

**PERFORMANCE EVALUATION AND ENHANCEMENT  
TECHNIQUES FOR INTENSITY MODULATED  
EARTH-SATELLITE FREE SPACE OPTICAL LINKS**

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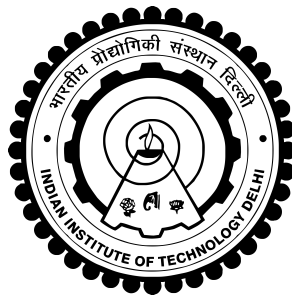
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Submitted

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

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2017

*Dedicated to*  
*my grandparents,*  
*my father Prof. M. Viswanathan,*  
*my mother Ms. K. S. Jayasree,*  
*my brother Vishnu Viswanath and*  
*my aunt Ms. S. Thankamani...*

# Certificate

This is to certify that the thesis titled “**Performance Evaluation and Enhancement Techniques for Intensity Modulated Earth-Satellite Free Space Optical Links**” being submitted by **Ms. Anjitha Viswanath** 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 August 2013 to January 2017. 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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Anjitha Viswanath

# Abstract

Free space optical (FSO) communication system has significant advantages over the other space systems. The use of photonics technology as compared to conventional RF technologies delivers crucial advantages such as higher data rates, narrow beam size, enhanced security, reduced mass, volume and power requirements and freedom from regulations on spectrum range. The major factor which limits FSO communication technology is the atmospheric channel which is often turbulent and may have haze, fog, clouds, rain, etc which degrade the link quality. We study the various techniques to mitigate these effects to have a feasible FSO communication link between an optical ground station (OGS) and a satellite.

This thesis studies the effect of various performance degrading factors such as weather conditions and atmospheric turbulence on intensity modulated/direct detection FSO earth-to-satellite uplink and satellite-to-earth downlink. The link performance is evaluated and compared in terms of bit error rate (BER) for three intensity modulation (IM) schemes viz., on-off keying (OOK),  $M$ -ary pulse position modulation ( $M$ -PPM) and  $M$ -ary differential PPM ( $M$ -DPPM) for both uplink and downlink. We obtain the combined channel state probability density functions and hence the BER expressions using appropriate models such as Kim model and Beer-Lambert's Law to incorporate weather conditions and log-normal and gamma-gamma models for atmospheric turbulence.

Atmospheric effect is more prominent in the uplink than the downlink mainly because of the additional degradation caused by the beam wander effect. It is observed that, for both uplink and downlink, the link performance deteriorates as we move from clear air condition to thin, light and moderate fog conditions and/or with increase in ground level turbulence and zenith angle. The presence of dense or thick fog and/or clouds owing to their large attenuation coefficient value may lead to link failure.  $M$ -PPM scheme with a larger value of the peak to

average power ratio (and hence a higher value of instantaneous power) gives the least BER followed by  $M$ -DPPM and OOK schemes. The performance further improves with increase in the order of the pulse modulation schemes. Also,  $2M$ -DPPM scheme shows almost the same performance level as that of  $M$ -PPM scheme.

Further, we investigate the various performance enhancement techniques such as transmitter spatial diversity for uplink and aperture averaging and receiver spatial diversity for downlink, respectively. The performance improves for all three schemes and the improvement is more at higher values of ground level turbulence and/or larger zenith angles. The level of improvement remains almost constant for different weather conditions.

Finally, using the range equation, we evaluate the minimum transmitter power requirements for both uplink and downlink in presence of different atmospheric conditions. The power requirement is higher for the uplink in comparison to the downlink.  $M$ -PPM scheme with transmitter diversity for uplink and aperture averaging and/or receiver diversity for downlink, respectively minimizes the amount of power that needs to be transmitted to achieve a desired performance level.

## सार

निः शुल्क अंतरिक्ष ऑप्टिकल (एफएसओ) संचार प्रणाली के अन्य अंतरिक्ष प्रणालियों के महत्वपूर्ण लाभ है। पारंपरिक आरएफ प्रौद्योगिकियों की तुलना में फोटोनिक्स प्रौद्योगिकी का उपयोग महत्वपूर्ण डेटा दर, संकीर्ण बीम आकार, बढ़ी हुई सुरक्षा, कम द्रव्यमान, मात्रा और बिजली की आवश्यकताओं और स्पेक्ट्रम सीमा पर नियमों से स्वतंत्रता जैसे महत्वपूर्ण लाभ प्रदान करता है। प्रमुख कारक, जो एफएसओ संचार प्रौद्योगिकी को सीमित करता है वायुमंडलीय चैनल है जो अक्सर अशांत होता है और धुंध, कोहरे, बादल, बारिश आदि हो सकता है, जो लिंक गुणवत्ता को नीचा करती हैं। ऑप्टिकल ग्राउंड स्टेशन (ओजीएस) और उपग्रह के बीच एक व्यावहारिक एफएसओ संचार लिंक के लिए इन प्रभावों को कम करने के लिए हम विभिन्न तकनीकों का अध्ययन करते हैं।

यह थीसिस विभिन्न प्रदर्शन अपमानजनक कारकों जैसे मौसम की स्थिति और तीव्रता पर वायुमंडलीय अशांति / प्रत्यक्ष पहचान एफएसओ पृथ्वी से उपग्रह अपलिंक और उपग्रह-टू-पृथ्वी डाउनलिंक लिंक के प्रभाव का अध्ययन करती हैं। प्रदर्शन का मूल्यांकन तीन तीव्रता मॉडलन (आईएम) योजनाओं के लिए बिट ऑफ रेट दर (बीईआर) की तुलना में तुलना की जाती है, ऑन-ऑफ कीइंग (ओओक), एम-आर्री पल्स स्थिति मॉड्यूलेशन (एम-पीपीएम) और एम-आर्री अपलिंक और डाउनलिंक दोनों के लिए अंतर पीपीएम (एम-डीपीपीएम) हम संयुक्त चैनल राज्य संभावना घनत्व कार्य को प्राप्त करते हैं और इसलिए बीएआर अभिव्यक्ति किम मॉडल और बीयर-लमबर्ट के कानून जैसे उचित मॉडल का प्रयोग करके मौसम की स्थिति को शामिल करते हैं और लॉग-सामान्य और गामा-गामा वायुमंडलीय अशांति के लिए मॉडल करते हैं।

डाउनलिंक की तुलना में वायुमंडलीय प्रभाव अपलिंक में अधिक प्रमुख है क्योंकि बीम घूमने वाला प्रभाव के कारण अतिरिक्त गिरावट का यह देखा जाता है कि, दोनों अपलिंक और डाउनलिंक के लिए, लिंक प्रदर्शन खराब हो जाता है क्योंकि हम स्पष्ट हवा की स्थिति से पतले, हल्के और मध्यम कोहरे की स्थिति में और / या जमीनी स्तर के अशांति और चरम कोण में वृद्धि के साथ। उनके बड़े क्षीणन गुणांक मूल्य के कारण घने या मोटी कोहरे और / या बादलों की उपस्थिति से असफलता से लिंक हो सकता है। औसत बिजली अनुपात (और इसलिए तात्कालिक शक्ति का एक उच्च मूल्य) के लिए पीक के बड़े मूल्य के साथ एम-पीपीएम योजना कम से कम बीईआर देता है, इसके बाद एम-डीपीपीएम और ओ ओ क योजनाएं पल्स मॉडुलन स्कीम के क्रम में वृद्धि के साथ प्रदर्शन में सुधार आता है। इसके अलावा, 2 एम-डीपीपीएम योजना एम-पीपीएम योजना के समान लगभग एक समान प्रदर्शन स्तर दिखाती है।

इसके अलावा, हम विभिन्न प्रदर्शन बढ़ाने तकनीकों की जांच करते हैं जैसे कि डाउनलिंक के लिए अपलिंक और एपर्चर औसत और रिसीवर स्थानिक विविधता के लिए ट्रांसमीटर स्थानिक विविधता, क्रमशः।

सभी तीन योजनाओं के लिए प्रदर्शन में सुधार होता है और ग्राउंड लेवल टर्बुलेन्स और / या बड़े चरम कोणों के बेहतर मूल्यों में सुधार अधिक होता है। विभिन्न मौसम स्थितियों के लिए सुधार का स्तर लगभग स्थिर रहता है।

अंत में, श्रेणी समीकरण का उपयोग करते हुए, हम न्यूनतम ट्रांसमीटर शक्ति का मूल्यांकन करते हैं विभिन्न वायुमंडलीय स्थितियों की उपस्थिति में अपलिंक और डाउनलिंक दोनों के लिए आवश्यकताओं डाउनलिंक की तुलना में अपलिंक के लिए बिजली की आवश्यकता अधिक है डाउनलिंक के लिए अपलिंक और एपर्चर एवरेजिंग और / या रिसेवर विविधता के लिए ट्रांसमीटर विविधता के साथ एम-पीपीएम योजना, क्रमशः बिजली की मात्रा को कम करता है, जिसे वांछित प्रदर्शन स्तर हासिल करने के लिए संचारित करने की आवश्यकता होती है।

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# Abbreviations

<b>AF</b>	<b>A</b> mplify and <b>F</b> orward
<b>AO</b>	<b>A</b> daptive <b>O</b> ptics
<b>APD</b>	<b>A</b> valanche <b>P</b> hoto <b>D</b> iode
<b>AWGN</b>	<b>A</b> dditive <b>W</b> hite <b>G</b> aussian <b>N</b> oise
<b>BER</b>	<b>B</b> it <b>E</b> rror <b>R</b> ate
<b>CF</b>	<b>C</b> ompress and <b>F</b> orward
<b>DAPPM</b>	<b>D</b> ifferential <b>A</b> mplitude <b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>DD</b>	<b>D</b> irect <b>D</b> etection
<b>DF</b>	<b>D</b> ecode and <b>F</b> orward
<b>DEF</b>	<b>D</b> etect and <b>F</b> orward
<b>DFB</b>	<b>D</b> istributed <b>F</b> eedback <b>L</b> aser
<b>DPIM</b>	<b>D</b> ifferential <b>P</b> ulse <b>I</b> nterval <b>M</b> odulation
<b>DPPM</b>	<b>D</b> ifferential <b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>EDFA</b>	<b>E</b> rbium <b>D</b> oped <b>F</b> iber <b>A</b> mplifier
<b>EGC</b>	<b>E</b> qual <b>G</b> ain <b>C</b> ombining
<b>ESA</b>	<b>E</b> uropean <b>S</b> pace <b>A</b> gency
<b>FEC</b>	<b>F</b> orward <b>E</b> rror <b>C</b> orrection
<b>FM</b>	<b>F</b> requency <b>M</b> odulation
<b>FPGA</b>	<b>F</b> ield <b>P</b> rogrammable <b>G</b> ate <b>A</b> rray
<b>FSO</b>	<b>F</b> ree <b>S</b> pace <b>O</b> ptics
<b>GEO</b>	<b>G</b> eostationary <b>E</b> arth <b>O</b> rbit
<b>HS</b>	<b>H</b> ufnagel and <b>S</b> tanley
<b>HVB</b>	<b>H</b> ufnagel <b>V</b> alley <b>B</b> oundary
<b>IM</b>	<b>I</b> ntensity <b>M</b> odulation

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<b>IR</b>	<b>I</b> nfra <b>R</b> ed
<b>ISR</b>	<b>I</b> ntelligence <b>S</b> urveillanc <b>e</b> and <b>R</b> econn <b>a</b> issanc <b>e</b>
<b>LAN</b>	<b>L</b> ocal <b>A</b> rea <b>N</b> etwork
<b>LD</b>	<b>L</b> aser <b>D</b> iode
<b>LEO</b>	<b>L</b> ow <b>E</b> arth <b>O</b> rb <b>i</b> t
<b>LoS</b>	<b>L</b> ine of <b>S</b> ight
<b>MAN</b>	<b>M</b> etropolitan <b>A</b> rea <b>N</b> etwork
<b>MIMO</b>	<b>M</b> ultiple <b>I</b> nput <b>M</b> ultiple <b>O</b> utput
<b>MISO</b>	<b>M</b> ultiple <b>I</b> nput <b>S</b> ingle <b>O</b> utput
<b>MRC</b>	<b>M</b> aximal <b>R</b> atio <b>C</b> ombining
<b>ND</b>	<b>N</b> eutral <b>D</b> ensity
<b>NRZ</b>	<b>N</b> on <b>R</b> eturn to <b>Z</b> ero
<b>OFDM</b>	<b>O</b> ptical <b>F</b> requency <b>D</b> ivision <b>M</b> ultiplexing
<b>OGS</b>	<b>O</b> ptical <b>G</b> round <b>S</b> tation
<b>OOK</b>	<b>O</b> n- <b>O</b> ff <b>K</b> e <b>y</b> ing
<b>OTG</b>	<b>O</b> ptical <b>T</b> urbulenc <b>e</b> <b>G</b> enerat <b>o</b> r
<b>PAM</b>	<b>P</b> ulse <b>A</b> mplitud <b>e</b> <b>M</b> odulation
<b>PAPM</b>	<b>P</b> ulse <b>A</b> mplitud <b>e</b> and <b>P</b> osition <b>M</b> odulation
<b>PAPR</b>	<b>P</b> eak to <b>A</b> verage <b>P</b> ower <b>R</b> atio
<b>pdf</b>	<b>p</b> robabilit <b>y</b> <b>d</b> ensit <b>y</b> <b>f</b> unct <b>i</b> on
<b>PDM</b>	<b>P</b> ulse <b>D</b> urati <b>o</b> n <b>M</b> odulation
<b>PFM</b>	<b>P</b> ulse <b>F</b> requenc <b>y</b> <b>M</b> odulation
<b>PIN</b>	<b>P</b> ositiv <b>e</b> <b>I</b> ntrinsic <b>N</b> egativ <b>e</b> (photodiode)
<b>PM</b>	<b>P</b> ulse <b>M</b> odulation
<b>PPM</b>	<b>P</b> ulse <b>P</b> osition <b>M</b> odulation
<b>PRBS</b>	<b>P</b> seudo <b>R</b> andom <b>B</b> it <b>S</b> equenc <b>e</b>
<b>PRF</b>	<b>P</b> ulse <b>R</b> epeati <b>o</b> n <b>F</b> requenc <b>y</b>
<b>PSD</b>	<b>P</b> ower <b>S</b> pectral <b>D</b> ensit <b>y</b>
<b>PSK</b>	<b>P</b> hase <b>S</b> hift <b>K</b> e <b>y</b> ing
<b>PWM</b>	<b>P</b> ulse <b>W</b> idth <b>M</b> odulation
<b>RF</b>	<b>R</b> adio <b>F</b> requenc <b>y</b>

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<b>rms</b>	<b>root mean square</b>
<b>RZ</b>	<b>Return to Zero</b>
<b>SC</b>	<b>Selection Combining</b>
<b>SIM</b>	<b>Subcarrier Intensity Modulation</b>
<b>SIMO</b>	<b>Single Input Multiple Output</b>
<b>SISO</b>	<b>Single Input Single Output</b>
<b>SLC</b>	<b>Submarine Laser Communication</b>
<b>SNR</b>	<b>Signal to Noise Ratio</b>
<b>TPPM</b>	<b>Truncated Pulse Position Modulation</b>
<b>UAV</b>	<b>Unmanned Aerial Vehicles</b>
<b>UV</b>	<b>Ultra Violet</b>
<b>VCSEL</b>	<b>Vertical Cavity Surface Emitting Laser</b>
<b>VHDL</b>	<b>Very high speed integrated circuit Hardware Description Language</b>
<b>WOC</b>	<b>Wireless Optical Communication</b>

# 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

$u$	Optical field
$\vec{R}$	Spatial vector
$t$	Time
$\lambda$	Wavelength
$k$	Wave number
$U_0$	Complex amplitude of monochromatic wave
$\sigma_0$	Noise variance for bit '0'
$\sigma_1$	Noise variance for bit '1'
$i_0$	Photocurrent for bit '0'
$i_1$	Photocurrent for bit '1'
$h$	Channel state
$C$	Channel capacity
$B$	Channel bandwidth
$R_b$	Bit rate
$E_b$	Bit energy
$N_0$	One sided power spectral density of noise
$A$	Aperture averaging factor
$\sigma_I^2$	Scintillation index
$P_{outage}$	Outage probability
$I$	Received beam irradiance
$T$	Number of transmitters
$R$	Number of receivers
$T_p$	Propagation duration

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$\Gamma$	Coding efficiency
$P_R$	Average received optical power
$P_T$	Average transmitted optical power
$P_1$	Peak power corresponding to bit '1'
$d_{min}$	Minimum distance between any two symbols
$h_l$	Atmospheric channel loss
$h_a$	Turbulence induced channel fading
$\sigma$	Atmospheric attenuation coefficient
$\alpha_m$	Molecular absorption coefficient
$\alpha_a$	Aerosol absorption coefficient
$\beta_m$	Molecular scattering coefficient
$\beta_a$	Aerosol scattering coefficient
$G$	Gain of optical transmit or receive antenna
$D$	Aperture diameter of transmitter or receiver
$sp$	Size parameter
$r_p$	Scattering efficiency factor
$n_r$	Real part of complex refractive index
$n(r_p)$	Volume concentration
$V$	Visibility
$N$	Cloud number concentration
$LWC$	Liquid water content
$\delta$	Particle size related coefficient
$l_0$	Inner scale of turbulence
$L_0$	Outer scale of turbulence
$C_n^2$	Refractive index structure parameter
$C_v^2$	Velocity structure parameter
$C_T^2$	Temperature structure parameter
$T_m$	Temperature
$P$	Atmospheric pressure
$Re$	Reynolds Number
$Q$	Personick $Q$ factor

$I_0$	Average value of received irradiance
$\alpha_k$	Effective number of scatterers
$\alpha$	Effective number of large scale eddies
$\beta$	Effective number of small scale eddies
$\theta$	Divergence angle
$L_{pe}$	Loss factor due to pointing error
$\alpha_{pe}$	Beam wander induced pointing error angle
$L_{fs}$	Free space path loss
$L$	Link length
$M$	Order of pulse modulation schemes
$T_b$	Bit duration
$T_{symbol}$	Symbol duration
$T_{slot}$	Slot duration
$\sigma_s^2$	Shot noise due to signal
$\sigma_b^2$	Shot noise due to background radiation
$\sigma_{sb}^2$	Signal-background beat noise
$\sigma_{bb}^2$	Background-background beat noise
$\sigma_T^2$	Receiver thermal noise
$R(\lambda)$	Spectral radiance of background noise
$h_0$	Height of transceiver above ground level
$w$	Wind speed
$f_I(I)$	Channel pdf in terms of received irradiance
$f_h(h)$	Channel pdf in terms of channel state
$\sigma_R^2$	Rytov variance
$H$	Altitude of the satellite
$\zeta$	Zenith angle
$W_0$	Beam radius at transmitter
$W$	Beam radius at receiver
$r_0$	Fried parameter
$(\Theta_0, \Lambda_0)$	Transmitter beam parameters
$(\Theta, \Lambda)$	Receiver beam parameters

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$M_A$	Number of non-zero amplitude levels in the symbol
$M_P$	Maximum number of slots in the symbol
$N_b$	PSD of background radiation
$R_L$	Load resistance
$m$	Number of spatial modes of background noise
$\eta$	Photodetector quantum efficiency
$b$	Optical filter bandwidth
$\Omega_s$	Solid angle subtended by source of background radiation
$\Omega_{FOV}$	Solid angle of receiver's field of view
$\Omega_{DL}$	Solid angle of diffraction limited field of view
$\rho_g$	Spatial coherence radius at ground level
$\rho_s$	Spatial coherence radius at satellite
$\theta_{FoV}$	Planar angle of receiver's FoV
$\nu$	Frequency