

Springer
Handbook *of*

Optical
Networks

Mukherjee

Tomkos

Tornatore

Winzer

Zhao

Editors

Springer Handbook of Optical Networks

Springer Handbooks provide a concise compilation of approved key information on methods of research, general principles, and functional relationships in physical and applied sciences. The world's leading experts in the fields of physics and engineering will be assigned by one or several renowned editors to write the chapters comprising each volume. The content is selected by these experts from Springer sources (books, journals, online content) and other systematic and approved recent publications of scientific and technical information.

The volumes are designed to be useful as readable desk book to give a fast and comprehensive overview and easy retrieval of essential reliable key information, including tables, graphs, and bibliographies. References to extensive sources are provided.

Springer Handbook of Optical Networks

Biswanath Mukherjee, Ioannis Tomkos,
Massimo Tornatore, Peter Winzer, Yongli Zhao
(Eds.)

With 838 Figures and 102 Tables



Springer

Editors

Biswanath Mukherjee
Dept. of Computer Science
University of California
Davis, CA, USA

Ioannis Tomkos
ECE Department
University of Patras
Patras, Greece

Massimo Tornatore
Politecnico di Milano
Milano, Italy

Peter Winzer
Nokia Bell Labs
Holmdel, NJ, USA

Yongli Zhao
Beijing University of Posts and Telecommunications
Beijing, China

ISBN 978-3-030-16249-8 e-ISBN 978-3-030-16250-4
<https://doi.org/10.1007/978-3-030-16250-4>

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG, part of Springer Nature.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

Optical networks have moved beyond traditional applications in telecommunications to become the infrastructure of choice whenever large amounts of information need to be transmitted. The broad spectrum inherent in the use of light and the unparalleled capability to spatially pack many parallel paths into fiber cables have led to an ever-broadening range of applications. Thousands of fibers interconnect buildings full of servers in massive datacenters that underlie internet services such as search and social media. Cables with hundreds of fibers form the backbone of metropolitan access networks and interconnect wireless base stations. At the same time, traditional long-haul services—both undersea and terrestrial—demand ever more capacity. Recent years have also seen a revolution in the technology of optical networking with the advent of coherent detection, which is now ubiquitous in long-haul and metro networks and advancing into more applications as costs decline.

This new handbook on optical networks provides a broad perspective on the field, offering a survey of the fundamental technologies of optical networks: fiber, devices, and subsystems through to systems based on those technologies, and finally to the architecture and applications of the networks themselves. The editors—Peter Winzer on subsystems and technologies, Biswanath Mukherjee on core networks, Ioannis Tomkos on datacenter and supercomputer networks, and Massimo Tornatore on access and wireless networks—have assembled an impressive list of chapter authors who have made important contributions to their fields. This volume provides a valuable look at today's optical networks.

September 2020

Robert W. Tkach



Robert W. Tkach
Director of Advanced
Photonics Research
Nokia Bell Laboratories

Preface

Optical communication systems form the backbone of today's communication and information society. Several billion kilometers of optical fiber are installed around the globe today—enough to wrap a string of glass as thin as a human hair around the globe more than 100 000 times. A cutting-edge optical communication system can transmit tens of terabits per second over trans-Pacific distances through a single strand of optical fiber, taking a mere 50 ms to link North America with South East Asia. Today's globally installed base of optical communication transponders is collectively capable of transmitting more than an exabit (an exabit is 1 000 petabits, 1 000 000 terabits, 1 000 000 000 gigabits, or 1 000 000 000 000 megabits) of information per second over short links (between tens of meters and a kilometer long) within a data center, tens of kilometers in mobile backhaul or fiber-to-the-home applications, hundreds of kilometers in metropolitan and regional networks, thousands of kilometers in transcontinental and submarine backbones, and even tens of thousands of kilometers or more in spaceborne satellite systems using free-space laser communications. In short, almost every bit of information we touch or consume today, whether it belongs to an Internet search, to a streamed video, or to a cellphone call, lives part of its life as an infrared photon within a gigantic global optical communications infrastructure.

It is the role of this Handbook to comprehensively describe and review the many underlying technologies that enable today's global optical communications infrastructure, as well as to explain current research trends that target continued capacity scaling and enhanced networking flexibility in support of unabated traffic growth fueled by ever-emerging new applications. Each chapter, written by world-renowned experts in its subject area, tries to paint a complete picture of that subject, from entry-level information to a snapshot of the respective state-of-the-art technologies and emerging research trends, in an effort to provide something useful for every reader—ranging from the novice who wants to get familiar with the field to the expert who wants a concise perspective on future trends.

Part A of this Handbook considers *optical subsystems for transmission and switching*, with chapters fo-

cus on topics ranging from optical fibers and cables to optical amplifiers and switches, optical transponders and their various subsystems, as well as fiber-optic communications systems, their scalability limitations, and ways to overcome these limitations in future system designs.

Part B of this Handbook reviews *core networks*, with chapters devoted to managing the vast fiber-optic communication infrastructure at the network-wide level. Topics range from the standards required to sustain an economically viable supplier ecosystem to algorithms used to route traffic and assign infrastructure resources within optical networks, cross-layer design, and network virtualization.

Part C of this Handbook is concerned with *datacenter and supercomputer networking*, which has design requirements and solutions that differ in several ways from those of other segments of the network. Topics include reviews of industry trends and requirements as well as transponder and switching considerations specific to those applications.

Part D of this Handbook addresses *optical access and wireless networks*, and is mostly geared towards solving the last-mile problem: connecting backbone networks to end users. This may be achieved directly via fiber or visible-light free-space communications, or indirectly over a mobile wireless radio infrastructure that is heavily supported by an associated fiber-optic network. Emerging areas such as spaceborne laser communications and optical communications in avionics and autonomous vehicles round off this part of the Handbook.

The Editors gratefully acknowledge all the valuable contributions from authors and peer reviewers who took much time out of their busy schedules to write or review chapters of this Handbook. The Editors also cordially thank Judith Hinterberg and Mary James from Springer for keeping everybody aligned, on time, and happy during the process.

Biswanath Mukherjee
Ioannis Tomkos
Massimo Tornatore
Peter Winzer
Yongli Zhao

About the Editors

Biswanath Mukherjee is a Distinguished Professor Emeritus at the University of California, Davis, CA, USA. He holds a PhD from the University of Washington, Seattle (1987) and a BTech (Hons) from the Indian Institute of Technology, Kharagpur (1980). He is also a Distinguished Professor and Founding Director of the Institute for Broadband Research and Innovation (IBRI) at Soochow University in China. He has been involved in several successful optical startups, including Ennetix, a SBIR-funded company specializing in AI-powered, application-centric network analytics for optimizing the user experience. Biswanath Mukherjee has served as program chair for several OFC, IEEE INFOCOM, and IEEE Advanced Networks and Telecom Systems (ANTS) conferences, and cofounded the latter. He is a Series Editor for Springer's book series on optical networks, and has served on several journal editorial boards, including *IEEE/ACM Transactions on Networking* and *IEEE Network*. He has received multiple awards for his scholarly and educational achievements, and was the winner of the IEEE Communications Society's inaugural (2015) Outstanding Technical Achievement Award "for pioneering work on shaping the optical networking area." He was made an IEEE Fellow in 2006.



Ioannis Tomkos is a Professor of Optical Communications at the Department of Electrical and Computer Engineering at the University of Patras, Greece. His current research focuses on the use of optical communications systems for 5G/6G and datacenter networks. He has held numerous positions in industry and academia in various countries around the world (e.g., USA, Spain, Cyprus, Italy, and Greece). His research group plays a consortium-wide leading role in over 25 EU-funded research projects, and he serves as Technical Manager on 10 major EU projects. His published works have received around 10,000 citations (*h-index* = 47). In 2018, Dr. Tomkos was elected an IEEE Fellow "for contributions in dynamic optical networks." He is also an IET Fellow (2010) and a Fellow of the Optical Society (2012).



Massimo Tornatore is an Associate Professor in the Department of Electronics, Information, and Bioengineering at Politecnico di Milano, where he received a PhD degree in 2006. He is also an Adjunct Professor at the University of California, Davis, CA, USA and a Visiting Professor at the University of Waterloo, Canada. His research interests include performance evaluation, the optimization and design of communication networks (with an emphasis on the application of optical networking technologies), cloud computing, and the application of machine learning to network management. He has participated in several EU R&D projects as well as several other projects in the US, Canada, and Italy. Massimo Tornatore is a member of the journal editorial boards of *IEEE Communication Surveys and Tutorials*, *IEEE Communication Letters*, *Photonic Network Communications*, and *Optical Switching and Networking*. He is also an active member of the technical program committees of various networking conferences, and a Senior Member of the IEEE.



Peter J. Winzer received his PhD in electrical engineering from the Technical University of Vienna, Austria, in 1998. Supported by the European Space Agency, he investigated spaceborne Doppler lidar and laser communications. From 2000 to 2019, he worked at Bell Labs (NJ, USA), where he focused on fiber-optic communication systems and networks and contributed to many high-speed optical transmission records and field trials of up to 1 Tbit/s per carrier. Peter Winzer is actively involved with the IEEE Photonics Society and the Optical Society (OSA). He has served as Editor-in-Chief of the IEEE/OSA *Journal of Lightwave Technology* and was Program/General Chair of ECOC and OFC. Dr. Winzer is a highly cited researcher, a Bell Labs Fellow, an IEEE Fellow, and a Fellow of the OSA, as well as an elected member of the US National Academy of Engineering. He has received multiple awards, including the John Tyndall Award.



Yongli Zhao is a Full Professor in the State Key Laboratory of Information Photonics and Optical Communications at Beijing University of Posts and Telecommunications (BUPT). He is a Senior Member of the IEEE and an IET Member. Yongli Zhao received his PhD from BUPT in 2010. He has received support from the Youth Talent Plan of Beijing City (2013) and the National Science Fund for Excellent Young Scholars in China (2018). In the past five years, he has chaired and participated in more than 30 research projects, including the National High Technology Research and Development Program in China, the National Basic Research Program of China, and National Natural Science Foundation of China (NSFC) projects. He was a Visiting Associate Professor at UC Davis in 2016–2017. His current research focuses on software-defined optical networks, elastic optical networks, datacenter networking, machine learning in optical networks, optical network security, and quantum key distribution networking.



About the Authors

Alejandro Aguado Martín

Center for Computational Simulation
Universidad Politécnica de Madrid
Madrid, Spain
a.aguadom@fi.upm.es

Rod C. Alferness

University of California Santa Barbara
Santa Barbara, CA, USA
alferness@ucsb.edu

Cristian Antonelli

Dept. of Physical and Chemical Sciences
University of L'Aquila
67100 L'Aquila, Italy
cristian.antonelli@univaq.it

Pablo Jesus Argibay-Losada

BITS
SBI Group
Tokyo, Japan
pargibay@ieee.org

Alireza Behbahani

Turbine Engine Division, Advanced Integrated
Controls and Prognostic / Diagnostic Systems
Group
Air Force Research Laboratory (AFRL)
Wright-Patterson Air Force Base, OH, USA
alireza.behbahani@us.af.mil

Keren Bergman

Dept. of Electrical Engineering
Columbia University
New York, NY, USA
bergman@ee.columbia.edu

Alberto Bononi

Dipt. di Ingegneria e Architettura
Università degli Studi di Parma
Lesignano de' Bagni (Parma), Italy
alberto.bononi@unipr.it

Brad Booth

Microsoft
Snohomish, WA, USA
brbooth@microsoft.com

Gabriella Bosco

Dept. of Electronics and Telecommunications
Politecnico di Torino
Torino, Italy
gabriella.bosco@polito.it

Nicola Calabretta

Dept. of Electrical Engineering
Technical University of Eindhoven
Eindhoven, The Netherlands
n.calabretta@tue.nl

Alberto Carrasco-Casado

Space Communications Laboratory
NICT – National Institute of Information and
Communications Technology
Tokyo, Japan
alberto@nict.go.jp

Fabio Cavaliere

Ericsson
Pisa, Italy
fabio.cavaliere@ericsson.com

Mohit Chamania

Dept. of Research and Development
ADVA Optical Networking SE
Berlin, Germany
mchamania@advaoptical.com

Sethumadhavan Chandrasekhar

Optical Transmission Research
Nokia Bell Labs
Holmdel, NJ, USA
s.chandrasekhar@ieee.org

Gee-Kung Chang

School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA
geekung.chang@ece.gatech.edu

Xi Chen

Optical Transmission Research
Nokia Bell Labs
Holmdel, NJ, USA
xi.v.chen@nokia-bell-labs.com

Dominique Chiaroni

Nokia Bell Labs France
Nozay, France
dominique.chiaroni@nokia-bell-labs.com

Brandon Collings

Lumentum
San Jose, CA, USA
brandon.collings@lumentum.com

Ronen Dar

Optical transmission systems
Nokia Bell Labs
Holmdel, NJ, USA
ronendar@yahoo.com

Robert D. Doverspike

Network Evolution Strategies, LLC
Tinton Falls, NJ, USA
r.d.doverspikeconsulting@gmail.com

Rudra Dutta

Dept. of Computer Science
North Carolina State University
Raleigh, NC, USA
rdutta@ncsu.edu

Jörg-Peter Elbers

Advanced Technology
ADVA Optical Networking SE
Martinsried, Germany
jelbers@adva.com

Mark Filer

Microsoft Corporation
Redmond, WA, USA

Marco Fiorentino

Hewlett Packard Labs
HPE
Palo Alto, CA, USA
marco.fiorentino@hpe.com

Pouya Fotouhi

Dept. of Electrical and Computer Engineering
University of California, Davis
Davis, CA, USA
pfotouhi@ucdavis.edu

Alexandre Graell i Amat

Dept. of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden
alexandre.graell@chalmers.se

Ashwin Gumaste

Computer Science and Engineering
Indian Institute of Technology, Bombay
Mumbai, India
ashwing@ieee.org

Hiroaki Harai

National Institute of Information and
Communications Technology
184-8795 Tokyo, Japan
harai@nict.go.jp

Takemi Hasegawa

Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Japan
hase@sei.co.jp

Alan Hill

Trinity College, CONNECT Telecommunications
Research Centre, School of Computer Science and
Statistics
University of Dublin
Dublin, Ireland
alanhill@timewave.f9.co.uk

Hiroki Ishikawa

Optical Communications Laboratory
Sumitomo Electric Industries, Ltd.
Yokohama, Japan
ishikawa-hiroki@sei.co.jp

Admela Jukan

ECE
TU Braunschweig
Braunschweig, Germany
ajukan@me.com

Jun-ichi Kani

NTT Access Network Service Systems Laboratories
NTT Corporation
Yokosuka, Japan
junichi.kani.wb@hco.ntt.co.jp

Daniel C. Kilper

Optical Sciences
University of Arizona
Tucson, AZ, USA
dkilper@optics.arizona.edu

Koteswararao Kondepu

Scuola Superiore Sant'Anna
Pisa, Italy
koteswararao.kondepu@sssup.it

David Larrabeiti

Universidad Carlos III de Madrid
Leganés, Spain
dlarra@it.uc3m.es

Xin Lin

Institute of Technology
Nakagawa Laboratories, Inc.
Tokyo, Japan
linxin@optinformation.com

Hong Liu

Google Inc.
Mountain View, CA, USA
hongliu@google.com

Victor Lopez

Telefonica
Madrid, Spain
victor.lopezalvarez@telefonica.com

Feng Lu

Wireless and Sensing Products Group
Semtech Corporation
San Jose, USA
flu@semtech.com

Andrea Marotta

DISIM
University of L'Aquila
L'Aquila, Italy
andrea.marotta@univaq.it

Ramon Mata-Calvo

Institute of Communications and Navigation
DLR – Deutsches Zentrum für Luft- und Raumfahrt
(German Aerospace Center)
Oberpfaffenhofen-Wessling, Germany
ramon.matacalvo@dlr.de

Tomokuni Matsumura

Nakagawa Laboratories, Inc.
Tokyo, Japan
tom@naka-lab.jp

David S. Millar

Mitsubishi Electric Research Laboratories
Cambridge, MA, USA
millar@merl.com

John E. Mitchell

Dept. of Electronic and Electrical Engineering
University College London
London, UK
j.mitchell@ucl.ac.uk

Biswanath Mukherjee

Dept. of Computer Science
University of California
Davis, CA, USA
bmukherjee@ucdavis.edu

Mehrdad Pakmehr

optoXense, Inc.
San Ramon, CA, USA
mp@optoxense.com

Nick Parsons

HUBER+SUHNER Polatis
Cambridge, UK
nick.parsons@hubersuhner.com

David Payne

Electrical Engineering
Trinity College Dublin
Dublin, Ireland
david.b.payne@btinternet.com

Thomas Pfeiffer

Bell Labs
Nokia
Stuttgart, Germany
thomas.pfeiffer@nokia-bell-labs.com

David Piehler

Dell Technologies
Santa Clara, CA, USA
david.piehler@dell.com

Pierluigi Poggiolini

Dept. of Electronics and Telecommunications
(DET)
Politecnico di Torino
Torino, Italy
pierluigi.poggiolini@polito.it

Josep Prat

Signal Theory and Communications Dept.
Universitat Politecnica de Catalunya (UPC)
Barcelona, Spain
jprat@tsc.upc.edu

Roberto Proietti

Dept. of Electrical and Computer Engineering
University of California, Davis
Davis, CA, USA
rproietti@ucdavis.edu

Chunming Qiao

Dept. of Computer Science & Engineering
University of Buffalo
Buffalo, NY, USA
qiao@buffalo.edu

Stojan Radic

Qualcomm Institute
University of California San Diego
La Jolla, CA, USA
sradic@ucsd.edu

George N. Rouskas

Dept. of Computer Science
North Carolina State University
Raleigh, NC, USA
rouskas@ncsu.edu

Marco Ruffini

Trinity College, CONNECT telecommunications
research centre, Computer Science and Statistics
The University of Dublin
Dublin, Ireland
marco.ruffini@tcd.ie

Sébastien Rumley

Dept. of Electrical Engineering
Columbia University
New York, NY, USA
rumley@ee.columbia.edu

Roland Ryf

Advanced Photonics Research
Nokia Bell Labs
Holmdel, NJ, USA
roland.ryf@nokia-bell-labs.com

Takashi Sasaki

Innovation Core SEI, Inc.
San Jose, CA, USA
sasaki@sei-innovation.com

Seb J. Savory

Dept. of Engineering
University of Cambridge
Cambridge, UK
sjs1001@cam.ac.uk

Laurent Schmalen

Communications Engineering Lab (CEL)
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
laurent.schmalen@kit.edu

Marco Secondini

Institute of Communication, Information and
Perception Technologies
Sant'Anna School of Advanced Studies
Pisa, Italy
marco.secondini@sssup.it

Paolo Serena

Dipt. di Ingegneria e Architettura
Università degli Studi di Parma
Parma, Italy
paolo.serena@unipr.it

M. Ashkan Seyedi

Hewlett Packard Labs
HPE
Palo Alto, CA, USA
ashkan.seyedi@hpe.com

Jane M. Simmons

Monarch Network Architects
Holmdel, NJ, USA
jsimmons@monarchna.com

Björn Skubic

Ericsson Research
Ericsson AB
Stockholm, Sweden
bjorn.skubic@ericsson.com

William A. Stange

Universal Technologies Corp.
Dayton, OH, USA
bstange@utcdayton.com

Suresh Subramaniam

George Washington University
Washington, USA
suresh@gwu.edu

Giuseppe Talli

Photonic Systems Group
Tyndall National Institute, University College Cork
Cork, Ireland
giuseppe.talli@tyndall.ie

Ioannis Tomkos

ECE Department
University of Patras
Patras, Greece
itom@ece.upatras.gr

Massimo Tornatore

Politecnico di Milano
Milano, Italy
tornator@elet.polimi.it

Paul Townsend

Photonics
Tyndall National Institute, University College Cork
Cork, Ireland
paul.townsend@tyndall.ie

Stephen J. Trowbridge

Optical Networking Business Unit
Nokia
Boulder, CO, USA
steve.trowbridge@nokia.com

Ryohei Urata

Google Inc.
Mountain View, CA, USA
ryohei@google.com

Amin Vahdat

Google Inc.
Mountain View, CA, USA
vahdat@google.com

Luca Valcarenghi

Istituto TeCIP
Scuola Superiore Sant'Anna
Pisa, Italy
luca.valcarenghi@sssup.it

Michael Vasilyev

Dept. of Electrical Engineering
University of Texas at Arlington
Arlington, TX, USA
vasilyev@uta.edu

Doutje Veen

Bell Labs Access Lab
Nokia
Murray Hill, NJ, USA
dora.van_veen@nokia-bell-labs.com

Ricard Vilalta

Centre Tecnològic de Telecomunicacions de
Catalunya (CTTC/CERCA)
Castelldefels, Spain
ricard.vilalta@cttc.es

Sebastian Werner

Dept. of Electrical and Computer Engineering
University of California, Davis
Davis, CA, USA
swerner@ucdavis.edu

Peter Winzer

Nokia Bell Labs
Holmdel, NJ, USA
peter.winzer@ieee.org

Lena Wosinska

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden
wosinska@chalmers.se

Mu Xu

Optical Center of Excellence
CableLabs
Louisville, CO, USA
m.xu@cablelabs.com

S.J. Ben Yoo

Dept. of Electrical and Computer Engineering
University of California, Davis
Davis, CA, USA
sbyoo@ucdavis.edu

Xiaosong Yu

Institute of Information Photonics and Optical
Communications (IPOC)
Beijing University of Posts and
Telecommunications (BUPT)
Beijing, China
xiaosongyu@bupt.edu.cn

Jie Zhang

Institute of Information Photonics and Optical
Communications (IPOC)
Beijing University of Posts and
Telecommunications (BUPT)
Beijing, China
lgr24@bupt.edu.cn

Yongli Zhao

Beijing University of Posts and
Telecommunications
Beijing, China
yonglizhao@bupt.edu.cn

Xiang Zhou

Google Inc.
Mountain View, CA, USA
xzhou@google.com

Contents

List of Abbreviations	XXVII
1 The Evolution of Optical Transport Networks	
<i>Rod C. Alferness</i>	1
1.1 Fundamental Developments	2
1.2 Transport Networks	3
1.3 Enter Optical Fiber Transmission	4
1.4 Single-Fiber Capacity as the Key Metric for Cost-Effective Optical Transmission Systems	5
1.5 High-Speed Time-Division Multiplexing (TDM) Transmission Systems	5
1.6 Wavelength-Division Multiplexed Transmission Systems	7
1.7 Bandwidth Management at the Optical Layer via Optical Add/Drops and Cross Connects	10
1.8 Driving Ultrahigh-Speed WDM and Beyond	15
1.9 Space-Division Multiplexing: The Next Era of Optical Networking ..	16
1.10 Optical Networking Applications Beyond Global Transport Networks	17
References	18
Part A Optical Subsystems for Transmission and Switching	
2 Optical Fiber and Cables	
<i>Takashi Sasaki, Takemi Hasegawa, Hiroki Ishikawa</i>	25
2.1 Transmission Fibers	26
2.2 Single-Mode Fibers (SMFs)	27
2.3 Multimode Fibers (MMFs)	34
2.4 Emerging Fibers	34
2.5 Optical Fiber Cables	36
References	44
3 Optical Amplifiers	
<i>Michael Vasilyev, Stojan Radic</i>	51
3.1 Erbium-Doped Fiber Amplifiers	52
3.2 Raman Amplifiers	65
3.3 Alternative Amplification Technologies	78
References	78
4 Optical Transponders	
<i>Gabriella Bosco, Jörg-Peter Elbers</i>	83
4.1 Evolution of Modulation Formats and Symbol Rates	86
4.2 Intensity Modulation with Direct Detection	88
4.3 Optical Duobinary with Direct Detection	99
4.4 Differential Phase Modulation with Interferometric Detection	105
4.5 IQ Modulation with Coherent Detection	113
4.6 Transponder Architectures	123
References	130

5	Optical Transponder Components	
	<i>Xi Chen, Sethumadhavan Chandrasekhar</i>	137
5.1	Lasers	138
5.2	Modulators	141
5.3	Photodetectors	146
5.4	Transmitter Hardware	147
5.5	Coherent Receiver Hardware	149
5.6	Integrated Transmitters and Receivers	152
	References	152
6	DSP for Optical Transponders	
	<i>Seb J. Savory, David S. Millar</i>	155
6.1	Historical Background	156
6.2	Preliminaries	157
6.3	Overview of DSP Algorithms	160
6.4	Orthonormalization and De-skew Algorithms	161
6.5	Static Equalization	161
6.6	Adaptive Equalization	164
6.7	Carrier and Timing Synchronization Algorithms	167
6.8	Forward Error Correction Coding	169
6.9	Current Research Trends	170
6.10	Future Opportunities	173
6.11	Closing Remarks	173
	References	174
7	Forward Error Correction for Optical Transponders	
	<i>Alexandre Graell i Amat, Laurent Schmalen</i>	177
7.1	History of Forward Error Correction in Optical Communications	179
7.2	A Glimpse at Fundamental Limits and Achievable Rates	183
7.3	Basics of Forward Error Correction	189
7.4	Soft-Decision Forward Error Correction	197
7.5	Hard-Decision Forward Error Correction	218
7.6	Coded Modulation—An Introduction	230
7.7	Evaluating Forward Error Correction Performance in Transmission Experiments	236
7.8	Conclusion and Outlook	246
	References	248
8	Optical Node Architectures	
	<i>Brandon Collings, Mark Filer</i>	259
8.1	Generalized Functions of an Optical Node	260
8.2	General Configuration and Functionality of a ROADM Node	261
8.3	General Performance Requirements of a ROADM Node	264
8.4	2-degree Fixed Optical Add/Drop Multiplexer (OADM) Node	265
8.5	2-degree ROADM Node	266
8.6	2- to 8-degree Broadcast-and-select Colored and Directional ROADM Node	269
8.7	2- to 8-degree Broadcast-and-select, Colorless and Directionless ROADM Node	270
8.8	4- to 16-degree Route-and-select, Colorless and Directionless ROADM Node	275

8.9	4- to 16-degree Route-and-select, Colorless, Directionless and Contentionless ROADM Node	277
8.10	Reach and Performance Dependencies	281
8.11	WSS Bandpass Filtering and Implications	283
8.12	Performance Monitoring and Wavelength Connection Validation ...	284
8.13	Looking Forward	285
	References	285
9	Fiber Nonlinearity and Optical System Performance	
	<i>Alberto Bononi, Ronen Dar, Marco Secondini, Paolo Serena, Pierluigi Poggiolini</i>	287
9.1	Modeling the Optical Fiber	288
9.2	Fiber Propagation: Numerical Methods	290
9.3	Fiber Propagation: Analytical Perturbation Modeling	292
9.4	From FWM to GN and EGN Models	293
9.5	Time-Domain Perturbative Model	307
9.6	Spatially-Resolved Perturbative Models and Their Applications	312
9.7	Multiplicative Models and Their Applications	315
9.8	Model-Specific Features	317
9.9	Impact of Specific Effects on NL Modeling	318
9.10	Applications	321
9.11	Nonlinearity Mitigation	326
9.12	Capacity of the Nonlinear Channel	333
9.13	Conclusion	339
9.A	Conversion Among SNR, Q -Factor, MI and GMI for the AWGN Channel	340
9.B	Detailed List of Symbols, Notation, and Conventions	341
	References	342
10	Space-Division Multiplexing	
	<i>Roland Ryf, Cristian Antonelli</i>	353
10.1	Basic Concepts in Space-Division Multiplexed Optical Networks	354
10.2	SDM Point-to-Point Links	355
10.3	Fiber Modes	361
10.4	Representation of Modes in Fibers	366
10.5	Mode Coupling and Unitary Propagation in SDM Fibers	372
10.6	SDM Transmission Experiments	380
10.7	Nonlinear Effects in SDM Fibers	382
10.8	Routing in SDM Networks	385
10.9	Conclusion	386
	References	387
 Part B Core Networks		
11	Carrier Network Architectures and Resiliency	
	<i>Robert D. Doverspike</i>	399
11.1	Today's Network Architectures	400
11.2	Network Resiliency in Today's Network	412
11.3	Evolution of Resiliency in Optical Networks	426
11.4	Summary and Future Directions	441
	References	444

12 Routing and Wavelength (Spectrum) Assignment	
<i>Jane M. Simmons, George N. Rouskas</i>	447
12.1 Terminology	449
12.2 Shortest-Path Routing Algorithms	451
12.3 Disjoint-Path Routing for Protection	453
12.4 Routing Strategies	456
12.5 Routing Order	458
12.6 Multicast Routing	458
12.7 Wavelength Assignment	460
12.8 Wavelength Assignment Algorithms	462
12.9 One-Step RWA	464
12.10 Impairment-Aware Routing and Wavelength Assignment	467
12.11 Flexible (Elastic) Optical Networks	469
12.12 Routing and Spectrum Assignment in Elastic Optical Networks	471
12.13 Conclusion	478
References	479
13 Standards for Optical Transport Networks	
<i>Stephen J. Trowbridge</i>	485
13.1 Optical Network History	486
13.2 OTN Signal Format	489
13.3 Digital Multiplexing	494
13.4 Client Mapping Methods, Tributary Slot Mappings, and Justification	494
13.5 OTN Clients	500
13.6 OTN Beyond 100 G	505
13.7 Optical Media Layer Management	507
13.8 OTN Client Interfaces	508
13.9 Conclusions	511
13.10 Interoperable OTN Line Interfaces	511
References	512
14 Traffic Grooming	
<i>Rudra Dutta, Hiroaki Harai</i>	513
14.1 Factors Motivating Traffic Grooming	513
14.2 The Original Traffic Grooming Problem	519
14.3 Wavelength-Waveband Grooming	526
14.4 Grooming for SDM Networks	529
14.5 Conclusion: Traffic Grooming—Other Arenas	531
References	533
15 Dynamic Control of Optical Networks	
<i>Mohit Chamania, Admela Jukan</i>	535
15.1 Background and Evolution of Control Planes	536
15.2 Path Computation Element (PCE)	540
15.3 Software-defined Networking (SDN)	543
15.4 Emerging Trends for Optical Network Operation	547
15.5 Summary and Final Remarks	550
References	551

16 Cross-Layer Design	
<i>Suresh Subramaniam, Koteswararao Kondepu, Andrea Marotta</i>	553
16.1 Physical Layer Impairment Sources and Models	554
16.2 Cross-Layer Routing and Wavelength Assignment	558
16.3 PLI-Aware Survivability	563
16.4 Application-Aware Metro-Access Programmable Architecture	567
16.5 SDN-Based Resource Allocation and Path Protection	572
16.6 Application-Aware Converged Wireless-Access Resource Scheduling	574
16.7 Conclusion	579
References	579
17 Optical Network Virtualization	
<i>Jie Zhang, Ricard Vilalta, Xiaosong Yu, Victor Lopez, Alejandro Aguado Martín</i>	583
17.1 Optical Networks	583
17.2 Network Operating System	586
17.3 Network Resources Virtualization in Optical Networks	590
17.4 Virtual Optical Network (VON)	594
17.5 Network Function Virtualization in Optical Networks	598
17.6 Conclusion	605
References	605
18 Metropolitan Networks	
<i>Ashwin Gumaste</i>	609
18.1 Metro Transport Network Architecture	610
18.2 SONET/SDH	611
18.3 Optical Transport Network (OTN)	613
18.4 Metro IP/MPLS	615
18.5 Metro Optical Network	618
18.6 Metro Ethernet	621
18.7 SDN and Metro Networks	626
18.8 Network Function Virtualization (NFV)	627
18.9 Best Practices for Metro Network Design	628
18.10 Summary	629
References	629
19 Energy Efficiency in Optical Networks	
<i>Daniel C. Kilper</i>	631
19.1 Energy and Optical Networks	631
19.2 Optical Components and Equipment	637
19.3 Energy-Efficient System and Network Architectures	643
19.4 Energy-Efficient Network Design	652
19.5 Standards, Guidance, and Data Sources	657
19.6 Conclusions	658
References	658
20 Optical Packet Switching and Optical Burst Switching	
<i>Pablo Jesus Argibay-Losada, Dominique Chiaroni, Chunming Qiao</i>	665
20.1 Technology Basics	666
20.2 Optical Burst Switching: Concept and Technology	667

20.3	Optical Packet Switching: Concept and Technology.....	677
20.4	General Conclusions.....	698
	References	698

Part C Datacenter and Super-Computer Networking

21	Evolving Requirements and Trends in Datacenter Networks	
	<i>Hong Liu, Ryohei Urata, Xiang Zhou, Amin Vahdat</i>	707
21.1	Intra-Datacenter Network	709
21.2	Inter-Datacenter Network	718
21.3	Conclusion	722
	References	723
22	Evolving Requirements and Trends of HPC	
	<i>Sébastien Rumley, Keren Bergman, M. Ashkan Seyedi, Marco Fiorentino</i> ..	725
22.1	Challenges of HPC	725
22.2	Defining High-Performance Computing	726
22.3	Contemporary High-Performance Interconnection Networks.....	732
22.4	Future of Optics in HPC Interconnects	746
22.5	Summary	751
	References	751
23	Intra-Datacenter Network Architectures	
	<i>Roberto Proietti, Pouya Fotouhi, Sebastian Werner, S.J. Ben Yoo</i>	757
23.1	Trends and Future Challenges of Cloud Data Centers	757
23.2	Data Center Topologies	760
23.3	Emerging Data Center Solutions with Photonics Technologies	766
23.4	Conclusions	774
	References	775
24	System Aspects for Optical Interconnect Transceivers	
	<i>Brad Booth, David Piehler</i>	779
24.1	Data Center Requirements	779
24.2	SMF Transmitter Toolkit	784
24.3	Optical Specifications	786
24.4	25 G/λ, 50 G/λ, and 100 G/λ Optical Technologies	787
24.5	Optical Packaging.....	789
24.6	The Future	792
	References	792
25	Optical Switching for Data Center Networks	
	<i>Nick Parsons, Nicola Calabretta</i>	795
25.1	Data Center Network Architecture: Requirements and Challenges ..	796
25.2	Data Center Network Architectures Based on Optical Circuit Switching.....	803
25.3	Data Center Network Architectures Based on Optical Packet/ Burst Switching	809
25.4	Perspective on Optical Switching Technologies in Future DCs.....	820
25.5	Conclusion and Discussion	821
	References	822

Part D Optical Access and Wireless Networks

26 Introduction to Optical Access Networks	
<i>Björn Skubic, Lena Wosinska</i>	831
26.1 Evolution of Fixed-Access Networks and Impact on Society	831
26.2 Access Network Architectures: Evolution and Trends	834
26.3 Optical Access Systems/Technologies and Standards	840
26.4 Comparison of Architectural Aspects of Different Systems and Technologies.....	843
26.5 Summary	847
References	847
27 Current TDM-PON Technologies	
<i>Jun-ichi Kani, Doutje van Veen</i>	849
27.1 Passive Optical Networks.....	849
27.2 Physical Layer Technologies	851
27.3 Access Control Technologies in TDM-PON	855
27.4 XG(S)-PON and 10G E-PON	860
27.5 Security and Privacy	864
27.6 Survivability	864
27.7 Energy Efficiency in PON	866
27.8 Technologies Beyond 10G PON	869
References	869
28 Emerging PON Technologies	
<i>Josep Prat, Luca Valcarenghi</i>	871
28.1 Hardware, PHY, and MAC of NG-PON2	872
28.2 Energy Efficiency in TWDM PONs	881
28.3 WDM-PONs	889
28.4 OFDMA-PONs	890
28.5 Ultra-Dense WDM-PONs.....	896
28.6 OCDMA-PONs	906
References	907
29 PON Architecture Enhancements	
<i>Thomas Pfeiffer</i>	913
29.1 Background	914
29.2 Wireless x-Haul over PON.....	914
29.3 Flexible Converged Metro-Access Networks Based on PON	924
29.4 Local Interconnects in Point-to-Multipoint Networks	928
29.5 Smart ODN.....	937
References	947
30 Long-Reach Passive Optical Networks and Access/Metro Integration	
<i>David Payne, Giuseppe Talli, Marco Ruffini, Alan Hill, Paul Townsend</i>	951
30.1 The History of LR-PON	952
30.2 Architectural Design for the End-to-End Network Using LR-PON	956
30.3 DBA and DWA Protocol Implications for LR-PON	965
30.4 Physical Layer Design	969

30.5	Experimental Results for LR-PON Architectures in End-to-End Networks	980
30.6	Summary	985
	References	985
31	Digital Optical Front-Haul Technologies and Architectures	
	<i>Fabio Cavaliere, David Larrabeiti</i>	989
31.1	Fronthaul Networks: Definitions and Terminology	989
31.2	Digital Fronthaul Standards	991
31.3	Physical-Layer Multiplexed Optical Fronthaul	993
31.4	Circuit Multiplexing of Fronthaul Links	996
31.5	Fronthaul over Packet	998
31.6	Evolution of Fronthaul Networks	1008
31.7	Conclusions	1010
	References	1010
32	Analog Optical Front-Haul Technologies and Architectures	
	<i>John E. Mitchell</i>	1013
32.1	Developments in Radio Access Networks	1014
32.2	General Overview of Analog Radio-Over-Fiber Technologies	1015
32.3	Analog Radio Over Fiber (A-RoF)	1019
32.4	Concluding Remarks	1027
	References	1028
33	Optical Networking for 5G and Fiber-Wireless Convergence	
	<i>Gee-Kung Chang, Mu Xu, Feng Lu</i>	1031
33.1	Challenges Associated with the Introduction of 5G	1032
33.2	Overview of Fiber-Wireless Integrated Fronthaul Systems in 5G	1036
33.3	Advanced Digital Signal Processing in 5G Converged Networks	1047
33.4	Summary	1054
	References	1054
34	Space Optical Links for Communication Networks	
	<i>Alberto Carrasco-Casado, Ramon Mata-Calvo</i>	1057
34.1	Principles of Free-Space Optical Communication	1058
34.2	Characteristics of the Atmospheric Channel	1068
34.3	Low-Earth-Orbit Satellite Communications	1073
34.4	Geostationary Satellite Communications	1082
34.5	Future Optical Satellite Networks	1094
	References	1099
35	Visible Light Communications	
	<i>Xin Lin, Tomokuni Matsumura</i>	1105
35.1	Overview of Visible Light Communication (VLC)	1105
35.2	Visible Light (VL) Sources	1107
35.3	VL Detectors	1112
35.4	VLC Techniques	1114
35.5	Current Applications	1119
	References	1122

36 Optical Communications and Sensing for Avionics	
<i>Alireza Behbahani, Mehrdad Pakmehr, William A. Stange</i>	1125
36.1 Fiber-Optic Communication	1125
36.2 Current and Future Flight Control Systems	1127
36.3 Fiber-Optic Sensors	1134
36.4 Conclusion	1144
References	1145
Subject Index	1151

List of Abbreviations

3R	reamplification–reshaping–retiming	ATMOS	asynchronous-transfer-mode optical switching
4-PAM	4-ary pulse amplitude modulation	AUI	attachment unit interface
4QD	four-quadrant detector	AWC	automatic wavelength controllers
5G NR	5G New Radio	AWG	arrayed waveguide grating
5GC	5G core	AWGN	additive white Gaussian noise
		AWGR	arrayed waveguide grating router

A

A-RoF	analog radio over fiber
AAA	authentication, authorization and accounting
ABNO	application-based network operation
ABRT	assured bandwidth restoration time
ACF	autocorrelation function
ACFS	approximate closed-form solution
ACL	access control list
ACN	access cloud network
ACO	analog coherent optics
ACT	active control technologies
ACTN	abstraction and control of transport networks
ADC	analog-to-digital converter
ADCT	adaptive diversity combining technique
ADM	add-drop multiplexer
ADSL	asymmetric digital subscriber line
AES	advanced encryption standard
AFDX	avionics full-duplex switched Ethernet
AFPM	asymmetric Fabry–Perot modulator
AGC	automatic gain control
AIMD	additive-increase-multiplicative-decrease
AIR	achievable information rate
AMCC	auxiliary management and control channel
AMP	asynchronous mapping procedure
ANN	artificial neural network
AOC	active optical cable
AoD	architecture-on-demand
AOM	acousto-optic modulator
AON	active optical network
APD	avalanche photodiode
APSK	amplitude and phase-shift keying
ARON	application-driven reconfigurable optical network
ARP	address resolution protocol
ARPANET	Advanced Research Projects Agency Network
AS-PCE	active stateful path computation element
ASE	amplified spontaneous emission
ASI	asymmetric information
ASIC	application-specific integrated circuit
ASON	automatic switched optical network
ASTN	automatic switched transport network
ATM	asynchronous transfer mode

B

BBG	baseband group
BBU	baseband unit
BDA	backbone destination address
BDD	bounded distance decoding
BDI	backward defect indication
BEC	binary erasure channel
BEI	backward error indication
BER	bit error rate
BFD	bidirectional forwarding detection
BFS	breadth-first search
BGA	ball grid array
BGP	border gateway protocol
BICM	bit-interleaved coded modulation
BIF	bend-insensitive fiber
BIM	baseband intensity modulation
BIP	bit-interleaved parity
BLSR	bidirectional line-switched ring
BMP	bit-synchronous mapping procedure
BMRx	burst-mode receiver
BOTDR	Brillouin optical time domain reflectometry
BP	belief propagation
BPD	balanced photodetector
BPDU	bridge protocol data unit
BPM	business process management
BPON	broadband PON
BPS	blind phase search
BPSK	binary phase-shift keying
BR	border router
BRAS	broadband remote-access server
BRF	bend-resistant fiber
BRPC	backward recursive path computation
BS	base station
BSA	bit-stream access
BSC	binary symmetric channel
BSS	business support software
BTC	block turbo code
BTS	base transceiver station
BTT	blade tip timing
BU	bandwidth update
BVT	bandwidth-variable transponder
BW	bandwidth
BXC	waveband cross-connect

C			
C-MCF	coupled multicore fiber	CORD	central office rearchitected as data center
C-RAN	centralized radio access network	COTS	commercial off-the-shelf
CA	carrier aggregation	CP	control plane
CA/CDA	channel aggregation/deaggregation	CPE	carrier-phase estimation
CaaS	computing-as-a-service	CPLD	complex programmable logic device
CAGR	compound annual growth rate	CPM	cross-phase modulation
CAP	carrierless amplitude and phase modulation	CPO	co-packaged optics
CAPEX	capital expenditure	CPRI	common public radio interface
CaTV	cable TV	CPS	confidential path segment
CAWG	cyclic arrayed waveguide grating	CPU	central processing unit
CB	coordinated beamforming	CQI	channel quality indicator
CBM	condition-based maintenance	CR-LDP	constrained routed label distribution protocol
CBR	constant bit rate	CRC	cyclic redundancy check
CC-MCF	coupled-core multicore fiber	CRI	color rendering index
CCDM	constant composition distribution matching	CRR	corner retroreflector
CCM	connectivity check message	CRUD	create, read, update, delete
CCR	carrier-to-crosstalk ratio	CRZ	chirped return-to-zero
CCS	centralized CS	CS	coordinated scheduling
CCSDS	Consultative Committee for Space Data Systems	CSC	customer SDN controller
CD	chromatic dispersion	CSCG	circularly symmetric complex Gaussian
CDC	colorless, directionless and contentionless	CSF	cutoff-shifted fiber
CDF	cumulative distribution function	CSI/CQI	channel state information channel quality indicator
CDM	code-division multiplexing	CSK	color-shift keying
CDN	content distribution network	CSM	circuit switch manager
CDR	clock and data recovery	CSMA	carrier sense multiple access
CE	carrier-Ethernet	CSP	constrained shortest path
CEI	common electrical interfaces	CSRZ	carrier-suppressed RZ
CEI IA	Common Electrical I/O Implementation Agreement	CTAG	customer tag
CFI	canonical format indicator	CTS	clear to send
CFM	connectivity fault management	CU	central unit
CFP	40G/100G form-factor	CW	continuous wave
CFP	C form-factor pluggable	CWDM	coarse wavelength-division multiplexing
CICQ	combined input-crosspoint queuing		
CIOQ	combined input-output queuing	D	
CIR	committed information rate	D-CPI	data-controller plane interface
CLI	command line interface	D-RAN	distributed radio access network
CMA	constant-modulus algorithm	D-RoF	digital radio over fiber
CMC	ceramic matrix composites	DA-RSA	distance-adaptive RSA
CMIS	common MIS	DAC	digital-to-analog converter
CMOS	complementary metal-oxide-semiconductor	DAS	distributed antenna system
CMP	chip multiprocessor	DBA	dynamic bandwidth assignment/allocation
cMTC	critical machine-type communication	DBORN	dual-bus optical ring network
CO	central office	DBP	digital backpropagation
Co-DBA	cooperative dynamic bandwidth assignment	DBR	distributed Bragg reflector
COI	channel-of-interest	DBRu	dynamic bandwidth report upstream
CoMP	coordinated multipoint	DCAE	data collection analytics and events
COP	Control Orchestration Protocol	DCC	digitized component carrier
CORBA	common object request broker architecture	DCF	dispersion-compensating fiber
		DCI	datacenter interconnection
		DCM	dispersion-compensation module
		DCN	data center network
		DCO	digital coherent optics
		DCT	dispersion compensation technique
		DCU	dispersion-compensating unit

DD	direct detection	eBCH	extended BCH
DD-LMS	decision directed least mean squared	ECL	external cavity laser
DDoS	distributed denial of service	ECMP	equal cost multipath
DECS	distributed engine control system	eCPRI	enhanced CPRI
DEI	drop eligibility indicator	EDB	electrical duobinary
DEMUX	demultiplexer	EDC	electronic dispersion compensation
demux	wavelength demultiplexer	EDFA	erbium-doped fiber amplifier
DetNet	deterministic networking	EDRS	European data relay system
DFB	distributed feedback	EEPROM	electronically erasable programmable read-only memory
DFE	decision-feedback equalizer	EF	exaFLOPS
DFTS-DMT	discrete Fourier transform spread DMT	EFEC	enhanced forward error correction
DGD	differential group delay	EGN	enhanced GN
DGEF	dynamic gain equalizing filter	EGT	exhaust gas temperature
DiffServ	differentiated services	EHF	extremely high frequency
DL	downlink	EIHP	equivalent isotropically radiated power
DMD	differential mode delay	ELF	extremely low frequency
DMF	dispersion-managed fibers	EM	expectation-maximization
DML	directly modulated laser	eMBB	enhanced mobile broadband
DMSC	discrete memoryless symmetric channel	EMI	electromagnetic interference
DMT	discrete multitone	EML	externally modulated laser
DN-MZM	double-nested Mach-Zehnder	EMP	extrinsic message passing
DNN	deep neural network	EMS	element management system
DNS	domain name server	ENOB	effective number of bits
DOCSIS	data over cable service interface specification	EOM	external optical modulator
DoD	Department of Defense	EON	elastic optical network
DOQ	distributed output-queued	EPC	evolved packet core
DP	dual-polarization	EPON	Ethernet PON
DPI	deep packet inspection	EPS	electronic packet switching
DPM	demarcation point monitor	ERO	explicit route object
DPSK	differential phase-shift keying	eRP	enhanced RP
DQPSK	differential quadrature phase-shift keying	ERPS	Ethernet ring protection switching
DR	dynamic range	ES	intercluster optical switch
DRBS	double Rayleigh backscattered signal	ESCON	enterprise systems connection
DS	downstream	ESS	emission sensing system
DSB-AM	double-sideband amplitude modulation	ETS	engineering test satellite
DSCP	differentiated services code point	EVC	Ethernet virtual circuit
DSF	dispersion-shifted fiber	EVM	error vector magnitude
DSL	digital subscriber line	EXP	experimental
DSLAM	digital subscriber line access multiplexer		
DSO	digital storage oscilloscope		
DSP	digital signal processing		
DU	distributed unit		
DVB	digital video broadcasting		
DWA	dynamic wavelength assignment		
DWBA	dynamic wavelength and bandwidth allocation		
DWDM	dense wavelength-division multiplexing		
DXC	digital cross-connect		
E			
E-NNI	external network-to-network interface		
E-PON	Ethernet PON		
E/O	electro-optic		
EAM	electroabsorption modulator		
EAT	electroabsorption transceiver		
EB	electronic buffer		
		F	
		FADEC	full authority digital electronic controller
		FASA	flexible access system architecture
		FB	flattened butterfly
		FBG	fiber Bragg grating
		FBL	fly-by-light
		FBNQ	fitting-based nonlinear quantization
		FBW	fly-by-wire
		FCAPS	fault identification, configuration, accounting, performance, security
		FCS	frame check sequence
		FDL	fiber delay line
		FDM	frequency-division multiplexing
		FEC	forward error correction
		FER	frame error rate
		FFE	feed-forward equalizer
		FIB	forwarding information base
		FIC	fabric interface chip

FICON	fibre connection
FIR	finite impulse response
FIT	failures in time
FLOPS	floating point operations per second
FLOW_MOD	flow table modification message
FM-HD	field modulation and heterodyne detection
FM-MFC	few-mode multicore fiber
FMDF	fiber main distribution frame
FMF	few-mode fiber
FML	frequency modulated laser
FOADM	fixed optical add/drop multiplexer
FOBS	fast optical burst selector
FOIC	FlexO interface
FOM	figure-of-merit
FOSS	fiber-optic sensing system
FOV	field of view
FP	Fabry–Pérot
FPA	focal-plane array
FPGA	field-programmable gate array
FPM	four-photon-mixing
FRLP	frequency-resolved LP
FRR	fast reroute
FSAN	full-service access network
FSC	fiber-switch capable
FSE	fast statistical estimation
FSO	free-space optics
FSOC	free-space optical communication
FSR	free spectral range
FTTH	fiber-to-the-home
FTTP	fiber to the premises
FTTx	fiber-to-the-home/building
FWA	fixed wireless access
FWI	forced wake-up indication
FWM	four-wave mixing

G

G-ACh	generic associated channel
G-LDPC	generalized LDPC
G-PON	gigabit-capable PON
GBIC	gigabit interface converter
GE-PON	gigabit Ethernet PON
GEM	G-PON encapsulation method
GEO	geostationary equatorial orbit
GF	gigaFLOPS
GFP	generic framing procedure
GigE	gigabit Ethernet
GMD	generalized minimum distance
GMI	generalized mutual information
GMP	generic mapping procedure
GMPLS	generalized multiprotocol label switching
gNB	next-generation node B
GOLD	ground/orbiter lasercomm demonstration
GPC	generalized product code
GPON	gigabit-capable PON
GPRS	general packet radio service

GSM	Global System for Mobile Communications
GTC	G-PON transmission convergence
GVD	group velocity dispersion

H

HAF	hole-assisted fiber
HALL	hierarchical all-to-all
HAP	high-altitude platform
HARQ	hybrid automatic repeat request
HC-PBGF	hollow-core PBGF
HDD	hard-decision decoding
HF	high-frequency
Hi-LIONS	hierarchical low-latency interconnect optical network switch
HICALI	high-speed communication with advanced laser instrument
HNLF	highly nonlinear fiber
HOM	high-order modulation
HOPR	hybrid optoelectronic router
HOS	hybrid optical switching
HOSA	hybrid optical switch architecture
HPC	high-performance computing
HPCG	high-performance conjugate gradient
HR-OSA	high-resolution optical spectrum analyzer
HSS	home subscriber server
HTS	high-throughput satellites
HTTP	hypertext transfer protocol

I

I-LPPM	inverted-LPPM
I-NNI	internal network-to-network interface
IA-RWA	impairment-aware routing and wavelength assignment
IaaS	Internet-as-a-service
IAD	intelligent access device
iBDD	iterative BDD
Ibpa	interblade phase angle
ICI	intercell interference
ICMP	internet control message protocol
ICR	integrated coherent receiver
ICT	information and communication technologies
ICTP	inter-channel termination protocol
ID	identification
IDA	ideal distributed amplification
IDC	inter-data-center
IE	information element
IF	intermediate frequency
IFFT	inverse fast Fourier transform
IFWM	intrachannel four-wave mixing
iGMDD-SR	iterative GMD decoding with scaled reliability
IGP	interior gateway protocol
IIR	intensity impulse response
IL	insertion loss

ILC	illumination-light communication	LIONS	low-latency interconnect optical network switch
ILM	incoming label map	LLDP	Link Layer Discovery Protocol
ILP	integer linear programming	LLID	logical link identifier
IM	intensity modulation	LLN	linear lightwave network
IMS	Internet protocol multimedia subsystem	LLR	log-likelihood ratio
IoT	Internet of things	LLU	local loop unbundling
IP	Internet protocol	LMP	link-management protocol
IP/MPLS	Internet protocol over multiprotocol label switching	LMS	least mean squares
IPC	input port interface card	LNA	low-noise amplifier
iPLC	integrated planar lightwave circuit	LO	local oscillator
IPoDWDM	IP over DWDM	LOGON	locally-optimal globally-optimal Nyquist
IPR	intellectual property rights	LPF	low-pass filter
IPSec	IP security	LR-PON	long-reach passive optical network
IS-IS-TE	intermediate system to intermediate system traffic engineering	LSA	link state advertisement
ISG	industry specification group	LSC	lambda-switch capable
ISI	intersymbol interference	LSE	least-squares equalization
ISIS-TE	intermediate system with traffic engineering	LSP	label-switched path
ISM	intelligent splitter monitor	LSR	label-switched router
ISP	Internet service provider	LTE	long term evolution
ITAG	intermediate service tag	LTM	linktrace message
ITU-T	International Telecommunication Union-Telecommunications	LUCE	laser-utilizing communications equipment
IXP	internet exchange point		
IXPM	intrachannel cross-phase modulation		

J

JDRS	Japan data relay system
JSF	Joint Strike Fighter
JSON	JavaScript object notation

L

L2SC	layer-2-switch capable
LAG	link aggregation group
LAN	local area network
LBS	location-based service
LC	line card
LCAS	link capacity adjustment scheme
LCE	laser communication equipment
LCOS	liquid crystal on silicon
LCP	local connection point
LCRD	laser communications relay demonstration
LCT	laser communications terminal
LDACS	L-band digital aeronautical communications system
LDC	linear divider/combiner
LDGD	largest differential group delay
LDP	label distribution protocol
LDPC	low-density parity check
LER	label edge router
LH	long-haul
LiFi	light-fidelity
LION	large-scale interconnect optical network

M

M2M	machine-to-machine
MAC	media access control
MAI	multiple access interference
MAN	metropolitan area network
MANO	management and network orchestration
MC-nodes	metro/core nodes
MCF	multicore fiber
MCLCD	Micius coherent laser communication demonstration
MCP	multiconstrained path
MCS	multicast switch
MCSB	maximal contiguous slot block
MD	mode dispersion
MD-ROADM	multidegree ROADM
MDIO	management data input/output
MDL	mode-dependent loss
MDM	mode division multiplexing
MDRU	movable and deployable resource unit
MDS	maximum distance separable
MDU	multiple dwelling unit
MEF	Metro Ethernet Forum
MEMS	microelectromechanical system
MEN	metro Ethernet network
MEP	maintenance end point
MET	multi-edge type
MFAS	multiframe alignment signal
MFD	mode-field diameter
MFH	mobile fronthaul
MGTC	minimum guaranteed transmission container content
MI	mutual information
MIB	management information base
MILP	mixed integer linear program

MIMO	multiple-input multiple-output	NGMN	next-generation mobile network
minEMBc	minimum effective modal bandwidth	NIC	network interface card
MP	mixed integer program	NLFT	nonlinear Fourier transform
MLC	multilevel coding	NLI	nonlinear interference
MLD	multilane distribution	NLPN	nonlinear phase noise
MMC	metal matrix composites	NLRI	network layer reachability information
MMF	multimode fiber	NMS	network management system
MMT	multiple match table	NOC	network operation center
mMTC	massive machine-type communication	NOMA	nonorthogonal multiplexing and multiple access
MMUX	mode multiplexer		
MMW	millimeter wave	NRZ	nonreturn-to-zero
MNH	multidomain network hypervisor	NSMS	nonintrusive stress measurement system
MOD	optical intensity modulator	NSNI	nonlinear signal–noise interaction
MONET	multiple wavelength optical network	NTE	network terminating equipment
MP	minimum path	NTP	network time protocol
MPCP	multipoint control protocol	NVM	nonvolatile memory
MPEG	Moving Picture Experts Group	NZDSF	nonzero dispersion-shifted fiber
MPI	multiple-path interference		
MPLC	Multiplane light convertor		
MPLS	multiprotocol label switching	0	
MPO	(multifiber) connector		
MPSK	<i>M</i> -level PSK constellation	O/E	optic-electro
MPTCP	multipath TCP	OA	optical amplifier
MR	maximum reach	OADM	optical add-drop multiplexer
MRR	microring resonator	OAI	open air interface
MS	maximum scattering	OAM	operation, administration and maintenance
MSA	multisource agreement		
MSM	metal-semiconductor-metal	OAP	optical access point
MSN	multiservice node	OBI	optical beat interference
MSTE	minimum spanning tree with enhancement	OBLC	optical burst line card
		OBO	on-board optics
MSTP	multiple spanning tree protocol	OBS	optical burst switching
MT	match table	OBSAI	Open Base Station Architecture Initiative
MTBF	mean time between failures	OBSC	optical burst switch card
MTSO	mobile telephone switching office	OC	OpenFlow controller
MTTR	mean time to repair	OCDM	optical code division multiplexing
MTU	maximum transmission unit	OCDMA	optical code division multiple access
MZI	Mach–Zehnder interferometer	Och	optical channel layer
MZM	Mach–Zehnder modulator	OCM	optical channel monitor
		OCS	optical circuit switching
		ODB	optical duobinary
		ODN	optical distribution network
		ODU	optical data unit
		OE-PCB	optoelectronic printed circuit board
		OEM	original engine manufacturers
		OEO	optical–electrical–optical
		OF	OpenFlow
		OF-CONFIG	OpenFlow Configuration
		OFDM	orthogonal frequency-division multiplexing
		OFDR	optical frequency domain reflectometry
		OFL	overfilled launch
		OFL	optical frequency locked loop
		OFS	optical flow switching
		OGS	optical ground station
		OICETS	optical inter-orbit communications engineering test satellite
		OLM	Optical Layer Monitoring
		OLO	optical local oscillator
		OLS	optical latching switch

N

NBI	northbound interface
NC	node controller
NCG	net coding gain
NCO	number-controlled oscillator
ND	nodal diameter
NETCONF	network configuration protocol
NetOS	network operating system
NF	noise figure
NFDM	nonlinear frequency-division multiplexing
NFS	Network File System
NFV	network function virtualization
NFVO	NFV orchestrator
NG-PON	next-generation PON
NG-RAN	next-generation radio access network
NGMI	normalized generalized mutual information

OLT	optical line terminal	PHY	physical layer
OM	output module	PIC	photonic integrated circuit
OMBc	overfilled modal bandwidth	PL	photonic lantern
OMCI	ONU management and control interface	PLI	physical-layer impairment
OMM	ODN management module	PLL	phase-locked loop
OMS	optical multiplex section	PLOAM	physical-layer operations, administration and maintenance
ONAP	open network automation platform		
ONOS	open network operating system	PLOu	upstream physical layer overhead
ONU	optical network unit	PLZT	planar lightwave circuit
OOK	on-off keying	PM	polarization multiplexing
OPA	optical parametric amplifier	PMD	polarization mode dispersion
OPEX	operational expenditure	PMF	probability mass function
OPLL	optical phase locked loop	PNF	physical network function
OPS	optical packet switching	POADM	packet optical add/drop multiplexer
OPU	optical channel payload unit	POD	portable data center
OQ	output-queueing	POF	protocol oblivious forwarding
ORI	open radio equipment interface	POL	passive optical LAN
OSFP	octal small form-factor pluggable	PON	passive optical network
OSNR	optical signal-to-noise ratio	PON-ID	PON identifier
OSPF	open shortest path first	POS	packet-over-SONET
OSS	operations support system	POTP	packet optical transport platform
OTDR	optical time domain reflectometry	PPM	pulse-position modulation
OTL	optical trunk line	PPRN	phase and polarization-rotation noise
OTL	optical transport lane	PQ	priority queuing
OTLC	optical transport lane	PRBS	pseudo-random binary sequence
OTN	optical transport network	PRC	primary reference clock
OTS	optical transmission section	PRONet	programmable optical network
OTSiG	optical tributary signal group	PSBT	phase-shaped binary transmission
OTU	optical transport unit	PSD	power spectral density
OVS	OpenVSwitch	PSF	point spread function
OXC	optical cross-connect	PSK	phase-shift keying
		PSP	principal states of polarization
		PTMP	point to multipoint
		PTP	precision time protocol
		PtP	point-to-point
		PTS	partial transmission sequence
		PUCCH	physical uplink control channel
		PUSCH	physical uplink shared channel
		PVC	permanent virtual circuit
		PW	pseudowire
		PWM	pulse-width modulation

P

PA	power amplification
PAM	pulse-amplitude modulation
PAM4	four-level pulse-amplitude modulation
PAPR	peak-to-average power ratio
PAS	probabilistic amplitude shaping
PBB	provider backbone bridging
PBC	polarization beam combiner
PBG	photonic band gap
PBGF	photonic band-gap fiber
PBS	polarization beam splitter
PBX	private branch exchange
PCB	printed circuit board
PCBd	physical control block downstream
PCC	path computation client
PCE	path computation element
PCEP	path computation element protocol
PCIe	peripheral component interconnect express
PCT	paired channel technology
PDCP	packet data convergence protocol
PDF	probability density function
PDG	polarization-dependent gain
PDH	plesiochronous digital hierarchy
PDL	polarization-dependent loss
PDM	polarization division multiplexing

Q

QAM	quadrature amplitude modulation
QKD	quantum key distribution
QoS	quality of service
QoT	quality of transmission
QPAR	quasi-passive reconfigurable node
QPSK	quadrature phase-shift keying
QSFP	quad small form-factor pluggable

R

RAID	redundant array of independent discs
RAM	random-access memory
RAN	radio access network
RAU	radio access unit
RCC	radio cloud center