Springer Handbook of Optical Networks

Mukherjee
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Winzer
Zhao
Editors

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(Eds.)

With 838 Figures and 102 Tables

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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.

Robert W. Tkach
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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

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 focusing 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
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Peter Winzer
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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 tech nical 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.

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Contents

Part C Datacenter and Super-Computer Networking

Part D Optical Access and Wireless Networks

List of Abbreviations

3R	reamplification–reshaping–retiming
4-PAM	4-ary pulse amplitude modulation
4QD	four-quadrant detector
5G NR	5G New Radio
5GC	5G core

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 combing 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
ATMOS	asynchronous-transfer-mode optical switching
AUI	attachment unit interface
AWC	automatic wavelength controllers
AWG	arrayed waveguide grating
AWGN	additive white Gaussian noise
AWGR	arrayed waveguide grating router

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

D

D-CPI	data-controller plane interface
D-RAN	distributed radio access network
D-RoF	digital radio over fiber
DA-RSA	distance-adaptive RSA
DAC	digital-to-analog converter
DAS	distributed antenna system
DBA	dynamic bandwidth assignment/allocation
DBORN	dual-bus optical ring network
DBP	digital backpropagation
DBR	distributed Bragg reflector
DBRu	dynamic bandwidth report upstream
DCAE	data collection analytics and events
DCC	digitized component carrier
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
DD-LMS	decision directed least mean squared
DDoS	distributed denial of service
DECS	distributed engine control system
DEI	drop eligibility indicator
DEMUX	demultiplexer
demux	wavelength demultiplexer
DetNet	deterministic networking
DFB	distributed feedback
DFE	decision-feedback equalizer
DFTS-DMT	discrete Fourier transform spread DMT
DGD	differential group delay
DGEF	dynamic gain equalizing filter
DiffServ	differentiated services
DL	downlink
DMD	differential mode delay
DMF	dispersion-managed fibers
DML	directly modulated laser
DMSC	discrete memoryless symmetric channel
DMT	discrete multitone
DN-MZM	double-nested Mach–Zehnder
DNN	deep neural network
DNS	domain name server
DOCSIS	data over cable service interface specification
DoD	Department of Defense
DOQ	distributed output-queued
DP	dual-polarization
DPI	deep packet inspection
DPM	demarcation point monitor
DPSK	differential phase-shift keying
DQPSK	differential quadrature phase-shift keying
DR	dynamic range
DRBS	double Rayleigh backscattered signal
DS	downstream
DSB-AM	double-sideband amplitude modulation
DSCP	differentiated services code point
DSF	dispersion-shifted fiber
DSL	digital subscriber line
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
eBCH	extended BCH
ECL	external cavity laser
ECMP	equal cost multipath
eCPRI	enhanced CPRI
EDB	electrical duobinary
EDC	electronic dispersion compensation
EDFA	erbium-doped fiber amplifier
EDRS	European data relay system
EEPROM	electronically erasable programmable read-only memory
EF	exaFLOPS
EFEC	enhanced forward error correction
EGN	enhanced GN
EGT	exhaust gas temperature
EHF	extremely high frequency
EIRP	equivalent isotropically radiated power
ELF	extremely low frequency
EM	expectation-maximization
eMBB	enhanced mobile broadband
EMI	electromagnetic interference
EML	externally modulated laser
EMP	extrinsic message passing
EMS	element management system
ENOB	effective number of bits
EOM	external optical modulator
EON	elastic optical network
EPC	evolved packet core
EPON	Ethernet PON
EPS	electronic packet switching
ERO	explicit route object
eRP	enhanced RP
ERPS	Ethernet ring protection switching
ES	intercluster optical switch
ESCON	enterprise systems connection
ESS	emission sensing system
ETS	engineering test satellite
EVC	Ethernet virtual circuit
EVM	error vector magnitude
EXP	experimental

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

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
minEMBc	minimum effective modal bandwidth
MIP	mixed integer program
MLC	multilevel coding
MLD	multilane distribution
MMC	metal matrix composites
MMF	multimode fiber
MMT	multiple match table
mMTC	massive machine-type communication
MMUX	mode multiplexer
MMW	millimeter wave
MNH	multidomain network hypervisor
MOD	optical intensity modulator
MONET	multiple wavelength optical network
MP	minimum path
MPCP	multipoint control protocol
MPEG	Moving Picture Experts Group
MPI	multiple-path interference
MPLC	Multiplane light convertor
MPLS	multiprotocol label switching
MPO	(multifiber) connector
MPSK	*M*-level PSK constellation
MPTCP	multipath TCP
MR	maximum reach
MRR	microring resonator
MS	maximum scattering
MSA	multisource agreement
MSM	metal-semiconductor-metal
MSN	multiservice node
MSTE	minimum spanning tree with enhancement
MSTP	multiple spanning tree protocol
MT	match table
MTBF	mean time between failures
MTSO	mobile telephone switching office
MTTR	mean time to repair
MTU	maximum transmission unit
MZI	Mach–Zehnder interferometer
MZM	Mach–Zehnder modulator

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
NGMN	next-generation mobile network
NIC	network interface card
NLFT	nonlinear Fourier transform
NLI	nonlinear interference
NLPN	nonlinear phase noise
NLRI	network layer reachability information
NMS	network management system
NOC	network operation center
NOMA	nonorthogonal multiplexing and multiple access
NRZ	nonreturn-to-zero
NSMS	nonintrusive stress measurement system
NSNI	nonlinear signal–noise interaction
NTE	network terminating equipment
NTP	network time protocol
NVM	nonvolatile memory
NZDSF	nonzero dispersion-shifted fiber

O

O/E	optic-electro
OA	optical amplifier
OADM	optical add-drop multiplexer
OAI	open air interface
OAM	operation, administration and maintenance
OAP	optical access point
OBI	optical beat interference
OBLC	optical burst line card
OBO	on-board optics
OBS	optical burst switching
OBSAI	Open Base Station Architecture Initiative
OBSC	optical burst switch card
OC	OpenFlow controller
OCDM	optical code division multiplexing
OCDMA	optical code division multiple access
OCh	optical channel layer
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
OFLL	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

OLT	optical line terminal
OM	output module
OMBc	overfilled modal bandwidth
OMCI	ONU management and control interface
OMM	ODN management module
OMS	optical multiplex section
ONAP	open network automation platform
ONOS	open network operating system
ONU	optical network unit
OOK	on–off keying
OPA	optical parametric amplifier
OPEX	operational expenditure
OPLL	optical phase locked loop
OPS	optical packet switching
OPU	optical channel payload unit
OQ	output-queuing
ORI	open radio equipment interface
OSFP	octal small form-factor pluggable
OSNR	optical signal-to-noise ratio
OSPF	open shortest path first
OSS	operations support system
OTDR	optical time domain reflectometry
OTL	optical trunk line
OTL	optical transport lane
OTLC	optical transport lane
OTN	optical transport network
OTS	optical transmission section
OTSiG	optical tributary signal group
OTU	optical transport unit
OVS	OpenVSwitch
OXC	optical cross-connect

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
PHY	physical layer
PIC	photonic integrated circuit
PL	photonic lantern
PLI	physical-layer impairment
PLL	phase-locked loop
PLOAM	physical-layer operations, administration and maintenance
PLOu	upstream physical layer overhead
PLZT	planar lightwave circuit
PM	polarization multiplexing
PMD	polarization mode dispersion
PMF	probability mass function
PNF	physical network function
POADM	packet optical add/drop multiplexer
POD	portable data center
POF	protocol oblivious forwarding
POL	passive optical LAN
PON	passive optical network
PON-ID	PON identifier
POS	packet-over-SONET
POTP	packet optical transport platform
PPM	pulse-position modulation
PPRN	phase and polarization-rotation noise
PQ	priority queuing
PRBS	pseudo-random binary sequence
PRC	primary reference clock
PROnet	programmable optical network
PSBT	phase-shaped binary transmission
PSD	power spectral density
PSF	point spread function
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

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