

**PERFORMANCE EVALUATION AND ENHANCEMENT TECHNIQUES
FOR OOK MODULATED TERRESTRIAL FREE SPACE OPTICAL LINK**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
AUGUST 2015**

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**PERFORMANCE EVALUATION AND ENHANCEMENT TECHNIQUES
FOR OOK MODULATED TERRESTRIAL FREE SPACE OPTICAL LINK**

by

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Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
NEW DELHI, INDIA**

August 2015

Certificate

This is to certify that the thesis titled “**Performance Evaluation and Enhancement Techniques for OOK Modulated Terrestrial Free Space Optical Link**” being submitted by **Ms. Prabhmandeep Kaur** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of the bonafide research work carried out by her. She has worked under our supervision and guidance during the period July 2012 to March 2015. She has fulfilled all the requirements for submission of the thesis which has reached the requisite standard.

The results contained in the thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Abstract

Free space optical (FSO) communication with its potential of high bandwidth over unlicensed optical wavelengths, immunity to electromagnetic interference (EMI), cost effectiveness, portability, etc. has emerged as a promising technology to meet the ever growing bandwidth requirement of present and emerging new generation communication systems. However, in the practical implementation of FSO systems, atmospheric conditions play an important role to determine quality of the link. The major challenges faced by a terrestrial FSO link are extinction effects due to absorption and scattering, atmospheric turbulence and misalignment/pointing errors.

The research work in this thesis is aimed at studying the performance impairments in a terrestrial FSO link and evaluating the link performance in terms of capacity, bit error rate (BER) and outage probability. An intensity modulated/direct detection (IM/DD) link employing on-off keying (OOK) signaling scheme is studied due to its low cost, simplicity and ease of commercial availability. An operating wavelength of 1550 nm is chosen because of its eye safety and lower scattering losses in haze/fog conditions. To describe the effect of weather, turbulence and pointing errors appropriate models (i.e., Kim model, gamma-gamma distribution and Rayleigh distribution, respectively) have been identified based on their mathematical tractability and validity range. Combined channel models are presented to characterize the effect of turbulence, weather conditions and pointing errors, simultaneously.

The performance of the link degrades severely as turbulence strength increases from weak to strong or the weather conditions deteriorate from very clear air to fog conditions. The presence of pointing errors further degrades the link performance. In

order to maintain a balance between the pointing errors and beam divergence losses, optimization of the beam divergence angle/beam waist becomes critically important. The effect of beam divergence angle/beam waist on the performance parameters has been investigated for various weather conditions and pointing error jitter. At an optimum value of beam divergence angle, a balance between the losses is obtained to provide best performance in terms of maximum capacity, minimum BER and outage probability. These optimum values remain almost constant for all the weather conditions, but increase as the normalized pointing error jitter is increased. Also, for beam divergence angles lower than the optimum values, performance of the FSO system is degraded more severely and rapidly as compared to values greater than the optimal.

Further, various performance enhancement techniques such as aperture averaging, spatial diversity (using an array of direct detection receivers and multi-input multi-output schemes) and low density parity check (LDPC) codes are investigated. The performance improvement is more pronounced as the turbulence strength is increased from weak to strong. Also the improvement by spatial diversity schemes in terms of diversity gain increases with increase in number of transmitters/receivers but remains almost constant in all weather conditions experiencing the same turbulence strength. A comparison of the spatial diversity schemes using point receivers with an aperture averaged link shows that due to constraint on the receiver aperture diameter, aperture averaging technique fails to give the same kind of performance as provided by the higher order diversity schemes. Also, LDPC coded links give a significant improvement in performance at higher signal-to-noise ratios. The improvement in terms of coding gain is seen to increase as the required BER performance is lowered. Since LDPC codes generated using random construction give error floors at lower BER, diversity schemes emerge as the preferred choice for performance enhancement of the link.

Acknowledgements

An attempt at any level cannot be satisfactorily completed without the support and guidance of learned people. I would like to express my deepest gratitude to my supervisors, Prof. V. K. Jain and Prof. Subrat Kar who helped me to put these ideas, well above the level of simplicity into something concrete. Their zeal for scientific excellence and constant encouragement has enriched my growth as a student and a researcher.

I wish to acknowledge the valuable suggestions from my student research committee members - Prof. Devi Chadha, Prof. M. R. Shenoy and Dr. Manav Bhatnagar. I also wish to express my sincere thanks to the Optical Communications Laboratory staff for their support and help during my research work. I would also like to thank the Department of Electrical Engineering at Indian Institute of Technology Delhi for providing best resources and a healthy academic environment to carry out my research work.

I am deeply indebted to my parents for their tremendous moral support. Without their blessings, the successful completion of my thesis would not have been possible. I would also like to thank my husband and my friends for their help and cooperation during my thesis work. Last but not the least, I thank my Guru for giving me the strength and resolve to stay focused and to face all the challenges. He has given me the power to believe in my passion and pursue my dreams. I could never have done this without the faith I have in him.

Prabhmandeep Kaur

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List of Symbols

α	Effective number of large scale eddies
$\alpha_{al,\lambda}$	Absorption coefficient due to aerosol particles
$\alpha_{ml,\lambda}$	Absorption coefficient due to molecular particles
α_{FOV}	Plane angle (in radians) of the conical field of view
$\mathcal{A}_o$	Amplitude of the unperturbed optical field
β	Effective number of small scale eddies
$\beta_{al,\lambda}$	Scattering coefficient due to aerosol particles
$\beta_{ml,\lambda}$	Scattering coefficient due to molecular particles
β_o^2	Spherical wave Rytov variance
β_{rain}	Scattering coefficient due to rain
χ_n	Log amplitude of the n^{th} order
δ_R	Distance between two points in inertial range
ε	Energy dissipation rate
η	Ratio of equivalent beam width and the pointing error standard deviation
η_{RIN}	Internal quantum efficiency of laser diode
ϵ_S	Error term or adjustment parameter
γ	Average electrical SNR
γ_{th}	Threshold level of SNR
Γ_c	Coding gain
κ	Spatial wave number
$\mathbb{L}$	Time slots in PPM
λ	Operating wavelength
Λ	Diffraction pattern
μ	Instantaneous received SNR
$\mathcal{M}$	APD gain factor
$\mathbb{M}$	Bits per symbol in PPM
ν	Dynamic viscosity
ω	Angular frequency of the optical wave
ω_c	Angular frequency of received signal
ω_{IF}	Intermediate frequency
ω_L	Angular frequency of optical local oscillator signal
Ω_{FOV}	Solid field of view angle

Ω_S	Solid angle subtended by source at receiver
ϕ_c	Phase of received signal
ϕ_L	Phase of optical local oscillator signal
φ_o	Phase of the unperturbed optical field
Φ_n	Power spectrum of refractive index fluctuations
Ψ_n	Complex phase perturbations of n^{th} order
$\mathbb{R}$	Detector responsivity
ρ	Pointing error
ρ_c	Coherence parameter
ϱ	Surface radiant reflectance
σ_χ^2	Log amplitude variance
σ_λ	Optical extinction/attenuation coefficient
$\sigma_{back-back}^2$	Noise variance due to beating of background radiation with itself
$\sigma_{back-shot}^2$	Background shot noise variance
$\sigma_{bulk-shot}^2$	Bulk current shot noise variance
$\sigma_{dark-shot}^2$	Dark current shot noise variance
$\sigma_{leakage-shot}^2$	Leakage current shot noise variance
$\sigma_{\ln I}^2$	Log irradiance variance
σ_n^2	Variance of additive white gaussian noise
σ_s^2	Variance of pointing error jitter
$\sigma_{sig-back}^2$	Noise variance due to beating of background radiation with signal
$\sigma_{sig-shot}^2$	Signal shot noise variance
σ_{th}^2	Thermal noise variance
σ_{total}^2	Total noise variance
σ_I^2	Scintillation index
σ_R^2	Rytov variance
σ_{RIN}^2	Relative intensity noise variance
τ_λ	Optical thickness or depth
θ	Beam divergence angle
θ_b	Diffraction limited beam divergence angle
θ_{opt}	Optimum beam divergence angle
ϑ	Volume scattering coefficient
a_o	Amplitude of optical wave at the transmitter
a	Radius of the receiver aperture
A	Aperture averaging factor
A_c	Amplitude of received signal
A_p	Cross-sectional area of scattering
A_r	Area of receiver aperture
A_t	Area of transmitter aperture
A_L	Amplitude of optical local oscillator signal
A_o	Fraction of power collected in absence of pointing error
B	Bandwidth of channel
B_e	Post detection electrical bandwidth
B_o	Bandwidth of optical bandpass filter

c	Speed of light
C	Channel Capacity
C_n^2	Refractive index structure parameter
C_v^2	Velocity structure constant
C_T^2	Temperature structure constant
$D_n(\delta_R)$	Refractive index structure function
D_r	Diameter of receiver aperture
D_t	Diameter of transmitter aperture
$D_v(\delta_R)$	Structure function for wind velocity
$D_T(\delta_R)$	Structure function for temperature fluctuations
e	Electronic charge
E_b	Energy per bit
E_c	Electric field of received signal
E_L	Electric field of optical local oscillator signal
F	Excess noise factor
F_o	Phase front radius of curvature
g	Girth of LDPC code
G_r	Effective antenna gain of receiver
G_t	Effective antenna gain of transmitter
h	Channel state
h_a	Turbulence induced fading
h_l	Atmospheric channel extinction loss
h_{mn}	Channel state from m^{th} transmitter to n^{th} receiver
h_o	Transmission loss of receiver optics
h_p	Pointing error loss
H	Parity check matrix of a LDPC code
H_λ	Peak spectral radiance
$i(t)$	Instantaneous photodetector current
I	Irradiance of the optical beam
$\hat{I}$	Normalized received irradiance
I_b	Bulk current
I_{beam}	Optical beam intensity
I_{max}	Maximum number of iterations
I_o	Mean received irradiance
I_s	Surface leakage current
k	Optical wave number
K_B	Boltzmann constant
$K_{Jj,i}^{x,l}$	Messages passed from variable node to check node
l	Distance between receiver and background source
l_f	Flow dimension
l_o	Inner scale of turbulent eddies
L	Amplitude levels in PAM
L_{fs}	Free space path loss
L_G	Beam divergence or geometric loss

$L_{i,j}^{x,l}$	Messages passed from check node to variable node
L_o	Outer scale of turbulent eddies
M	Number of transmit apertures
n	Refractive index
n'	Particles per unit volume per unit increment in radius
n_1	Random fluctuating term of refractive index
n_o	Mean value of refractive index
n_r	Real part of complex refractive index
N	Number of receive apertures
N_λ	Spectral radiance
N_o	Single sided power spectral density of additive white gaussian noise
N_p	Number of particles per unit volume
P	Atmospheric pressure
$P(t)$	Instantaneous received optical power
P_e	Probability of error
P_{out}	Outage probability
P_r	Average received optical power
P_t	Average transmitted power
P_B	Background radiation power
P_{Bref}	Background power due to reflection
P_{Bsca}	Scattered background power
P_L	Power of optical local oscillator signal
Q_r	Personick Q factor
Q_s	Scattering efficiency factor
r	Radial distance from the beam center
r_c	Code rate
r_p	Radius of particle
R	Spatial vector
R_b	Bit rate
R_L	Equivalent load resistance of receiver circuit
Re	Reynolds number
t	Time
T	Temperature in Kelvin
$T(\lambda, z)$	Transmittance
T_b	Bit duration

List of Abbreviations

ADSL	Asymmetric digital subscriber line
AM	Amplitude modulation
AO	Adaptive optics
APD	Avalanche photodiode
AWGN	Additive white gaussian noise
BER	Bit error rate
CATV	Cable television
CW	Continuous wave
DAPPM	Differential amplitude pulse position modulation
DD	Direct detection
DFB	Distributed feedback laser
DHPIM	Dual header pulse interval modulation
DMC	Discrete memoryless channel
DPIM	Digital pulse interval modulation
DPPM	Differential pulse position modulation
ECC	Error control coding
EDFA	Erbium doped fiber amplifier
EGC	Equal gain combining
EMI	Electromagnetic interference
ESA	European space agency
FEC	Forward error correction
FFT	Fast fourier transform
FM	Frequency modulation
FOV	Field of view
FSO	Free space optical
FTTH	Fiber to the home
HAP	High altitude platform
IEC	International electrotechnical commission
IFFT	Inverse fast fourier transform
i.i.d.	independent and identically distributed
IM	Intensity modulation
ISI	Intersymbol interference
KS	Kolmogorov-Smirnov

LAN	Local area network
LD	Laser diode
LDPC	Low density parity check
LED	Light emitting diode
LoS	Line-of-sight
MAN	Metropolitan area network
MISO	Multi-input single output
MIMO	Multi-input multi-output
MPE	Maximum permissible exposure
MRC	Maximal ratio combining
MSB	Most significant bit
MTBF	Mean time between failures
MVR	Meteorological visibility range
NASA	National aeronautics and space administration
NRZ	Non-return-to-zero
OFDM	Orthogonal frequency division multiplexing
OLO	Optical local oscillator
OOK	On-off keying
OWC	Optical wireless communication
PAM	Pulse amplitude modulation
PAPR	Peak-to-average power ratio
PAT	Pointing, acquisition and tracking
pdf	probability density function
PDM	Pulse duration modulation
PFM	Pulse frequency modulation
PIN	P-intrinsic
PM	Phase modulation
PPM	Pulse position modulation
PSK	Phase shift keying
PWM	Pulse width modulation
RF	Radio frequency
RIN	Relative intensity noise
RS	Reed Solomon
RZ	Return-to-zero
SeIC	Selection combining
SIM	Subcarrier intensity modulation
SIMO	Single input multi-output
SISO	Single input single output
SNR	Signal-to-noise ratio
SPA	Sum product algorithm
TIA	Transimpedance amplifier
VCSEL	Vertical cavity surface emitting laser
WDM	Wavelength division multiplexing
WFS	Wave-front sensor