Optical Networks

Series editor
Biswanath Mukherjee, Davis, California, USA

More information about this series at http://www.springer.com/series/6976

Hemani Kaushal • V.K. Jain • Subrat Kar

Free Space Optical Communication

Springer

Hemani Kaushal
Electronics and Communication
The NorthCap University
Gurgaon, Haryana, India

V.K. Jain
Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India

Subrat Kar
Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, India

ISSN 1935-3839 ISSN 1935-3847 (electronic)
Optical Networks
ISBN 978-81-322-3689-4 ISBN 978-81-322-3691-7 (eBook)
DOI 10.1007/978-81-322-3691-7

Library of Congress Control Number: 2016963412

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer (India) Pvt. Ltd.
The registered company address is: 7th Floor, Vijaya Building, 17 Barakhamba Road, New Delhi 110 001, India

Thanks to our families for their affection and endless support!!

Preface

In recent years, the technology of optical communication has gained importance due to high bandwidth and data rate requirements. This book focuses on free-space optical (FSO) communication that is capable of providing cable-free communication at very high data rates (up to Gbps). Unlike radio frequency communication that has restricted bandwidth due to its limited spectrum availability and interference, FSO communication has license-free spectrum as of now. This technology finds its application in terrestrial links, deep space/inter-satellite links, unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), and uplink and downlink between space platform, aircrafts, and other ground- based fixed/mobile terminals. It provides good privacy with flexible interconnection through a distributed or centralized communication system. It is a growing area of research these days due to its low power and mass requirement, bandwidth scalability, unregulated spectrum, rapid speed of deployment/redeployment, and cost-effectiveness. However, despite many advantages, the performance of FSO communication system is influenced by unpredictable atmospheric conditions, and this undoubtedly poses a great challenge to FSO system designers. The primary factors that deteriorate the FSO link performance are absorption, scattering, and turbulence. Out of these, the atmospheric turbulence is a major challenge that may lead to serious degradation in the link performance and make the communication link infeasible. This book gives the basic understanding of FSO communication system and lays emphasis on improving the performance of FSO link in turbulent atmosphere.

The purpose of this book is to cover the basic concepts of FSO communication system and provide the readers with sufficient in-depth knowledge to design a wireless optical link. The intended readers for this book include engineers, designers, or researches who are interested in understanding the phenomena of laser beam propagation through the atmosphere. This book primarily focuses on outdoor wireless communication, though a little briefing on indoor wireless communication is given in the introductory chapter. Although this book is based on the doctoral work of the first author, it has been completely rewritten and expanded to cover basic concepts of FSO communication system from readers' point of view.

This book has been organized into seven chapters. Chapter 1 provides an overview of FSO technology with historical background and its various applications. Chapter 2 gives a comprehensive coverage of FSO channel models and various atmospheric losses encountered during beam propagation through the atmosphere including free-space loss, pointing loss, absorption, and scattering loss. This is followed by the description of atmospheric turbulence and its effects on the laser communication, i.e., beam wander, beam spreading, beam scintillation, spatial coherence degradation, and image dancing. Various models for the atmospheric turbulent channel are presented. Chapter 3 discusses various components of FSO communication system. It provides description of optical transmitter, amplifiers, and receiver. The design of optical receiver that takes into account different types of detectors, noise sources, and receiver performance in terms of signal-to-noise ratio is presented. Finally, various issues involved in the link design like choice of operating wavelength, aperture diameter, and receiver bandwidth are discussed. Chapter 4 deals with the most challenging aspect of FSO communication system, i.e., acquisition, tracking, and pointing. The initial linkup or acquisition time puts a limit on the overall performance of the system, and hence, it is an essential system design constraint. Various subsystems involved in the accurate pointing of narrow laser beam toward the target are presented in this chapter. Chapter 5 presents bit error rate (BER) performance of FSO link for coherent and noncoherent modulation schemes. Chapter 6 discusses various techniques for improving link performance, i.e., aperture averaging, spatial diversity, coding, adaptive optics, relay-assisted FSO, etc. Finally, the last chapter describes in detail how the optical system designers can calculate link budgets.

Gurgaon, India — Hemani Kaushal
New Delhi, India — V.K. Jain
New Delhi, India — Subrat Kar

Contents

List of Figures

List of Tables

List of Symbols

θ_s	Planar emission angle
α_a	Aerosol absorption coefficient
α_m	Molecular absorption coefficient
α_r	Angular pointing error
α_T	Transmitter truncation ratio
β	Modulation index
β_a	Aerosol scattering coefficient
$\beta_{fog}(\lambda)$	Specific attenuation of fog
β_m	Molecular scattering coefficient
$\Delta\lambda_{filter}$	Bandwidth of optical band pass filter
ϵ_T	Root sum square of two-axis pointing bias error
η	Quantum efficiency of the detector
η_λ	Narrow-band filter transmission factor
η_R	Receiver optics efficiency
η_{TP}	Transmitter pointing loss factor
η_T	Transmitter optics efficiency
γ	Atmospheric attenuation coefficient
Γ_2	Mutual coherence function of second order
Γ_{code}	Coding gain
γ_i	Instantaneous SNR
γ_R	Receiver obscuration ratio
γ_s	Scattering angle
γ_T	Transmitter obscuration ratio
κ	Scalar spatial frequency
Λ	Receiver beam parameter (amplitude change due to diffraction)
λ	Operating wavelength
λ_0	Transmitter beam parameter (amplitude change due to diffraction)
λ_B	Rate of arrival of background photons
λ_s	Rate of arrival of signal photons
$\langle r_c^2 \rangle$	Beam wander displacement variance
$\mathbb{L}$	Constraint length of code

$\mathbb{P}$	Peak-to-average power ratio of the signal
$\mathbf{R}$	Rainfall rate
$\mathbf{V}$	Characteristic velocity
$\mathcal{F}$	Fresnel length
$\mathcal{M}$	Avalanche multiplication factor
$\mathtt{r}$	Radius of atmospheric particles
$\mathtt{h}$	Planck's constant
ν	Operating frequency
ν_k	Kinematic viscosity
Ω_b	Beam solid angle
Ω_{FOV}	Solid angle receiver field of view
ω_{IF}	Intermediate frequency
ω_L	Frequency of local oscillator
Ω_S	Stellar or point source field of view
Ω_s	Emission angle
ω_s	Frequency of incoming signal
ϕ	Phase of transmitted signal
Φ_n	Power spectral density of refractive index fluctuations
Ψ	Complex phase fluctuations
ρ	Correlation among beams
σ_b^2	Background noise current variance
σ_d^2	Detector dark current noise variance
σ_I^2	Scintillation index
σ_l^2	Variance of log-irradiance
σ_{pe}	Effective pointing error displacement
σ_R^2	Rytov variance
σ_s^2	Signal shot noise variance
σ_{Th}^2	Thermal noise variance
σ_{tilt}	RMS turbulence-induced wavefront tip/tilt
σ_T	Root sum square of two-axis jitter
σ_x^2	Variance of large-scale irradiance fluctuations
σ_y^2	Variance of small-scale irradiance fluctuations
$\sigma_{\ln x}^2$	Variance of large-scale log-irradiance
$\sigma_{\ln y}^2$	Variance of small-scale log-irradiance
τ	Optical depth
Θ	Receiver beam parameter (amplitude change due to refraction)
θ	Zenith angle
Θ_0	Transmitter beam parameter (amplitude change due to refraction)
θ_0	Isoplanatic angle
θ_{div}	Beam divergence
θ_{FOV}	Angular field of view of receiver
θ_H	Azimuth pointing error angle
θ_{jitter}	Beam jitter angle
θ_{unc}	Area of uncertainty in solid angle

θ_V	Elevation pointing error angle
$\triangle f_c$	Coherence bandwidth
$\triangle t_c$	Coherence time
ε	Overlap factor
ξ	Normalized distance variable
ξ_t	Safety margin against high-frequency fluctuations
A	Photodiode area
A_0	Amplitude of Gaussian beam
A_f	Aperture averaging factor
A_R	Effective area of the receiver
A_s	Surface area
B	Signal bandwidth
B_d	Doppler spread
B_o	Optical filter bandwidth
C	Channel capacity
c	Velocity of light
C_n^2	Refractive index structure constant
C_t^2	Temperature structure constant
C_v	Velocity structure constant
D	OFDM bias component
D_R	Receiver aperture diameter
D_t	Structure function for temperature
D_n	Structure function for refractive index
D_v	Structure function for wind velocity
E_{LO}	Local oscillator signal voltage
E_R	Received signal voltage
e_L	Electric field of local oscillator
e_s	Electric field of incoming signal
F	Excess noise factor
f	Signal frequency
F'	Phase front radius of curvature of the beam at the receiver plane
F_0	Phase front radius of curvature of the beam at the transmitter plane
F_n	Noise figure
G_R	Receiver gain
G_T	Transmitter gain
H	Altitude of the satellite
h	Plank's constant
h_0	Altitude of the transmitter
H_B	Background radiance of extended sources
I	Irradiance/intensity
I_0	Irradiance without turbulence
I_λ	Exo-atmospheric solar constant
I_{BG}	Background noise current
I_{db}	Bulk dark current
I_{ds}	Surface dark current

I_d	Dark current
I_p	Photodetector current
k	Wave number
K_B	Boltzmann's constant
K_b	Average number of noise photons
k_b	Number of information or data bits
k_{eff}	Ionization ratio
K_s	Average number of signal photons
L_0	Turbulent eddy outer scale size
l_0	Turbulent eddy inner scale size
l_f	Dimension of turbulent flow
L_G	Beam divergence loss
L_p	Pointing loss
L_R	Transmission loss of receiver optics
L_s	Space loss factor
m	Number of memory registers
N	Number of receivers
n	Index of refraction
n_0	Mean value of index of refraction
N_B	Irradiance energy densities of point sources
n_c	Length of code
N_r	Number of total receiver scan area repeats
n_{sp}	Spontaneous emission factor
N_t	Number of total transmitter scan area repeats
P'	Atmospheric pressure
P_{acq}	Probability of acquisition
P_B	Background noise power
P_{ce}	Probability of chip error
$P_{detection}$	Probability of detection
P_{ew}	Probability of word error
P_e	Probability of error
P_L	Power of local oscillator
P_R	Received power
P_{sp}	Amplifier spontaneous output noise power
P_s	Power of incoming signal
P_T	Transmitted power
q	Electronic charge
R	Link range
r	Spatial separation of two points in space
r_0	Atmospheric coherence length
R_b	Bit rate
R_{dwell}	Receiver dwell time
R_L	Load resistance
Re	Reynolds number
S_n	Noise power spectral density

T	Absolute temperature in Kelvin
T'	Atmospheric temperature
T_θ	Transmittance factor
T_a	Atmospheric transmittance
T_b	Bit duration
T_{dwell}	Transmitter dwell time
T_m	Multipath spread
T_{SS}	Single scan acquisition time
T_{ss}	Beam spread due to atmospheric turbulence
T_s	Slot width
U	Electric field
W	Effective beam radius at the receiver
W_0	Transmitter beam size
w_c	Number of 1s in each column in sparse matrix
W_e	Effective spot size in turbulence
W_{LT}	Long-term spot size
w_r	Number of 1s in each row in sparse matrix
p	Size distribution coefficient of scattering
V	Visibility range

List of Abbreviations

AF	Amplify-and-Forward
AM	Amplitude Modulation
AO	Adaptive Optics
APD	Avalanche Photodetector
ASE	Amplified Spontaneous Emission
ATP	Acquisition, Tracking, and Pointing
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSTS	Boost Surveillance and Tracking System
CALIPSO	Cloud-Aerosol Lidar and IR Pathfinder Satellite Observation
CCD	Charge-Coupled Devices
CDF	Cumulative Distribution Function
CF	Compress-and-Forward
DAPIM	Differential Amplitude Pulse Interval Modulation
DAPPM	Differential Amplitude Pulse Position Modulation
DEF	Detect-and-Forward
DHPIM	Dual Header Pulse Interval Modulation
DOLCE	Deep Space Optical Link Communications Experiment
DPIM	Differential Pulse Interval Modulation
DPPM	Differential Pulse Position Modulation
EGC	Equal-Gain Combining
ESA	European Space Agency
ETS	Engineering Test Satellite
FDM	Frequency Division Multiplexing
FIR	Far-Infrared
FM	Frequency Modulation
FOU	Field of Uncertainty
FOV	Field of View
FPA	Focal Pixel Array
FSO	Free-Space Optical

FSOI	FSO Interconnect
GOLD	Ground/Orbiter Lasercomm Demonstration
GOPEX	Galileo Optical Experiment
HAP	High-Altitude Platform
IF	Intermediate Frequency
IM/DD	Intensity Modulated/Direct Detection
IR	Infrared
ISRO	Indian Space Research Organisation
JPL	Jet Propulsion Laboratory
KIODO	KIrari's Optical Downlink to Oberpfaffenhofen
LCS	Laser Cross-Link Subsystem
LD	Laser Diode
LDPC	Low-Density Parity Check
LED	Light-Emitting Diode
LIR	Long-Infrared
LO	Local Oscillator
LOLA	Airborne Laser Optical Link
LOS	Line-of-Sight
LPF	Low-Pass Filter
MEMS	Microelectromechanical System
MIR	Mid-infrared
MISO	Multiple Input Single Output
MLCD	Mars Laser Communication Demonstration
MLSD	Maximum Likelihood Sequence Detection
MOLA	Mars Orbiter Laser Altimeter
MRC	Maximum-Ratio Combining
NASA	National Aeronautics and Space Administration
NBF	Narrow-Band Filter
NEA	Noise Equivalent Angle
NIR	Near-Infrared
NRZ	Non-return to Zero
NSDA	National Space Development Agency
OICETS	Optical Inter-orbit Communications Engineering Test Satellite
OOK	On-Off Keying
OTG	Optical Turbulence Generator
PAA	Point Ahead Angle
PAM	Pulse Amplitude Modulation
PAPM	Pulse Amplitude and Pulse Position Modulation
PAPR	Peak-to-Average Power Ratio
PCB	Printed Circuit Board
PDF	Probability Density Function
PER	Packet Error Rate
PPM	Pulse Position Modulation
QAM	Quadrature Amplitude Modulation
QAPD	Quadrant Avalanche Photodetector

QPIN	Quadrant P-Intrinsic
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
ROSA	RF Optical System Study for Aurora
RSS	Root Sum Square
RZ	Return to Zero
SC	Selection Combining
SFTS	Space Flight Test System
SILEX	Space Intersatellite Link Experiment
SIR	Short-Infrared
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SOLACOS	Solid State Laser Communications in Space
SROIL	Short-Range Optical Intersatellite Link
TES	Tropospheric Emission Spectrometer
TPPM	Truncated PPM
UAV	Unmanned Aerial Vehicle
VLC	Visible Light Communication
VLSI	Very-Large-Scale Integration
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WOC	Wireless Optical Communication
WPAN	Wireless Personal Area Network