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FIBER OPTIC AND ATMOSPHERIC OPTICAL COMMUNICATION

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Preface

This book is intended for scientists, engineers, and designers who would like to learn about optical communications and about the operation and service of optical wireless (atmospheric) and wired (fiber optic) communication links, laser beam systems, and fiber optic multiuser networks. It will be useful to undergraduate and postgraduate students alike and to practicing scientists and engineers.

Over the preceding forty years, many excellent books have been published about different aspects of optical waves and about laser beam propagation in both atmospheric links and within guiding structures, such as fiber optic cables. Wireless and wired communications have often been described separately without taking note of their similarities. In this monograph, we consider both media and describe techniques for transmitting information over such channels when the optical signals are corrupted by the fading that is typical of such communication links because of the existence of artificial (man-made) and/or natural sources of fading.

This monograph methodically unifies the basic concepts and the corresponding mathematical models and approaches to describing optical wave propagation in material media, in waveguide structures and fiber optic structures, and in the troposphere (the lowest layer of the atmosphere). It describes their similarity to other types of electromagnetic waves, e.g. radio waves, from other regions of the electromagnetic spectrum.

Without entering into an overly deep and detailed description of the physical and mathematical fundamentals of the atmosphere as a propagation channel or of the fiber optic structure as a waveguide structure, this monograph focuses the reader's attention on questions related to the coding and decoding that is useful when using such channels. In particular, the monograph analyzes different types of fading and their sources and considers types of modulation that mitigate the effects of fading.

The monograph briefly describes several sources of optical radiation, such as lasers, and presents several particularly relevant optical signal detectors.

The monograph contains material about the atmospheric communication channel, including the effects of atmospheric turbulence and different kinds of hydrometeors, such as aerosols, rain, snow, and clouds, on optical wave propagation in an atmospheric link. The principal goal of this book is to explain the effects of fading and energy loss in information-carrying optical signals. We consider the various situations that occur in the atmospheric link and, finally, show how to mitigate the effects of natural phenomena such as turbulence and hydrometeors that affect the propagation of optical rays and laser beams through the atmosphere.

This book introduces the reader to fading and describes its dispersive nature. It considers fading of optical waves propagating in the irregular turbulent atmosphere in close proximity to the ground surface and elucidates its relation to similar signal dispersive fading phenomena that occur in fiber optic channels where there is a wired link.

The book is organized as follows. Part I consists of two chapters. Chapter 1 describes the fundamental aspects of optical wireless and wired communication links and of the spectrum of optical waves. It also provides a description of the evolution of optical networks (from first to fifth generation networks). End-to-end descriptions of optical channels are provided. Block diagrams of the receiver (the detector of optical waves) and the transmitter (the radiator of optical waves) are given, and information transfer though the channel is described. In Chapter 2, the similarities between radio and optical waves are described. The description makes use of some of the fundamental notions of wave electrodynamics. In particular, the differential and integral presentation of optical waves is developed from Maxwell's equations. Maxwell's equations are also presented in the form of phasors. The principal features of optical wave propagation in material media, both dielectric and conductive, are described. Finally, the reflection and refraction of optical waves from the boundary of two media is described via the introduction of the parameters of refraction (instead of the dielectric and magnetic parameters of the medium), and the effect of total internal reflection, one the main features in any guiding structure (including a fiber optic cable), is considered. There are exercises at the end of Chapter 2.

Part II, which describes the fundamentals of optical communication, consists of six chapters. The first chapter, Chapter 3, describes types of optical signals propagating through wireless or wired communication links. Both continuous and discrete channels are considered, and the relation between them is described. In Chapter 3, we show that for non-correlated optical waves or signals, the average powers of a continuous signal and of a discrete signal (e.g. pulse) are equivalent. The reader is then asked to consider the bandwidth of the signals and to note that one is narrowband and the other wideband. A mathematical/statistical framework is then established for considering these signals in the space, time, and frequency domains. Chapter 4 presents the fundamental principles of discrete signal coding and decoding. The effects of white Gaussian noise on such signals are described briefly and both linear and nonlinear codes are considered. The error probability when decoding such codes is considered for a variety of decoding algorithms for cyclic codes, Reed–Solomon codes, etc. Finally, a general scheme for decoding cyclic codes is developed. In Chapter 5, we apply what we have learned about coding and decoding to optical communication links. Low density parity check codes are considered in detail. Finally, the coding process in optical communication links is described and a comparative analysis of different codes is presented. Chapter 6 considers the effects of fading as it occurs in real optical communication and describes how it is caused by various sources of multiplicative noise. It is shown that by considering signal parameters (pulse duration and bandwidth) and parameters related to channel coherency (in time and frequency), fading phenomena can be described as flat or frequency selective, as slow (in the time domain) or large scale (in the space domain), or as fast (in the time domain) or small scale (in the space domain). Next, mathematical descriptions of fast and slow fading are provided by using the Rayleigh or Rice distribution, gamma-gamma distribution, and the Gaussian distribution. Chapter 7 deals with the modulation of optical signals in wireless and wired communication links. It starts by describing types of analog modulation: analog amplitude modulation and analog phase and frequency modulation, considering them as two types of a general angle modulation of continuous optical signals. The relation between the spectral bandwidths of the two last types of modulation, phase and frequency modulation, is considered, and their signal-to-noise (SNR) ratio is analyzed. Finally, several types of digital signal modulation are presented briefly: amplitude shift keying, phase shift keying, and frequency shift keying. There are several exercises at the end of Chapter 7.

In Chapter 8, optical sources and detectors are described. A brief description of the fundamentals of emission and absorption of optical waves is given. Then the operational characteristics of laser sources and diodes, as well as other types of photodiodes, are briefly described, and several types of modulation schemes that can be used with lasers are demonstrated. Finally, the operational characteristics of photodiodes are presented, and a clear description of the relations between the optical and electrical parameters of typical diode-based schemes is given.

Part III consists of two chapters. In Chapter 9, guiding structures related to fiber optical ones are briefly described. The reader is shown two types of fiber optic structures: step-index fiber and graded-index fiber. Their parameters are determined and described. Next, the propagation of optical waves in fiber optic structures is analyzed, and it is shown that frequency dispersion is an issue when dealing with multimode propagation in such guiding structures. These dispersion properties are examined in Chapter 10, where the corresponding multimode dispersion parameters are presented for the two types of fiber optic cables described in Chapter 9: step-index and graded-index fiber. This modal dispersion is compared with material dispersion caused by the inhomogeneous structure of the material along the length of the fiber. The data loss caused by these two types of dispersion for two kinds of codes – non-return-to-zero (NRZ) codes and return-to-zero (RZ) codes – mentioned in Chapter 1 is described.

Part IV consists of a single chapter. Chapter 11 describes the propagation of optical waves in the atmosphere, considered as an inhomogeneous gaseous structure, and briefly describes the main parameters used to describe the atmosphere. The content of the atmosphere is presented briefly. In particular, in Chapter 11 the structure of aerosols and their dimensions, concentration, spatial distribution of aerosols' sizes, and their spectral extinction and altitude localization are briefly presented. Then, the existence of various water and ice particles, called hydrometeors, in the inhomogeneous atmosphere, their spatial and altitudinal distribution, size distribution, and their effects on optical wave propagation are briefly discussed. Atmospheric turbulent structures caused by temperature and humidity fluctuations combined with turbulent mixing by wind and convection-induced random changes in the air density of the atmosphere (as an irregular gaseous medium) are briefly discussed. Next, the scintillation phenomenon caused by an optical wave passing through the turbulent atmosphere is analyzed. The corresponding formulas for the scintillation index of signal intensity variation are presented as the main parameter of signal fading in the turbulent atmosphere caused by scattering phenomena from turbulent structures. Finally, the corresponding functions used to describe such scattering are described so that the relation between the scintillation index and the fading parameters can be elucidated.

Part V, concerning signal data flow transmission in wireless and fiber optic communication links, consists of one chapter. Chapter 12 starts with definitions related to the characteristics of a communication link: capacity, spectral efficiency, and bit error rate (BER). These important, well-known parameters are presented in a unified manner both for atmospheric and fiber optic channels via the fading parameter, K. Use is made of its relation to the scintillation index that was described in the previous chapter. The relation between the characteristic parameters of the communication link and the fading parameter are described by unified unique formulas and corresponding algorithms. Our understanding of these quantities allows us to perform relevant computations and present clear graphical illustrations for both NRZ and RZ signals.

This book provide a synthesis of several physical and mathematical models in order to present a broad and unified approach for the prediction of data stream parameters for various types of codes used with optical signals traversing optical channels, whether atmospheric or fiber optic, having similar fading time/dispersive effects caused by a variety of sources. In the atmosphere, scattering is due to turbulent structures and hydrometeors; in fiber optic structures, it is due to multimode effects and inhomogeneities in the cladding or core.

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Abbreviations

AFD	average fade duration
AM	amplitude modulation
ASK	amplitude shift keying
AWGN	additive white Gaussian noise
BCH	Bose–Chaudhuri–Hocquenghem (codes)
BER	bit error rate
BM	Berlekamp–Massey (iterative algorithm)
BPSK	binary phase shift keying
BSC	binary symmetric channel
BW	bandwidth
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
C/I	carrier-to-interference ratio
CR	Carson rule
CW	continuous wave
DD	direct detection
EM	electromagnetic (wave, field)
erfc(·)	complementary error function (probability)
F	noise figure
FFF	flat fast fading
FM	frequency modulation
FSF	flat slow fading
FSFF	frequency-selective fast fading
FSK	frequency shift fading
FSSF	frequency-selective slow fading
GIF	gradient-index fiber
HPBW	half power bandwidth
IF	intermediate frequency
Im	imaginary part (of complex number)
IM	intensity modulation
IR	infrared optical spectrum
ISI	inter-symbol interference

LCR	level crossing rate
LD	laser diode
LED	light-emitting diode
LF	likelihood function
LLR	log likelihood ratio
LOS	line-of-sight
LP	linearly polarized (mode)
LPI	low probability of interception
MAD	material dispersion (of fiber optic cable)
MD	multimode dispersion (of fiber optic cable)
MDS	maximum distance separable (codes)
MF	median frequency (band)
NA	numerical aperture of fiber optic guiding structure
NLOS	non-line-of-sight
NRZ	non-return-to-zero (code)
PD	photodiode
PDF	probability density function
PG	processing gain
PGZ	Piterson–Gorenstein–Zincler (algorithm)
PiN	P-type – intrinsic – N-type (detector)
PM	phase modulation
PMD	polarization mode dispersion
PSD	power spectral density
PSK	phase shift keying
QPSK	quadrature phase shift keying
Re	real part (of complex number)
RF	radio frequency (wave or signal)
RS	Reed–Solomon (codes)
RZ	return-to-zero (code)
SIF	step-index fiber
S/N	signal-to-noise ratio
SNR	signal-to-noise ratio
$(\mathrm{SNR})_{\mathrm{in}}$	signal-to-noise ratio at the input of the detector
$(\mathrm{SNR})_{\mathrm{out,\,AM}}$	signal-to-noise ratio at the output of the detector for AM signal
$(\mathrm{SNR})_{\mathrm{out,\,FM}}$	signal-to-noise ratio at the output of the detector for FM signal
TE	transverse electric wave
TIR	total intrinsic energy
TM	transverse magnetic wave
UV	ultraviolet optical spectrum
VS	visible optical spectrum
W	energy of depletion zone
W_g	band-gap energy

Nomenclature

$\mathbf{A}$ – arbitrary vectors of electromagnetic field
$\mathbf{B}$ – vector of induction of magnetic field
$\mathbf{E}$ – vector of electric field component of the electromagnetic wave
$\mathbf{E}(z, t)$ – 2-D vector of electrical component of the electromagnetic wave
$\widetilde{\mathbf{E}}(z)$ – phasor of the electrical component of the electromagnetic wave
$\mathbf{D}$ – vector of electric field displacement or vector induction of electric field
$\mathbf{H}$ – vector of magnetic field component of the electromagnetic wave
$\mathbf{H}(z, t)$ – 2-D vector of magnetic field component of the electromagnetic wave
$\widetilde{\mathbf{H}}(z)$ – phasor of the magnetic field component of the electromagnetic wave
$\mathbf{j}$ – vector of electric current density
$\mathbf{J}$ – vector of the full current in medium/circuit
$\mathbf{j}_c$ – conductivity current density
$\mathbf{j}_d$ – displacement current density
$\mathbf{k}$ – wave vector
$\mathbf{M}$ – momentum of the magnetic ambient source
$\mathbf{P}$ – vector of polarization
A_c – amplitude of carrier signal
A_m – amplitude of modulated signal
B_c – coherence bandwidth
B_D – Doppler spread bandwidth
B_f – maximum bandwidth of the modulating signal
B_F – equivalent RF bandwidth of the bandpass filter
B_ω – detector bandwidth
B_Ω – bandwidth of multiplicative noise
$C_{\mathrm{BSC}} = 1 - \eta(p)$ – capacity of binary symmetric channel
p – probability of 0 or 1
f_c – frequency of carrier signal
f_D – Doppler shift
f_m – frequency of modulated signal
B_S – signal bandwidth

C – channel capacity
$C(D)$ – effective cross-section of rain drops as function of their diameter D
$\mathbf{C}_1$ – square $(k \times k)$-matrix
$\mathbf{C}_2$ – matrix of dimension $(k \times n - k)$
$\mathbf{C} = \mathbf{C}_1^{-1}\mathbf{C}_2$ – product of inverse $\mathbf{C}_1$ matrix and regular $\mathbf{C}_2$ matrix
$\mathbf{C}$ – $(m \times m)$-cyclic permutation matrix
$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ – velocity of light in free space
C_n^2 – refraction structure parameter
$C_{\mathrm{NRZ}} \times l = \frac{0.7}{\Delta(\tau/l)}$ – capacity per length l of fiber for propagation of NRZ pulses
$C_{\mathrm{RZ}} \times l = 0.875$ (Mbit/c) $\times$ km – capacity per length l of fiber for propagation of RZ pulses
$d\mathbf{l}$ – differential of the vector of a line l
$d\mathbf{S}$ – differential of the vector of a surface S
$d\mathbf{V}$ – differential of the vector of a volume V
$D_m = 0.122 \cdot R^{0.21}$ mm – diameter of rain drops, R – rainfall rate (in mm/h)
D_p – polarization mode dispersion factor (in fiber optic cables)
e – charge of electron
E_b – energy of one transmitted bit
E_x, E_y, E_z – components of the electric field of the wave in the Cartesian coordinate system
$d_H(\mathbf{x}, \mathbf{y})$ – Hamming distance
$\mathbf{G}$ – generator matrix
G – photo-conductive gain of the light detector
$g(t)$ – a signal's envelope as a function of time
I – light intensity
$\mathbf{I}_k$ – unit $(k \times k)$-matrix
$h = 6.625 \cdot 10^{-34}$ J $\cdot$ s – Planck's constant
$h\nu_{ji}$ – energy of photon; j and i are steady states of atoms and electrons, $j > i$
H_W – parity matrix,
$H(\tau) = -\tau \ln \tau - (1-\tau)\ln(1-\tau)$ – entropy of the binary ensemble with parameter $\tau = t/n$, $\tau > p$
$i = \sqrt{-1}$ – the unit imaginary number
$J_m(qr)$ – Bessel function of the first kind and of order m
J_{ph} – photocurrent intensity
K – Ricean fading parameter
k_f – frequency deviation constant of frequency modulation
$k_m = (A_m/A_c)$ – modulation index of amplitude modulation
$k = 1.38 \cdot 10^{-23}$ J/K – Boltzmann's constant
$\kappa_0 = \frac{2\pi}{L_0}$ – spatial wave number for outer turbulence scale
$\kappa_m = \frac{2\pi}{l_0}$ – spatial wave number for inner turbulence scale
k_θ – phase deviation constant of phase modulation

$K_m(qr)$ – modified Hankel function or Bessel function of the second kind and of order m
$K_{\alpha-\beta}[\cdot]$ – modified Bessel function of the second kind of order $(\alpha - \beta)$
L – path loss or attenuation of optical signal
l_0 – inner scale of atmospheric turbulence
L_0 – outer scale of atmospheric turbulence
$l_1 \equiv l_{co} \sim 1/\rho_0$ – coherence length between two coherent points of turbulence
$\ell_F \sim \sqrt{L/k}$ – first Fresnel zone scale, L – range, $k = 2\pi/\lambda$ – wave number
$l_3 \sim R/\rho_0 k$ – scattering disk (turbulence) scale
LP_{01} $(m = 0)$ – linear polarized mode with $m = 0$ in fiber optic cable
LP_{11} $(m = 1)$ – linear polarized mode with $m = 1$ in fiber optic cable
M – material dispersion factor
$m(x)$ – codeword
$m(t)$ – modulated message signal
$\langle m(t) \rangle$ – average value of the modulated message signal
$M_0 \approx -0.095\ \mathrm{ps/(nm \cdot km)}$ – material dispersion factor at wavelength of
np – mean optical power
$n(r)$ – aerosol particle distribution in the atmosphere
$n = n' - jn''$ – complex refractive index, $n' = \sqrt{\varepsilon'/\varepsilon_0}$ – real part, $n'' = \sqrt{\varepsilon''/\varepsilon_0}$ – imaginary part
$n_{\mathrm{eff}} \equiv n_1 \sin\theta_i$ – effective refractive index
$N_0 = 8 \cdot 10^3\ \mathrm{m^{-2}\ mm^{-1}}$ – constant number of rain drops
N_0 – white noise power spectral density
$N_{\mathrm{add}} = N_0 B_\omega$ – additive (Gaussian) noise power
N_{mult} – spectral density of multiplicative noise
$N_{\mathrm{mult}} = N_{\mathrm{mult}} B_\Omega$ – multiplicative noise power
$N(D)$ – distribution of rain drops as function of their diameter D
$dN(r)$ – number of aerosols having radius between r and $r + dr$
p – pressure in millibars, or pascals or mm Hg
P_r – optical power incident on the detector surface
P_{oIII} – error probability
P_m – mean optical power received by the detector
$P_g(f)$ – PSD of the envelope $g(t)$
P_r – optical signal power
$P_r(e)$ – evaluated probability of the error
$P(h)$ – atmospheric pressure as function of altitude h
$P_m = \langle m^2(t) \rangle$ – power of the modulated message signal
$P(\phi_i) = (2\pi)^{-1}$ – ray phase distribution probability function
R – coefficient of reflection from boundary of two media
R – data rate
R – detector responsivity
$Re = V \cdot l/\nu$ – Reynolds number
r_R – optical ray path length