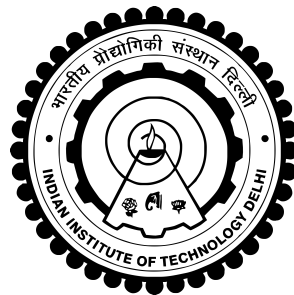


# **PERFORMANCE ANALYSIS AND ENHANCEMENT OF FREE SPACE OPTICAL SATELLITE LINKS**

**POOJA GOPAL**



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

AUGUST 2016

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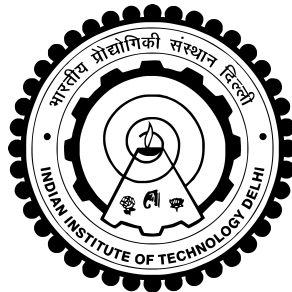
by

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Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy*  
to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

AUGUST 2016

# Certificate

This is to certify that the thesis titled “**Performance Analysis and Enhancement of Free Space Optical Satellite Links**” being submitted by **Ms. Pooja Gopal** to the **Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy**, is a record of bona-fide research work carried out by her under our guidance and supervision during the period of July 2012 to January 2016. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this 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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Pooja Gopal

# Abstract

The growing demand for bandwidth in conventional wireless communication systems and access networks has kindled the need for research on wireless optical communication, most popularly known as Free Space Optical (FSO) communication. FSO links offer very high bandwidth which is several orders of magnitude higher than that offered by Radio Frequency (RF) links and also provide several other advantages such as unlicensed wavelengths, immunity to electromagnetic interference, etc. The RF satellite communication systems have grown steadily over the years and today they must compete with optical fibers in carrying voice, data and video signals. The geostationary satellites are preferred for such high capacity links since they appear to be fixed at a point in space and can establish links with one-third of the Earth's surface. By shifting the frequency of operation in satellite systems to the optical range, several challenges faced by conventional RF systems such as frequency reuse and bandwidth limitations can be overcome. In spite of several advantages, presence of the atmospheric turbulence can lead to severe degradation in the link performance which may render the link infeasible even in clear atmospheric conditions. Therefore, techniques to mitigate the turbulence effect on the FSO satellite downlink and uplink need to be explored.

The research work reported in this thesis aims at studying the effect of atmospheric turbulence on the performance of FSO satellite links between the Earth and a geostationary satellite. The power spectral analysis of various Intensity Modulation (IM) schemes is carried out from which we can draw inference on the metrics used to compare the different schemes. The Bit Error Rate (BER) performance of both the downlink and uplink is evaluated and compared for all IM schemes. It is observed that the effect of turbulence is less severe on the downlink as compared to the uplink. The performance enhancement of the downlink using aperture averaging and receiver spatial diversity is evaluated. It is found that aperture averaging

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is more effective than receiver spatial diversity in an FSO satellite downlink. Using either of the above techniques, the performance of the downlink in the presence of turbulence can be made comparable to its performance in the absence of turbulence. The performance improvement of FSO satellite uplink using transmitter spatial diversity and adaptive modulation technique is studied. In the first technique, arrangement of transmitters to minimize correlation between received beams is considered. The second technique is based on the pre-channel estimation at the transmitter. Further, the effect of these performance enhancement techniques on the channel capacity is evaluated for both uplink and downlink.

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# Abbreviations

<b>FSO</b>	<b>Free Space Optics</b>
<b>RF</b>	<b>Radio Frequency</b>
<b>LAN</b>	<b>Local Area Network</b>
<b>SNR</b>	<b>Signal to Noise Ratio</b>
<b>BER</b>	<b>Bit Error Rate</b>
<b>AWGN</b>	<b>Additive White Gaussian Noise</b>
<b>CSI</b>	<b>Channel State Information</b>
<b>pdf</b>	<b>probability density function</b>
<b>DF</b>	<b>Decode and Forward</b>
<b>AF</b>	<b>Amplify and Forward</b>
<b>EGC</b>	<b>Equal Gain Combining</b>
<b>MRC</b>	<b>Maximum Ratio Combining</b>
<b>SC</b>	<b>Selection Combining</b>
<b>FEC</b>	<b>Forward Error Correction</b>
<b>SISO</b>	<b>Single Input Single Output</b>
<b>SIMO</b>	<b>Single Input Multiple Output</b>
<b>MISO</b>	<b>Multiple Input Single Output</b>
<b>MIMO</b>	<b>Multiple Input Multiple Output</b>
<b>ESA</b>	<b>European Space Agency</b>
<b>NASA</b>	<b>National Aeronautics and Space Administration</b>
<b>RI</b>	<b>Refractive Index</b>
<b>HVB</b>	<b>Hufnagel Valley Boundary</b>
<b>HS</b>	<b>Hufnagel and Stanley</b>
<b>SLC</b>	<b>Submarine Laser Communication</b>

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<b>PAT</b>	<b>P</b> ointing <b>A</b> cquisition and <b>T</b> racking
<b>WSF</b>	<b>W</b> ave <b>S</b> tructure <b>F</b> unction
<b>GEO</b>	<b>G</b> eostationary <b>E</b> arth <b>O</b> rbital
<b>EDFA</b>	<b>E</b> rbium <b>D</b> oped <b>F</b> iber <b>A</b> mplifier
<b>IM</b>	<b>I</b> ntensity <b>M</b> odulation
<b>OOK</b>	<b>O</b> n- <b>O</b> ff <b>K</b> eyping
<b>PPM</b>	<b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>DPPM</b>	<b>D</b> ifferential <b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>PAPM</b>	<b>P</b> ulse <b>A</b> mplitude and <b>P</b> osition <b>M</b> odulation
<b>DAPPM</b>	<b>D</b> ifferential <b>A</b> mplitude <b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>DPIM</b>	<b>D</b> ifferential <b>P</b> ulse <b>I</b> nterval <b>M</b> odulation
<b>DAPIM</b>	<b>D</b> ifferential <b>A</b> mplitude <b>P</b> ulse <b>I</b> nterval <b>M</b> odulation
<b>PSD</b>	<b>P</b> ower <b>S</b> pectral <b>D</b> ensity
<b>NRZ</b>	<b>N</b> on <b>R</b> eturn to <b>Z</b> ero
<b>FOV</b>	<b>F</b> ield <b>O</b> f <b>V</b> iew
<b>SLER</b>	<b>S</b> lot <b>E</b> rror <b>R</b> ate
<b>SER</b>	<b>S</b> ymbol <b>E</b> rror <b>R</b> ate
<b>PIN</b>	<b>P</b> ositive <b>I</b> ntrinsic <b>N</b> egative (photodiode)
<b>IM/DD</b>	<b>I</b> ntensity <b>M</b> odulation/ <b>D</b> irect <b>D</b> etection
<b>CSI</b>	<b>C</b> hannel <b>S</b> tate <b>I</b> nformation

# Physical Constants

Speed of Light  $c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-1}$

Boltzmann Constant  $k_B = 1.380\,648\,81 \times 10^{-23} \text{ m}^2\text{kg s}^{-2}\text{K}^{-1}$

Planck Constant  $h = 6.626\,069\,57 \times 10^{-34} \text{ m}^2\text{kg s}^{-1}$

Radius of the Earth  $R_E = 6.371 \times 10^6 \text{ m}$

# Symbols

$l_0$	Inner scale of turbulence (m)
$L_0$	Outer scale of turbulence (m)
$C_n^2$	Refractive index structure parameter ( $\text{m}^{-2/3}$ )
$C_T^2$	Temperature structure parameter
$T$	Temperature (K)
$\mathbb{P}$	Pressure ( $\text{Nm}^{-2}$ )
$h$	Height above ground level (m)
$w$	High altitude rms wind speed ( $\text{ms}^{-1}$ )
$V_g$	Wind speed near the ground ( $\text{ms}^{-1}$ )
$\sigma_I^2$	Scintillation index
$I$	Received irradiance ( $\text{Wm}^{-2}$ )
$P$	Received power (W)
$\langle P \rangle$	Average received power (W)
$\langle I \rangle$	Average received intensity ( $\text{Wm}^{-2}$ )
$\langle I_0 \rangle$	Average received intensity at the optical axis ( $\text{Wm}^{-2}$ )
$\gamma$	Instantaneous received SNR
$s$	Channel state
$p_I(I)$	channel pdf in terms of received irradiance
$p_I(s)$	channel pdf in terms of channel state
$p(\gamma)$	channel pdf in terms of instantaneous received SNR
$X$	Impact of large scale eddies
$Y$	Impact of small scale eddies
$\sigma_X^2$	Large scale scintillation

$\sigma_Y^2$	Small scale scintillation
$\alpha$	Positive parameter related to $\sigma_X^2$
$\beta$	Positive parameter related to $\sigma_Y^2$
$\sigma_R^2$	Rytov variance
$\theta$	Beam divergence angle (radian)
$\mathbb{A}$	Aperture averaging factor
$k$	Wave number ( $\text{m}^{-1}$ )
$\mathbb{L}_{fs}$	Space loss factor
$\mathbb{T}$	Transmittance
$\mathbb{L}_{bd}$	Beam divergence loss factor
$\mathbb{L}_p$	Pointing loss factor
$\gamma(\lambda)$	Extinction coefficient
$\alpha_m(\lambda)$	Molecular absorption coefficient
$\alpha_a(\lambda)$	Aerosol absorption coefficient
$\beta_m(\lambda)$	Molecular scattering coefficient
$\beta_a(\lambda)$	Aerosol scattering coefficient
$D_B$	Received beam diameter (m)
$F_0$	Phase front radius of curvature at transmitter (m)
$\langle \beta_a^2 \rangle$	Angle of arrival fluctuation (radian <sup>2</sup> )
$\lambda$	Wavelength (m)
$h_0$	Height above ground of transceiver (m)
$H$	Altitude of the satellite (m)
$\zeta$	Zenith angle (degree)
$W_0$	Beam radius at transmitter (m)
$W$	Beam radius at receiver (m)
$(\Theta_0, \Lambda_0)$	Transmitter beam parameters
$(\Theta, \Lambda)$	Receiver beam parameters
$L$	Link length (m)
$r_0$	Fried parameter (m)
$\alpha_{pe}$	Beam wander induced pointing error (m)
$\xi$	Normalized distance variable

$\sigma_{pe}^2$	Pointing error variance ( $\text{m}^2$ )
$M$	Order of modulation
$S(f)$	Power spectral density ( $\text{WHz}^{-1}$ )
$S_c(f)$	Continuous part of $S(f)$ ( $\text{WHz}^{-1}$ )
$S_d(f)$	Discrete part of $S(f)$ ( $\text{WHz}^{-1}$ )
$P(f)$	Fourier transform of pulse shape
$T_p$	Pulse duration (s)
$R(k)$	Auto-correlation function ( $\text{W}^2$ )
$m_a$	Mean value of the signal (W)
$f$	Frequency (Hz)
$L_A$	Number of non-zero amplitude levels in the symbol
$L_P$	Maximum number of slots in the symbol
$A_m$	Amplitude of one level (W)
$L_{avg}$	Average symbol length
$B$	Bandwidth (Hz)
$R$	Date rate (bps)
$\sigma_N^2$	Noise variance ( $\text{W}^2$ )
$N_b$	PSD of background radiation ( $\text{WHz}^{-1}$ )
$R_L$	Load resistance ( $\Omega$ )
$m$	Number of spatial modes of background noise
$D_s$	Diameter of background radiation source (m)
$D$	Receiver aperture diameter (m)
$T_{sym}$	Symbol duration (s)
$\mathbb{R}$	Responsivity of photodiode ( $\text{AW}^{-1}$ )
$A$	Area of receiver aperture ( $\text{m}^2$ )
$\mu$	Average received SNR
$\tau_c$	channel correlation time (s)
$\rho_c$	Spatial correlation width (m)
$\rho_0$	Spatial coherence radius (m)
$\langle I \rangle$	Average received irradiance ( $\text{Wm}^{-2}$ )
$\Omega_s$	Solid angle subtended by source of background radiation (steradian)

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$\Omega_{FOV}$	Solid angle of receiver's field of view (steradian)
$\Omega_{DL}$	Solid angle of diffraction limited field of view (steradian)
$\theta_{FOV}$	Planar angle of receiver's field of view (radian)
$\sigma_N^2$	Total noise at the receiver ( $W^2$ )
$\sigma_s^2$	Shot noise due to signal ( $W^2$ )
$\sigma_b^2$	Shot noise due to background radiation ( $W^2$ )
$\sigma_{sb}^2$	Signal-background beat noise ( $W^2$ )
$\sigma_{bb}^2$	Background-background beat noise ( $W^2$ )
$\sigma_T^2$	Receiver thermal noise ( $W^2$ )
$R(\lambda)$	Spectral radiance of background noise ( $Wm^{-3}$ )
$C_s$	Shannon capacity (bps)
$C_o$	Capacity with outage (bps)
$\gamma_{min}$	Minimum received SNR below which there is an outage
$P_{out}$	Outage probability