i.e. especially when channel state information (CSI) is not known) using saturated optical amplifiers (OAs) is shown. Different atmospheric turbulence models (discussed in Chapter 3) are used to describe the various turbulence levels and various evaluation methods such as the Gaussian Approximation (GA), Chernoff Bound (CB), Modified Chernoff Bound (MCB), and the Saddle Point Approximation (SPA) are used to approximate the bit error rate (BER). The BER, in the presence of amplified spontaneous emission (ASE) noise, is shown for various turbulence levels and

the implications of using both adaptive (to channel state) and non-adaptive decision threshold schemes are analysed. An investigation to determine the optimum non-adaptive decision threshold when a saturated preamplifier is used in single link FSO communication systems is carried out. The benefits of amplifier saturation, for example in the form of effective scintillation reduction when a non-adaptive decision threshold scheme is utilized at the receiver are presented. Part of the work in this Chapter led to publication in the Institution of Engineering and Technology (IET) Optoelectronics Journal [1].

5.2 Overview of single link FSO communication systems

The past three decades have witnessed the emergence of FSO communication as a viable approach for terrestrial short range access networks. The catalysts for the development of the FSO communication systems are the rising demands for higher bandwidth and technological developments in optoelectronics such as sensitive detectors and high power transmitters [2-4]. Compared to the traditional radio frequency (RF) and millimetre wave systems, FSO communication systems has advantages such as improved security of information and absence of spectrum licensing requirements [5-7]. Though FSO systems offer many advantages, their practical implementation is highly susceptible to unpredictable severe atmospheric conditions [2, 8]. The received optical signal also experiences fluctuation due to atmospheric turbulence. These fluctuations lead to a reduction in system performance [3, 8, 9]. To achieve the desired BER, appropriate fade mitigation techniques should be employed [10]. Various techniques that have been proposed in the literature

include aperture averaging [2, 11], error correcting codes with interleaving [12], spatial diversity [4, 9, 13, 14], maximum likelihood sequence detection (MLSD) [15] and the use of a saturated OA [16-18].

While OAs may be used in a number of configurations to extend reach or improve receiver sensitivity in optical fibre systems [19], they can also be similarly used in FSO communication systems [3]. Unfortunately, the OA is not a perfect device as it generates optical noise in the form of ASE. As discussed in Chapter 2, the ASE noise further generates beat noises known as spontaneous-spontaneous and signal-spontaneous beat noises [3, 4]. Naturally, the OA saturates at large input signals and gives reduced gain but, while it is not the usual mode of operation for an optical preamplifier, there is no fundamental reason not to operate optical preamplifiers in the saturation regime [19] and indeed this strategy may have advantages. The gain saturation process has been found useful for suppressing atmospherically induced scintillation in the experimental works of Abtahi *et al.* [18] and Ciaramella *et al.* [20]. The ability of saturated OAs to suppress scintillation has also been theoretically shown by Yiannopoulos *et al.* [16] and Boucouvalas *et al.* [17] where they considered the effective fade probability. The non-linear amplification property of a saturated semiconductor OA (SOA) was mentioned in [21] but since CSI was assumed known, the BER results obtained were not able to show that suppressing scintillation in the absence of CSI was beneficial.

5.3 Single link optically preamplified FSO receiver model

Considering a direct detection (DD) scheme with NRZ-OOK modulation, an optically preamplified receiver model for a single link FSO communication system is shown in Fig. 5.1.

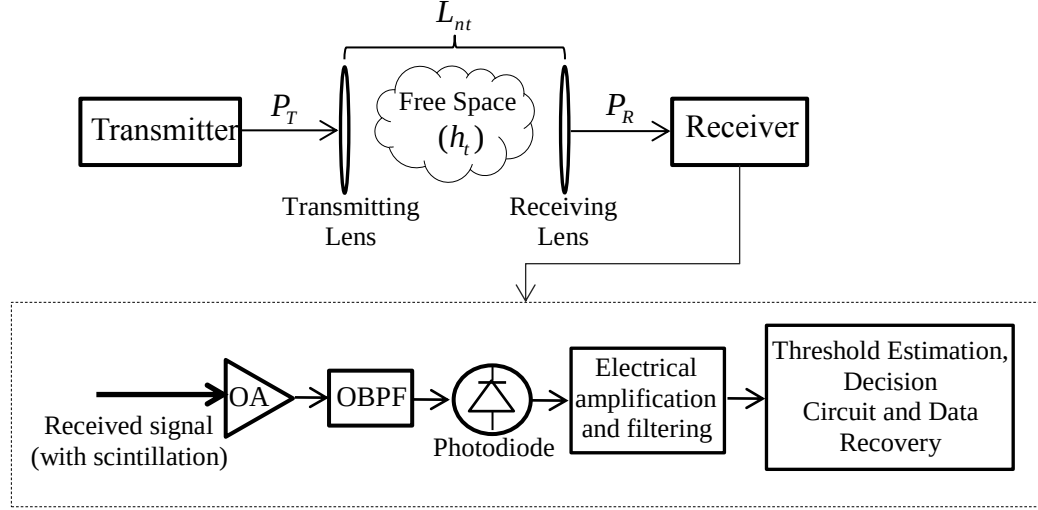


Fig. 5.1: Single link FSO communication system with an optically preamplified receiver model.

Note that the analysis presented in this section only deals with the optical signal power incident on the receiving lens (P_R) which can be obtained by a straightforward subtraction (for analysis in dB) of the turbulence-free fixed path loss (L_{nt}) from the transmitted optical signal power (P_T). A complete system analysis is presented in Chapter 6. In Fig. 5.1, the receiving lens (which couples the laser beam through a fibre into the OA) is assumed to be perfectly aligned with the transmitting lens and an optical band pass filter (OBPF) is used to reduce the ASE noise produced by optical amplification [3]. After the filtering operation, a photodiode (PD) of responsivity $R = \eta q / h\nu$ where q is

the electronic charge, η is the quantum efficiency, h is the Planck constant and ν is the frequency of the optical carrier is used for optical-to-electrical (O/E) conversion of the information-carrying signal followed by electrical amplification and filtering. A decision circuit (with a synchronisation subsystem) is then used to compare the received signal to a defined decision threshold and determine the transmitted data bit [3, 4].

5.3.1 Decision thresholding schemes

In a non-turbulent link, an optimal non-adaptive decision threshold is realistically achievable for a particular received power. However, the use of a non-adaptive decision threshold is not optimal in a turbulent link due to fluctuations in the signal levels [22]. To achieve an optimal performance in a turbulent link, an adaptive decision threshold that can constantly track the noise and signal levels is required [10, 22] i.e. this is achievable if CSI is known. For example, this adaptive decision threshold can be obtained by using a Kalman filter [22]; which constantly tracks the variances and means of the bit level and updates the detection threshold thereby reducing the possibility of detection errors [22]. Practically implementing the adaptive decision threshold for a given receiver is challenging and expensive due to the measurement precision and circuitry constraints required [23]. As a result of this difficulty, FSO link designers often prefer to make use of a non-adaptive decision threshold (based on a long term average received power) and include a link margin large enough to accommodate the turbulence induced scintillation [8].

5.3.1.1 Adaptive decision threshold

Now, considering a preamplified receiver system in a fading OOK FSO link where a GA is made for the noise in the received signal, the BER for a near optimal adaptive decision threshold, conditioned on h_t , is given as [3].

$$BER(h_t) = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{Q(h_t)}{\sqrt{2}} \right) \right] \quad (5.1)$$

where h_t describes the varying channel loss or gain due to atmospheric turbulence and the Q factor,

$$Q(h_t) = \frac{i_1(h_t) - i_0(h_t)}{\sigma_1(h_t) + \sigma_0(h_t)} \quad (5.2)$$

where the mean signal level at the sampling instant with OA input power P_{OAin_x} , $i_x = GRP_{OAin_x}$ for transmitted data bits, $x \in \{0,1\}$. This emerges from the binary symmetric channel assumption and there is a corresponding formula for the threshold which would be almost optimal if the noise was truly Gaussian. As NRZ-OOK signals are used, the power in a ONE

$P_{OAin_1} = \frac{2r}{r+1} P_{OAin_{av}}$, the power in a ZERO $P_{OAin_0} = \frac{2}{r+1} P_{OAin_{av}}$ where

$r = P_{OAin_1} / P_{OAin_0}$ is the extinction ratio, $P_{OAin_{av}}$ is the average power at the OA

input (i.e. the average power over the data stream when $h_t = 1$) and G is the gain (can be either fixed or saturated depending on $P_{OAin_{av}}$) of the OA. The total

noise current variance $\sigma_x^2 = \sigma_{sx-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{sh,x}^2 + \sigma_{th}^2$ where the signal-

spontaneous beat noise $\sigma_{sx-sp}^2 = 4GR^2 P_{OAin_x} N_0 B_e$, the shot noise

$\sigma_{sh,x}^2 = 2qR(GP_{OAin_x} + m_t N_0 B_{opt})B_e$ and the spontaneous-spontaneous beat noise $\sigma_{sp-sp}^2 = 2m_t R^2 N_0^2 B_{opt} B_e \left(1 - \frac{B_e}{2B_{opt}}\right)$. σ_{th}^2 is the receiver thermal noise variance, B_{opt} is the OBPF bandwidth, m_t is the number of polarisation states parameter (1 or 2) and $B_e = R_b/2$ is the receiver noise equivalent bandwidth where R_b is the bit rate. The ASE noise is described by its power spectral density (PSD) $N_0 = \frac{1}{2}(NFG - 1)h\nu$ where NF is the noise figure [3]. Note that for a non-amplified receiver system, $G=1$, $N_0 = 0$ and then the receiver thermal noise is the dominant impairment (i.e. $\sigma_0 = \sigma_1 = \sigma_{th}$) [19].

5.3.1.2 Saturated OA mitigation of turbulence with a non-adaptive decision threshold

The idea of using OAs for the suppression of turbulence induced scintillation is based on exploiting the OA's gain saturation characteristics under the assumption of appropriately fast gain dynamics relative to turbulence. This assumption is valid since a SOA and a erbium-doped fibre amplifier (EDFA) have gain recovery dynamics of around 10 GHz and 5 kHz respectively while turbulence fluctuations are around 1 kHz [3, 16, 24]. The OA gain G is implicitly related to the instantaneous optical signal power at the OA input P_{in} as shown below [19]

$$P_{in} = \frac{P_{sat}}{G-1} \ln\left(\frac{G_{ss}}{G}\right) \quad (5.3)$$

where $P_{in} = P_{OAin_{av}} h_t$, and where G_{ss} and P_{sat} are the small signal (fixed) gain and the internal saturation power of the OA respectively. Note that $G \rightarrow G_{ss}$ when $\frac{P_{in}}{P_{sat}} \rightarrow 0$. As shown in (5.3), the OA is able to adjust its gain to new power levels by providing higher gains to lower input powers and lower gains to higher input powers thereby allowing for its use in scintillation suppression. This essentially instantaneous equalization property of the saturated OA results in more stable average output power (reduced fluctuations) and thus, an optical receiver with a non-adaptive decision threshold can be straightforwardly deployed when an optical preamplifier placed after the turbulent link can nevertheless be driven into saturation [16]. The optical signal power at the output of the OA is obtained as

$$P_{out}(P_{in}) = G(P_{in})P_{in} \quad (5.4)$$

Now, the non-adaptive decision threshold, assumed set to a long term average received power at the photodiode, can be obtained by statistically averaging (5.4) over the atmospheric turbulence PDF and it is formulated as

$$i_D = R \int_0^\infty P_{out}(P_{in}) f_{GG}(h_t) dh_t \quad (5.5)$$

5.4 Single link BER analysis

The BER is the key performance attribute commonly used for FSO communication system analysis [19]. The BER analysis of the single link FSO communication system is evaluated by using the GA, CB, MCB, and the SPA

methods. Note that the CB, MCB and SPA evaluation methods require a moment generating function (MGF) for the signal plus noise to obtain the BER [3, 25].

5.4.1 BER analysis using Gaussian Approximation

By making a GA assumption for the noise, a BER, conditioned on the instantaneous loss (or gain) state of the turbulent channel h_t , is given as [25]

$$BER(h_t) = \frac{1}{2} \left[\frac{1}{2} \operatorname{erfc} \left(\frac{i_D - i_0(h_t)}{\sqrt{2\sigma_0^2(h_t)}} \right) + \frac{1}{2} \operatorname{erfc} \left(\frac{i_1(h_t) - i_D}{\sqrt{2\sigma_1^2(h_t)}} \right) \right] \quad (5.6)$$

The value of i_D in (5.6) can be defined in such a way as to justify the use of Q and adaptive thresholding (and hence equation (5.1)) or by (5.5) in the non-adaptive thresholding case. In the adaptive case it varies with h_t , in the case of (5.5) it does not vary with h_t . In the adaptive case, the decision threshold conditioned on h_t , is given as [25, 26]

$$i_D = \frac{i_1(h_t)\sigma_0(h_t) + i_0(h_t)\sigma_1(h_t)}{\sigma_1(h_t) + \sigma_0(h_t)} \quad (5.7)$$

Now the average BER obtained by statistically averaging the conditioned BER over the turbulence PDF is given as [3]

$$BER_{av} = \int_0^\infty BER_{em}(h_t) f_{atm}(h_t) dh_t \quad (5.8)$$

where *em* (i.e. GA, CB, MCB and SPA) refers to the evaluation method used to obtain the instantaneous BER and *atm* (i.e. LN, GG, K or NE) is the

atmospheric turbulence model used to represent the different turbulence regimes.

5.4.2 BER analysis using MGF methods

The MGF of an optical signal -which also accounts for the ASE noise- is given by [3, 25]

$$M_{Y_x}(s) = \frac{e^{\frac{RG_{ss}P_{OAx}}{1-(RN_0 s/T)}}}{(1-(RN_0 s/T))^L} \quad (5.9)$$

where s is a standard parameter in the MGF transform domain, $L = B_{opt}m_tT$ and T is the bit period. By including the effect of thermal noise, the MGF is given by [3, 25]

$$M_{Z_x}(s) = M_{th}(s)M_{Y_x}(s) \quad (5.10)$$

where the thermal noise MGF, $M_{th}(s) = e^{\frac{\sigma_{th}^2 s^2}{2}}$.

The CB (known to give an upper bound on the BER [25]), conditioned on h_t , is given as [3, 25]

$$BER_{CB}(h_t) = \frac{1}{2} \left[e^{-s_0 i_{DCB}} M_{Z_0}(s_0 | h_t) + e^{s_1 i_{DCB}} M_{Z_1}(-s_1 | h_t) \right] \quad (5.11)$$

The MCB (which has been shown to give a tighter bound on the BER [25]), conditioned on h_t , is given as [3, 25]

$$BER_{MCB}(h_t) = \frac{1}{2} \left[\frac{e^{-s_0 i_{DCB}} M_{Z_0}(s_0 | h_t)}{s_0 \sqrt{2\pi\sigma_{th}^2}} + \frac{e^{s_1 i_{DCB}} M_{Z_1}(-s_1 | h_t)}{s_1 \sqrt{2\pi\sigma_{th}^2}} \right] \quad (5.12)$$

The SPA of the BER, conditioned on h_t , is given as [25]

$$BER_{SPA}(h_t) = \frac{1}{2} \left[\frac{e^{-s_0 i_{DSPA}} M_{Z_0}(s_0 | h_t)}{s_0 \sqrt{2\pi\psi_0''(-s_0 | h_t)}} + \frac{e^{s_1 i_{DSPA}} M_{Z_1}(-s_1 | h_t)}{s_1 \sqrt{2\pi\psi_1''(s_1 | h_t)}} \right] \quad (5.13)$$

where functions $\psi_0(-s_0 | h_t)$ and $\psi_1(s_1 | h_t)$ are given as

$$\psi_0(-s_0 | h_t) = \ln \left[\frac{e^{-s_0 i_{DSPA}} M_{Z_0}(s_0 | h_t)}{s_0} \right] \quad (5.14)$$

$$\psi_1(s_1 | h_t) = \ln \left[\frac{e^{s_1 i_{DSPA}} M_{Z_1}(-s_1 | h_t)}{s_1} \right] \quad (5.15)$$

A near optimal adaptive decision threshold for the CB can be obtained by differentiating the CB BER with respect to the decision threshold and equating the result to zero [3, 25, 27]. By conditioning the result on h_t , the near optimal adaptive decision threshold for the CB is given as [25, 27]

$$i_{DCB} = \ln \left(\frac{s_0 M_{Y_0}(s_0 | h_t)}{s_1 M_{Y_1}(-s_1 | h_t)} \right) / (s_0 + s_1) \quad (5.16)$$

Even though tighter bounds are obtained by optimising s_0 and s_1 separately, it is computationally convenient to set $s = s_0 = s_1 > 0$. Note that the optimal adaptive decision threshold for the CB shown in (5.16) is also valid for the MCB and SPA [3, 25, 27]. Also, since (5.5) corresponds to the case where the decision threshold is assumed set to a long term average received power at the photodiode, it can also be applied as the non-adaptive decision threshold when approximating the BER with MGF methods. The average BER can then be

obtained for the CB, MCB and SPA evaluation methods by substituting (5.11), (5.12) and (5.13) in (5.8).

5.5 Results and Discussions

The parameters used for the numerical analysis are shown in Table 5.1 and 5.2. The OA gain is allowed to respond freely, using complete saturation characteristic and incorporating the effect of ASE noise on the saturated operation. For the purpose of this analysis, an OA that can be driven into gain saturation ($P_{sat} = 5$ dBm) is referred to as a saturated gain OA and an OA that cannot be driven into gain saturation ($P_{sat} \rightarrow \infty$) is referred to as a fixed gain OA. A baseline (unimpaired) receiver sensitivity of -23 dBm corresponding to a BER of 10^{-12} is used to obtain the receiver thermal noise current (i.e. 7×10^{-7} A) [3].

Table 5.1: Parameters used for numerical analysis in a single link optically preamplified FSO link.

Parameter	Symbol	Value
Optical wavelength	λ	1550 nm
Bit rate	R_b	2.5 Gb/s
OBPF bandwidth	B_{opt}	70 GHz
Noise figure	NF	5 dB
Quantum efficiency	η	0.8
Extinction ratio	r	10 dB

Fig. 5.2 shows the BER curves for different turbulence regimes in a single FSO link. In Fig. 5.2(a), the advantage of including a preamplifier at the receiver is shown as the BER curves for a fixed gain preamplified receiver and

a non-amplified receiver has a power difference of around 20 dB at a target BER of 10^{-12} . When a non-adaptive decision threshold is used in Fig. 5.2(b), a non-amplified receiver gives BER floors at high (poor) BER values ($> 10^{-3}$) in all turbulence regimes because unlike the adaptive decision threshold in Fig. 5.2(a), a non-adaptive decision threshold does not properly take the power fluctuations caused by atmospheric turbulence into consideration. However, when a saturated gain preamplifier is used at the receiver, low (better) BER values ($< 10^{-8}$ for $\sigma_R^2 = 0.1$) are obtained because a saturated gain preamplifier suppresses scintillation by adjusting its gain to the fluctuating power levels. A comparison of the BER curves for a fixed gain preamplified receiver and a non-amplified receiver with non-adaptive decision thresholds in Figs. 5.2(c) and 5.2(b) respectively shows a consistent power difference of around 20 dB across all turbulence regimes but BER floors at high BER values ($> 10^{-3}$) were obtained in both cases across all turbulence regimes. This shows that a fixed gain preamplifier can be used to improve receiver sensitivity but it cannot suppress scintillation.

As mentioned in [16, 17] and shown in Figs 5.2(b) and 5.2(d), the BER performance of a saturated gain preamplified receiver reaches an optimal level when the power at the preamplifier input is comparable with its P_{sat} value. For instance, the BER curve ($\sigma_R^2 = 0.1$) for a saturated gain preamplified receiver in Fig. 5.2(b) reaches an optimal value at an average received power of around 5 dBm; which is the P_{sat} value of the preamplifier.

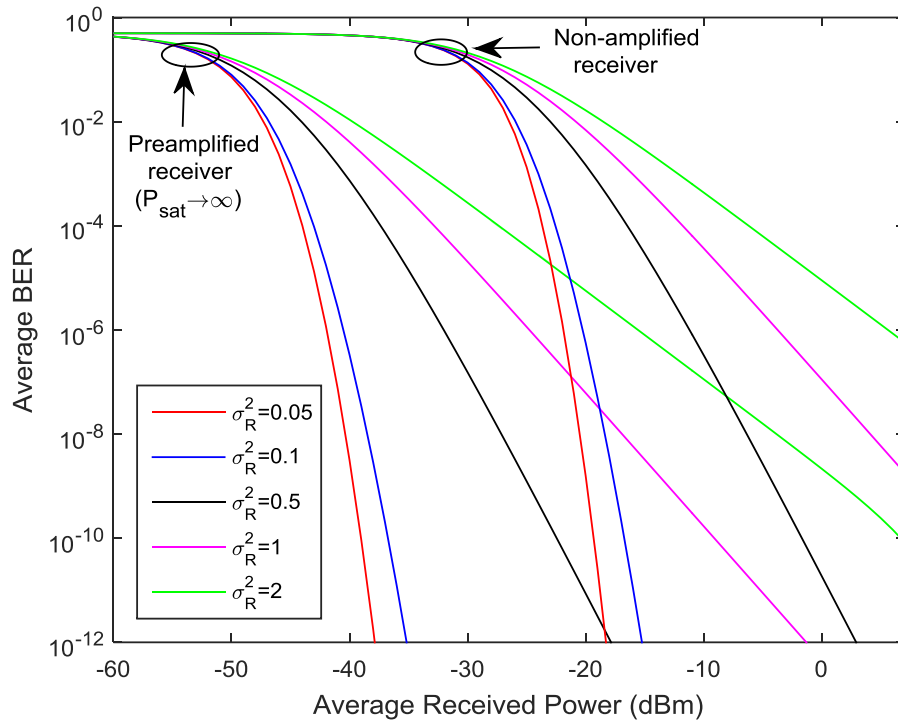


Fig. 5.2 (a) Non-amplified receiver and fixed gain preamplified receivers - Adaptive decision threshold.

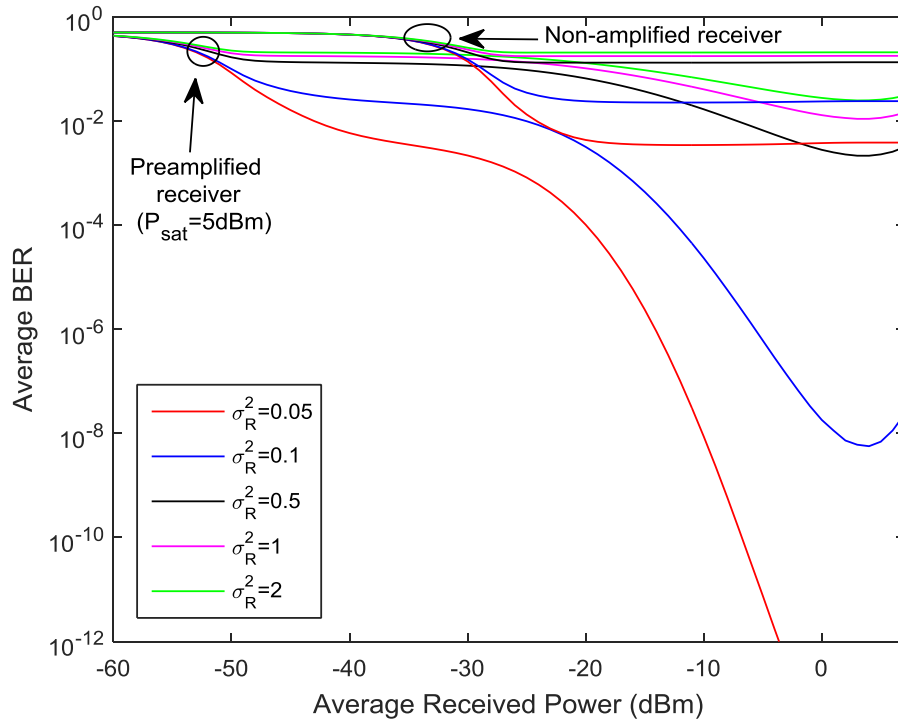


Fig. 5.2 (b) Non-amplified receiver and saturated gain preamplified receivers – Non-adaptive decision threshold.

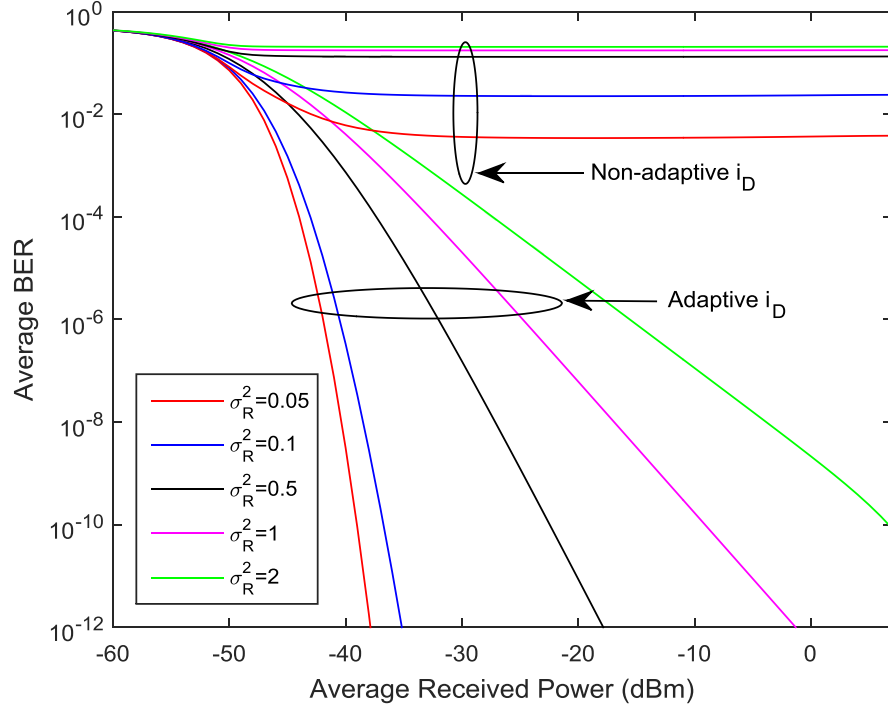


Fig. 5.2 (c) Adaptive and non-adaptive decision thresholds - Fixed gain preamplified receiver.

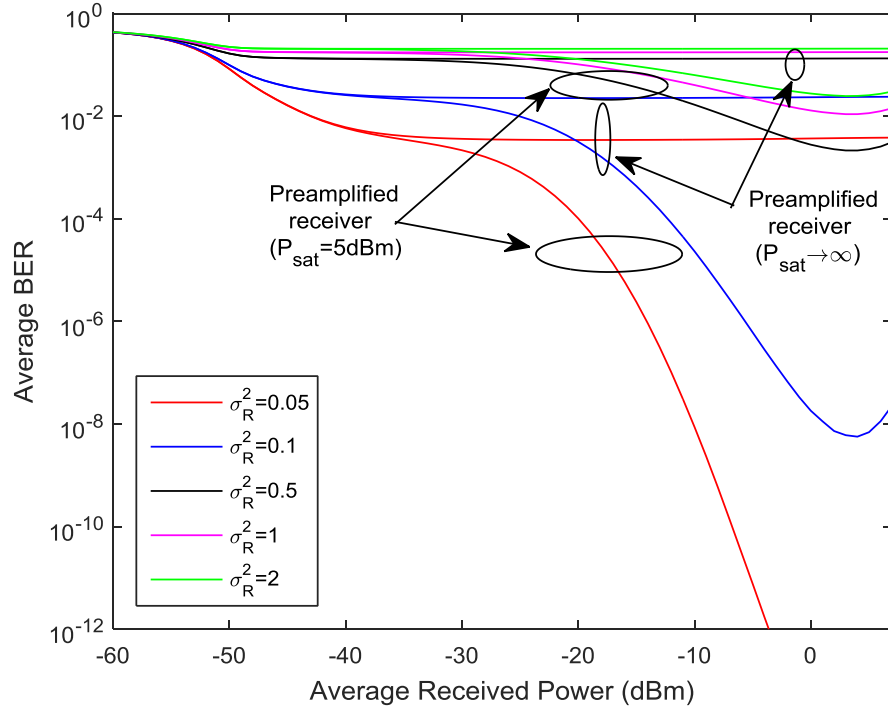


Fig. 5.2 (d) Fixed and saturated gain preamplified receivers - Non-adaptive decision threshold.

Fig. 5.2: Average BER (with GA and GG) against average received power for different turbulence regimes in a single FSO link ($G_{ss} = 25$ dB).

While there is no fundamental reason not to operate optical preamplifiers in the saturation regime, an optical preamplifier with a high P_{sat} value would only be driven into gain saturation if the input power is also high. If a high input power is required to drive the preamplifier into gain saturation, the power at the preamplifier output may have to be reduced (i.e. by introducing an optical fibre and additional attenuation) before it arrives at the receiver because high powers can eventually overload the receiver. Alternatively, preamplifier gain saturation can be achieved with a low power if the P_{sat} value of the preamplifier is also low thereby avoiding the possibility of overloading the receiver.

Fig. 5.3 shows the BER curves for different G_{ss} values while considering a saturated gain preamplified receiver with a non-adaptive decision threshold in a single FSO link. As mentioned above, Fig. 5.3 clearly also shows that the BER performance reaches an optimal level when the power at the preamplifier input is comparable with the P_{sat} values. This attribute can also be seen to be consistent for the different G_{ss} values shown in Fig. 5.3. However, the BER performance improves as the G_{ss} value increases. This is due to the fact that (i.e. as evident in the OA gain saturation characteristics shown in (5.3)) an increase in the G_{ss} value allows wider range of powers to be received while providing more gain to the input signal.

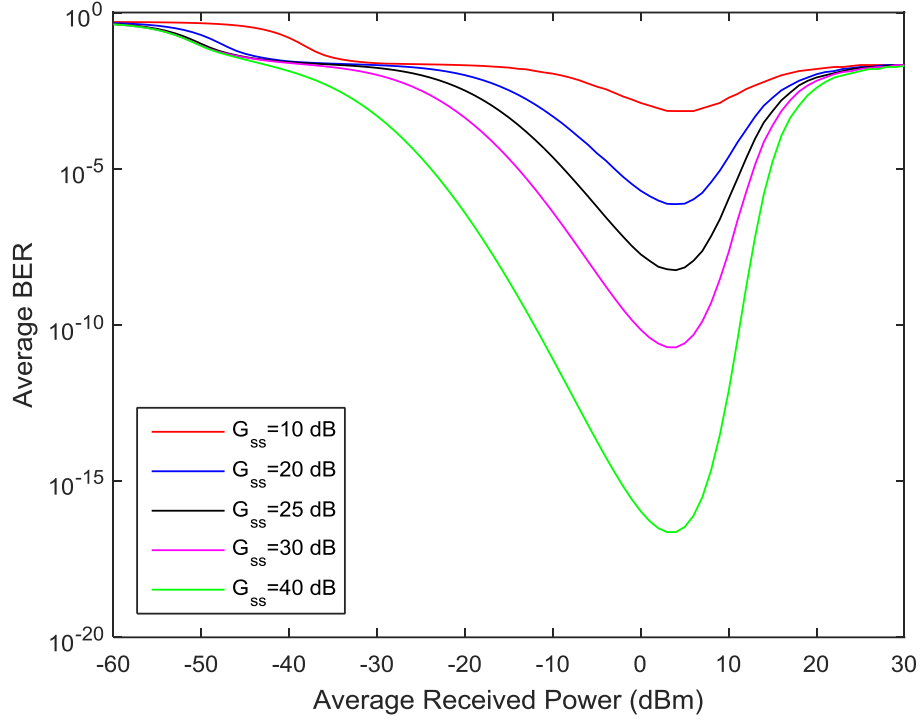


Fig. 5.3: Average BER (GA used with GG) against average received power for a saturated gain preamplified receiver with a non-adaptive decision threshold ($\sigma_R^2 = 0.1$, $P_{sat} = 5$ dBm).

In Figs. 5.2 and 5.3, the non-adaptive decision threshold used is assumed set to a long term average received power at the photodiode (i.e. the decision threshold level, D_{rel} is fixed midway between i_1 and i_0). This decision threshold can be regarded as corresponding to $D_{rel} = 0.5$. Fig. 5.4 shows the minimum BER values that can be obtained at different threshold levels (using a non-adaptive decision threshold) of a saturated gain preamplified receiver while considering various G_{ss} values. As expected, the BER performance increases as the G_{ss} value increases. Also, for all the various G_{ss} values, the best performances are observed when $D_{rel} \approx 0.2$.

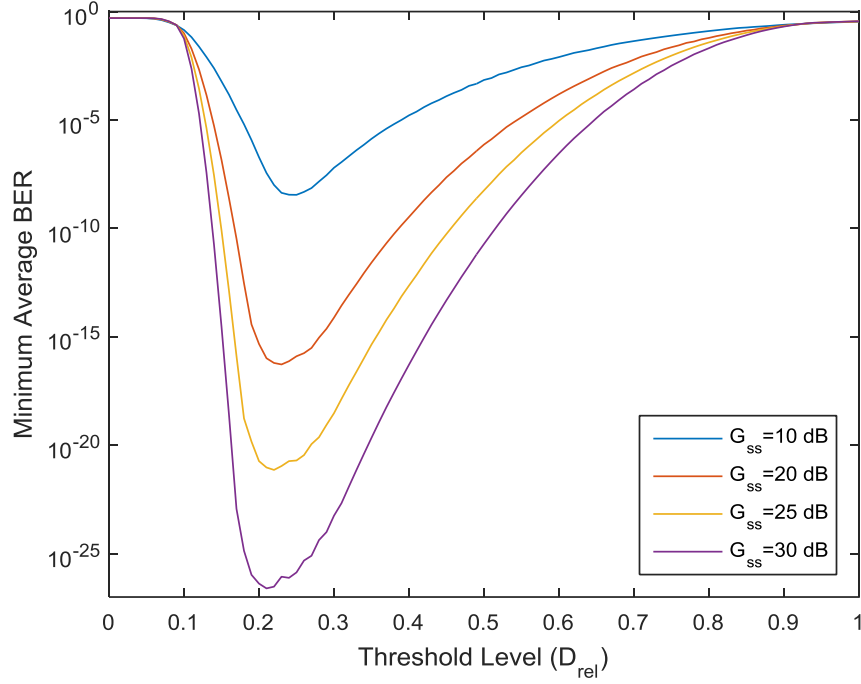


Fig. 5.4: Minimum average BER (with GA and GG) against threshold level (long term average received power) for a saturated gain preamplified receiver using a non-adaptive decision threshold ($\sigma_R^2 = 0.1$, $P_{sat} = 5$ dBm).

The values used to model the weak to strong turbulence regimes in Fig. 5.5 are shown in Table 5.2.

Table 5.2: Parameters used to model different turbulence regimes in a single link optically preamplified FSO link

Parameter	Atmospheric turbulence regimes			
	Weak	Moderate	Strong	Saturated
σ_R^2	0.1	1.5	3.5	30
α	21.59	4.05	4.23	8.65
β	19.82	1.98	1.36	1.02

Fig. 5.5 shows the BER curves for different turbulence regimes in a single FSO link. In Fig. 5.5(a) where a fixed gain preamplified receiver with an adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak,

moderate, strong and saturated turbulence regimes. As mentioned in [2, 3, 28] and shown in Fig. 5.5(a), the LN distribution (BER of 10^{-12} achievable with a received optical power of about 36dBm) gives a better performance when compared to the GG distribution (BER of 10^{-12} achievable with a received optical power of about 34dBm) in the weak turbulence regime. However, the GG distribution has been shown to be more accurate when both are compared with experimental results [2, 3, 28-30]. Also, as the turbulence strength decreases from the saturated turbulence regime to the weak turbulence regime, the BER performance becomes better. This increase in BER performance occurs because when the turbulence strength reduces, there is a proportional decrease in the fluctuation of the received optical signal at the receiver. In Fig. 5.5(b) where a fixed gain preamplified receiver with an adaptive decision threshold is used, the GG distribution is used to describe the strong and saturated turbulence regimes, the K turbulence distribution is used to describe the strong turbulence regime and the NE turbulence distribution is used to describe the saturated turbulence regime. In the strong turbulence regime, the GG distribution is shown to perform better than the K distribution at higher received optical power values ($> -35\text{dBm}$) and in the saturated turbulence regime, the NE distribution is shown to perform better than the GG distribution for all the received optical power values considered. It should however be noted that (for the parameters considered) the best BER performance ($\approx 10^{-8}$) is not good enough for a reliable communication link. In order to have a more reliable communication link in the strong and saturated turbulence regimes, other performance optimising measures such as a forward error correction (FEC) technique with interleaving can be introduced [3, 12].

In Fig. 5.5(c) where a fixed gain preamplified receiver with a non-adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak, moderate, strong and saturated turbulence regimes. Also, the K and the NE turbulence distributions were used to describe the strong and saturated turbulence regimes respectively. Unlike the BER values ($\approx 10^{-12}$) obtained in Fig. 5.5(a) where an adaptive decision threshold is used, BER floors at high BER values ($> 10^{-2}$) are obtained in all the turbulence regimes in Fig. 5.5(c). The BER floors are obtained because of the inability of a non-adaptive decision threshold to adapt to fluctuations in the received optical signal. However, a non-adaptive decision threshold can be used to obtain better BER performances as shown in Fig. 5.5(d). In Fig. 5.5(d) where a saturated gain preamplified receiver with a non-adaptive decision threshold is used, the LN distribution is used to describe the weak turbulence regime and the GG distribution is used to describe the weak, moderate, strong and saturated turbulence regimes. Unlike the poor BER performances shown in Fig 5.5(c) where a non-adaptive decision threshold was also used at the receiver, the introduction of a saturated gain preamplifier allows for improved BER performances shown in Fig 5.5(d). While all the BER results shown in Fig 5.5(c) were more than 10^{-2} , better BER results ($< 10^{-10}$ for LN and GG) are shown in Fig. 5.5(d). It is also noticed that the merits of using a saturated gain preamplified receiver is mainly evident in the weak turbulence regime as shown by the LN and GG distributions.

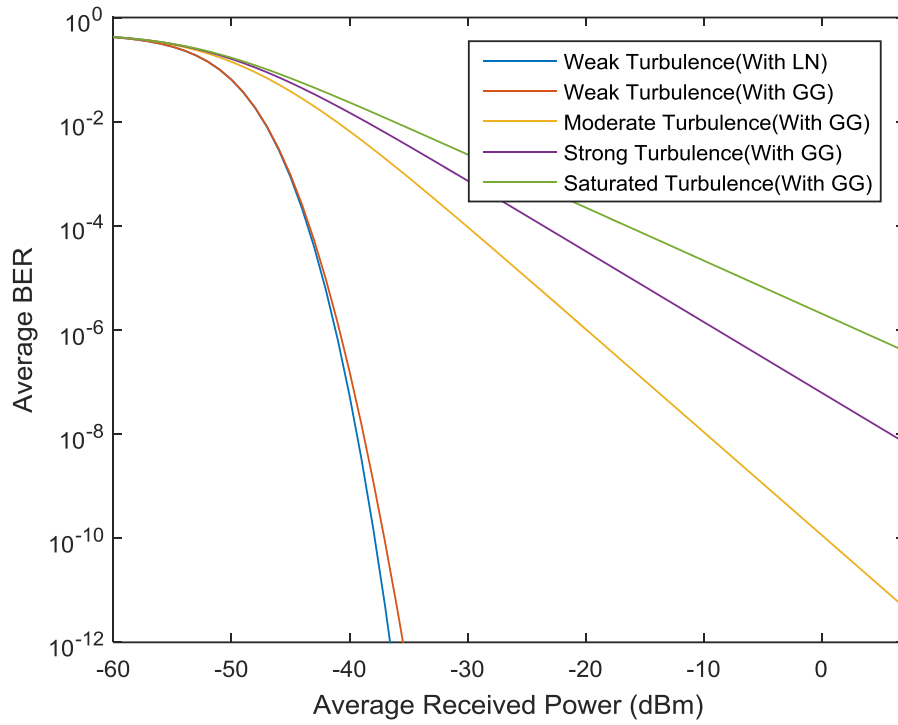


Fig. 5.5 (a) Weak, moderate, strong and saturated turbulence regimes - Fixed gain preamplified receiver with an adaptive decision threshold ($P_{sat} \rightarrow \infty$).

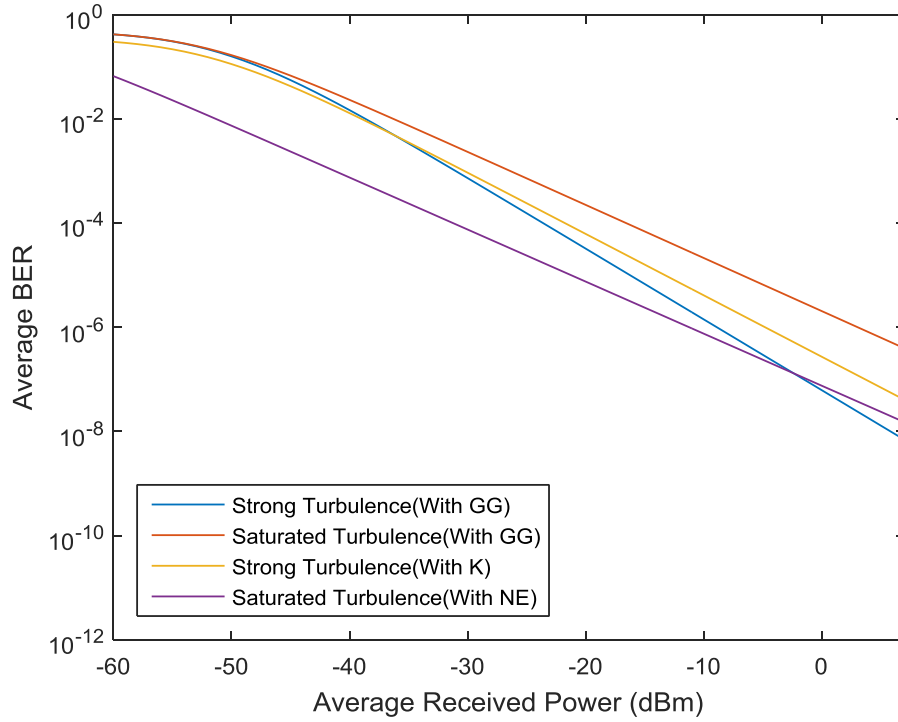


Fig. 5.5 (b) Strong and Saturated turbulence regimes - Fixed gain preamplified receiver with an adaptive decision threshold ($P_{sat} \rightarrow \infty$).

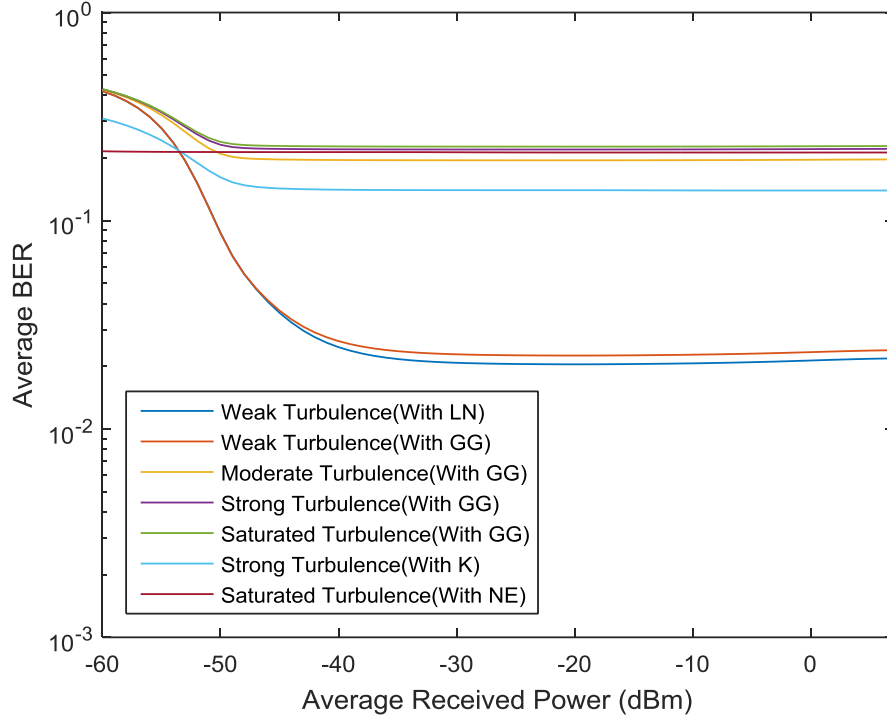


Fig. 5.5 (c) Weak, moderate, strong and saturated turbulence - Fixed gain preamplified receiver with non-adaptive decision threshold ($P_{sat} \rightarrow \infty$).

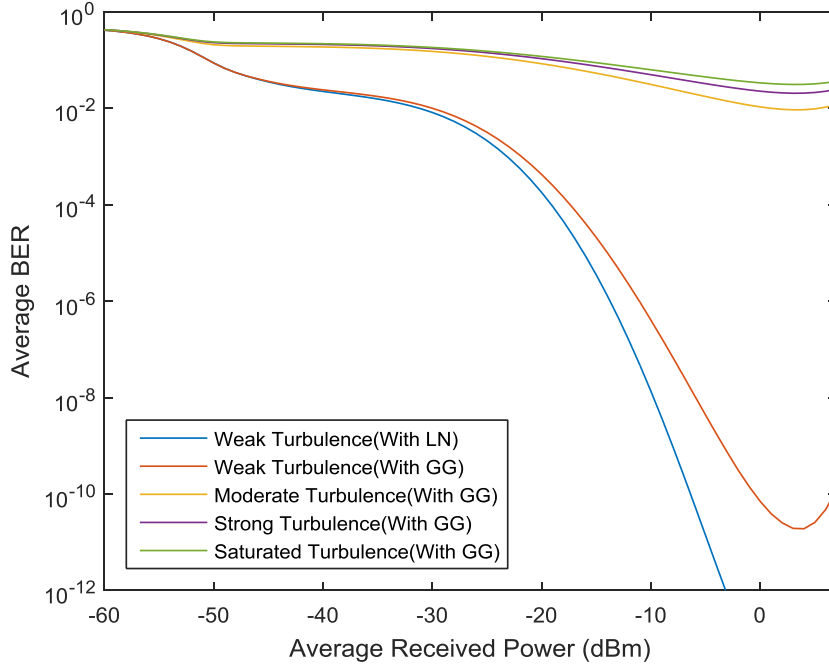


Fig. 5.5 (d) Weak, moderate, strong and saturated turbulence regimes - Saturated gain preamplified receiver with a non-adaptive decision threshold ($P_{sat} = 5$ dBm).

Fig. 5.5: Average BER (with GA) against average received power for different turbulence regimes ($G_{ss} = 25$ dB).

A noticeable similarity between the results for a non-adaptive and an adaptive decision threshold is the better BER performance observed with the LN distribution compared to the GG distribution in the weak turbulence regime. As mentioned in earlier results and shown in Fig. 5.5(d), when a saturated gain preamplified receiver with a non-adaptive decision threshold is used, optimal BER performances are obtained when the P_{sat} value of the preamplifier is comparable to the received optical power.

Fig. 5.6 shows the BER curves for different BER evaluation methods in a single FSO link. The BER results are shown for an adaptive and a non-adaptive decision threshold when a fixed gain preamplified receiver is used. When a non-adaptive decision threshold is used, poor BER performances ($> 10^{-2}$) are shown for the different BER evaluation methods. However, better BER performances ($\approx 10^{-12}$) are noticed with an adaptive decision threshold. The SPA performs better than the GA while the CB and MCB gives upper bounds (worse BER performance) on the GA. Fig. 5.6 also shows similar BER performances for the CB and MCB. It is noteworthy that the BER curves for the different BER evaluation methods are dependent on factors such as the turbulence strength and the choice of receiver filters [3, 25].

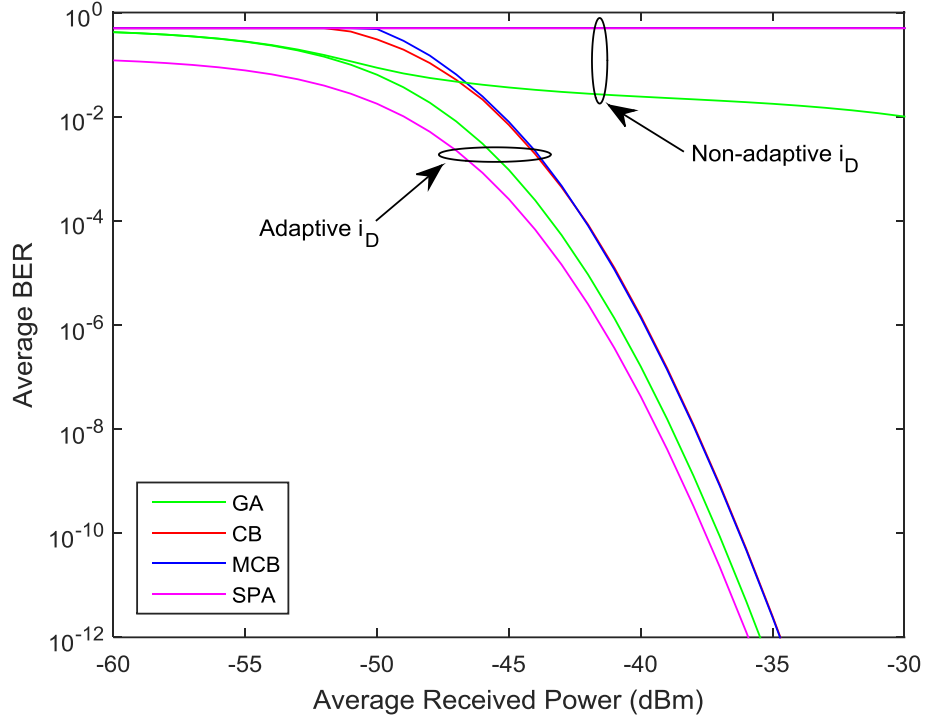


Fig. 5.6: Average BER (with GG) against average received power for different BER evaluation methods ($\sigma_R^2 = 0.1$, $G_{ss} = 30$ dB, $P_{sat} \rightarrow \infty$).

5.6 Summary

This Chapter examined the performance of single link FSO communication systems in a turbulent atmosphere. Performance modelling in the presence of ASE noise was shown. The use of a saturated preamplifier was investigated and the BER results obtained showed its ability to suppress scintillation when CSI is not known and a non-adaptive decision threshold is used. Results from investigations to determine the optimum non-adaptive decision threshold for the GA were also shown. This Chapter also showed that in a turbulent atmosphere, preamplifier saturation does not improve receiver sensitivity when an adaptive decision threshold is used at the receiver. This is because the adaptive threshold mitigates the scintillation impact, leaving saturation to be a

signal power impairment. Saturation was shown to be primarily helpful in the preamplifier when a (less complex) non-adaptive decision threshold is used at the receiver. This threshold benefits from a more stable input power to the photodiode caused by saturation providing higher gains to lower amplifier input powers and lower gains to higher amplifier input powers. Thus the argument for introducing a saturated preamplifier, against having no amplifier at all, is that the saturation mitigates the significant sensitivity impairment caused by the atmospheric scintillations. A saturated preamplifier also showed improvement when compared with an otherwise identical non-saturating preamplifier since a saturated preamplifier is able to provide some scintillation suppression. Even though the results presented show that the performance of an adaptive decision threshold is superior to a non-adaptive decision threshold (especially in higher turbulence regimes) for both saturated and fixed gain preamplified receivers, the practical implementation of an adaptive decision threshold is far more complicated and costly. It has been shown in this Chapter that the ability of a saturated gain preamplifier to suppress scintillation in single link FSO communication systems is only meaningful for system performance when a non-adaptive decision threshold is used at the receiver. Therefore the use of a non-adaptive decision threshold with a saturated gain preamplified receiver is recommended for scintillation suppression in single link FSO communication systems since good performance is achievable without the need of further complexity in the circuitry and processing.

5.7 References

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Chapter 6

Cascaded OA FSO Communication Systems

6.1 Introduction

This Chapter discusses the performance of a free-space optical (FSO) communication system in a turbulent atmosphere employing an optical amplifier (OA) cascade to extend reach. The effects of operating OAs in the saturated and fixed gain regimes in a non-return-to-zero (NRZ) on-off keying (OOK) cascaded OA FSO communication system are discussed and the suppression of scintillation (i.e. especially when channel state information (CSI) is not known) using one or more saturated OAs is considered. Monte Carlo (MC) simulation techniques are used to model the probability distributions of the optical signal power, amplified spontaneous emission (ASE) noise, optical signal to noise ratio (OSNR) and the average bit error rate (BER) due to scintillation. The BER, in the presence of ASE noise, is shown for various turbulence levels, all modelled with a gamma-gamma distribution (discussed in Chapter 3). The implications of using both adaptive (to channel state) and non-adaptive decision threshold schemes are also analysed. The

merits of amplifier saturation when a non-adaptive decision threshold scheme is employed at the receiver for different atmospheric turbulence regimes, are presented. The cascaded OA FSO link is first considered from a general system perspective, and then specific system implementations are shown. Part of the work in this Chapter led to publication in the Institution of Engineering and Technology (IET) Optoelectronics Journal [1].

6.2 Overview of cascaded OA FSO communication systems

FSO communication has recently attracted significant interest in research and development activities because of the advantages it offers compared to radio frequency (RF) and optical fibre communication systems [2-9]. Despite all the possible benefits of deploying FSO systems, their capabilities are limited by atmospheric conditions [10-12]. In addition, the performance of FSO systems are greatly affected by atmospheric turbulence [13]. These undesirable effects are even more pronounced when an FSO system is required for longer distances [14]. Specifically, the effect of atmospheric turbulence is highly significant at communication distances greater than 1 km as it results in fading i.e. fluctuations of the optical signal transmitted through the atmosphere [8, 15, 16]. In order to obtain the desired performance especially over long distances, suitable turbulence alleviation methods are required. Various techniques such as cooperative diversity and multi-hop transmission (i.e. amplify-and-forward (AF) [14, 17-20] and decode-and-forward (DF) relaying [21, 22]) have been proposed in the literature for practically implementing an FSO communication system over longer distances. While some of these techniques are costly and

complex, others did not sufficiently analyse the effect of the accumulated ASE noise which becomes more prevalent with increased number of relays.

6.3 Cascaded OA FSO communication system

Fig. 6.1 shows a cascaded OA FSO communication system model. In a cascaded OA FSO link (and also often in conventional optically preamplified receiver), the basic receiver sensitivity at the photodiode (PD) input becomes less useful in evaluating system performance due to the accumulation of ASE noise. It is therefore necessary to determine the optical power and the ASE noise at each OA stage. When these two quantities are known, the OSNR, which can be related to the BER [23] is then obtainable. Due to the random effect of atmospheric turbulence, analytical methods are stretched by multiple links when used. Therefore, MC simulation techniques are used here to model the cascaded OA FSO communication system. By using MC methods, random samples of the power fluctuation due to atmospheric turbulence are determined for each interamplifier section of the OA cascade and histograms approximating to the probability density functions (PDF) corresponding to the turbulence distribution used are obtained for the accumulated power, ASE noise and OSNR PDFs at each OA stage. Each interamplifier section of the cascaded OA FSO link is assumed statistically independent in its turbulence.

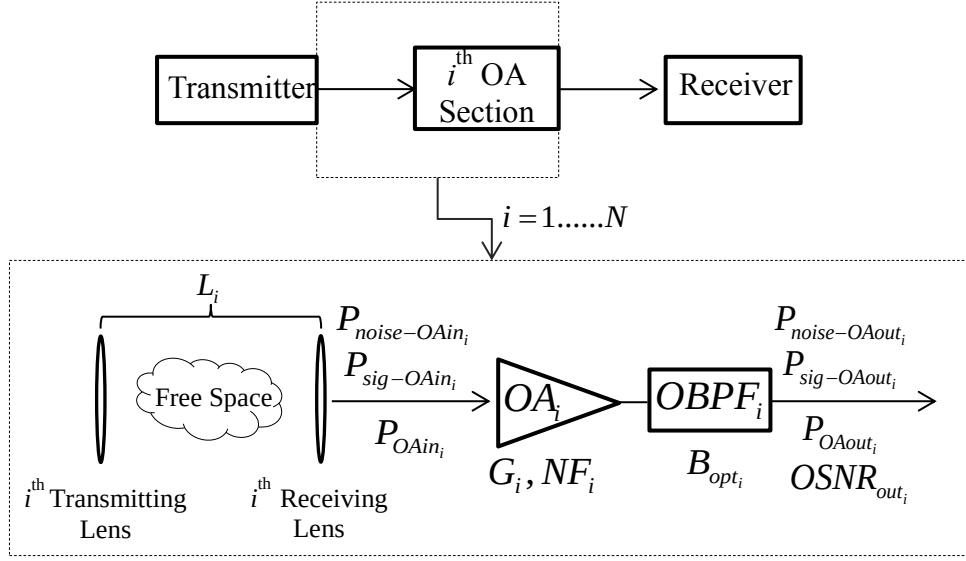


Fig. 6.1: A cascaded OA FSO communication system model.

With the assumption of a clean atmosphere, the total loss in each interamplifier section of the cascaded OA FSO link $L_i = L_{nt_i} h_{GG_i}$ ($i = 1, \dots, N$) where h_{GG_i} represents the gamma-gamma random variable describing the fluctuations due to atmospheric turbulence before the i 'th OA and N represents the total number of OAs in the cascade. L_{nt_i} represents the turbulence-free fixed path loss (< 1) (i.e. defined by the attenuation due to geometric spread and atmospheric propagation [24]) and it is given as [25]

$$L_{nt_i} = \left(\frac{d_{rx_i}}{\phi_i D_i} \right)^2 \alpha_i \quad (i = 1, \dots, N) \quad (6.1)$$

where d_{rx_i} and ϕ_i represents the receiving lens diameter and beam divergence angle for each interamplifier section of the cascaded OA FSO link respectively.

$\alpha_i = 10^{(-\alpha_{D_i} D_i / 10)} (i = 1, \dots, N)$ represents the atmospheric attenuation in each

interamplifier section of the cascaded OA FSO link where α_{Di} and D_i represents the atmospheric attenuation factor and length of each interamplifier section of the cascaded OA FSO link respectively.

6.3.1 Cascaded OA OSNR analysis

The total power at the input of the i 'th OA is given as

$$P_{OAin_i} = P_{sig-OAin_i} + P_{noise-OAin_i} \quad (i = 1, \dots, N) \quad (6.2)$$

The signal power at the input of the i 'th OA is given as

$$P_{sig-OAin_i} = P_{sig-OAout_{i-1}} L_i \quad (i = 2, \dots, N) \quad (6.3)$$

For the first OA, $P_{sig-OAin_1} = P_T L_1$ where P_T is the transmitted optical signal power. The ASE power spectral density (PSD) at the input of the i 'th OA is given as

$$N_{o-OAin_i} = N_{o-OAout_{i-1}} L_i \quad (i = 2, \dots, N) \quad (6.4)$$

For the first OA, $N_{o-OAin_1} = 0$. The ASE power at the input of the i 'th OA is given as

$$P_{noise-OAin_i} = m_t B_{opt} N_{o-OAin_i} \quad (i = 1, \dots, N) \quad (6.5)$$

At the i 'th OA, the self ASE PSD is given as

$$N_{o-OA_i} = \frac{1}{2} (NFG_i (P_{OAin_i}) - 1) h\nu \quad (i = 1, \dots, N) \quad (6.6)$$

where NF is the noise figure, h is the Planck constant and ν is the frequency of the optical carrier The self ASE power is given as

$$P_{noise-OA_i}(P_{OAin_i}) = m_t B_{opt} N_{0-OA_i} \quad (i = 1, \dots, N) \quad (6.7)$$

The gain of the i 'th OA $G_i(P_{OAin_i})$ ($i = 1, \dots, N$) is implicitly related to the total power at the input of the i 'th OA P_{OAin_i} as shown below [23]

$$P_{OAin_i} = \frac{P_{sat_i}}{G_i(P_{OAin_i}) - 1} \ln \left(\frac{G_{ss_i}}{G_i(P_{OAin_i})} \right) \quad (i = 1, \dots, N) \quad (6.8)$$

where G_{ss_i} and P_{sat_i} are the small signal (fixed) gain and the internal saturation power of the i 'th OA respectively. Note that $G_i(P_{OAin_i}) \rightarrow G_{ss_i}$ when $\frac{P_{OAin_i}}{P_{sat_i}} \rightarrow 0$. After amplifying the optical signal with a gain

$G_i(P_{OAin_i})$ ($i = 1, \dots, N$), the signal power at the output of the i 'th OA is given as

$$\begin{aligned} &P_{sig-OAout_i}(P_{sig-OAin_i}, P_{noise-OAin_i}) \\ &= G_i(P_{sig-OAin_i} + P_{noise-OAin_i}) P_{sig-OAin_i} \quad (i = 1, \dots, N) \end{aligned} \quad (6.9)$$

The ASE power at the output of the i 'th OA is given as

$$\begin{aligned} &P_{noise-OAout_i}(P_{sig-OAin_i}, P_{noise-OAin_i}) \\ &= G_i(P_{sig-OAin_i} + P_{noise-OAin_i}) P_{noise-OAin_i} + P_{noise-OA_i}(P_{OAin_i}) \quad (i = 1, \dots, N) \end{aligned} \quad (6.10)$$

The ASE PSD at the output of the i 'th OA is given as

$$N_{o-OAout_i} = N_{o-OAin_i} G_i + N_{o-OA_i} \quad (i = 1, \dots, N) \quad (6.11)$$

The total power at the output of the i 'th OA is given as

$$P_{OAout_i} = P_{sig-OAout_i} + P_{noise-OAout_i} \quad (i = 1, \dots, N) \quad (6.12)$$

Now, the OSNR at the output of the i 'th OA is given as

$$OSNR_{out_i}(P_{sig-OAin_i}, P_{noise-OAin_i}) = \frac{P_{sig-OAout_i}(P_{sig-OAin_i}, P_{noise-OAin_i})}{P_{noise-OAout_i}(P_{sig-OAin_i}, P_{noise-OAin_i})} \quad (i = 1, \dots, N) \quad (6.13)$$

Note that here the OSNR is defined over B_{opt} rather than a standardised bandwidth (such as 12.5 GHz) as is sometimes the practice.

6.3.2 Cascaded OA BER analysis

By making a GA assumption for the noise, the BER for each interamplifier section of the cascaded OA FSO link, conditioned on the instantaneous loss (or gain) state of each turbulent interamplifier section h_{GG} , is given as [26]

$$BER(P_{OAin_{av}}, h_{GG}) = \frac{1}{2} \left[\frac{1}{2} \operatorname{erfc} \left(\frac{i_D - i_0(P_{OAin_{av}}, h_{GG})}{\sqrt{2\sigma_0^2(P_{OAin_{av}}, h_{GG})}} \right) + \frac{1}{2} \operatorname{erfc} \left(\frac{i_1(P_{OAin_{av}}, h_{GG}) - i_D}{\sqrt{2\sigma_1^2(P_{OAin_{av}}, h_{GG})}} \right) \right] \quad (6.14)$$

where

$$i_x = RP_{OAin_x} \quad (6.15)$$

for transmitted data bits, $x \in \{0, 1\}$ and P_{OAin_x} is the OA input power. $R = \eta q / h\nu$ represents the PD responsivity where q represents the electronic charge, η represents the quantum efficiency, h represents the Planck constant and ν represents the frequency of the optical carrier. As NRZ-OOK signals are used with direct detection, the power in a ONE

$$P_{OAin_1} = \frac{2r}{r+1} P_{OAin_{av}} \quad (6.16)$$

and the power in a ZERO

$$P_{OAin_0} = \frac{2}{r+1} P_{OAin_{av}} \quad (6.17)$$

The total noise current variance

$$\sigma_x^2 = \sigma_{sx-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{th}^2 \quad (6.18)$$

where the signal-spontaneous beat noise

$$\sigma_{sx-sp}^2 = 4R^2 P_{OAin_x} N_0 B_e \quad (6.19)$$

and the spontaneous-spontaneous beat noise

$$\sigma_{sp-sp}^2 = 2m_t R^2 N_0^2 B_{opt} B_e \left(1 - \frac{B_e}{2B_{opt}} \right) \quad (6.20)$$

The ASE noise is described by its PSD

$$N_0 = \frac{P_{OAin_{av}}}{m_t B_{OSNR} OSNR} \quad (6.21)$$

By adapting (6.14), the relationship between the OSNR and the BER immediately after the i 'th OA section is derived as

$$\begin{aligned}
 & BER_i \\
 &= \frac{1}{2} \left[\frac{1}{2} \operatorname{erfc} \left(\frac{A_{0_i} \text{OSNR}_{out_i}}{\sqrt{B \text{OSNR}_{out_i} + C + W_i \text{OSNR}_{out_i}^2}} \right) \right. \\
 & \quad \left. + \frac{1}{2} \operatorname{erfc} \left(\frac{A_{1_i} \text{OSNR}_{out_i}}{\sqrt{B r \text{OSNR}_{out_i} + C + W_i \text{OSNR}_{out_i}^2}} \right) \right] \quad (6.22)
 \end{aligned}$$

where

$$A_{0_i} = \frac{i_{D_i} (r+1) - 2RP_{sig-OAout_i}}{2RP_{sig-OAout_i} (r+1)} \quad (i = 1, \dots, N) \quad (6.23)$$

$$A_{1_i} = \frac{2rRP_{sig-OAout_i} - i_{D_i} (r+1)}{2RP_{sig-OAout_i} (r+1)} \quad (i = 1, \dots, N) \quad (6.24)$$

and the value of i_{D_i} depends on the decision thresholding scheme (discussed in Chapter 5) used at the receiver,

$$B = \frac{4B_e}{(r+1)m_t B_{opt}} \quad (6.25)$$

$$C = \frac{B_e (2B_{opt} - B_e)}{2m_t B_{opt}^2} \quad (6.26)$$

and

$$W_i = \frac{\sigma_{th}^2}{2R^2 P_{sig-OAout_i}^2} \quad (i = 1, \dots, N) \quad (6.27)$$

Due to the multiple links involved in a cascaded OA FSO communication system, it is time-saving and computationally convenient to obtain power and OSNR PDFs at each OA stage. The average BER can then be approximated from the power and OSNR PDFs. By applying the transformation of random

variables technique, the relationship between the OSNR and BER (analysed in log terms for brevity sake) is given as

$$P_{\log BER_i}(\log BER_i) = P_{OSNR_{out_i}}(OSNR_{out_i}) \frac{\partial OSNR_{out_i}}{\partial \log BER_i} \quad (i = 1, \dots, N) \quad (6.28)$$

where $P_{\log BER_i}(\log BER_i)$ represents the logBER PDF immediately after the i 'th OA section, $P_{OSNR_{out_i}}(OSNR_{out_i})$ represents the OSNR PDF immediately after the i 'th OA section and $\frac{\partial OSNR_{out_i}}{\partial \log BER_i}$ can be derived from (6.22). Thus, the average

BER immediately after the i 'th OA section is obtained as

$$BER_{ave_i} = \int_{-\infty}^{\log 0.5} 10^{\log BER_i} P_{\log BER_i}(\log BER_i) d \log BER_i \quad (i = 1, \dots, N) \quad (6.29)$$

6.4 Results and Discussion

The parameters used for the numerical analysis and MC simulations are shown in Tables 6.1, 6.2 and 6.3. Note that the assumptions made in Chapter 5 are also made here. The OA gain responds freely, using complete saturation characteristic and incorporating the effect of ASE noise on the saturated operation. An OA that can be driven into gain saturation ($P_{sat} = 5$ dBm) is referred to as a saturated gain OA and an OA that cannot be driven into gain saturation ($P_{sat} \rightarrow \infty$) is referred to as a fixed gain OA.

Table 6.1: Parameters used for numerical analysis and MC simulations in cascaded OA FSO links.

Parameter	Symbol	Value
Optical wavelength	λ	1550 nm
Bit rate	R_b	2.5 Gb/s
Transmitted optical power	P_T	20 dBm
OA small signal gain	G_{ss}	25 dB
OBPF bandwidth	B_{opt}	70 GHz
Noise figure	NF	5 dB
Quantum efficiency	η	1
Extinction ratio	r	10 dB

6.4.1 A General System Perspective

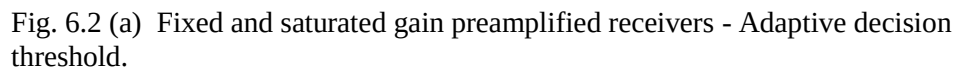
The parameters required for the design of each interamplifier section of a cascaded OA FSO link are shown in Table 6.2. Since all these design parameters can be represented by the σ_R^2 and L_{nt} per section [15, 25] as shown in equations (6.1) and (3.8), fixed σ_R^2 and L_{nt} values per section are used for the analysis. Having these two fixed values is manageable and ensures the possibility of mapping results into a variety of practical realizations. Therefore, for each interamplifier section of the cascaded OA FSO link, a general system perspective is taken and how a specific implementation will achieve the fixed parameters is not specified. This should inform understanding of section 6.4.1. However, the mapping is then performed in section 6.4.2 by defining specific values for the physical design parameters.

Table 6.2: Design parameters required for each interamplifier section in a cascaded OA FSO link.

Design Parameter	Symbol
Receiving lens diameter	d_{rx}
Beam divergence angle	ϕ
Atmospheric channel attenuation	α_D
Link length	D
Refractive index structure constant	C_n^2

Fig. 6.2 shows the BER curves for different turbulence regimes in a cascaded OA FSO link. In Fig. 6.2a, it is shown that when $\sigma_R^2 = 0.1$, a BER value less than 10^{-10} is achievable at the fourth and third OA position in the cascade when a fixed and saturated gain OA cascade is used respectively. This shows that when an adaptive decision threshold is used at the receiver, a fixed gain OA cascade performs better than a saturated gain OA cascade because while the OA gain remains constant (i.e. G_{ss}) in a fixed gain OA cascade, it decreases ($< G_{ss}$) in a saturated gain OA cascade.

In Fig. 6.2b where a non-adaptive decision threshold is used at the receiver, high BER values ($> 10^{-3}$) are obtained in all turbulence regimes for a fixed gain OA cascade but low BER values ($< 10^{-6}$ when $\sigma_R^2 = 0.1$) can be obtained at the first OA position in a saturated gain OA cascade. In Figs. 6.2a and b, the BER curves for the fixed and saturated gain OA cascades are shown to converge after the 9th OA position because since $G_{ss} < 1/L_{nt}$, the powers at the input of the OAs in the saturated gain OA cascade ultimately becomes insufficient to drive the OAs into saturation making the performance similar to a fixed gain OA cascade that has net loss. Note that the overall BER



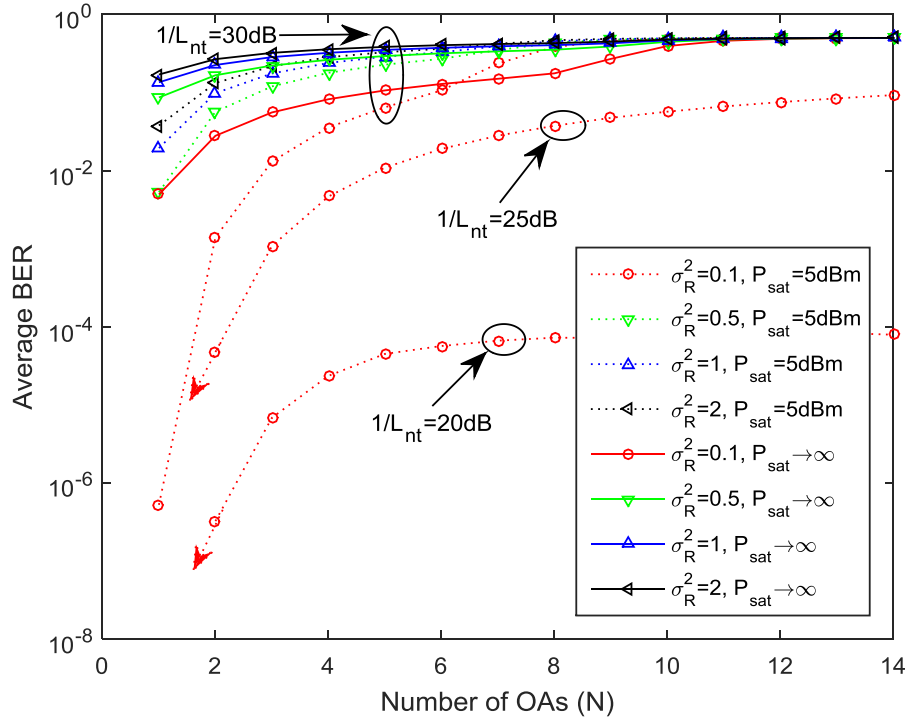


Fig. 6.2 (b) Fixed and saturated gain preamplified receivers - Non-Adaptive decision threshold.

Fig. 6.2: Average BER at different OA positions in a cascaded OA FSO link. Arrow indicates that the next data point is effectively zero.

Fig. 6.3 shows the BER curves for different turbulence regimes in a cascaded OA FSO link. The data points occur at integer multiples of the section losses i.e. as we move rightwards the number of OAs increases at each data point. In Fig. 6.3a where an adaptive threshold is used at the receiver, the BER performances are shown to perform better when the number of OAs in the cascade is increased (i.e. reduced $1/L_{nt}$ per interamplifier section). Also, the BER performance ($1/L_{nt} = 25$ dB) for a fixed gain OA cascade is seen to outperform a saturated gain OA cascade by around 40 dB at a target BER of 10^{-10} .

In Figs. 6.3a and b, the BER curves ($\sigma_R^2 = 0.5$) for a saturated gain OA cascade show that an adaptive decision threshold outperforms a non-adaptive decision threshold, however, an improved performance is noted for the non-adaptive decision threshold when $\sigma_R^2 = 0.1$. Even though Fig. 6.3b does not show very low BER values, it clearly shows improved performances when a saturated gain OA cascade is used and the lower BER results obtained when $1/L_{nt} = 20$ dB show that frequent low gain saturated amplification can keep the fades down to a manageable level. Naturally still more frequent saturated amplification can lead to further improvement.

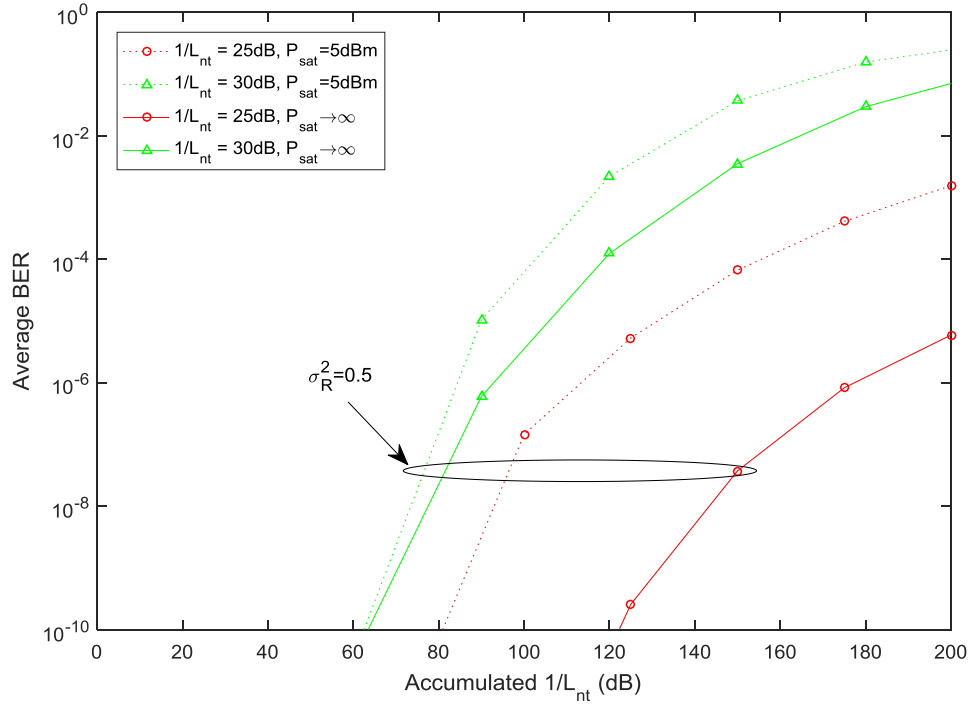


Fig. 6.3 (a) Fixed and saturated gain preamplified receivers - Adaptive decision threshold.

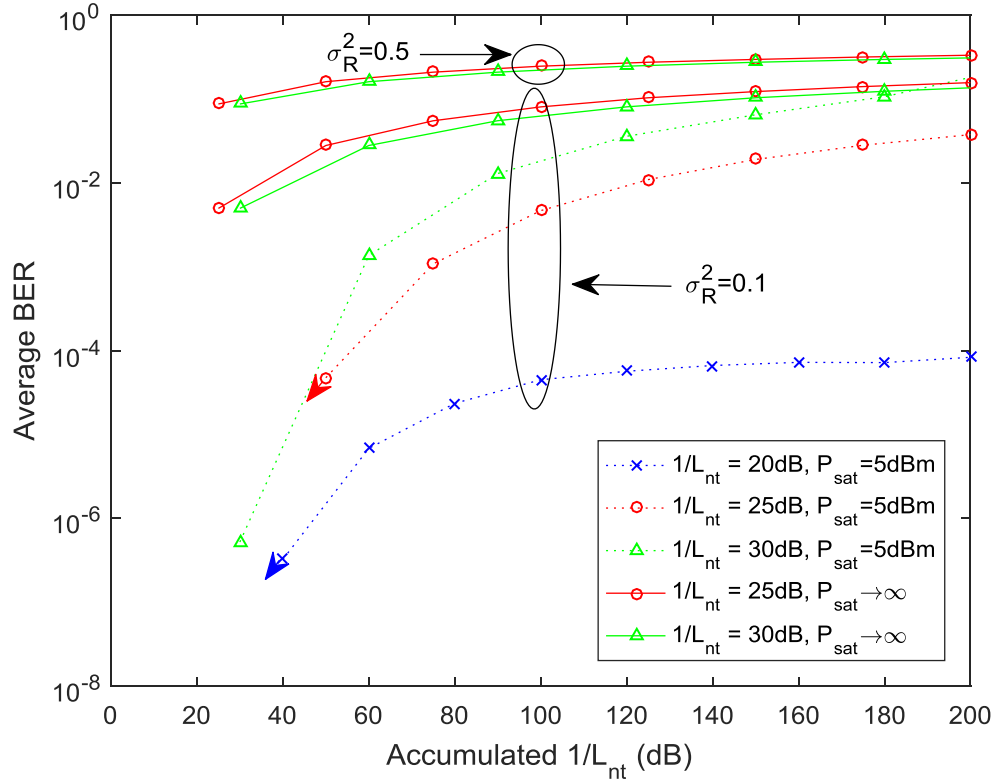


Fig. 6.3 (b) Fixed and saturated gain preamplified receivers - Non-Adaptive decision threshold.

Fig. 6.3: Average BER against accumulated L_{nt} in a cascaded OA FSO link. Arrows indicate that the next data point is effectively zero.

Fig. 6.4 shows the BER curves for different accumulated L_{nt} values in a cascaded OA FSO link. The values chosen are such as to give approximately the same overall accumulated system loss ($8 \times 25 = 200$ dB, $10 \times 20 = 200$ dB, $14 \times 15 = 210$ dB). In Fig. 6.4a, the BER curves obtained for a fixed gain OA cascade shows that a BER of 10^{-12} is obtained at around $\sigma_R^2 = 0.98$ and $\sigma_R^2 = 0.26$ when 10 and 8 OAs are used respectively. For a saturated gain OA cascade, a BER of 10^{-12} is obtained at around $\sigma_R^2 = 1.12$, $\sigma_R^2 = 0.44$ and $\sigma_R^2 = 0.09$ when 14, 10 and 8 OAs are used respectively.

While this further indicates that a fixed gain OA cascade performs better than a saturated gain OA cascade when an adaptive decision threshold is used at the receiver, the reverse is the case in Fig. 6.4b where a non-adaptive decision threshold is used at the receiver as a saturated OA cascade is shown to perform better because the BER curve obtained for a saturated gain OA cascade shows that a BER of 10^{-12} is obtained at around $\sigma_R^2 = 0.1$ when 14 OAs are used while high BER values ($> 10^{-2}$) are obtained regardless of the number of OA used for a fixed gain OA cascade.

In addition to the BER, the performance of a FSO communication link can be investigated by determining the outage possibility. In order to know if an outage has occurred in a cascaded OA FSO link, the OSNR PDF at each OA position is obtained and used to determine if the target BER has been achieved at that OA position. Outage occurs at the OA position where the target BER is not achieved.

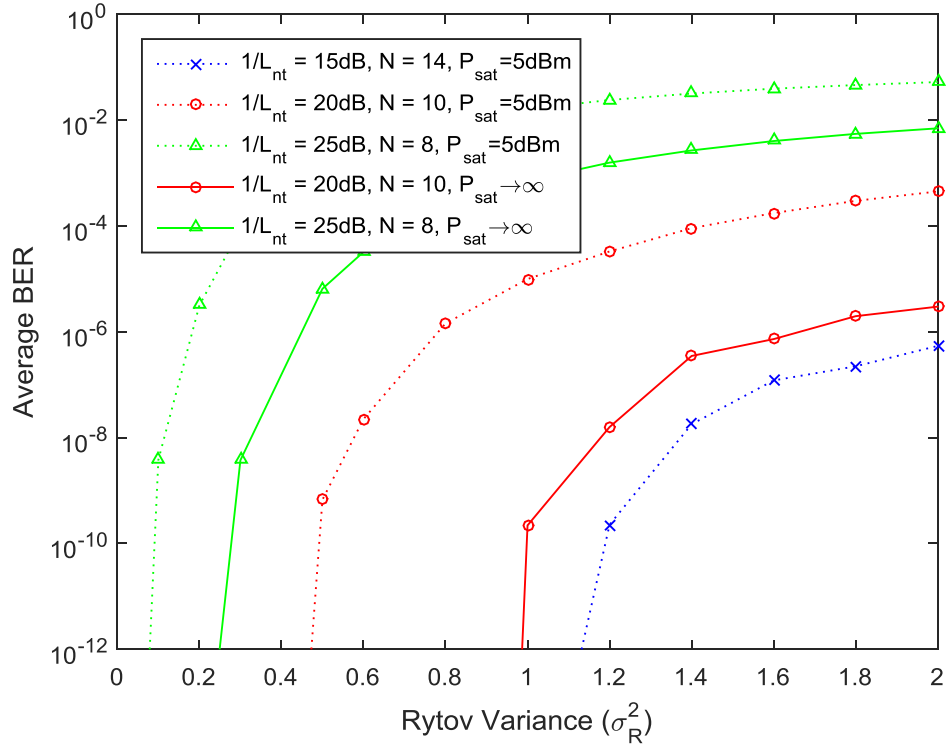


Fig. 6.4 (a) Fixed and saturated gain preamplified receivers - Adaptive decision threshold.

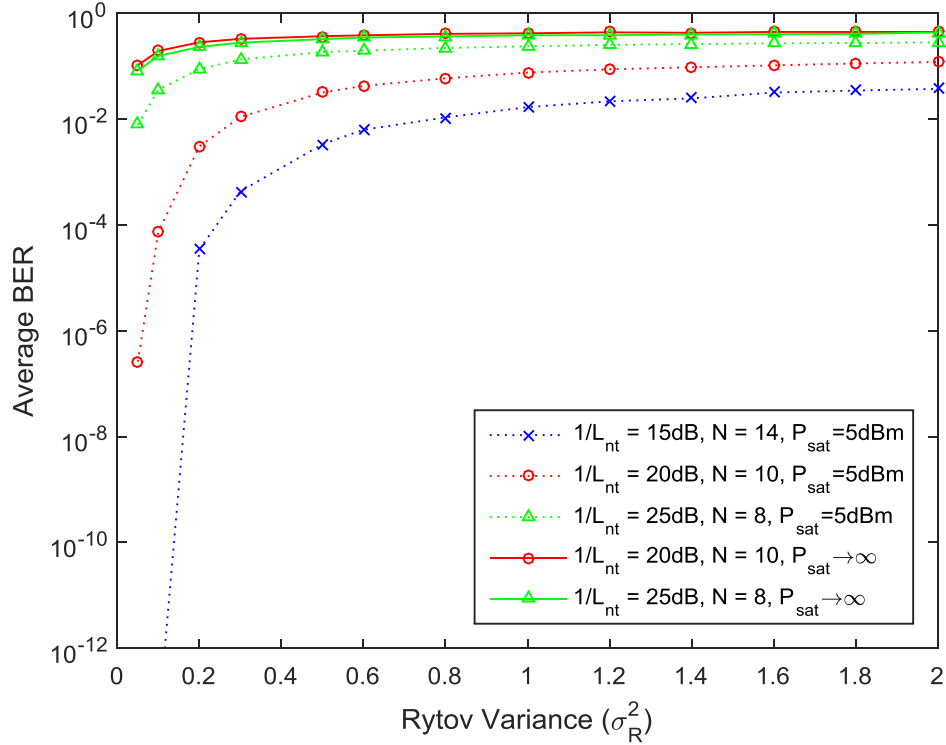


Fig. 6.4 (b) Fixed and saturated gain preamplified receivers - Non-Adaptive decision threshold.

Fig. 6.4: Average BER against per OA section Rytov variance in a cascaded OA FSO link. Arrows indicate that the next data point is effectively zero.

In Fig. 6.5, a target BER of 10^{-9} (i.e. corresponding to an OSNR value of 13.6dB with an adaptive decision threshold) is assumed. To determine if the target BER has been achieved at a particular OA position, the position of the OSNR PDF relative to 13.6dB must be known. In Fig. 6.5, it is also assumed that an outage will occur at an OA position if up to 1 percent of the OSNR PDF at that OA position is less than 13.6dB. In other words, if at least 99 percent of the OSNR PDF at a particular OA position is more than 13.6dB, the target BER is assumed to have been achieved at that OA position.

The number of OAs that can achieve a target BER of 10^{-9} is shown in Fig. 6.5 for different turbulence regimes. In Fig. 6.5a, when $\sigma_R^2 = 0.1$ and $1/L_{nt} = 20$ dB (each per OA section), a target BER of 10^{-9} can be achieved up to the 10th OA in both saturated and fixed gain OA cascades. This is due to the fact that the turbulence strength is weak and the OA gain fully compensate for the turbulence-free fixed path loss in each interamplifier section of the link. For a higher $1/L_{nt}$ value and turbulence strength (i.e. $\sigma_R^2 = 2$ and $1/L_{nt} > 40$ dB), a target BER of 10^{-9} can only be achieved at the 1st OA in both the saturated and fixed gain OA cascades due to the increased fluctuation and inability of the OA gain to compensate for the turbulence-free fixed path loss in each interamplifier section of the link. Also, the number of OAs that can achieve a target BER of 10^{-9} when a fixed gain OA cascade is used as shown in Fig. 6.5b mostly exceeds that of a saturated gain OA cascade shown in Fig. 6.5a because saturation causes gain reduction which ultimately results in reduced performance.

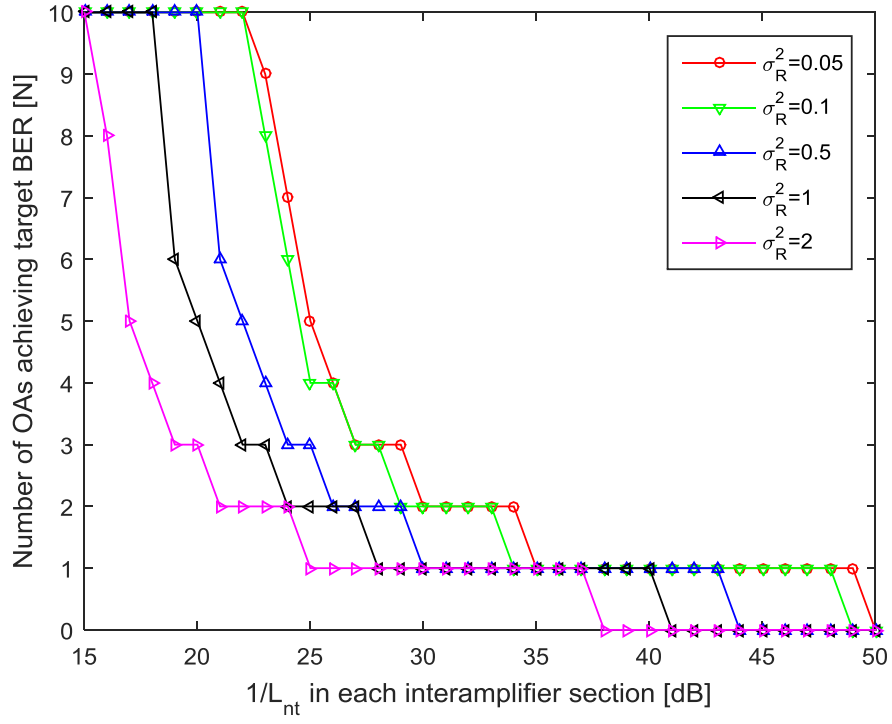


Fig. 6.5 (a) Saturated gain OA cascade - Adaptive decision threshold.

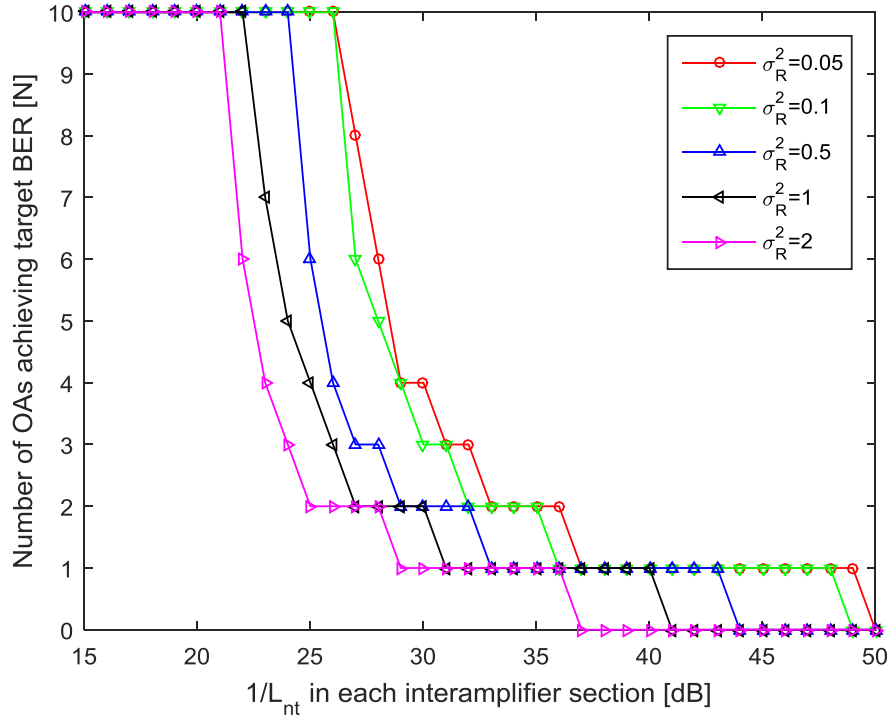


Fig. 6.5 (b) Fixed gain OA cascade - Adaptive decision threshold.

Fig. 6.5: Number of OAs achieving target BER against $1/L_{nt}$ per interamplifier section in a cascaded OA FSO link (target BER = 10^{-9}).

This further confirms earlier assertions that saturation is primarily helpful in the preamplifier when a non-adaptive decision threshold is used at the receiver.

6.4.2 Specific System Implementation

As earlier mentioned in section 6.4.1 and shown in Table 6.2, the defined L_{nt} and σ_R^2 for each interamplifier section of a cascaded OA FSO link can be mapped into a variety of specific per section design parameters. With the assumption of a clean atmosphere, an atmospheric channel attenuation (α_D) of 0.2dB/km is used [25]. Note that link length is normalised (by taking deviations due to the analytical modelling of the transmitting and receiving lens into consideration) such that starting point for the optical signal propagation (i.e. $D = 0$ km) corresponds to $1/L_{nt} = 0$ dB. In Table 6.3, when $1/L_{nt} = 35$ dB and $\sigma_R^2 = 0.1$ (i.e. design B), the achievable communication distance of each interamplifier section of the cascaded OA FSO link is 2.161 km.

Table 6.3: Mapping L_{nt} and σ_R^2 per section into specific design parameters in cascaded OA FSO links.

Design	A	B	C	D	E	F
$1/L_{nt}$ (dB)	35	35	30	30	25	20
σ_R^2	0.5	0.1	0.5	0.1	0.1	0.1
d_{rx} (m)	4×10^{-2}	7×10^{-2}	3.5×10^{-2}	4×10^{-2}	9×10^{-2}	5×10^{-2}
ϕ (rad)	1×10^{-3}	1.7×10^{-3}	8.5×10^{-4}	1×10^{-3}	2.5×10^{-3}	1.5×10^{-3}
C_n^2 (m ^{-2/3})	6.4×10^{-15}	1.2×10^{-15}	1.7×10^{-14}	3.7×10^{-15}	1.3×10^{-14}	4.8×10^{-14}
D (m)	2101	2161	1225	1190	591	290

The BER curves in Fig. 6.6 show the possibility of extending reach in FSO communication systems with an OA cascade while assuming the use of the

design parameters in Table 6.3. In Fig. 6.6a where an adaptive decision threshold is used in design A, a BER of 10^{-10} is achievable at an overall distance of almost 4 km (with $N = 2$) in both fixed and saturated gain OA cascades. In design C, the achievable distance reduces to just over 2.5km (with $N = 2$) in both fixed and saturated gain OA cascades. The achievable distance of design C relative to design A reduces because lower turbulence-free fixed path loss values naturally results in shorter communication distances. In Fig. 6.6b where a non-adaptive decision threshold is used, the BER curves obtained show that the optical signal is able to travel for longer distances at lower BER values along an OA cascade with saturated gain OAs than with fixed gain OAs. At 2.5 km, design D is able to achieve lower BER values ($<10^{-2}$) with saturated gain OAs compared with using fixed gain OAs ($>10^{-2}$). Also, it is shown in Fig. 6.6b that increasing the number of OAs (i.e. reducing $1/L_{nt}$) yields improved BER performances. For instance, design F is able to achieve a BER of around 10^{-4} while design E achieved a higher BER value ($\approx 10^{-2}$) at a distance of about 4km. Ultimately, the overall BER performance can be improved by using an OA with a higher small signal gain value or reducing the distance of each interamplifier section of the cascaded OA FSO link.

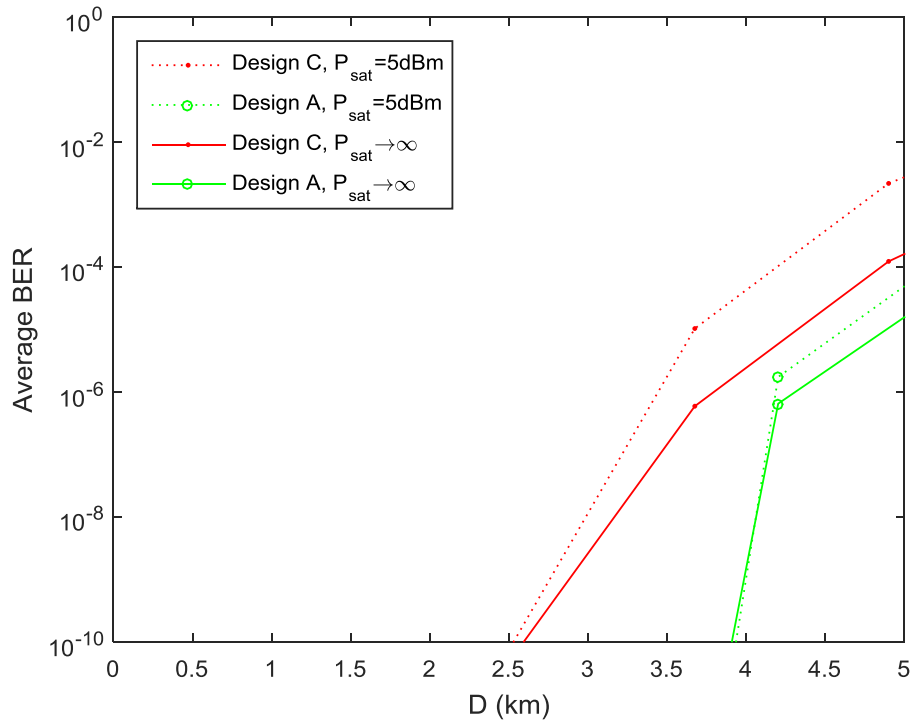


Fig. 6.6 (a) Fixed and saturated gain preamplified receivers - Adaptive decision threshold.

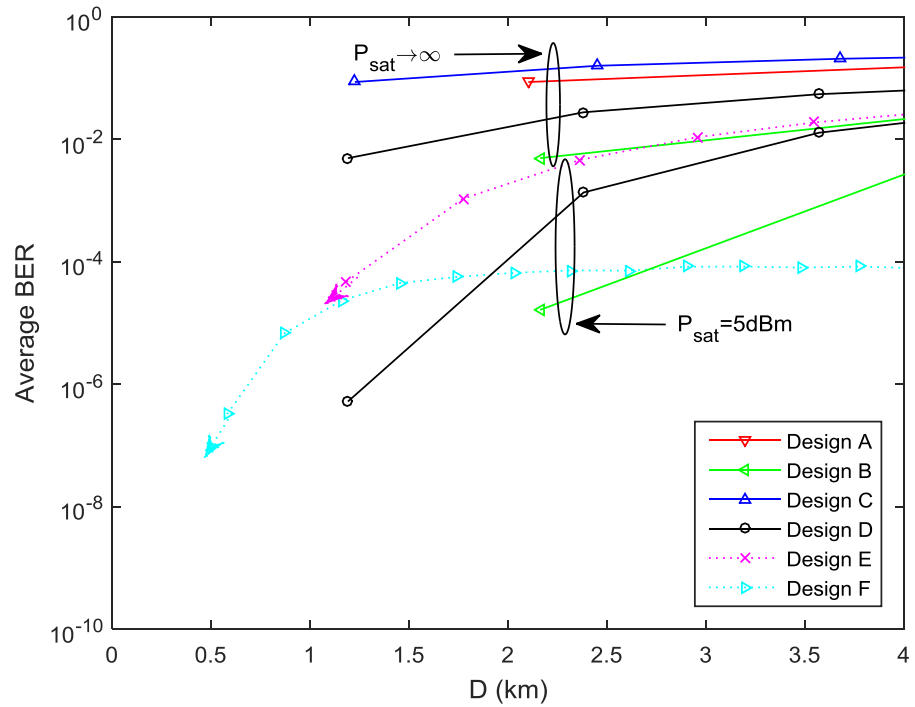


Fig. 6.6 (b) Fixed and saturated gain preamplified receivers - Non-Adaptive decision threshold.

Fig. 6.6: Average BER against distance in a cascaded OA FSO link. Arrows indicate that the next data point is effectively zero.

6.5 Summary

This Chapter examined the performance of a FSO communication system in a turbulent atmosphere employing an OA cascade to extend reach by applying analytical and MC simulation techniques. Performance modelling with MC simulation which allows the gain of each OA in the cascade to respond freely, using complete saturation characteristic and incorporating the effect of ASE noise on the saturated operation was shown. The use of a saturated gain OA as a preamplifier at the receiver was investigated and the BER results obtained for the cascaded OA FSO link showed its ability to suppress scintillation when CSI is not known and a non-adaptive decision threshold is used at the receiver. The presented results also showed that an OA cascade can be successfully used to extend reach in FSO communication systems and that the optimal cascade scheme with a non-adaptive receiver would use frequent low gain saturated amplification (Note that frequent amplification has an attendant cost implications). In all turbulence regimes, the results presented show that the performance of an adaptive decision threshold is superior to a non-adaptive decision threshold for both fixed and saturated gain preamplified receivers but its practical implementation especially for an OA cascade will be very costly and difficult to analyse. It has also been shown that in a turbulent atmosphere, OA saturation is primarily beneficial when a non-adaptive decision threshold is used at the receiver. Therefore, due to its reduced complexity and cost, the use of a non-adaptive decision threshold with saturated gain OA cascade is recommended for scintillation suppression and communication reach extension in FSO communication systems.

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Chapter 7

WDM FSO Communication Systems

7.1 Introduction

This Chapter discusses wavelength-division multiplexing (WDM) free-space optical (FSO) links with particular emphasis on the impact of atmospheric turbulence and interchannel crosstalk on system performance. The Chapter begins with an introduction to WDM systems and highlights the importance of passive optical networks (PONs) for simultaneous data transmission between multiple users. An overview of optical amplification and crosstalk in WDM systems is also presented. By using Monte Carlo (MC) simulation techniques to obtain the average bit error rate (BER), considering the effect of amplified spontaneous emission (ASE) noise (applicable to amplified systems) and modelling the various turbulence regimes with the lognormal and gamma-gamma distributions, various WDM PON FSO systems are considered and compared. The comparisons are made by determining the average BER and the capability of each system with respect to the attainable link length.

7.2 Overview of WDM communication systems

The growing popularity of the internet and the need for the simultaneous use of network services by multiple subscribers has brought about the need for network providers to provide high and stable bandwidths across multiple channels [1, 2]. In order to satisfy this increasing demand for data usage, technologies based on optical communications (such as PONs) have been proposed due to the advantages they offer over radio frequency (RF) based communication systems such as high speeds and large bandwidths [3]. PONs provides broadband services and they are being recognised as viable alternatives to copper-based access networks. Compared to copper-based access networks, PONs offer advantages such as not requiring any active components, having a wide bandwidth and being used as a backhaul to wireless base stations [1, 4-6]. The physical implementation of PONs (typically reaching up to 20 km but extendable further to reduce operation and equipment costs [1, 4, 7]) involves the connection of an optical line termination (OLT) to optical network units (ONUs) which can be situated in places such as buildings (fibre-to-the-building (FTTB)), homes (fibre-to-the-home (FTTH)) and curb (fibre-to-the-curb (FTTC)) [8].

A variant of the PON, the WDM PON; where each subscriber is assigned a different channel/wavelength, is seen as the most promising choice for a reliable access network [9]. A WDM PON has attributes such as high security, sufficient capacity (able to satisfy bandwidth demands) and being easily upgradeable but its high equipment cost and complicated operation (especially in the access network) makes its practical deployment problematic. Methods

involving the use of low-cost transmitters have been proposed to alleviate this problem [9-13]. To realise multiplexing (combination of multiple wavelengths for parallel transmission in a single fibre [14]) and demultiplexing (separation of a combination of wavelengths into distinct separate wavelengths [14]) in WDM systems, it is common to use devices based on arrayed waveguide grating (AWG) due to their low chromatic dispersion. However, due to the cost and intricacy of AWG-based devices, other multiplexing techniques such as free-space diffraction-grating have been proposed [6].

The optical amplifiers (OAs) modelled in Chapters 5 and 6 were restricted to single wavelength systems and, as mentioned in Chapter 2, OAs can naturally be integrated with WDM systems since a single OA can concurrently amplify signals at different wavelengths within the gain region [15]. Under these circumstances, assuming that an OA is not to favour particular wavelength channels systematically, it will be necessary to ensure gain flatness at least in the small signal regime. In choosing a gain flat OA for FSO links, it remains necessary to ensure the gain dynamics are fast enough to track atmospheric fluctuations. While the gain dynamics in both EDFAs and SOAs are fast enough to track the atmospheric turbulence fluctuations (as mentioned in Chapter 5), EDFAs are preferable for WDM systems since they do not introduce gain crosstalk (from cross-gain modulation (CGM)) into the system. Furthermore to continue to benefit from the turbulence mitigation, whilst avoiding gain crosstalk, it is necessary to ensure that individual channels saturate independently. This will be harder to achieve with an SOA than with an EDFA [16-19].

Crosstalk (which substantially reduces system performance) occurs in communication systems either due to optical component imperfections or power transmission between different channels caused by non-linear effects [20]. It is particularly common in WDM networks due to the presence of multiple wavelengths and the effect is further exacerbated in FSO links due to atmospheric turbulence [8]. In the upstream of WDM FSO links, where the desired and crosstalk signals are assumed to follow independent paths, the fluctuations caused by atmospheric turbulence in both the desired and crosstalk signals pose a major limitation to system performance [6].

Presently, optical fibre communication links (combined with dense WDM (DWDM)) have been used to obtain transmission speeds greater than 1 Tb/s (in the network core) but the high setup cost of fibre in the access region and lack of flexibility is currently diverting attention to FSO communication links. While FSO links are increasingly gaining recognition due to the advantages they offer such as low cost, simplicity, immunity to electromagnetic interference, flexibility and no licensing requirements, they are limited by requirements such as the need for optical-electrical-optical (OEO) conversion at various terminals and susceptibility to impairments such as atmospheric impairments, pointing and coupling loss [3, 21-23]. The impact of interchannel crosstalk in non-amplified and amplified FSO communication systems was investigated in [6, 24, 25]. In [6] where the OOK modulation format was used, an adaptive decision thresholding scheme was assumed at the receiver and the OAs used in [6] and [25] were only operated in the unsaturated gain regime. In this Chapter, a MC simulation approach is used to analyse non-amplified and amplified WDM PON FSO systems using adaptive and non-adaptive decision

thresholds. For amplified systems, results are obtained for instances where the OA gain is either in the fixed or saturated gain regime.

7.3 WDM FSO communication system configuration

Two WDM channels are considered in this Chapter to generate the fundamental understanding of how such a system operates and can be modelled. Clearly the multi-wavelength case (proposed for future work) is more complex but basic understanding of how it will work can come from this underpinning. Fig. 7.1 shows a PON-like WDM FSO upstream communication system model. Note that even though the first transmitter in Fig. 7.1 is shown to transmit the desired signal and the second transmitter is shown to transmit the crosstalk signal, the reverse could also be the case. In other words, each transmitter sees itself as the only transmitter transmitting the desired signal. In Fig. 7.1, both the desired and crosstalk signals are sent through lenses into the atmosphere. Note that while propagating through the atmospheric channel, the desired and crosstalk signal paths are assumed (with proper alignment) to be independent of each other such that they do not interact either in the atmosphere or at the receiving lenses. After both signals are collected by their respective receiving lenses (which are assumed to be at the same location e.g. rooftop), they are multiplexed and amplified before onward transmission through an optical fibre. At the receiving end, the signals are demultiplexed and received by their respective receivers. Interchannel crosstalk (the crosstalk type investigated in this Chapter) is caused by imperfections in the demultiplexer and it is more severe in WDM FSO links due to the fluctuations in the crosstalk signal [6, 25].

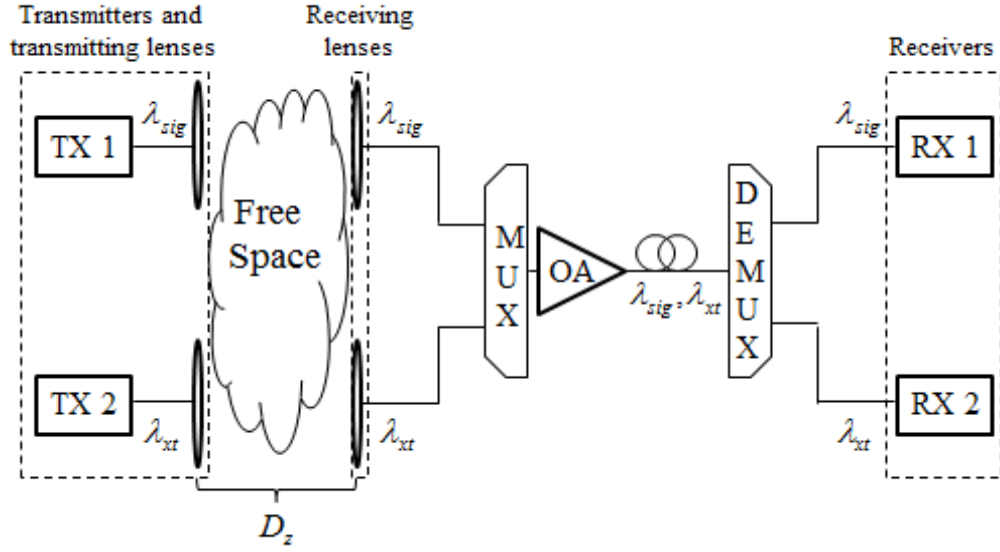


Fig. 7.1: A PON-like WDM FSO upstream communication system.

7.4 WDM FSO system modelling and BER analysis

For computational convenience, a MC simulation technique is used to model the WDM FSO communication system. With the MC simulation approach, the BER analysis (with respect to the ‘desired signal’ receiver) is first carried out for a random sample after which averaging takes place over all the samples to obtain the average BER. By assuming that the desired and crosstalk signals (each transmitted with signal power P_{t_z} for $z \in \{sig, xt\}$) are propagated in a clear atmosphere, the total loss in the FSO link $L_z = L_{nt_z} h_z$ where h_z represents the random variable describing the fluctuations due to atmospheric turbulence and L_{nt_z} ; which represents the turbulence-free fixed path loss (< 1) is given as [25]

$$L_{nt_z} = \left(\frac{d_{rx_z}}{d_{bD_z}} \right)^2 \alpha_z \quad (7.1)$$

where d_{rx_z} represents the receiving lens diameter and $d_{bD_z} = \phi_z D_z$ represents the beam diameter due to diffraction alone where ϕ_z represents the transmitter beam divergence angle. $\alpha_z = 10^{(-\alpha_{D_{\phi_0 z}} D_z / 10)}$ represents the atmospheric attenuation in the FSO link where $\alpha_{D_{\phi_0 z}}$ represents the atmospheric attenuation factor. The signal power at the receiving lens $P_{lens_z} = P_{t_z} L_z$. The multiplexed signals are amplified with an OA with gain G and ASE power spectral density (PSD) $N_0 = 0.5(NFG - 1)h\nu$ where NF is the noise figure. The OA gain G is implicitly related to P_{in_z} as shown below [8]

$$P_{in_z} = \frac{P_{sat}}{G - 1} \ln \left(\frac{G_{ss}}{G} \right) \quad (7.2)$$

where G_{ss} and P_{sat} are the small signal (fixed) gain and the internal saturation power of the OA respectively. At the decision circuit, the mean desired signal current level at the sampling instant is given as

$$i_{sig_x} = RP_{r_{sig_x}} \quad (x \in \{0,1\}) \quad (7.3)$$

where the desired signal power in a ONE $P_{r_{sig_1}} = (2r(P_{lens_{sig}} GL_{fibre})) / (r + 1)$ where $P_{lens_{sig}}$ represents the desired signal power at the input of the desired signal receiving lens ($Lens_{rx_{sig}}$), L_{fibre} represents the fibre loss, r represents the extinction ratio and the desired signal power in a ZERO $P_{r_{sig_0}} = P_{r_{sig_1}} / r$. Also, the mean crosstalk signal current level at the sampling instant is given as

$$i_{xt_y} = RP_{r_{xt_y}} \quad (y \in \{0,1\}) \quad (7.4)$$

where the crosstalk signal power in a ONE $P_{r_{xt1}} = (2r(P_{lens_{xt}} GL_{fibre} L_{demux})) / (r+1)$

where $P_{lens_{xt}}$ represents the crosstalk signal power at the input of the crosstalk

signal receiving lens ($Lens_{rx_{xt}}$), L_{demux} represents extra loss experienced when

the demultiplexer couples the crosstalk signal with the desired signal

photodiode and the crosstalk signal power in a ZERO $P_{r_{xt0}} = P_{r_{xt1}} / r$. The total

noise current variance is given as

$$\sigma_{sig_x, xt_y}^2 = \sigma_{sig_x, sp}^2 + \sigma_{xt_y, sp}^2 + \sigma_{sp, sp}^2 + \sigma_{sh, sp}^2 + \sigma_{sh_{sig_x}, xt_y}^2 + \sigma_{th}^2 \quad (x \in \{0,1\}; y \in \{0,1\}) \quad (7.5)$$

where the signal-spontaneous beat noise is given as

$$\sigma_{sig_x, sp}^2 = 4R^2 P_{r_{sig_x}} N_0 B_e, \quad (7.6)$$

the crosstalk-spontaneous beat noise is given as

$$\sigma_{xt_y, sp}^2 = 4R^2 P_{r_{xt_y}} N_{0-xt} B_e, \quad (7.7)$$

where $N_{0-xt} = N_0 L_{demux}$ represents the ASE PSD at the signal receiver but at or

near the crosstalk wavelength. The spontaneous-spontaneous beat noise is

given as

$$\sigma_{sp-sp}^2 = 2m_t R^2 N_0^2 B_{opt} B_e \left(1 - \frac{B_e}{2B_{opt}} \right), \quad (7.8)$$

the ASE shot noise is given as

$$\sigma_{sh-sp}^2 = 2m_t q R N_0 B_{opt} B_e \quad (7.9)$$

and the total shot noise (due to the desired and crosstalk signals) is given as

$$\sigma_{sh_{sig_x,xt_y}}^2 = 2qR \left(P_{r_{sig_x}} + P_{r_{xt_y}} \right) + m_t N_0 B_{opt} \mathcal{B}_e \quad (x \in \{0,1\}; y \in \{0,1\}) \quad (7.10)$$

Now, the instantaneous BER (i.e. obtained after a single MC iteration) is given as

$$BER = \frac{1}{4} \left[\frac{1}{2} \operatorname{erfc} \left(\frac{i_D - (i_{sig_0} + i_{xt_0})}{\sqrt{2\sigma_{sig_0,xt_0}^2}} \right) + \frac{1}{2} \operatorname{erfc} \left(\frac{i_D - (i_{sig_0} + i_{xt_1})}{\sqrt{2\sigma_{sig_0,xt_1}^2}} \right) \right. \\ \left. + \frac{1}{2} \operatorname{erfc} \left(\frac{(i_{sig_1} + i_{xt_0}) - i_D}{\sqrt{2\sigma_{sig_1,xt_0}^2}} \right) + \frac{1}{2} \operatorname{erfc} \left(\frac{(i_{sig_1} + i_{xt_1}) - i_D}{\sqrt{2\sigma_{sig_1,xt_1}^2}} \right) \right] \quad (7.11)$$

where i_D represents the decision thresholding scheme used at the receiver, for an adaptive decision threshold, it is given as

$$i_D = \frac{\sigma_{sig_1,xt_0} (i_{sig_0} + i_{xt_1}) + \sigma_{sig_0,xt_1} (i_{sig_1} + i_{xt_0})}{\sigma_{sig_1,xt_0} + \sigma_{sig_0,xt_1}} \quad (7.12)$$

and for a non-adaptive decision threshold (note that this is a fixed value equal to the long term average of the desired and crosstalk signal powers), it is given as

$$i_D = \frac{R \sum_{n=1}^N (P_{sig_n} + P_{xt_n})}{N} \quad (7.13)$$

where n represents the trial counter, N represents the total number of trials used for the MC simulation, the desired signal power at the receiver

$P_{sig_n} = P_{lens_{sig_n}} GL_{fibre}$ and the crosstalk signal power at the receiver

$P_{xt_n} = P_{lens_{xt_n}} GL_{fibre} L_{demux}$. The average BER is then given as

$$BER_{ave} = \frac{\sum_{n=1}^N BER_n}{N} \quad (7.14)$$

7.5 Results and Discussion

The parameters used for the MC simulation are shown in Table 7.1. Note that all the transmitters and receivers used in this analysis are assumed to have the same beam divergence angle and lens diameter respectively. The signal transmitting lens ($Lens_{tx_{sig}}$) is assumed to be pointed directly at $Lens_{rx_{sig}}$ and the crosstalk transmitting lens ($Lens_{tx_{xt}}$) is assumed to be pointed directly at $Lens_{rx_{xt}}$. Note that the lognormal distribution is used to represent the weak turbulence regime ($\sigma_R^2 < 1$) and the gamma-gamma distribution is used to represent the moderate to strong turbulence regimes ($\sigma_R^2 \geq 1$). This approach was necessary due to the limitations of the gamma-gamma distribution at very short distances. For brevity sake, the desired signal is referred to as ‘signal’ and the crosstalk signal is referred to as ‘crosstalk’. Just like in earlier Chapters, the OA gain is allowed to respond freely, using the complete saturation characteristic and incorporating the effect of ASE noise on the saturated operation. Also, an OA that cannot be driven into gain saturation ($P_{sat} \rightarrow \infty$) is referred to as a fixed gain OA and an OA that can be driven into gain saturation ($P_{sat} = 5$ dBm) is referred to as a saturated gain OA. Results are obtained for the weak ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$) and strong ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$) turbulence regimes.

Table 7.1: Parameters used for MC simulations in WDM FSO links.

Parameter	Symbol	Value
Transmitted optical power (Maximum permitted)	P_t	10 dBm
Desired signal wavelength	λ	1550 nm
Bit rate	R_b	2.5 Gb/s
OA small signal gain	G_{ss}	25 dB
OBPF bandwidth	B_{opt}	76 GHz
Noise figure	NF	5 dB
Quantum efficiency	η	0.8
Extinction ratio	r	10 dB
PON fibre length	D_{fibre}	20 km
PON fibre loss	$\alpha_{D_{fibre}}$	0.2 dB/km
Atmospheric channel loss	$\alpha_{D_{fo}}$	0.2 dB/km
Receiving lens diameter	d_{rx}	4 cm
Beam divergence angle	ϕ	1 mrad

The WDM FSO systems considered includes non-amplified systems with an adaptive decision threshold (NOAADT), non-amplified systems with a non-adaptive decision threshold (NOANADT), fixed gain amplified systems with an adaptive decision threshold (FOAADT), fixed gain amplified systems with a non-adaptive decision threshold (FOANADT) and saturated gain amplified systems with a non-adaptive decision threshold (SOANADT). In each case, results are obtained for instances where $P_{lens_{sig}}$ and $P_{lens_{xt}}$ are only affected by L_{sig} and L_{xt} respectively. Results are also shown for instances where a power control algorithm (PCA) ensures that at any receiving instant, the same turbulence-free powers (equal to the power received from the farthest transmitter) are received by both receiving lenses. In a more general sense (i.e. for any WDM system where it is assumed that all the receiving lenses are situated at the same location), the PCA is actualised by turning down the

powers of all the transmitters (except the farthest transmitter; which is used as reference). Since the PON fibre length is assumed fixed, any reference to link lengths refers to the lengths of the FSO link.

Fig. 7.2 shows the BER curves for different WDM FSO systems when $L_{demux} = 15$ dB and $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. The BER curves are obtained for instances when the signal and crosstalk link lengths are always equal (i.e. $D_{sig} = D_{xt}$). In Fig. 7.2(a) where a PCA is not included, the NOAADT, NOANADT, FOAADT, FOANADT and SOANADT are able to achieve a BER of 10^{-12} at 0.82 km, 0.6 km, > 2 km, 0.82 km and 0.87 km respectively. In Fig. 7.2(b) where a PCA is included, the NOAADT, NOANADT, FOAADT, FOANADT and SOANADT are able to achieve a BER of 10^{-12} at 0.82 km, 0.6 km, > 2 km, 0.8 km and 0.91 km respectively. Also, as expected, Fig. 7.2(a) and Fig. 7.2(b) shows that the PCA has no impact on system performance when the signal and crosstalk link lengths are always equal. Note that results for FOAADT are not shown in Fig. 7.2 because they are out of the plot range (> 2 km).

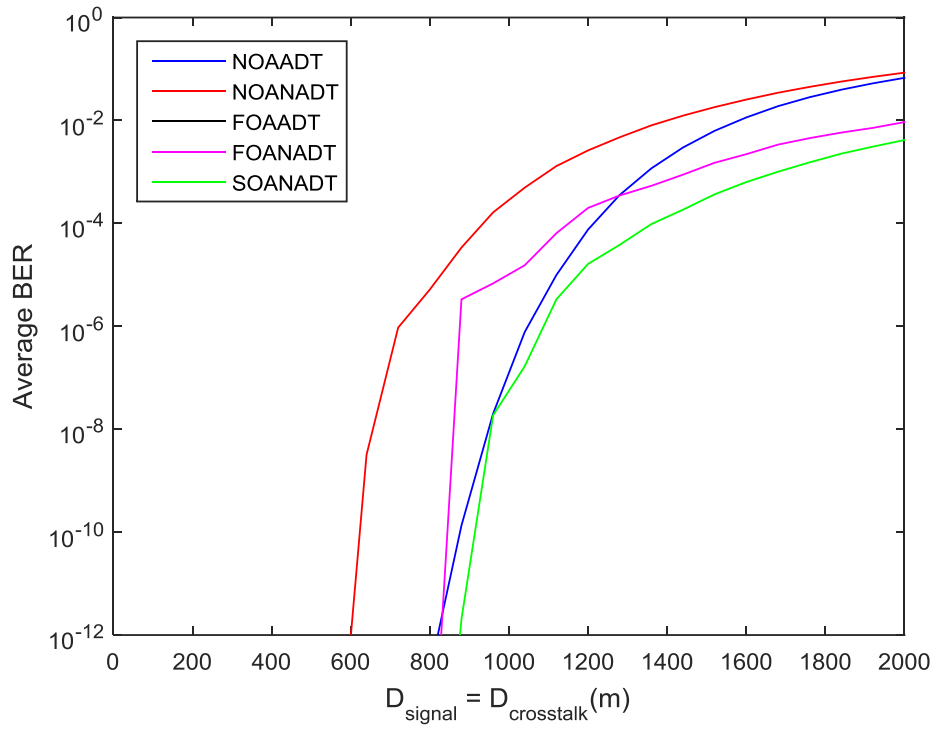


Fig. 7.2 (a) No PCA.

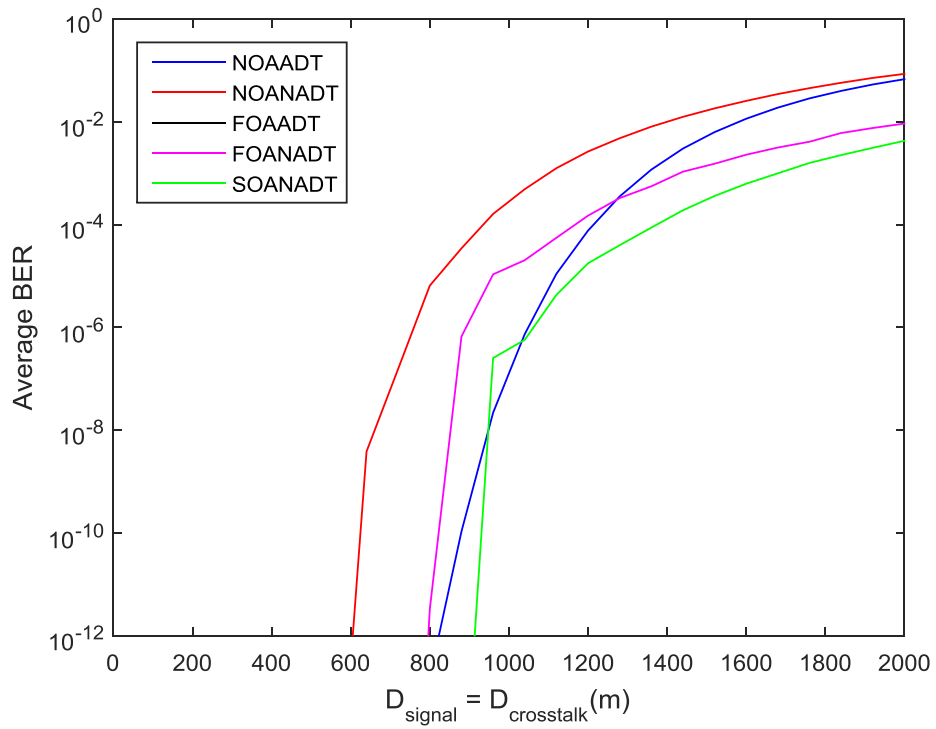


Fig. 7.2 (b) With PCA.

Fig. 7.2: Average BER against distance in a WDM FSO system ($L_{\text{demux}} = 15$ dB and $C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

Fig. 7.3 shows the average BER values obtained without a PCA at different signal and crosstalk link lengths when $L_{demux} = 30$ dB and $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. The benefit of including an amplifier in a WDM FSO link is highlighted by comparing the systems with an adaptive decision threshold (NOAADT and FOAADT). In the FOAADT, a BER of less than 10^{-12} is attainable at signal and crosstalk link lengths of 2 km compared to the NOAADT where BER values higher than 10^{-2} are obtained for the same distance. Also, a BER of less than 10^{-12} is always achievable with the FOAADT when the signal and crosstalk link lengths are at about 2 km and more than 0.1 km respectively. This is a huge improvement on the NOAADT where BER values less than 10^{-12} can only always be achieved when the signal link length is less than 0.5 km and the crosstalk link length is at least 2 km. For the systems with a non-adaptive decision threshold (NOANADT, FOANADT and SOANADT), amplification is also advantageous and has more significant effect on system performance (especially for turbulence mitigation) when the OA is operated in the saturation regime. For instance, among the three systems, the longest distances achieving a BER of 10^{-12} (i.e. $D_{sig} \approx 1$ km and $D_{xt} = 2$ km) were obtained with the SOANADT. This, once again, shows the importance of using a saturated OA with a non-adaptive decision threshold. For any particular signal link length, the system performance is naturally expected to improve as the crosstalk link length increases (i.e. lower crosstalk power). However some instances in Fig. 7.3 show a reduction in system performance as the crosstalk link length increases. This can be attributed to an increase in atmospheric turbulence effects due to longer propagation distances.

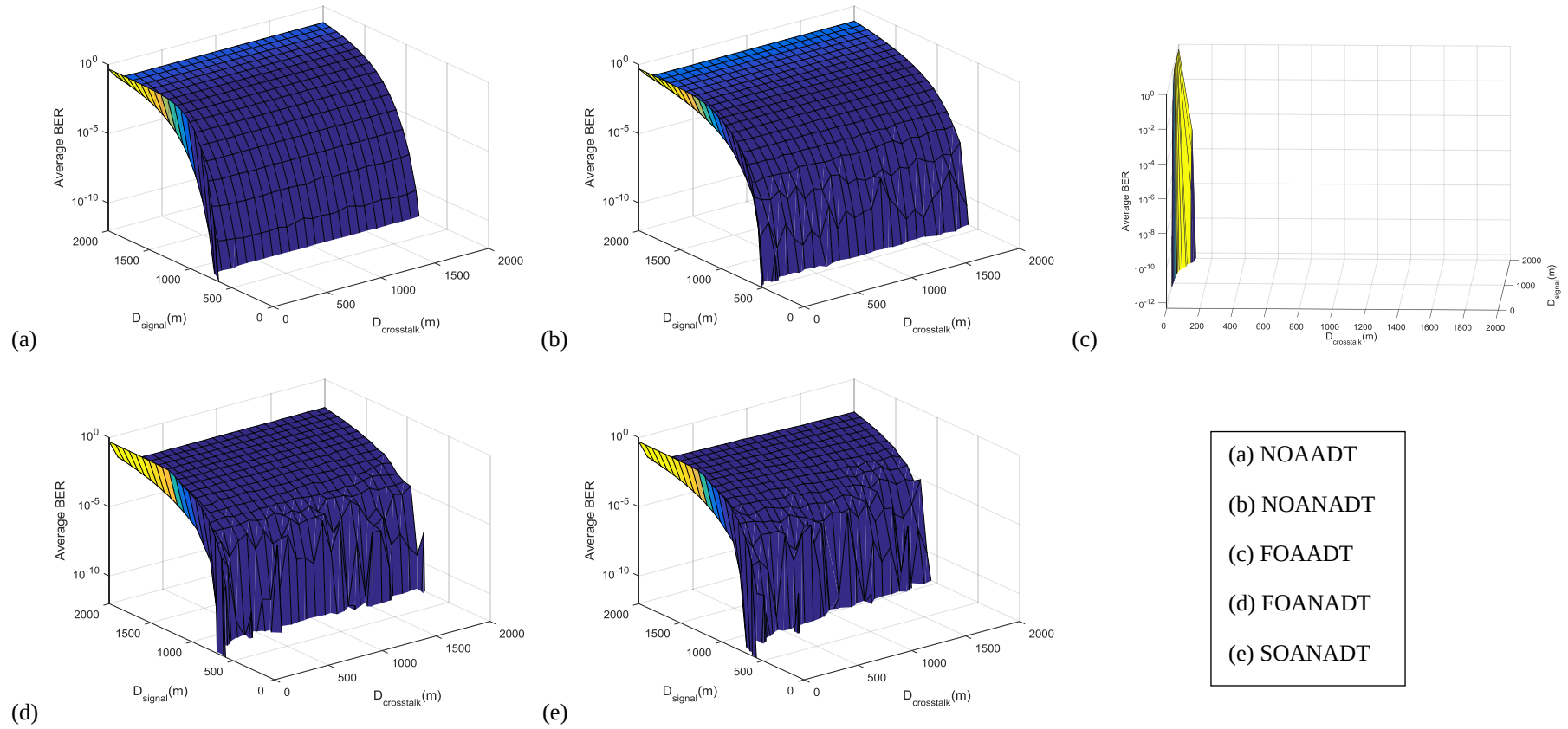


Fig. 7.3: Average BER at various transmitting distances for a WDM FSO system without a PCA ($L_{demux} = 30$ dB and $C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

In other words, while the crosstalk adversely affects the performance of WDM FSO systems, the system performance also largely depends on the turbulent state of the atmosphere.

Figs. 7.4 to 7.12 show the capability of a various WDM FSO system in different turbulence regimes. A summary of the best performances is given in Table 7.2. In all the figures, for different L_{demux} and target BER values, results for systems not including a PCA and systems including a PCA are shown in (a) - (d) and (e) - (h) respectively.

The following should be noted for a better understanding of Figs. 7.4 to 7.12;

- Each figure grid represents the length of the signal and crosstalk links relative to the positions of the signal and crosstalk receiving lenses (both at 0 km).
- Longer signal and crosstalk lengths mean lower signal and crosstalk powers respectively.
- The yellow coloured areas on the grid represent the distances at which the system has achieved the target performance.
- Compared to earlier results (Figs. 7.2 and 7.3) which are for a single ‘desired’ receiver, the results presented were obtained with the assumption that either of the two receivers could be the desired receiver.

Fig. 7.4 shows the capability of a NOAADT WDM FSO system for instances where $C_n^2 = 10^{-13} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$, the target BER is 10^{-9} and a

PCA is not applied, a maximum link length of about 0.4 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.4(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.4(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.32 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.4(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.4(f) when a PCA is applied. When $L_{demux} = 30$ dB, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.48 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.4(c) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.4(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.4 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.4(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.4(h) when a PCA is applied.

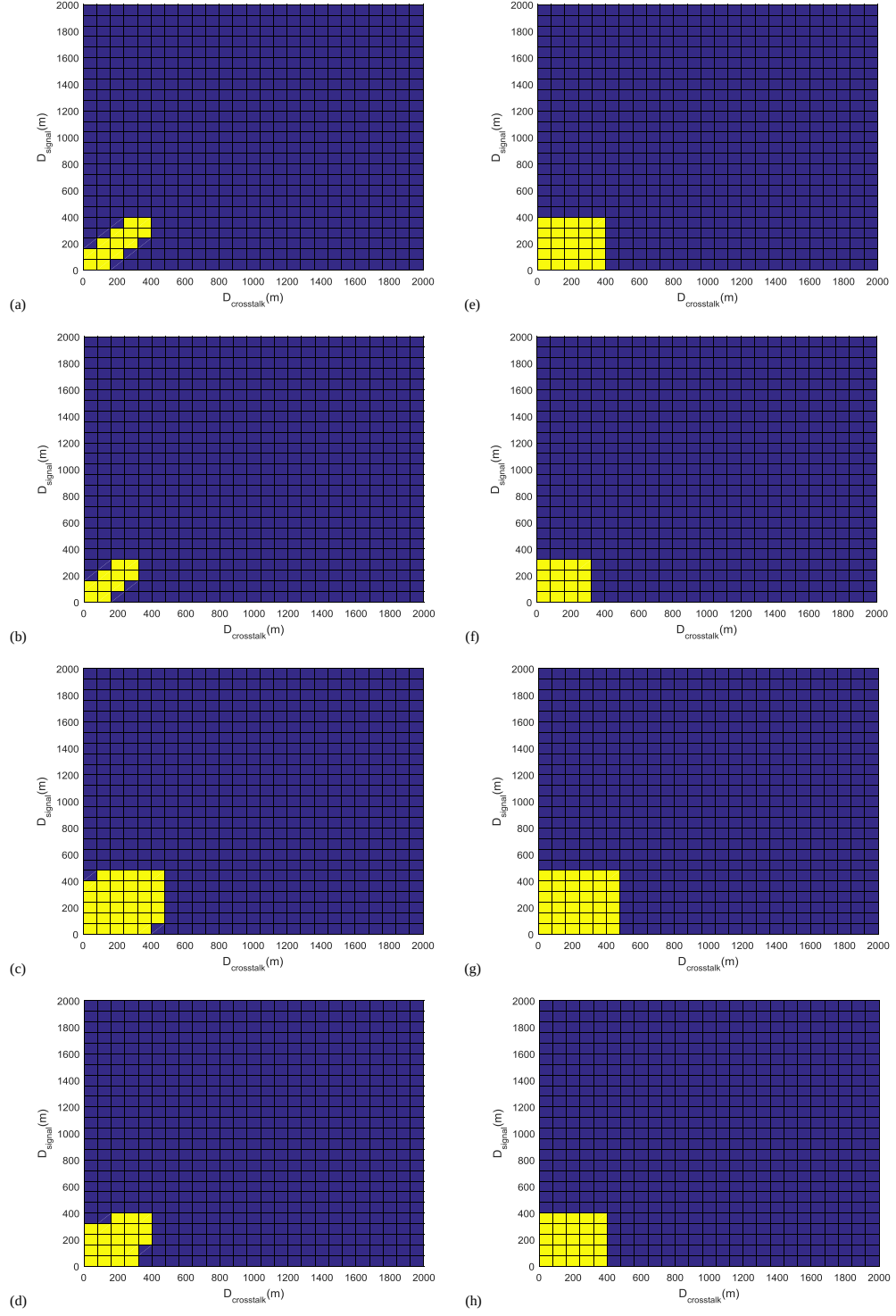


Fig. 7.4: Capability of a NOAADT WDM FSO system ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

Fig. 7.5 shows the capability of a NOAADT WDM FSO system for instances where $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. When $L_{\text{demux}} = 15 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 1.12 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.5(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.5(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.88 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.5(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.5(f) when a PCA is applied. When $L_{\text{demux}} = 30 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 1.12 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.5(c) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.5(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.88 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.5(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.5(h) when a PCA is applied.

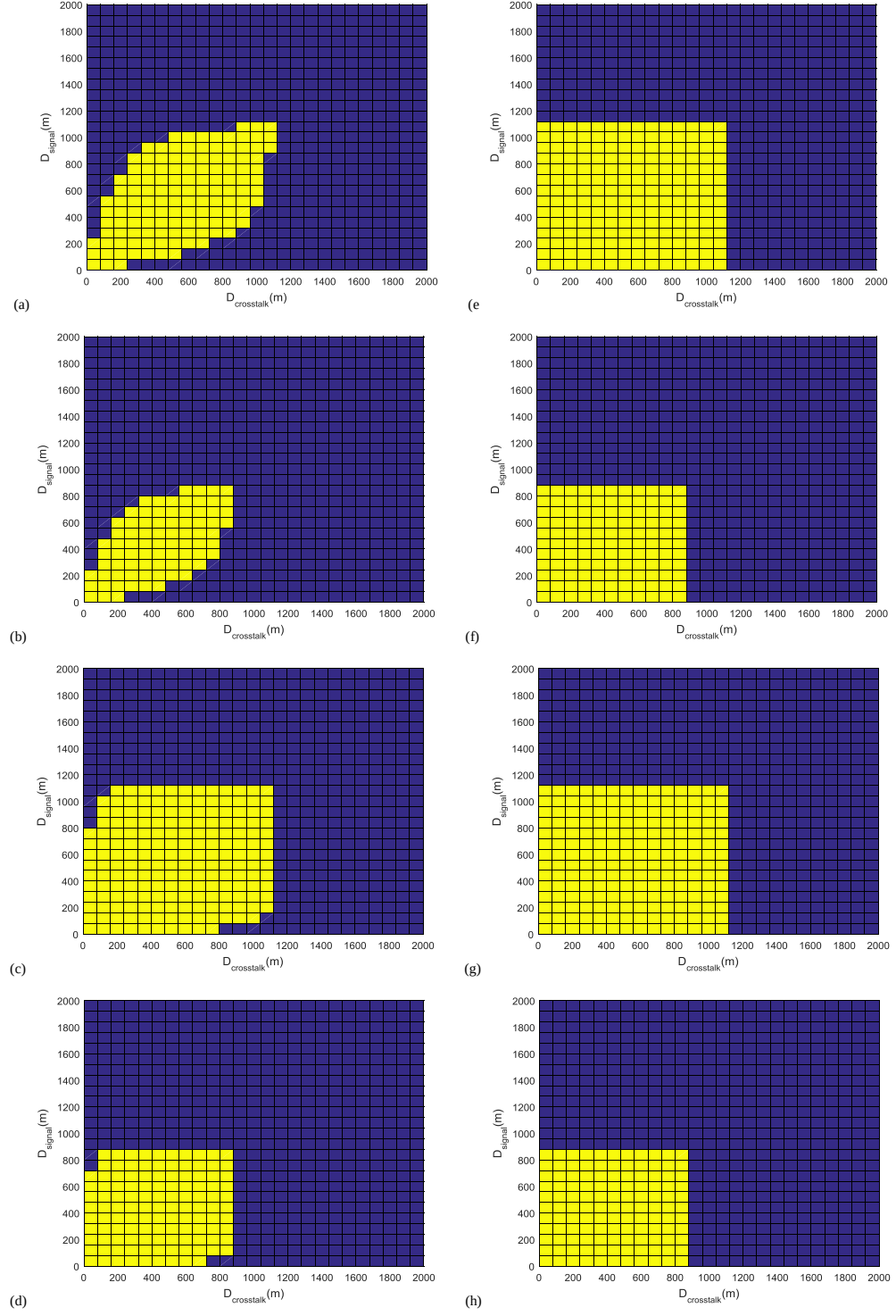


Fig. 7.5: Capability of a NOAADT WDM FSO system ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

Fig. 7.6 (not very descriptive but included for consistency) shows the capability of a NOANADT WDM FSO system with $C_n^2 = 10^{-13} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$ and the target BER is 10^{-9} , a maximum link length of about 0.08 km is achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.6(a) and Fig. 7.6(e) respectively). By reducing the target BER to 10^{-12} , a maximum link length of about 0.08 km is also achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.6(b) and Fig. 7.6(f) respectively). When $L_{demux} = 30 \text{ dB}$ and the target BER is 10^{-9} , a maximum link length of about 0.08 km is achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.6(c) and Fig. 7.6(g) respectively). By reducing the target BER to 10^{-12} , a maximum link length of about 0.08 km is also achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.6(d) and Fig. 7.6(h) respectively).

Fig. 7.7 shows the capability of a NOANADT WDM FSO system for cases where $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.8 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.7(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.7(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.64 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.7(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.7(f) when a PCA is applied.

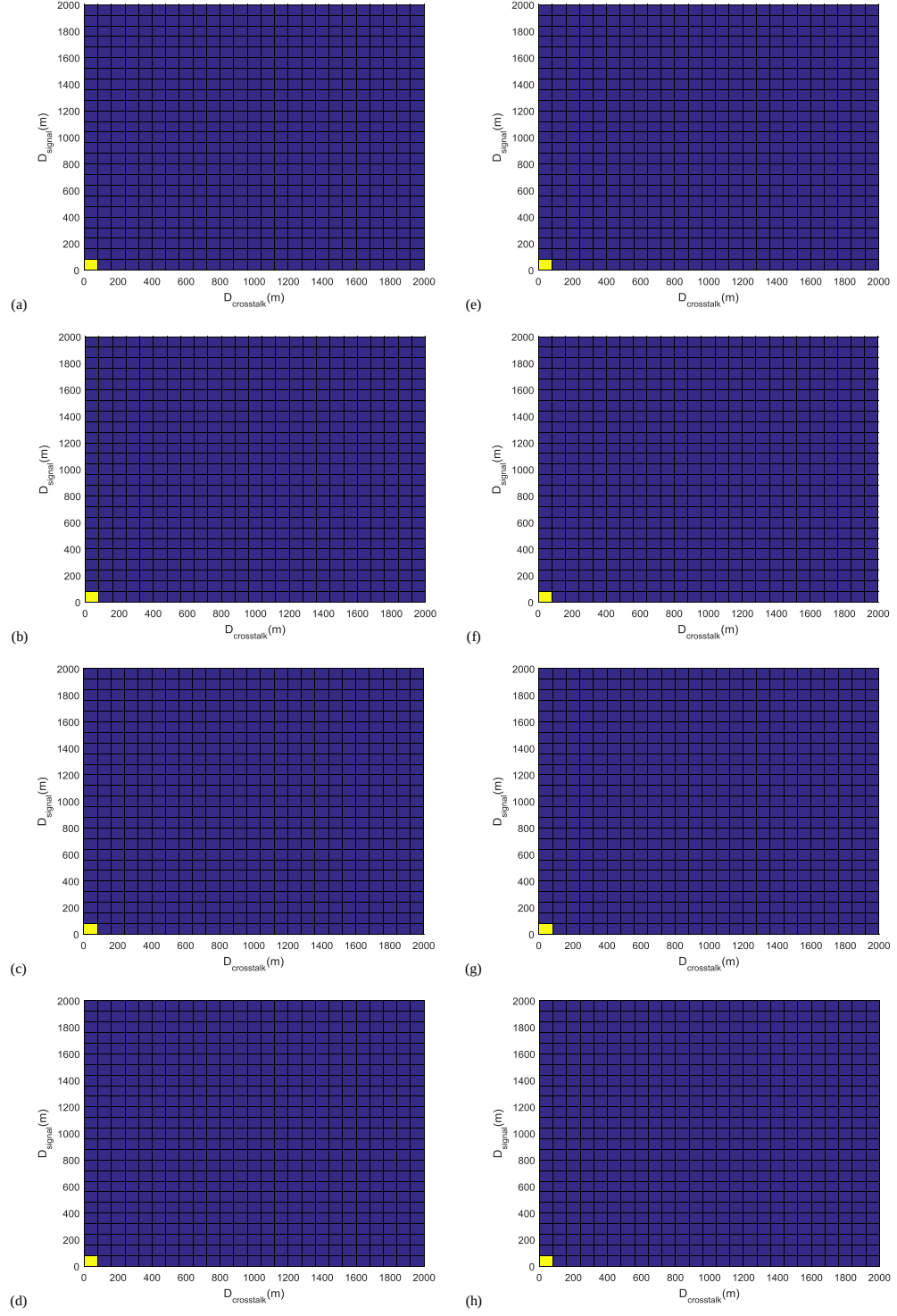


Fig. 7.6: Capability of a NOANADT WDM FSO system ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

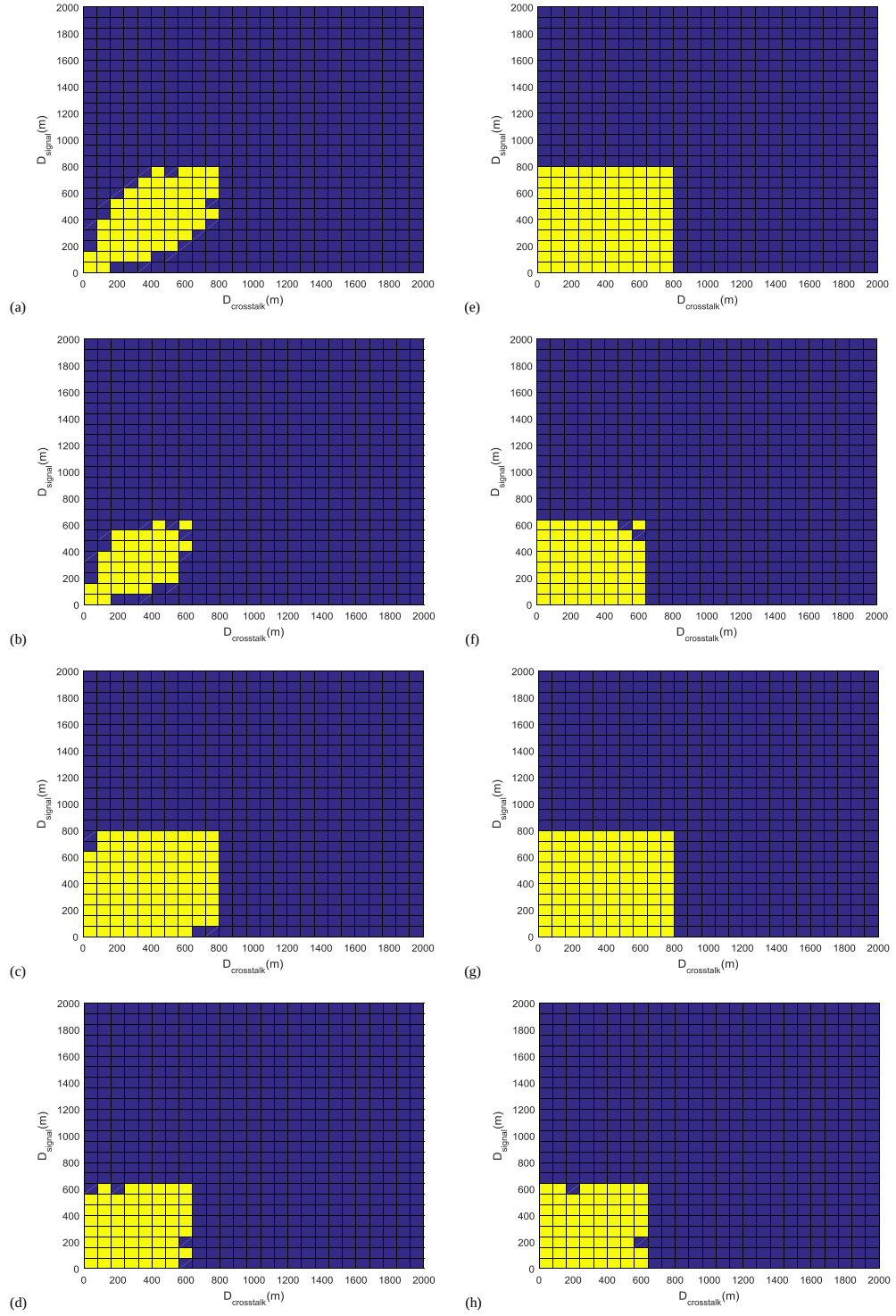


Fig. 7.7: Capability of a NOANADT WDM FSO system ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

- | | |
|--|--|
| (a) $L_{\text{demux}} = 15$ dB, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15$ dB, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15$ dB, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15$ dB, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30$ dB, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30$ dB, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30$ dB, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30$ dB, target BER = 10^{-12} , With PCA |

When $L_{demux} = 30$ dB, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.8 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.7(c) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.7(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.64 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.7(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.7(h) when a PCA is applied.

Fig. 7.8 shows the capability of a FOAADT WDM FSO system for cases where $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. When $L_{demux} = 15$ dB, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of 2 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.8(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.8(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of 2 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.8(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.8(f) when a PCA is applied.

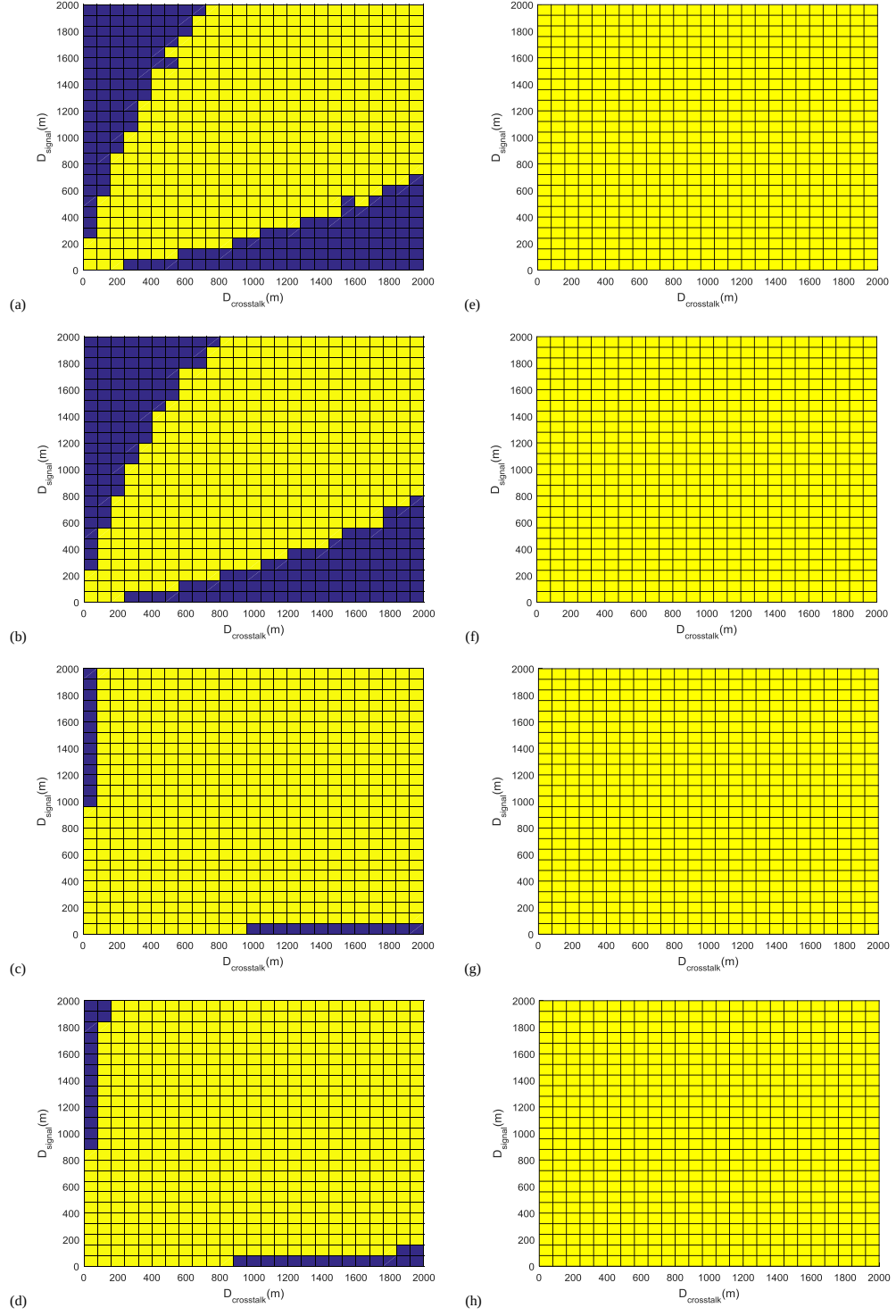


Fig. 7.8: Capability of a FOAADT WDM FSO system ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

- | | |
|--|--|
| (a) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

When $L_{demux} = 30$ dB, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of 2 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.8(c) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.8(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of 2 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.8(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.8(h) when a PCA is applied.

Fig. 7.9 shows the capability of a FOANADT WDM FSO system for cases where $C_n^2 = 10^{-13} \text{ m}^{-2/3}$. When $L_{demux} = 15$ dB and the target BER is 10^{-9} , a maximum link length of about 0.08 km is achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.9(a) and Fig. 7.9(e) respectively). By reducing the target BER to 10^{-12} , a maximum link length of about 0.08 km also is achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.9(b) and Fig. 7.9(f) respectively). When $L_{demux} = 30$ dB, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.08 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.9(c) and increased system capability is observed (maximum link length of about 0.16 km is achievable when the signal and crosstalk link lengths are equal) when a PCA is applied as shown in Fig. 7.9(g). By reducing the target BER to 10^{-12} , a maximum link length of about 0.08 km is achievable when the signal and

crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.9(d) and Fig. 7.9(h) respectively).

Fig. 7.10 shows the capability of a FOANADT WDM FSO system for cases where $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.88 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.10(a) and increased system capability is observed at unequal distances (with increased maximum link length of about 1.04 km) when a PCA is applied as shown in Fig. 7.10(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.88 km is also achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.10(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.10(f) when a PCA is applied. When $L_{demux} = 30 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 1.04 km is achievable as shown in Fig. 7.10(c) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.10(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.88 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.10(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.10(h) when a PCA is applied.

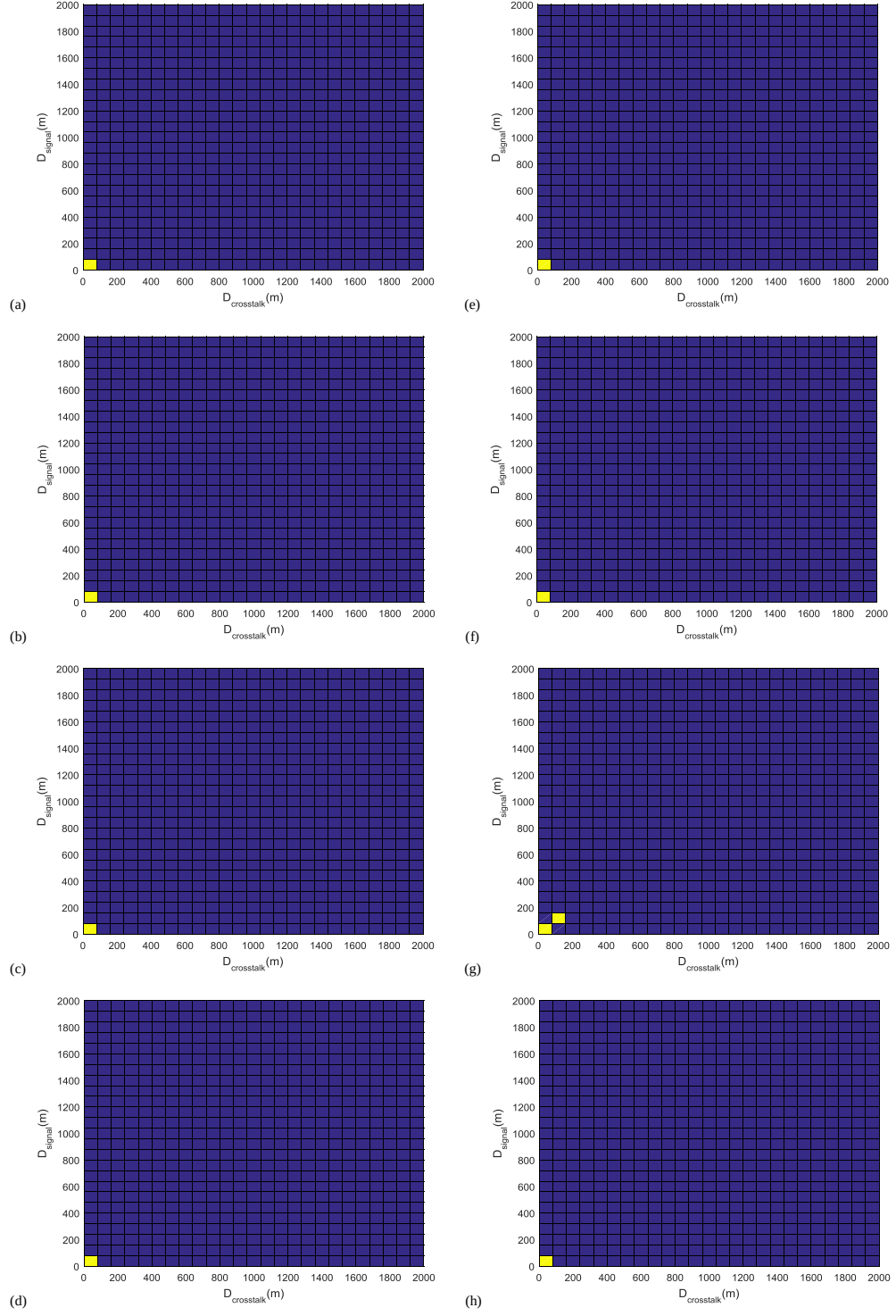


Fig. 7.9: Capability of a FOANADT WDM FSO system ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$).

- | | |
|--|--|
| (a) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{demux} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{demux} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

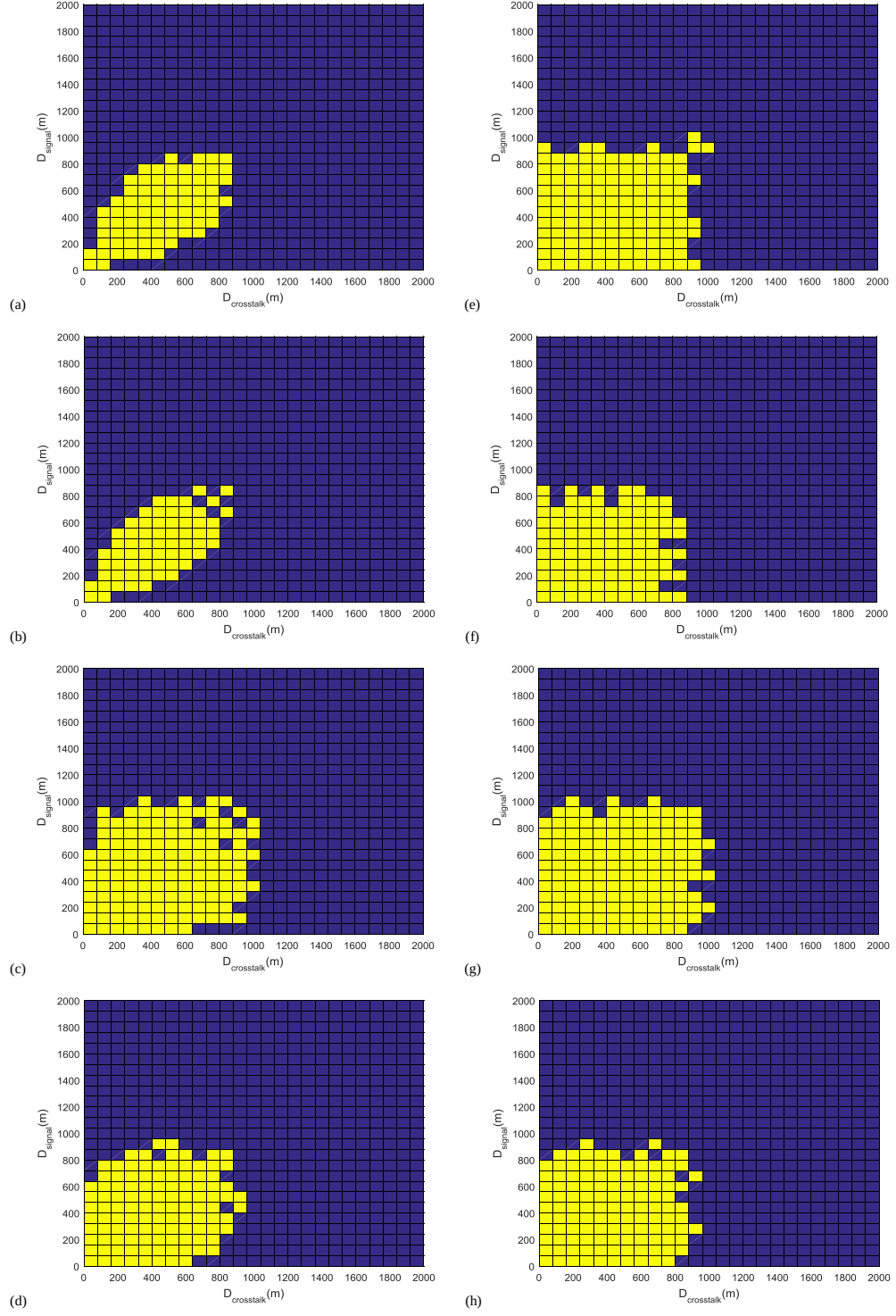


Fig. 7.10: Capability of a FOANADT WDM FSO system ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

Fig. 7.11 shows the capability of a SOANADT WDM FSO system for cases where $C_n^2 = 10^{-13} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 0.16 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.11(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.11(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 0.16 km is also achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.11(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.11(f) when a PCA is applied. When $L_{demux} = 15 \text{ dB}$ and the target BER is 10^{-9} , a maximum link length of about 0.16 km is achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.11(c) and Fig. 7.11(g) respectively). By reducing the target BER to 10^{-12} , a maximum link length of about 0.16 km is also achievable when the signal and crosstalk link lengths are equal (without or with a PCA as shown in Fig. 7.11(d) and Fig. 7.11(h) respectively).

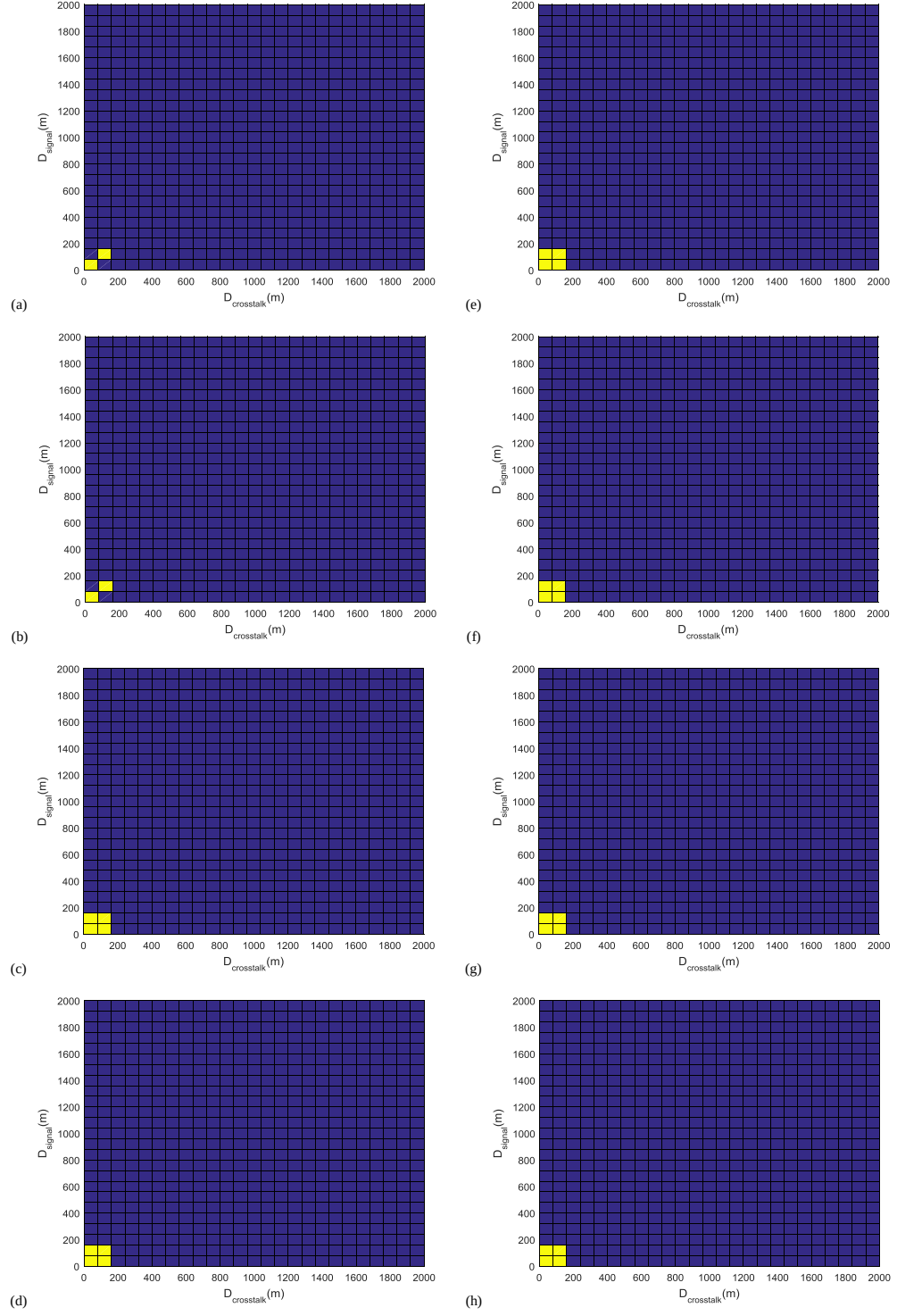


Fig. 7.11: Capability of a SOANADT WDM FSO system ($C_n^2 = 10^{-13} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

Fig. 7.12 shows the capability of a SOANADT WDM FSO system for cases where $C_n^2 = 10^{-15} \text{ m}^{-2/3}$. When $L_{demux} = 15 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 1.12 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.12(a) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.12(e). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 1.04 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.12(b) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.12(f) when a PCA is applied. When $L_{demux} = 30 \text{ dB}$, the target BER is 10^{-9} and a PCA is not applied, a maximum link length of about 1.12 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.12(c) and increased system capability is observed (maximum link length of about 1.28 km is achievable) at unequal distances when a PCA is applied as shown in Fig. 7.12(g). By reducing the target BER to 10^{-12} without applying a PCA, a maximum link length of about 1.12 km is achievable when the signal and crosstalk link lengths are equal as shown in Fig. 7.12(d) and increased system capability is observed at unequal distances when a PCA is applied as shown in Fig. 7.12(h) when a PCA is applied.

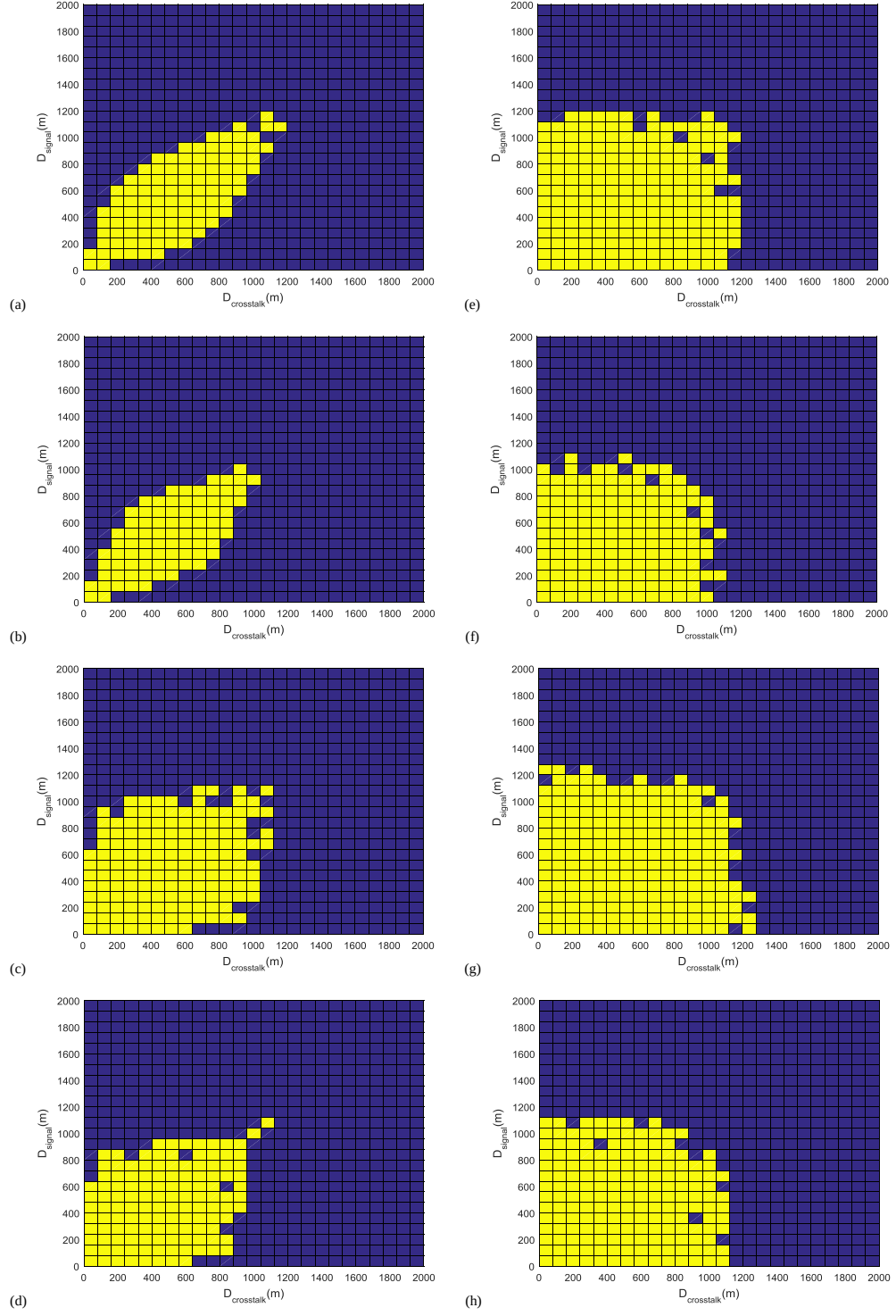


Fig. 7.12: Capability of a SOANADT WDM FSO system ($C_n^2 = 10^{-15} \text{ m}^{-2/3}$).

- | | |
|---|---|
| (a) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , No PCA | (e) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (b) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , No PCA | (f) $L_{\text{demux}} = 15 \text{ dB}$, target BER = 10^{-12} , With PCA |
| (c) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , No PCA | (g) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-9} , With PCA |
| (d) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , No PCA | (h) $L_{\text{demux}} = 30 \text{ dB}$, target BER = 10^{-12} , With PCA |

Conclusively, in each of the WDM FSO systems considered above, the best results (shown in Table 7.2) in terms of achievable propagation distance were obtained with a PCA when $C_n^2 = 10^{-15} \text{ m}^{-2/3}$ and $L_{demux} = 30 \text{ dB}$. Note that even though a target BER of 10^{-9} clearly gave better results, Table 7.2 shows comparisons for a target BER of 10^{-12} since it is generally considered as a benchmark of acceptable performance in optical communication systems.

Table 7.2: Achievable propagation distance at a target BER of 10^{-12} with a PCA when $C_n^2 = 10^{-15} \text{ m}^{-2/3}$ and $L_{demux} = 30 \text{ dB}$.

System	Achievable distance (km)
NOAADT	0.88
NOANADT	0.64
FOAADT	2
FOANADT	0.96
SOANADT	1.12

As shown in Table 7.2, for the system parameters used, the NOANADT and the FOAADT gave the worst and best performances respectively. This shows the importance of optical amplification and threshold tracking to system impaired by atmospheric turbulence, ASE noise and interchannel crosstalk. It has been established that atmospheric turbulence-induced scintillation can be mitigated by operating an OA (in amplified systems) in the saturated gain regime or using an adaptive decision threshold (in non-amplified systems) but the question of which of the two approaches is more effective for scintillation reduction arises. There is no straightforward answer to this question due to factors such as the parameters used and the atmospheric condition (i.e. the turbulence level and in this case, the presence of interchannel crosstalk). As

shown in Table 7.2, the SOANADT produced a superior performance compared to the NOAADT. This is not to conclude that the saturated gain OA approach is more effective than the use of an adaptive decision threshold. However, it indicates that the SOANADT provides a viable alternative for short distance communication (i.e. < 2 km).

7.6 Summary

This Chapter examined the performance of a WDM FSO communication system in a turbulent atmosphere by applying MC simulation techniques. Results obtained in this Chapter showed that even when the crosstalk power is very small compared to the signal power, the fluctuations in the crosstalk due to atmospheric turbulence may have an adverse effect on system performance. Also, out of all the WDM FSO systems considered, the FOAADT showed the best performance (i.e. BER of 10^{-12} at a minimum link length of 2 km) with or without PCA due to optical amplification and the use of an adaptive decision threshold. As expected, a reduction (improvement) of the target BER leads to a decrease in the attainable link length and an increase in the L_{demux} value leads to an increase in system performance. The PCA has also shown to be beneficial to system performance since all the results obtained show that the introduction of a PCA only improves system performance. It is however noteworthy that (in contrast to the single wavelength systems analysed in Chapters 5 and 6) the SOANADT performed better than the NOAADT. This is because the OA in the SOANADT is well driven into the saturation regime (due to the combination of the signal and crosstalk powers at the OA input) thereby

elaborating the advantage of using a non-adaptive decision threshold. Lastly, even though the use of an adaptive decision threshold with optical amplification has once again proved to give the best results in FSO links, the use of a saturated gain OA with a non-adaptive decision threshold has the capacity to provide acceptable performances when the OA input power is high enough. Earlier finding in Chapter 5 has shown that making the OA's input power comparable to P_{sat} ensures optimal turbulence mitigation. However, care has to be taken not to overload the receiver.

7.7 References

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Chapter 8

Conclusions and Further Works

8.1 Introduction

The optical signals propagated through the atmosphere are impaired by scintillation, amplified spontaneous emission (ASE) noise, crosstalk (especially in wavelength-division multiplexed (WDM) networks and semiconductor optical amplifiers (SOAs)), beam spreading and atmospheric attenuation. This work has explored ways of improving the reliability of free-space optical (FSO) communication systems. This Chapter recaps the main findings in this work, presents conclusions and makes suggestions for further work.

8.2 General summary and conclusions

Chapter 1 introduced the thesis and detailed an overview of FSO communication systems. A review of FSO communication system basics and components was presented in Chapter 2. The features and attributes of FSO communication systems were presented and the components used at the

transmitting and receiving ends were reviewed. The optical amplification process was also reviewed and different types of optical amplifiers (OAs) were examined and compared. Linear crosstalk and the different types of noise present in the receiver circuitry such as thermal and shot noises were discussed. The atmospheric channel, modelling of system parameters in a turbulent atmosphere with Monte Carlo (MC) simulation techniques and some scintillation reduction methods were reviewed in Chapter 3. Chapter 4 reviewed the modulation, demodulation and performance evaluation methods employed in this work.

The on-off keying (OOK) modulation format (the modulation format of choice in this work) is popularly used in optical communication systems due to its computational ease and simplicity but it performs poorly in a turbulent atmosphere when its usual decision threshold (i.e. a non-adaptive decision threshold) is used. To obtain optimal performances with the OOK modulation format in a turbulent atmosphere, an adaptive decision threshold that can constantly track the power fluctuations (due to the atmospheric turbulence-induced scintillation) is required at the receiver. Since the practical implementation of this adaptive decision threshold is challenging and expensive (as highlighted in Chapter 5), efforts were made in this work to devise ways of improving system performance when the OOK modulation format is used in a turbulent atmosphere with a non-adaptive decision threshold.

A single link FSO communication system was investigated in Chapter 5 and a general expression was derived for the non-adaptive decision threshold. The

Gaussian Approximation (GA) was first used to evaluate system performance and a comparison between non-amplified and fixed gain preamplified systems showed that in both systems, acceptable BER performances ($<10^{-12}$) were obtained when an adaptive decision threshold was used at the receiver and poor BER performances ($>10^{-3}$) were obtained when a non-adaptive decision threshold was used at the receiver. Nevertheless, the preamplified systems required less power to achieve the same performance as the non-amplified systems. When a saturated gain preamplified system was used with a non-adaptive decision threshold, BER performances better than 10^{-8} were obtained in the weak turbulence regime. Further analyses were performed to determine the optimum decision threshold when a saturated gain preamplified system was used with a non-adaptive decision threshold. Turbulence distributions such as the lognormal, gamma-gamma, K and negative exponential were used to describe the fluctuations due to atmospheric turbulence and other performance evaluation methods such as the Chernoff Bound (CB), Modified Chernoff Bound (MCB), and Saddle Point Approximation (SPA) were also used to analyse system performance. An analysis was performed for a fixed gain preamplified system and results obtained (with Rytov variance, $\sigma_R^2 = 0.1$ and small signal gain, $G_{ss} = 30$ dB) showed that when a non-adaptive decision threshold was used at the receiver, the MGF based methods and the GA all gave unacceptable BER performances ($>10^{-2}$). Results for an adaptive decision threshold showed that the MGF based methods and the GA all gave acceptable BER performances ($<10^{-12}$). However, at a target BER of 10^{-12} , the CB and MCB (having similar performances) predicts lower power

efficiency (compared to the GA and SPA) with a power difference of about 4.4 dB and 6.6 dB from the GA and SPA respectively.

The ideas developed in Chapter 5 were extended to Chapter 6 where a cascaded OA FSO communication system was analysed and each interamplifier section of the cascaded OA FSO communication system was assumed to be statistically independent in its turbulence. The cascaded OA (with fixed and/or saturated gain) FSO communication system was then analysed (with adaptive and non-adaptive decision thresholds). A closed form expression was derived for the relationship between the BER and the optical signal to noise ratio (OSNR) for each interamplifier section of the OA cascade and MC simulation techniques were used to model the impact of atmospheric turbulence on system performance. The system performances (in terms of the obtainable average BER and the achievable propagation distance) were first presented from a general system perspective before specific system implementations were shown. For the general system perspective, fixed σ_R^2 and path loss ($1/L_{nt}$) values were used to represent each interamplifier section of the OA cascade. Results obtained showed that after 4 interamplifier sections (with $\sigma_R^2 = 0.1$ and $1/L_{nt} = 30$ dB per section), the fixed and saturated gain OA cascades achieved BER values of about 10^{-10} and 10^{-7} respectively when an adaptive decision threshold was used. With a non-adaptive decision threshold, the obtained BER values were reduced to about 10^{-1} and 5×10^{-2} for the fixed and saturated gain OA cascades respectively. The fixed values were then mapped into specific physical design parameters (i.e. the receiving lens diameter (d_{rx}), beam divergence angle (ϕ), link length (D) and refractive

index structure constant (C_n^2). For instance, in each interamplifier section, $\sigma_R^2 = 0.5$ and $1/L_{nt} = 35$ dB can be mapped into $d_{rx} = 4 \times 10^{-2}$ m, $\phi = 1 \times 10^{-3}$ rad, $C_n^2 = 6.4 \times 10^{-15} \text{ m}^{-2/3}$ and $D = 2.101$ km. Using these specific design parameters, results obtained showed that at a distance of 4 km, the fixed and saturated gain OA cascades both gave BER values of about 5×10^{-10} when an adaptive decision threshold was used. With a non-adaptive decision threshold, the obtained BER values were reduced to about 3×10^{-2} and 5×10^{-3} for the fixed and saturated gain OA cascades respectively. The results obtained for the non-adaptive decision threshold can be improved by applying measures such as using the optimum threshold level investigated in Chapter 5, applying forward error correction (FEC) with interleaving and using an OA with a higher G_{ss} value.

In Chapter 7, WDM passive optical network (PON) FSO hybrid communication systems were analysed while taking atmospheric turbulence, interchannel crosstalk and ASE noise into consideration. The WDM PON FSO systems were analysed (with non-adaptive and adaptive decision thresholds) for instances where the OA is operated in either saturated or fixed gain regimes and results were presented in terms of the obtainable average BER and achievable link length. MC simulation techniques were used to model the effects of atmospheric turbulence on system parameters and a power control algorithm (PCA) was incorporated into the system. In order to develop a basic understanding of how a WDM PON communication system works, two WDM channels were considered in this work since a fundamental understanding of how two channels work is expected to be beneficial for the analysis of more

channels. The WDM FSO systems considered were non-amplified systems with an adaptive decision threshold (NOAADT), non-amplified systems with a non-adaptive decision threshold (NOANADT), fixed gain amplified systems with an adaptive decision threshold (FOAADT), fixed gain amplified systems with a non-adaptive decision threshold (FOANADT) and saturated gain amplified systems with a non-adaptive decision threshold (SOANADT). By including a PCA when $L_{demux} = 30$ dB and $C_n^2 = 10^{-15} \text{ m}^{-2/3}$, a target BER of 10^{-12} was achieved at a propagation distance of about 0.88 km, 0.64 km, 2 km, 0.96 km and 1.12 km for a NOAADT, NOANADT, FOAADT, FOANADT and SOANADT respectively.

The following conclusions are drawn from the work performed in this thesis.

- Optical amplification improves the sensitivity of an optical receiver regardless of the scintillation level and the thresholding scheme used at the receiver.
- The use of a non-adaptive decision threshold with a fixed gain preamplified system in a turbulent atmosphere will generally result in an unacceptable performance.
- Under the same operating conditions, an adaptive decision threshold will always perform better than a non-adaptive decision threshold (for both fixed and saturated gain preamplified receivers) due to its ability to constantly track the optical signal power fluctuations in a turbulent channel.
- In a turbulent atmosphere where channel state information (CSI) is known, using an adaptive decision threshold with a saturated gain

preamplified system will not show how saturated OAs mitigate scintillation, in fact, saturation will generate a lower performance (compared to a fixed (small signal) gain preamplified system) because saturation causes reduction in OA gain.

- In a turbulent atmosphere where channel state information (CSI) is not known and a non-adaptive decision threshold is used for a preamplified system, acceptable BER performances (which can be further improved by using an OA with a higher G_{ss} value and/or applying forward error correction (FEC) with interleaving) can be obtained provided that the OA is operated in the gain saturation regime.
- An optimum non-adaptive decision can be obtained for a saturated gain preamplified system.
- The optimal scheme for a cascaded OA FSO communication system using a non-adaptive decision threshold receiver would use frequent low gain saturated amplification even though the cost implications has to be considered.
- Compared to a single link FSO communication system where a non-amplified system with an adaptive decision threshold performed better than a saturated gain preamplified system with a non-adaptive decision threshold, a saturated gain amplified WDM FSO system with a non-adaptive decision threshold is superior to a non-amplified WDM FSO system with an adaptive decision threshold. Note that this conclusion is made based on the system parameters used in this work.
- Due to its reduced cost and complexity, the use of a non-adaptive decision threshold with saturated gain OAs (either as preamplifiers or

line OAs) are recommended for scintillation mitigation in FSO communication systems.

8.3 Suggestions for further work

Based on the contents of this thesis, suggestions for further work are detailed below.

- The natural progression of the work in this thesis is to experimentally substantiate the results presented in Chapters 5, 6 and 7.
- The WDM PON FSO communication system analysed in Chapter 7 was limited to two wavelength channels. The analysis of multiple channels can be attempted analytically and with MC simulation techniques. Some use of the central limit theorem may be possible in certain cases.
- The OA used for the WDM PON FSO communication system in Chapter 7 was assumed to saturate individual channels independently. Attempts can be made to model the joint saturation of the different channels.
- The main performance metric considered in this work is the average BER, the outage probability is also a viable performance metric and can be investigated for the single link, cascaded OA and WDM PON FSO communication systems.
- Investigations can be performed on how a saturated gain preamplified FSO receiver can be used to combat pointing and coupling loss. The impact of aperture averaging can also be investigated.

- The performance evaluation with moment generation function (MGF) methods considered in Chapter 5 was limited to a fixed gain preamplified receiver in a single link FSO communication system with adaptive and non-adaptive decision thresholds. The MGF methods can be used to evaluate the performance of a saturated gain preamplified receiver with a non-adaptive decision threshold. It can also be extended to the cascaded OA and WDM FSO communication systems in Chapters 6 and 7 respectively. MC simulation techniques with MGF (note that this approach is time consuming) methods can also be investigated.
- The work in this thesis was limited to the OOK modulation format. Pulse position modulation (PPM) and subcarrier intensity modulation (SIM) cannot benefit from the scintillation mitigation capability of saturated gain OAs because they do not have a decision threshold but their performance with a cascaded OA FSO communication system can be investigated.
- Spatial diversity can be incorporated into the single link and cascaded OA FSO systems in Chapters 5 and 6 respectively either as multiple transmitters sending signals to a single receiver (MISO), multiple transmitters sending signals to multiple receivers (MIMO) or a single transmitter sending signals to multiple receivers (SIMO). The effects of using adaptive and non-adaptive decision thresholds can be investigated. The impact of optical amplification (with fixed or saturated gain) to such a system can also be investigated.