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


PRABHMANDEEP KAUR

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI



AUGUST 2015

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

by


**PRABHMANDEEP KAUR**

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.

Prof. V. K. Jain
Thesis Supervisor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110 016
India.

Prof. Subrat Kar
Thesis Supervisor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110 016
India.

# 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

# Contents

# List of Figures

# List of Tables

# List of Symbols

| | |
|---|---|
| $\alpha$ | Effective number of large scale eddies |
| $\alpha_{al,\lambda}$ | Absorption coefficient due to aerosol particles |
| $\alpha_{ml,\lambda}$ | Absorption coefficient due to molecular particles |
| $\alpha_{FOV}$ | Plane angle (in radians) of the conical field of view |
| $\mathcal{A}_o$ | Amplitude of the unperturbed optical field |
| $\beta$ | Effective number of small scale eddies |
| $\beta_{al,\lambda}$ | Scattering coefficient due to aerosol particles |
| $\beta_{ml,\lambda}$ | Scattering coefficient due to molecular particles |
| $\beta_o^2$ | Spherical wave Rytov variance |
| $\beta_{rain}$ | Scattering coefficient due to rain |
| $\chi_n$ | Log amplitude of the $n^{th}$ order |
| $\delta_R$ | Distance between two points in inertial range |
| $\varepsilon$ | Energy dissipation rate |
| $\eta$ | Ratio of equivalent beam width and the pointing error standard deviation |
| $\eta_{RIN}$ | Internal quantum efficiency of laser diode |
| $\epsilon_S$ | Error term or adjustment parameter |
| $\gamma$ | Average electrical SNR |
| $\gamma_{th}$ | Threshold level of SNR |
| $\Gamma_c$ | Coding gain |
| $\kappa$ | Spatial wave number |
| $\mathbb{L}$ | Time slots in PPM |
| $\lambda$ | Operating wavelength |
| $\Lambda$ | Diffraction pattern |
| $\mu$ | Instantaneous received SNR |
| $\mathcal{M}$ | APD gain factor |
| $\mathbb{M}$ | Bits per symbol in PPM |
| $\nu$ | Dynamic viscosity |
| $\omega$ | Angular frequency of the optical wave |
| $\omega_c$ | Angular frequency of received signal |
| $\omega_{IF}$ | Intermediate frequency |
| $\omega_L$ | Angular frequency of optical local oscillator signal |
| $\Omega_{FOV}$ | Solid field of view angle |

| | |
|---|---|
| $\Omega_S$ | Solid angle subtended by source at receiver |
| $\phi_c$ | Phase of received signal |
| $\phi_L$ | Phase of optical local oscillator signal |
| $\varphi_o$ | Phase of the unperturbed optical field |
| $\Phi_n$ | Power spectrum of refractive index fluctuations |
| $\Psi_n$ | Complex phase perturbations of $n^{th}$ order |
| $\mathbb{R}$ | Detector responsivity |
| $\rho$ | Pointing error |
| $\rho_c$ | Coherence parameter |
| $\varrho$ | Surface radiant reflectance |
| $\sigma_\chi^2$ | Log amplitude variance |
| $\sigma_\lambda$ | Optical extinction/attenuation coefficient |
| $\sigma^2_{back-back}$ | Noise variance due to beating of background radiation with itself |
| $\sigma^2_{back-shot}$ | Background shot noise variance |
| $\sigma^2_{bulk-shot}$ | Bulk current shot noise variance |
| $\sigma^2_{dark-shot}$ | Dark current shot noise variance |
| $\sigma^2_{leakage-shot}$ | Leakage current shot noise variance |
| $\sigma^2_{\ln I}$ | Log irradiance variance |
| $\sigma_n^2$ | Variance of additive white gaussian noise |
| $\sigma_s^2$ | Variance of pointing error jitter |
| $\sigma^2_{sig-back}$ | Noise variance due to beating of background radiation with signal |
| $\sigma^2_{sig-shot}$ | Signal shot noise variance |
| $\sigma^2_{th}$ | Thermal noise variance |
| $\sigma^2_{total}$ | Total noise variance |
| $\sigma_I^2$ | Scintillation index |
| $\sigma_R^2$ | Rytov variance |
| $\sigma^2_{RIN}$ | Relative intensity noise variance |
| $\tau_\lambda$ | Optical thickness or depth |
| $\theta$ | Beam divergence angle |
| $\theta_b$ | Diffraction limited beam divergence angle |
| $\theta_{opt}$ | Optimum beam divergence angle |
| $\vartheta$ | 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 |
| $H_\lambda$ | 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 |
| $N_\lambda$ | 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 |
| SelC | 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 |