PERFORMANCE ANALYSIS AND ENHANCEMENT OF FREE SPACE OPTICAL SATELLITE LINKS

POOJA GOPAL

INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2016

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by

POOJA GOPAL

Bharti School of Telecommunication Technology and Management

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.

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

Dr. Subrat Kar
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi - 110 016
India

Acknowledgements

I would like to express my most sincere regards to my research supervisors, Prof. V. K. Jain and Prof. Subrat Kar for their guidance and inspiration. They have been very tolerant and empathetic in giving me the freedom to manage both my research work and personal life with ease. Also, their valuable and timely suggestions helped take the research in the right direction. My work with them has been an abundantly enriching experience which will never be forgotten.

I would like to show my gratitude for the valuable criticisms provided by my student research committee members - Prof. Devi Chadha, Prof. M. R. Shenoy and Dr. Manav Bhatnagar. I would like to thank the Bharti School of Telecom Technology and Management, IIT Delhi for providing all requisite resources and the academic environment suitable for carrying out this research work peacefully. I would also like to thank all my friends in IIT who have made my stay in Delhi very memorable.

I will always be indebted to my parents, Gopala and Usharani, parents-in-law, Anand and Padmavathi, my sister, Punya and brother, Prathik and all members of my family for their blessings and constant moral support. I cannot thank enough my husband, Pradeep for his benevolence and abundant patience. I would like to add special thanks to my niece Sanvi and my nephews Yajwin, Samanyu, Talin and Pradyun for their love and for giving me immense joy every time I think of them.

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 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

FSO	**F**ree **S**pace **O**ptics
RF	**R**adio **F**requency
LAN	**L**ocal **A**rea **N**etwork
SNR	**S**ignal to **N**oise **R**atio
BER	**B**it **E**rror **R**ate
AWGN	**A**dditive **W**hite **G**aussian **N**oise
CSI	**C**hannel **S**tate **I**nformation
pdf	**p**robability **d**ensity **f**unction
DF	**D**ecode and **F**orward
AF	**A**mplify and **F**orward
EGC	**E**qual **G**ain **C**ombining
MRC	**M**aximum **R**atio **C**ombining
SC	**S**election **C**ombining
FEC	**F**orward **E**rror **C**orrection
SISO	**S**ingle **I**nput **S**ingle **O**utput
SIMO	**S**ingle **I**nput **M**ultiple **O**utput
MISO	**M**ultiple **I**nput **S**ingle **O**utput
MIMO	**M**ultiple **I**nput **M**ultiple **O**utput
ESA	**E**uropean **S**pace **A**gency
NASA	**N**ational **A**eronautics and **S**pace **A**dministration
RI	**R**efractive **I**ndex
HVB	**H**ufnagel **V**alley **B**oundary
HS	**H**ufnagel and **S**tanley
SLC	**S**ubmarine **L**aser **C**ommunication

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

Physical Constants

Speed of Light	c	$=$	$2.997\,924\,58 \times 10^{8}\ \mathrm{ms^{-1}}$
Boltzmann Constant	k_B	$=$	$1.380\,648\,81 \times 10^{-23}\ \mathrm{m^{2}kg\ s^{-2}K^{-1}}$
Planck Constant	h	$=$	$6.626\,069\,57 \times 10^{-34}\ \mathrm{m^{2}kg\ s^{-1}}$
Radius of the Earth	R_E	$=$	$6.371 \times 10^{6}\ \mathrm{m}$

Symbols

l_0	Inner scale of turbulence (m)
L_0	Outer scale of turbulence (m)
C_n^2	Refractive index structure parameter ($\mathrm{m}^{-2/3}$)
C_T^2	Temperature structure parameter
T	Temperature (K)
$\mathbb{P}$	Pressure (Nm^{-2})
h	Height above ground level (m)
w	High altitude rms wind speed (ms^{-1})
V_g	Wind speed near the ground (ms^{-1})
σ_I^2	Scintillation index
I	Received irradiance (Wm^{-2})
P	Received power (W)
$\langle P \rangle$	Average received power (W)
$\langle I \rangle$	Average received intensity (Wm^{-2})
$\langle I_\mathrm{o} \rangle$	Average received intensity at the optical axis (Wm^{-2})
γ	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
σ_X^2	Large scale scintillation

σ_Y^2	Small scale scintillation
α	Positive parameter related to σ_X^2
β	Positive parameter related to σ_Y^2
σ_R^2	Rytov variance
θ	Beam divergence angle (radian)
$\mathbb{A}$	Aperture averaging factor
k	Wave number (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^2)
λ	Wavelength (m)
h_0	Height above ground of transceiver (m)
H	Altitude of the satellite (m)
ζ	Zenith angle (degree)
W_0	Beam radius at transmitter (m)
W	Beam radius at receiver (m)
(Θ_0, Λ_0)	Transmitter beam parameters
(Θ, Λ)	Receiver beam parameters
L	Link length (m)
r_0	Fried parameter (m)
α_{pe}	Beam wander induced pointing error (m)
ξ	Normalized distance variable

σ_{pe}^2	Pointing error variance (m^2)
M	Order of modulation
$S(f)$	Power spectral density (WHz^{-1})
$S_c(f)$	Continuous part of $S(f)$ (WHz^{-1})
$S_d(f)$	Discrete part of $S(f)$ (WHz^{-1})
$P(f)$	Fourier transform of pulse shape
T_p	Pulse duration (s)
$R(k)$	Auto-correlation function (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)
σ_N^2	Noise variance (W^2)
N_b	PSD of background radiation (WHz^{-1})
R_L	Load resistance (Ω)
$\mathfrak{m}$	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 (AW^{-1})
A	Area of receiver aperture (m^2)
μ	Average received SNR
τ_c	channel correlation time (s)
ρ_c	Spatial correlation width (m)
ρ_0	Spatial coherence radius (m)
$\langle I \rangle$	Average received irradiance (Wm^{-2})
Ω_s	Solid angle subtended by source of background radiation (steradian)

Ω_{FOV}	Solid angle of receiver's field of view (steradian)
Ω_{DL}	Solid angle of diffraction limited field of view (steradian)
θ_{FOV}	Planar angle of receiver's field of view (radian)
σ_N^2	Total noise at the receiver (W^2)
σ_s^2	Shot noise due to signal (W^2)
σ_b^2	Shot noise due to background radiation (W^2)
σ_{sb}^2	Signal-background beat noise (W^2)
σ_{bb}^2	Background-background beat noise (W^2)
σ_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)
γ_{min}	Minimum received SNR below which there is an outage
p_{out}	Outage probability