OPTICAL BIT ERROR RATE

An Estimation Methodology

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The content of this book is intended to have illustrative and educational value and it should not be regarded as a complete specification for the design of optical networks. The information presented in this book is adapted from standards and from the author's research activities; however, although a serious effort has been made, the author does not warranty that changes have not been made and typographical errors do not exist. The reader is encouraged to consult the most current standards recommendations and manufacturer's data sheets.

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To a world in which errors can be predicted, detected,
and corrected to better than 1 in 100,000,000,000,000

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Preface

The key objectives in telecommunications—wired, wireless, or optical—are safe and cost-effective transportation and prompt delivery of the client's undamaged data. How this is done, and what technology is used to do it, is of less concern to the paying customer and of more concern to us, the telecommunications technologists. As an example, when we ship a box with some goods in it, we never ask about the specifications of the transportation equipment. We ask *when* it will be delivered and *how much* it costs, with assurance that it will be delivered undamaged.

Having said that, in megatransportation modern telecommunications systems that transport aggregate information at terabits per second, the safe and intact delivery of client's data must be guaranteed. However, unlike boxes that can be seen and touched, data are flowing at the speed of light and in massive quantities. Therefore, corrective mechanisms must be built in at the receiver end that verify the proper delivery of data at an unprecedented quality level—one failure or less in 100,000,000,000,000 bits delivered.

DWDM (Dense Wavelength Division Multiplexing), like many differently colored threads brought together to a thin rope, is a relatively new technology that enables bandwidth scalability to levels not possible before. The receiving end performs the reverse function; it unravels the rope to its constituent colored threads. Each of these "threads" is modulated to bit rates up to 40 GHz, and, thus, the potential aggregate bandwidth in a single strand of fiber is currently in excess of peta-bits per second* (1 Pbit/s = 1,000,000,000,000,000 bits) and at distances over hundreds of kilometers. As such, the sophistication of the data path as well as of the receiving end cannot be overemphasized.

An information channel that is realized with a modulated optical frequency or wavelength is termed an *optical channel*. However, as many optical channels travel in a fiber strand, many interesting phenomena take place. Light interacts with mat-

*Currently, terabits per second is reality. However, if the continuous spectrum from under 1300 to over 1600nm is deployed, and the channel separation is reduced, theoretically petabits per second will become a reality of the future.

ter, which interacts with light, and, as a result, although the transmitted signal was of high quality, the received signal may have been contaminated. Therefore, the amount of signal contamination needs to be estimated, monitored, and detected at the receiver so that the actual signal performance can be compared with the expected (one out of 10^{-12}) and, if it does not meet this criterion, then some remedial action must be taken based on recovery and protection strategies that are built into the system and network.

This is the second book on performance of optical channels, systems, and networks. The first book was *Fault Detectability in DWDM: Towards Signal Quality and System Robustness* (IEEE Press, 2001). This is also the fifth book on DWDM. The first book, *DWDM Networks, Components and Technology* (Wiley/IEEE 2003) provides a comprehensive treatment, with focus on the DWDM networks and how DWDM technology is employed in advanced optical systems and networks. *Introduction to DWDM Technology: Data in a Rainbow* (IEEE Press, 2000) provides an insight into the working of optical technology and an introduction to DWDM systems and networks. *Fault Detectability in DWDM* provides a treatise on fault mechanisms of DWDM components, systems, and networks and how they correlate and are detected. *Next Generation SONET/SDH: Voice and Data* (Wiley/IEEE 2004) provides a description of the next generation DWDM-based optical network and the protocols that make possible voice and data convergence over the same optical network. *Understanding SONET/SDH and ATM: Communications Networks for the Next Millennium* (IEEE Press, 1999) provides a description of the legacy SONET/SDH and ATM networks and protocols.

The objective of this book goes beyond describing optical components and their parameters, systems, and networks. The main objectives are to describe sources that affect the quality of optical signal and to provide the theoretical foundation on which the signal quality at the receiver and the performance of the optical channel are estimated, monitored, and detected. This book treats optical channels as memoryless and the signals as modulated with the most traditional on-off technique; channels with memory or multilevel modulation that are applicable to other transmission media are the subject of other textbooks and also of current research. With this objective in mind, this book reviews the fundamentals of optical communications, including modulation, the fiber as an optical transmission medium, the receiver and transmitter, jitter, and wander. It discusses factors affecting the signal quality and sources of optical noise and jitter, and how they affect the optical signal and the optical signal to noise ratio (OSNR). It clarifies the meaning of errored bits and defines bit error ratio and rate, and optical bit error rate (OBER). It discusses noise sources at the receiver, it provides a probabilistic and statistical analysis of errored bits, and links BER with SNR. It describes the eye diagram as a visualizing tool that quantifies the quality of the received signal, describes eye-diagram statistical sampling, and how BER, Q-factor, and SNR are estimated from it. It also presents a cost-efficient method for the automatic estimation of BER, Q-factor, and SNR using integrated circuitry at the receiver. This book also reviews forward error correction coding (FEC) methods, and how FEC and the estimation methodology can work together to achieve better performance.

Throughout this book there are numerical examples for pedagogical purposes. However, the real value of examples cannot be properly appreciated unless one is in a position to visualize the impact of changing parameters on the quality of the signal and quality of optical transmission. This book bridges this void by including a CD-ROM that contains ten real-life exercises that can be simulated by the reader (user, in this case) interactively. These problems are selected to cover a wide spectrum of link-layer problems, from simple attenuation to dispersion and even forward error correction. The objective of this CD-ROM and the ten problems that are simulated are described in Appendix B.

As in the previous books, it is my hope that this book will excite many communications engineers, system designers, and network architects and will stimulate many questions relevant to optical communications from DWDM network and engineering technologists as well as researchers wishing to go a step further into the interesting field of channel characterization and signal quality assessment. It is my hope that this excitation and stimulation will culminate in the design of more robust, efficient, and cost-effective optical systems and networks. I wish you happy and easy reading.

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Constants, Conversions, and Useful Formulae

LIST OF PHYSICAL CONSTANTS

c	velocity of light in free space	$2.99792458 \times 10^{-8}$ m/sec
e	electron charge	1.60218×10^{-19} Coulomb
m_e	mass of electron	9.1085×10^{-28} gram
m_p	mass of proton	1.67243×10^{-24} gram
m_n	mass of neutron	1.67474×10^{-24} gram
m_E	mass of earth	5.983×10^{27} gram
E_e	rest energy of electron	0.51098 MeV
ε_0	permitivity of free space	8.8542×10^{-12} Farad/m
μ_0	permeability of free space	$4\pi \times 10^{-7}$ Henry/m
h	Planck's constant	$6.6260755 \times 10^{-34}$ Joule-sec
k	Boltzmann's constant	1.38×10^{-23} Joule/°K
N_A	Avogadro's number	6.0221×10^{23}/mol
Z_0 (μ_0/ε_0)	impedance of free space	376.731 Ohm (Ω)
g	acceleration due to gravity	9.80665 m/sec^2 = 980.665 cm/sec^2
π	dimensionless number, pi	3.141593+
e	base of natural logarithm	2.7182818+
n (SiO_2)	refractive index for SiO_2, 0.8 wt % F	1.65
n (Si)	refractive index for Si	3.43
n (Ge)	refractive index for Ge	4.02

LIST OF CONSTANTS

Density of pure water at 3.98°C	1 g/ml
Density of air (at 0°C and 760 mmHg)	1.293×10^{-3} g/cm^3
Velocity of sound in air (at 0°C and 760 mmHg)	331.7 m/sec
Velocity of sound in water (at 20°C)	1470 m/sec

Refractive index (n) of PMMA acrylic (red)	1.489
Refractive index (n) of polystyrene (red)	1.584
dn/dT of PMMA acrylic	-8.0×10^{-5}/°C
dn/dT of polystyrene	-12.0×10^{-5}/°C
Linear expansion coefficient of PMMA acrylic	6.74×10^{-5}/cm/°C
Linear expansion coefficient of polystyrene	8.0×10^{-5}/cm/°C

USEFUL CONVERSIONS

1° of angle = 60 minutes = 3600 seconds = 1.7453 rads = 2.778×10^{-3} circumference
1 circumference = 360° = 2π
1 rad = 360°/2π = 0.1592 circumference = 57.296°
1 meter = 100 cm = 1000 mm = 10^6 μm = 39.37 in = 3.280833 ft = 1.09361 yd
1 km = 3300 ft
1 μm = 0.04 mils
1 nm = 10 angstroms (Å)
1 inch = 2.540005 cm
1 liter = 1000.027 cm^3 = 33.8147 fl oz = 0.26418 gal
1 ounce = 28.34953 grams
1 atmosphere = 1.0133 bar = 14.696 lb/in^2
0° C = 273 K = 32°F
1 Joule (abs) = 1 Newton-meter = 1 Watt-second =1×10^{-7} ergs
= 1 V-Coulomb = 9.4805×10^{-4} Btu
1 HP (electrical) = 746.00 W
1 HP (mechanical) = 745.70 W = 0.70696 Btu/sec
1 eV = 1.6×10^{-12} erg = 1.60218×10^{-19} Joule
1 wavelength (red) = 632.8 nm
1 wavelength (green) = 546.07 nm
1 wavelength (blue) = 488 nm
10 wavelengths (red) = 0.00025 inches

USEFUL FORMULAE

Probability:
$P(A) = 1 - P(A)$

Permutations:
N objects can be permuted in $n!$ ways

Combinations:
$C(n; r) = n!/[r!(n-r)!]$
$C(n; r) = C(n; n-r)$

OR rule:
$P(A \text{ or } B) = P(A) + P(B) - P(A \text{ and } B)$

XOR rule:
$P(A \text{ XOR } B) = P(A) + P(B)$

Conditional probability:
$P(A|B) = P(A \text{ and } B)/P(A)$
$P(B|A) = 1 - P(B|A)$
$P(A \text{ and } B) = P(A)\, P(A|B) = P(B)\, P(A|B)$

Independent events:
$P(A \text{ and } B) = P(A)P(B)$
$P(A \text{ and } B \text{ and } C) = P(A)P(B)P(C)$
$P(A|B) = P(A)$

Ordered events:
$P(A \text{ before } B) = P(A)/[P(A) + P(B)]$

Baye's theorem a sample space S is partitioned into n mutually exclusive events A_i; B is any event in S. Then for any i:
$P(A_i|B) = [P(A_i)P(B|A_i)]/[P(A_1)P(B|A_1) + P(A_2)P(B|A_2) + \ldots + P(A_n)P(B|A_n)]$

Binomial distribution (Bernoulli trials)
$P(k \text{ successes in } n \text{ trials}) = C(n; k)p^k q^{n-k}$

Geometric distribution:
$P(n) = (1 - p)^{n-1}p$; n is the number of trials

Poisson distribution:
$P(k) = e^{-\lambda}\lambda^k/k!$ for $k = 0, 1, 2, \ldots$; λ is a parameter

Series:
$e^x = \Sigma x^k/k!$; sum is from $k = 0$ to infinity

Properties of logarithms
1. $\log(AB) = \log A + \log B$
2. $\log(A/B) = \log A - \log B$
3. $\log(A^N) = N \log A$
4. $\log\{N\text{root}(A)\} = (1/N)\log A$
5. $\log 10 = 1$
6. $\log 1 = 0$
7. $\log A = \log(e) \ln A$

8. log (e) = log(2.71828+) = 0.434294
9. ln 10 = 2.30258+
10. ln 2.71828 = 1
11. log A = +log A, where $A > 1$
12. log A = –log|A|, where $0 < A < 1$
13. log($A + B$) not equal to log A + log B

Notice: This book contains device specifications for illustrative and educational purposes. As specifications are under continuous change, no responsibility is assumed for correctness. The reader is encouraged to consult the latest versions of standards as well as the most current manufacturer's data sheets.