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Roadmap

Roadmap on optical communications

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Abstract

The Covid-19 pandemic showed forcefully the fundamental importance broadband data communication and the internet has in our society. Optical communications forms the undisputable backbone of this critical infrastructure, and it is supported by an interdisciplinary research community striving to improve and develop it further. Since the first 'Roadmap of optical communications' was published in 2016, the field has seen significant progress in all areas, and time is ripe for an update of the research status. The optical communications area has become increasingly diverse, covering research in fundamental physics and materials science,

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high-speed electronics and photonics, signal processing and coding, and communication systems and networks. This roadmap describes state-of-the-art and future outlooks in the optical communications field. The article is divided into 20 sections on selected areas, each written by a leading expert in that area. The sections are thematically grouped into four parts with 4–6 sections each, covering, respectively, hardware, algorithms, networks and systems. Each section describes the current status, the future challenges, and development needed to meet said challenges in their area. As a whole, this roadmap provides a comprehensive and unprecedented overview of the contemporary optical communications research, and should be essential reading for researchers at any level active in this field.

Keywords: optical communications, hardware, algorithms, networks, systems

Contents

Acronyms

Acronym	Meaning	Section
3D	Three-dimensional	5, 6, 12
4G	Fourth generation	19
5G	Fifth generation	1, 12, 15, 19
6G	Sixth generation	1, 12, 15, 19
ACTN	Abstraction and control of traffic-engineered networks	13
ADC	Analog-to-digital converter	9
AI	Artificial intelligence	7, 13
API	Application programming interface	13
ASE	Amplified spontaneous emission	12
ASIC	Application-specific integrated circuit	4
AWGN	Additive white Gaussian noise	10, 11
BBU	Baseband unit	17
BCH	Bose, Ray-Chaudhuri, Hocquenghem	10
BDFA	Bismuth-doped fiber amplifier	3, 7
BER	Bit error rate	10
BM	Burst mode	15
BVT	Bandwidth-variable transponder	12
C-Rx	Coherent receiver	15
C-Tx	Coherent transmitter	15
CD	Chromatic dispersion	15
CDC	Colorless, directionless, and contentionless	12
CDR	Clock data recovery	14
CM	Continuous mode	15
CMA	Constant modulus algorithm	18
CMOS	Complementary metal–oxide–semiconductor	4
CPO	Co-packaged optics	5
CV	Computer vision	8
CWDM	Coarse wavelength-division multiplexing	14
DAC	Digital-to-analog converter	4, 9
DAS	Distributed acoustic sensing	18
DC	Data center	12
DFE	Decision-feedback equalization	14
DPD	Digital pre-distortion	9
DS	Downstream	15
DSP	Digital signal processing	1, 4, 15, 18, 21
DT	Digital twin	13
DWDM	Dense wavelength-division multiplexing	16
EDFA	Erbium-doped fiber amplifier	1, 6, 7, 12
EDWA	Erbium-doped waveguide amplifier	3
EGN	Enhanced Gaussian noise	9, 11
EON	Elastic optical network	12
FA	Fiber amplifier	3
FBA	Fiber Brillouin amplifier	3
FEC	Forward error correction	1, 10, 15, 16
FFE	Feedforward equalization	14
FM-MCF	Few-mode multi-core fiber	6
FMF	Few-mode fiber	2, 6
FOPA	Fiber-optical parametric amplifier	3
FRA	Fiber Raman amplifier	3
FSO	Free-space optical	19
FT-LO	Fast tunable local oscillator	15
FTTA	Fiber through the air	19
GN	Gaussian noise	7, 9
GS	Geometric shaping	11
HAPS	High-altitude platform station	19
HCF	Hollow-core fiber	2, 12
HD	Hard decision	10
HNLF	Highly nonlinear fiber	3
IEEE	Institute of Electrical and Electronics Engineers	15

(Continued.)

Acronyms (Continued.)

IF	Intermediate frequency	17
ILA	In-line amplifier	13
IM/DD	Intensity modulation and direct detection	1, 15, 21
InP	Indium phosphide	4
IP	Internet protocol	13
ISD	Information spectral density	7
ISRS	Interchannel stimulated Raman scattering	7, 12
ITU-T	International Telecommunication Union Telecommunication Standardization Sector	6, 12
LD	Laser diode	21
LDPC	Low-density parity-check	10, 15
LED	Light-emitting diode	21
LO	Local oscillator	15, 17
MB	Multiband	12
MC-EDFA	Multicore erbium-doped fiber amplifier	6
MCF	Multicore fiber	2, 6, 12, 13, 16
MD-GS	Multidimensional geometric shaping	11
MDL	Mode-dependent loss	6
MF	Multifiber	12
MIMO	Multiple-input multiple-output	6, 12, 21
ML	Machine learning	8, 12, 13
MMF	Multimode fiber	2, 6, 12, 13
MPLC	Multiplane light conversion	6
MPLS	Multiprotocol label switching	12, 13
MPO	Multifiber push-on	6
MSA	Multisource agreement	15
MUI	Multiuser information theory	11
MZM	Mach–Zehnder modulator	4, 5, 17
NBI	Northbound interface	13
NCG	Net coding gain	10
NFV	Network function virtualization	12
NLI	Nonlinear interference	7, 12
NLP	Natural language processing	8
NN	Neural network	8
NPR	Noise-to-power ratio	9
NRZ	Non-return-to-zero	15
NTN	Nonterrestrial network	19
O-OFDM	Optical orthogonal frequency division multiplexing	21
OA	Optical amplifier	3
OBI	Optical beat interference	15
ODN	Optical distribution network	15
OGGS	Optical ground gateway station	19
OH	Overhead	10
OLS	Optical line system	13
OLT	Optical line termination	15
ONU	Optical network unit	15
OOK	On–off keying	15
OSFP	Octal small-form-factor pluggable	14
OSNR	Optical signal-to-noise ratio	8, 12
OTSi	Optical tributary signal	13
P2MP	Point-to-multipoint	15
P2P	Point-to-point	15
PAM	Pulse amplitude modulation	14, 15
PAS	Probabilistic amplitude shaping	11
PAT	Positioning, acquisition, and tracking	19
PD	Photodiode	4
PDFA	Praseodymium-doped fiber amplifier	3
PDL	Polarization-dependent loss	10
PIA	Phase-insensitive amplifier	3
PIC	Photonic integrated circuit	3, 20

(Continued.)

Acronyms (Continued.)

Acronym	Meaning	Section
PON	Passive optical network	15
PPLN	Periodically poled lithium niobate	3
PS	Probabilistic shaping	11
PSA	Phase-sensitive amplifier	3
PSM	Parallel single-mode	14
QAM	Quadrature amplitude modulation	10, 11
QC	Quantum communication	20
QKD	Quantum key distribution	12, 13, 20
QoE	Quality-of-experience	12
QoT	Quality-of-transmission	12
RE	Rare earth	3
RF	Radio frequency	4, 19, 21
RIS	Reconfigurable intelligent surface	21
RL	Reinforcement learning	8
ROADM	Reconfigurable optical add–drop multiplexer	12, 13
RRH	Remote radio head	17
RS	Reed–Solomon	10, 15
Rx	Receiver	15
SBI	Southbound interface	13
SC-MCF	Strongly coupled multicore fiber	6
SD	Soft decision	10
SDM	Space-division multiplexing	1, 2, 3, 4, 6, 7, 12, 13, 16
SDN	Software-defined networking	12, 13
SE	Spectral efficiency	1, 11
SerDes	Serializer/deserializer	14
SiGe	Silicon germanium	4
SiP	Silicon photonics	4, 14
SMF	Single-mode fiber	2, 6, 12
SNR	Signal-to-noise ratio	7, 10, 11
SOA	Semiconductor optical amplifier	3, 7
SOH	Silicon-organic hybrid	4
SSE	Spatial spectral efficiency	6
SSMF	Standard single-mode fiber	15
SXC	Spatial cross-connect	6
T-LO	Tunable local oscillator	15
TDFA	Thulium-doped fiber amplifier	3, 7
TDM	Time-division multiplexing	15
TE	Transverse electric	5
TIA	Transimpedance amplifier	9
Tx	Transmitter	15
US	Upstream	15
UWB	Ultrawideband	7
VLC	Visible light communication	21
WC-MCF	Weakly-coupled multicore fiber	6
WDM	Wavelength-division multiplexing	1, 3, 6, 7, 11, 12
WSS	Wavelength-selective switch	12

1. Introduction

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Background

The worldwide tele- and data communications networks are key enablers for today's information-centric society. The need to transmit and receive digital information, be it in the form of online meetings, digital messages, media streaming or other information retrieval, is becoming a necessity, which was not least highlighted during the Covid-19 pandemic in 2020–2022. Underpinning this infrastructure is more than 50 years of research and development in optical communications, and today's internet would not have been possible without it.

The research field of optical communications is diversifying. While the first decades since the pioneering fiber experiments in the early 1970s focused on developing point-to-point fiber links with increasing data rates and distances, a wide range of new research directions have emerged, in parallel, aimed at integrating optical communication systems into the modern, connected society. The targets are now not only data rates and distances, but also flexibility, scalability, cost, and security.

The first *Roadmap of optical communication* [1] was published in 2016, and the time has come for an update with an outlook for the coming years in this dynamic research area.

The race for data rates and distance

Optical fiber communications achieves the combination of high bandwidths and long distances by exploiting high-frequency optical carrier waves over a low-loss transmission medium, commonly the silica (SiO_2) optical fiber. A way of presenting the historical developments of the optical fiber transmission technology is, therefore, to plot the evolution in terms of the product of the transmitted data rates (in Gb/s) and transmission distances (in km), as shown in figure 1. This illustrates half a century of unprecedented growth—10 orders of magnitude—which has been enabled by a number of key technical innovations and developments. Until around 1990, state-of-the-art systems used intensity modulation and direct-detection (IM/DD) of a single wavelength channel. Improved performance was mainly achieved by developing silica fibers with low loss and lasers and detectors with high bandwidths, transmitting in the low-loss wavelength regime of silica.

The invention of the erbium-doped fiber amplifier (EDFA) in the late 1980s led to dramatic improvements since (i) the optical amplification enabled very long (transoceanic) transmission distances by periodic compensation of the fiber attenuation and (ii) several wavelength channels could be amplified and transmitted in parallel through the same fiber, which is known as wavelength-division multiplexing (WDM). While WDM technology alone sustained exponential growth for another 15 years, to the early 2000s, there were still improvements to be had. One key aspect was the modulation format, which up until that time had been limited to simple intensity modulation, whereas the electromagnetic carrier wave can be more efficiently modulated by exploiting its phase and polarization properties as well. The development of coherent receiver technologies based on digital signal processing (DSP) around 2005–2010 solved this problem and enabled modulation with increased spectral efficiency, along with algorithms to digitally track and mitigate transmission impairments. Having exploited amplitude, phase, polarization, time, and wavelength, the only remaining option to increase the throughput is by using more parallel spatial channels, either via parallel cores (or fibers) or by exploiting multiple modes in a single core. Such space-division multiplexing (SDM) schemes have been used most recently to reach the highest points in figure 1.

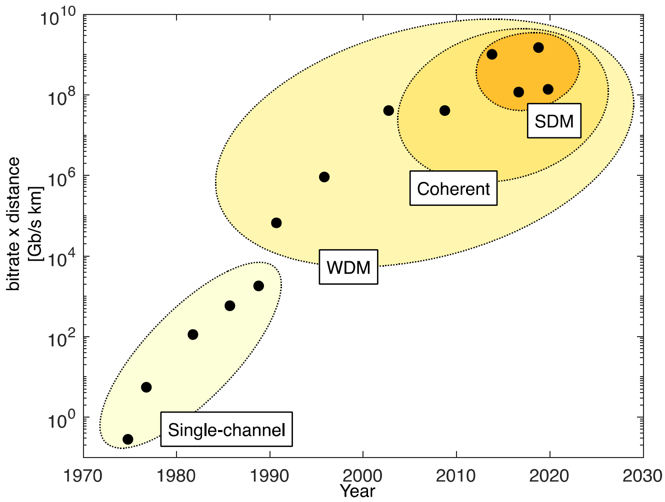

Figure 1. The evolution of the bitrate-distance product of state-of-the-art fiber communication links as function of time. The data points represent published research advancements, which are detailed in table 1.

The underlying data for figure 1 is shown in table 1 and shows when, in time, particular technologies became available. It is noteworthy that forward error correction (FEC) and advanced modulation formats were adopted relatively late in optical communications compared to radio communications. The reason is the high symbol rates used, which have always been limited by the bandwidths of the electronic and optoelectronic hardware. In the last 15 years, DSP algorithms, capable of throughputs of 40–100 Gb s^{-1} and beyond, have become available, thus paving the way for the coherent receiver technology used in the state-of-the art links. Further record experiments in various respects are summarized in sections 4 and 7.

A connected society

To enable the modern connected society, including the internet, fast point-to-point communication links alone are not

Table 1. Selected state-of-the art transmission results over time, partly plotted in figure 1. The data rate/fiber column is the product of the preceding five columns. Bold numbers indicate world records at the time. SE = spectral efficiency.

Year	References	First Author	Symbol rate (Gbaud)	SE (bits/symb)	WDM channels	SDM channels	FEC Code rate	Data rate/fiber (Gbits s^{-1})	Data rate/wavelength (Gbits s^{-1})	Distance (km)	Bitrate·dist product (Gbit s^{-1} km)
1975	[2]	Uchida	0.12	1	1	1	1	0.12	0.12	2	0.24
1977	[3]	Sugimoto	0.40	1	1	1	1	0.40	0.40	12	4.80
1982	[4]	Yamada	2	1	1	1	1	2.0	2.0	51	100
1986	[5]	Gnauck	8	1	1	1	1	8.0	8.0	68.3	**550**
1989	[6]	Iqbal	11	1	1	1	1	11	11	151	**1700**
1991	[7]	Bergano	5	1	1	1	1	5.0	5.0	1.4×10^4	7.0×10^4
1996	[8]	Bergano	5.33	1	20	1	0.94	100	5.0	9500	9.5×10^7
1996	[9]	Onaka	20	1	55	1	1	1.0×10^3	20	150	1.65×10^5
2003	[10]	Cai	12.3	1	373	1	0.81	300	10	1.1×10^4	4.1×10^7
2009	[11]	Charlet	27.8	4	164	1	0.90	590	100	2550	$\mathbf{4.2 \times 10^7}$
2014	[12]	Igarashi	30	4	201	7	0.83	1.4×10^5	100	7326	$\mathbf{1.0 \times 10^9}$
2017	[13]	Soma	12	11	740	114	0.9	$\mathbf{1.0 \times 10^7}$	118	11.3	1.1×10^8
2018	[14]	Olsson	3	**17.3**	10	1	0.84	2.2	43.6	50	2.2×10^4
2019	[15]	Puttnam	24.5	8	345	19	0.55	7.16×10^5	109	2010	$\mathbf{1.4 \times 10^9}$
2023	[16]	Puttnam	24.5	16	750	114	0.68	$\mathbf{2.3 \times 10^7}$	268	13	3.0×10^8
2024	[17]	Puttnam	25.5	13.2	**1505**	1	0.75	3.8×10^5	252	50	1.9×10^7
2022	[18]	Nakamura	176	14.0	1	1	0.88	2110	**2110**	240	5.2×10^5
2022	[19]	Mardoyan	**260**	4	1	1	0.78	816	816	100	8.2×10^4

sufficient. Equally important are the methods to connect the links into *networks,* and to provide supporting services and applications. Modern communication networks need to be flexible and scalable, to provide seamless integration between fiber and wireless transmission media, and to provide security and fault tolerance, as well as low delay. Such research directions have become increasingly important in the last 10–20 years, while the rate of progress in data rate times distance and related link metrics have slowed down, as illustrated in figure 1.

What is clear is that, in order to see significant growth and benefit to society, we need to embrace the *diversity* of the field, i.e. researchers need to work in parallel on hardware (both optical and electronic), algorithms/information theory, systems and networks. Therefore, we have structured this roadmap in four parts: (i) hardware, (ii) algorithms, (iii) networks and (iv) systems, where the former two address issues underlying the physical layer, and the related trade-offs between increasing performance and reducing costs. The latter parts address the higher layers in the communication stack, which comprise the functionality and design of the whole network, as well as some emerging areas for optical communications. The central question and motivation for this roadmap is: *Which are the most promising research directions for optical communications in the coming years?*

Overview of this roadmap

Hardware

The huge growth shown in figure 1 was initially enabled entirely by hardware advances, such as the silica fiber, the EDFA and the coherent transmitter and receiver technologies. The question is whether there is any conceivable hardware that can take us even further. In sections 2 and 3, promising developments in **fiber and amplifier technology** are surveyed. For example, new fiber designs may have advantages beyond the standard single-mode silica fiber in terms of attenuation and latency. Is it possible to design amplifiers that are more efficient and have less noise than the EDFA, and if so, what technologies and wavelengths are most suitable? Sections 4 and 5 present the challenges in **transceiver design** that require co-integration of photonic and electronic hardware; **photonic integration** is an area in its infancy compared to semiconductor electronics. Sections 6 and 7 address the two dimensions that remain to be exploited in order to increase the spectral efficiency further, namely the usage of multiple lightpaths via **spatial multiplexing** and additional WDM spectrum **beyond the EDFA's C-band**.

Algorithms

Whilst algorithms have made significant progress in the last few years, following the development of the coherent receiver and high-speed DSP circuits, some key areas are still in rapid development. In particular, the use of **machine learning and neural networks** may provide unforeseen gains in the DSP design and implementation, and is discussed in section 8. The **silica fiber nonlinearity** remains the most challenging cause of transmission impairments and its mitigation strategies will likely be in research focus for the foreseeable future, as discussed in section 9. To establish the ultimate **transmission capacity and ways to achieve it** is still an open central research question in optical fiber transmission, which is the focus of section 10, whereas the related issue of finding **forward error-correction algorithms** with reasonable complexity suitable for the high throughputs of optical links is treated in section 11.

Networks

The various types of optical communication networks and different applications pose different design challenges. **Long-haul and metropolitan networks**, presented in section 12, are still in significant development, whereas **software-defined networking** is, as discussed in section 13, an emerging area with unprecedented flexibility. **Data-center networks**, which is possibly the largest-growing area commercially right now, are surveyed in section 14. They are of central importance for present and future information services, by enabling large-scale centralized data storage and processing. The **access** part of the network, i.e. the part closest to the end-users, and its particular demands are presented in section 15.

Systems

Submarine fiber systems is an example of links with very specific design challenges, e.g. with respect to power delivery and redundancy, and are presented in section 16. **Radio-over-fiber** research, which is described in section 17, highlights how transmission over fiber can complement radio communications such as fifth generation (5G)/sixth generation (6G) mobile networks. The fact that installed fiber links can have a secondary use in **sensing,** to measure, e.g. earthquakes, city traffic, or damages to the fiber structure itself, is the topic of section 18. The roadmap concludes in sections 19–21 with three emerging areas that are in intense development. They are **free-space optical communications** with potential applications in deep-space links, **quantum communications**, which exploits the quantum nature of light to provide ultimate security or transmission sensitivity, and **visible light communications**, which combines lighting with communications.

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2. Transmission fibers

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Status

For more than 40 years, optical fibers have formed the backbone of global communications. Continued research and improvement in this essential physical-layer technology is needed to support the global circulation of an exponentially increasing data traffic. This will require continued symbiotic improvements in the whole optical communication ecosystem, with optical fibers that keep evolving in directions that enable increased data throughputs at a reduced cost of service, and transmission systems that adapt progressively better to the physical limits of the optical fiber channel in order to exploit its bandwidth ever more efficiently.

The most conventional telecommunication-grade optical fibers made of a single glass core and either single-mode (SMF) or (highly) multimode (MMF) fiber have already undergone five decades of continuous improvements. In many aspects, they have reached performance close to fundamental limits and the margin for improvement is becoming progressively smaller. The search for enhanced performance will therefore result in additional diversification, where a larger variety of application-optimized fibers will be developed in an effort to achieve performance and economic benefits, improved usability or novel functionalities. Meanwhile, after a decade of intense development in the lab, SDM fibers of either few-mode (FMF) or multicore fiber (MCF) type, as well as the potentially ground-breaking hollow-core fibers (HCFs), will start to become commercially available. Market penetration will happen initially in niche, low-volume applications, and might gradually increase if the numerous remaining challenges are overcome and the cost–benefits of the technology meet the market requirements.

Current and future challenges

The evolution path of all the technologies mentioned above will be driven by a number of common grand challenges.

In the long-haul transmission sector, both terrestrial and submarine, all fiber technologies will be challenged to provide solutions that, in combination with transmission system equipment, will offer the highest possible link data throughput at the lowest possible cost per bit and energy per bit. Development will follow two directions. At a fiber level, the only remaining degree of freedom left seems to be that of further spectral expansion beyond the C and L band (see section 7). The challenge for novel fibers is to minimize deleterious interchannel nonlinear effects. At a cable level, substantial research will be conducted to increase the overall cable throughput by further increasing the cabled fiber density. The overall 'cable throughput' will likely replace 'fiber pair throughput'—which is saturating and close to fundamental limits—as the most meaningful figure of merit to assess and compare the potential of any new technology.

At the opposite end of the transmission distance range, short-reach applications will drive the development of fiber technologies capable of offering improved connectivity between data centers, equipment racks, transceivers and even integrated circuits. Key to success here will be the practicality and overall cost effectiveness of the full solution, including end interconnections, lasers, and transceiver electronics.

Backward compatibility with the large base of installed fiber will also be an aspect that all new technologies will need to confront. This might eventually favor conventional fiber designs in the most traditional legacy applications; however, green-field installations in and around hyperscale data centers will provide the opportunity for proof-of-concept of the newest and least proven technologies. All solutions will initially be required to provide power-efficient, practical, and cost-effective interconnections to the traditional SMF, and ways to perform these in the field.

All fibers that differ from the standard single-core, 125 micrometer glass diameter will also need the support of a dedicated ecosystem of customized optical components and test-and-measurement equipment, which might slow down their widespread diffusion.

Finally, new fiber design challenges (and related opportunities) will emerge to enable the growth of new functionalities supported by the telecom network, such as long-distance distributed sensing or improved data transmission security through quantum-secure transmission protocols coexisting with classical signals.

Advances in science and technology to meet challenges

One of the main research directions for single-core SMF will be towards reduced-diameter fibers. After decades where space in ducts and cables was abundant and the 125/250 μm glass/coating diameter of fibers seemed adequate, there is now a strong incentive to reduce the fiber's outer diameter. This will allow more compact terrestrial cables, fitting more fibers into existing congested micro-ducts, as well as 'cable SDM' solutions resulting in larger and denser terrestrial cables containing well over 1000 fibers, and in submarine cables housing an increasing number of fiber pairs in the standard 17 or 20 mm diameter format. While 125/200 μm fibers are already established, research is pushing towards even smaller dimensions, with 125/180, 125/165, and 80/165 μm options currently under investigation [20, 21]. By working in synergy with coating and cabling developers, fiber research will need to identify and standardize the minimum practical dimension that still ensures adequate optical performance. Puncture resistance of thin coatings, microbend-induced penalties, backward compatibility, and the cost/benefit of introducing more expensive but more bend-robust trench profiles in the core will be the main challenges in the near future. In addition, SMF research will investigate the path towards fibers with even larger core effective area for improved nonlinear penalty mitigation. Fibers with effective areas beyond 150 μm^2 start to operate in a quasi-single-mode regime. Here, the downside for a reduction in nonlinear-induced penalties will be the onset of multipath interference from parasitic high-order modes; this creates linear impairments and the potential need for DSP compensation [22]. Only time will tell if the advantages outweigh the disadvantages.

Single-core MMF, in combination with vertical-cavity surface-emitting lasers (VCSELs), will still be the cost-driven solution of choice for the smallest enterprise data centers. Research must investigate designs and standards beyond OM5, capable of transmitting 800 or 1600 Gb s^{-1} over up to 100 m distances, for example through cores larger than 50 μm [23].

Multicore SDM fibers have achieved impressive progress over the last decade. An ITU study group has started working on their standardization, and the technology is now nearing commercial deployment. In long haul, after initial explorations of large core counts, research seems to have settled onto more practical versions with a lower number of cores (e.g. 4) that can fit in the standard 125 μm glass diameter. Both coupled and uncoupled core varieties have now approached the loss of single-core versions, $\sim$0.155 dB km^{-1} [24, 25]. Techno-economic considerations will likely determine which version will be ultimately favored by the market. Submarine MCF cable prototypes have been shown to be able to support transoceanic transmission distances in loop experiments with multicore amplifiers [26], indicating that the technology will compete with SMFs with reduced outer dimensions to become the solution of choice for submarine SDM cables. The winner will be determined by the performance of the whole link, including fan-in and fan-out devices and splices (for which the MCF loss is still high), as well as by practicalities and techno-economic considerations. For shorter reaches, the MCF technology will keep developing large-core-count fibers for improved connectivity in fiber-hungry data-center applications. Research will focus on practical ways to interconnect them to transceivers or integrated optoelectronics chips. Bidirectional transmission in a single MCF, as opposed to the more standard use of fiber pairs, will likely receive further attention beyond current exploratory studies [27], due to the resulting reduction in crosstalk and consequent increase in the allowed core density. Few-mode single-core fibers will aim to carve themselves some space in the data center interconnect (DCI) space, where information spatial density is key and the short distances might require no or only light multiple-input multiple-output (MIMO) processing [28].

Over the next decade, HCF technology will also consolidate. New designs will be proposed and tested for high-volume production and ultra-wideband long-haul transmission. They will need to demonstrate the capacity to reproduce in large volumes and at a low production cost the impressive loss values of $<$0.11 dB km^{-1} reported in a hero experiment [29], and potentially improve the loss further. Their low-latency, virtually non-existent nonlinearity, and potential for many tens of THz of ultralow-loss bandwidth can in principle impact many application areas. Hybrid HCF–SMF spans for link extension through nonlinear mitigation, and petabit/second (Pb/s) unrepeatered transmission through 2–300 km [30] could be some of their first applications; long-haul transmission at 3–5 times the SMF throughput seems also possible but requires the concurrent development of efficient ultra-wideband amplifiers. No immediate roadblock seems apparent from early recirculating loop experiments reaching several thousand kilometers [31], but more work on splice loss and fiber outer diameter reduction, as well as some initial standardization will be needed. While the transmission ecosystem will naturally drive the alignment of HCF technology to the spectral bands of current interest for solid core fibers, e.g. around 850–1000 nm as well as in the O, C and L band, the ultrawide bandwidth of these HCFs and their apparent ability to achieve ultralow loss anywhere between 800 and 2000 nm [32] might create opportunities for new transmission windows at alternative wavelengths where novel amplifiers and/or optoelectronics components can provide technological advantages.

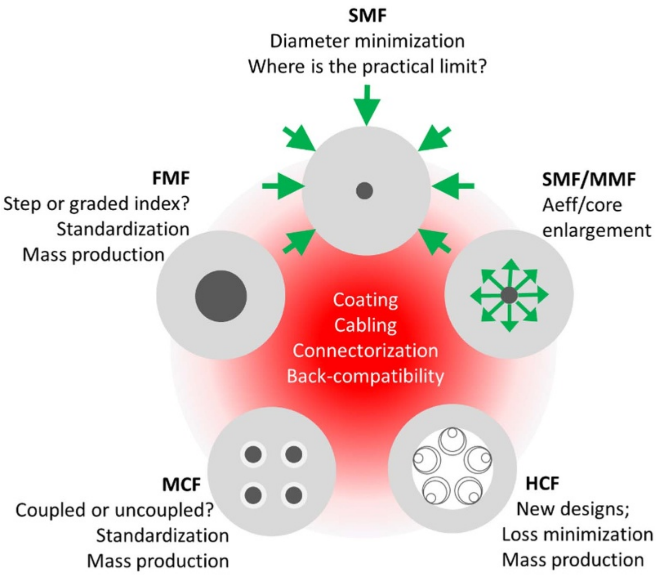

Figure 2. Research directions for the main fiber design types: SMF (standard single-core, single-mode fiber); MMF (highly multimode fiber); FMF (few-mode single-core fiber); MCF (multi-core fiber); HCF (hollow-core fiber).

Concluding remarks

Having exhausted all possibilities for 'easy wins,' fiber research will inevitably have to explore more complicated designs, in the quest for increased data transmission throughput in the optical network, and shown schematically in figure 2. It is hard to imagine the emergence of a new fiber technology able to take over large market shares from currently existing single-core fiber solutions. However, the evolutionary and revolutionary approaches discussed here are likely to find an application space where they can enjoy some advantage over more traditional and consolidated solutions. This will bring further diversification to the fiber-optics portfolio. Success or failure of every new fiber design will be, as always, decided by the market.

Acknowledgments

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3. Amplifiers

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Status

The modern information society is underpinned by the global deployment of optical fiber communication systems in which optical amplifiers (OAs) play an essential role. OAs are devices that directly amplify optical signals in the optical domain by exploiting stimulated emission. Several material platforms that provide stimulated emission for optical signals have been extensively studied to realize various OA technologies. They include rare earth (RE)-doped fiber amplifiers (FAs) such as EDFAs, fiber Raman/Brillouin amplifiers (FRAs/FBAs), semiconductor optical amplifiers (SOAs), bismuth-doped fiber amplifiers (BDFAs), and fiber-optical parametric amplifiers (FOPAs). Figure 3 shows a flowchart for categorizing these OA technologies. The first branch in the figure indicates whether the OA is phase-sensitive or -insensitive. Phase-sensitive amplifiers (PSAs) are realized through coherent additions of the waves generated via parametric mixing processes such as the four-wave mixing in optical fibers; thus, they amplify or deamplify depending on the phase of the input signal with respect to the pump and idler waves. PSAs can offer noiseless amplification, whereas phase-insensitive amplifiers (PIAs) have noise figures that are no better than the quantum limit at 3 dB. As PSAs require precise alignment of the optical phases and states of polarization, their practicality remains considerably limited. FOPAs operate as PIAs when the idler input is absent.

EDFAs are the most commercially successful optical amplifiers on the grounds of high and wide-band gain in the lowest-loss window of the transmission fibers, i.e. either C- or L-band, high efficiency, low noise, and ~10 ms luminescence lifetime leading to exceptional performance for the simultaneous amplification of dense WDM signals [33]. However, some other OA technologies have found their inherent applications for which EDFAs cannot be used and, thus, have also been commercialized. For example, FRAs based on stimulated Raman scattering of the glass molecules of transmission fibers operate as almost ideal distributed amplifiers whereas EDFAs operate as lumped amplifiers [34]. In principle, distributed amplifiers outperform lumped amplifiers in terms of noise characteristics. However, as FRAs operate optimally at a relatively low gain limited by double Rayleigh backscattering [35], they have been used complementarily with EDFAs to improve the noise characteristics. Another example is SOAs, which can have gain in almost any band in the infrared region by engineering semiconductor materials and the bandgap of the compound semiconductor waveguides; also, SOAs are integratable in photonic integrated circuits (PICs) [36]. However, SOAs have luminescence lifetimes comparable to the clock period of the optical signals wherein the gain saturation tends to distort the amplified optical signals [37]. Quantum dot-based SOAs have shorter lifetimes with higher temperature stability than bulk-type SOAs. Efforts have been made to develop erbium-doped waveguide amplifiers (EDWAs) for integration. However, the doping concentration of erbium ions is intrinsically limited to achieve sufficient gain within the limited length of the waveguide. FBAs are unique in that the gain band is extremely narrow, typically of the order of 10 MHz, as determined by the linewidth of the excited acoustic phonons of the fiber; additionally, they intrinsically suffer from very high thermal noise. However, FBAs recently found intriguing applications that exploit the narrow gain bandwidth to

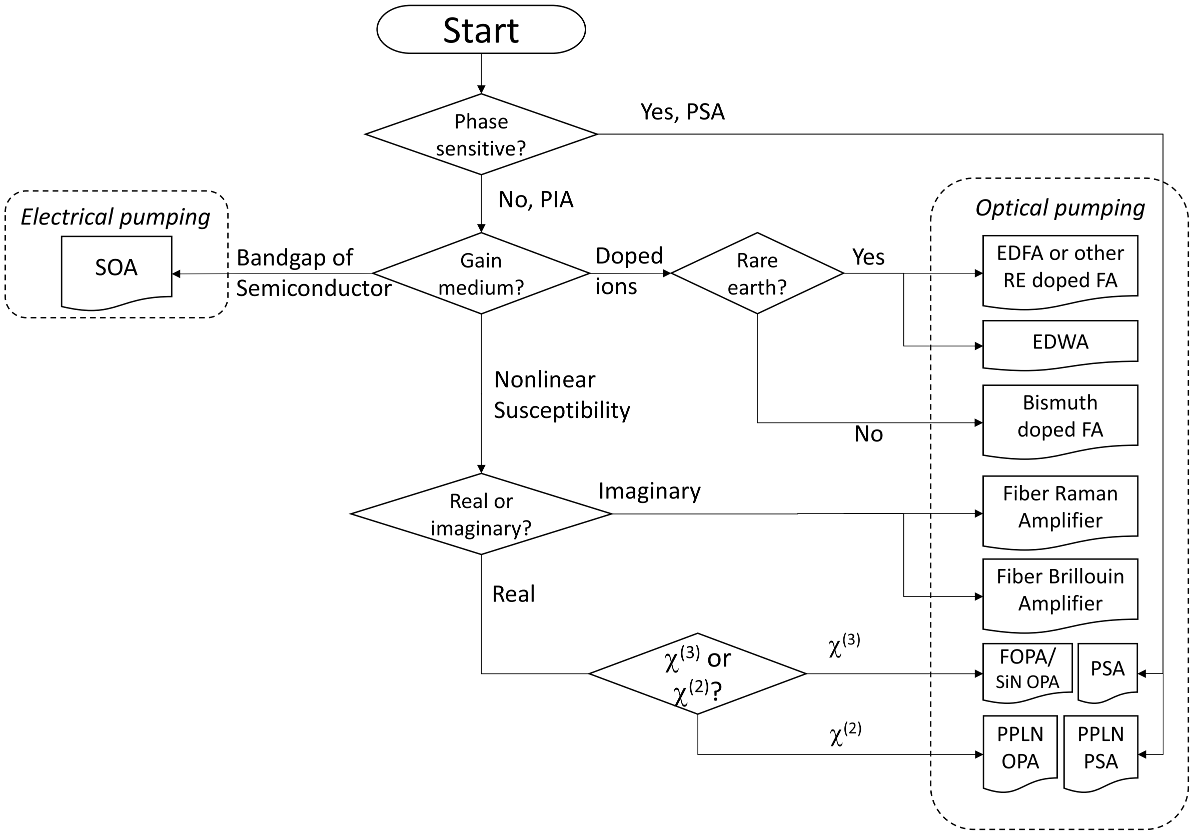

Figure 3. Categorization of OA technologies. PSA: phase sensitive amplifier; PIA: phase insensitive amplifier; FOPA: fiber-optical parametric amplifier; RE: rare earth; FA: fiber amplifier; EDF(W)A: erbium-doped fiber (waveguide) amplifier; FWM: four-wave mixing; SOA: semiconductor optical amplifier; OPA: optical parametric amplifier; PPLN: periodically poled Lithium Niobate.

improve the quality of local oscillators for coherent detection [38].

Current and future challenges

Further dramatic increases in the network capacity, network coverage, and computing power are required to realize the future digital infrastructure in the forthcoming 6G mobile era. Consequently, optical fiber communication systems must enhance both the per-fiber capacity and parallelism to significantly increase the overall data-transfer/processing capability of the digital infrastructure. Therefore, OA technologies need to expand the operating band from the present C-/L-band to other bands [39] and better support parallelism associated with the newly deployed multi-fiber cable systems, including SDM systems. SDM systems require the optical gain and noise characteristics to be equalized over all WDM and SDM channels. It depends on system configurations how to increase the overall capacity by optimally combining the expansion of the transmission band and SDM (see section 6 for details).

Another important challenge is the integration of the higher functionalities. Next-generation optical transport will no longer be point-to-point or static but will be highly virtualized and reconfigurable to form complex multi-point-to-multi-point optical networks, based on disaggregated hardware platforms that deal with easy-to-use, cost-effective, pluggable 'white-box' optical modules. Generally, integration conceals the difficulty of handling photonic devices on a mass-production basis. Consequently, the integration of optical amplifiers into highly functional PICs such as optical transceivers, co-packaged optics, optical switches, and photonic accelerators to aid massive computing will be important. Subsequently, the expansion of the gain band and integration are addressed.

Advances in science and technology to meet challenges

(i) Expansion of the gain band: figure 4 shows the gain band map for various OA technologies. First, we discuss O-band amplifiers because the short-reach data center optical interconnects operating in the O-band will require optical amplification for further scaling. For this purpose, praseodymium (Pr^{3+})-doped FAs (PDFAs) have been developed [40]. However, PDFAs are based on fluoride fibers that must be hermetically sealed for reliability, thus hindering their widespread use. Recently developed BDFAs are based on silica fibers. Unlike RE-doped FAs, the gain band

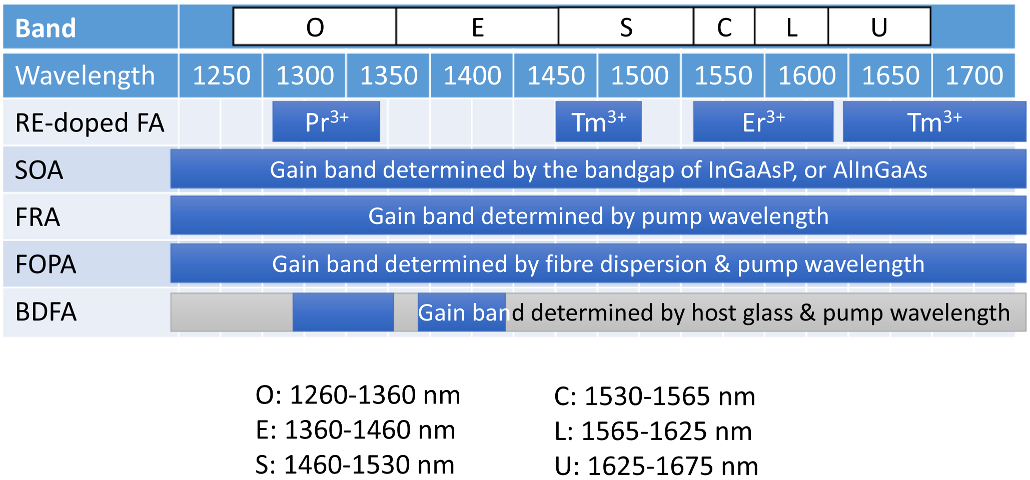

Figure 4. Gain band map of various OA technologies.

of BDFAs is determined by the pump wavelength and the composition of the host silica fiber (see section 5 of [39]). For O-band operation, the pump wavelength ranges between 1200 and 1300 nm. BDFAs and SOAs operating in the O-band have been commercialized. For coarse WDM signals, SOAs must be operated in the linear regime such that nonlinear gain response does not degrade the signal quality [37].

To further expand the signal bandwidth beyond the C + L-band, SOAs whose gain spans continuously over 100 nm containing the C + L-band have been demonstrated to successfully amplify more than 100 Tb s^{-1} WDM signals [41]. A higher operating power with many WDM signals suppresses the SOA nonlinear gain dynamics (see section 3 of [37]). The FRAs are also useful for expanding the gain band. The virtue of FRAs is that the gain profile is continuously broad because of the amorphous nature of silica glass, and the pump wavelength dictates the wavelength of the gain without changing the profile. In fact, properly prepared multi-wavelength pumping achieves a continuous flat gain profile spanning over 100 nm without employing gain-flattening filters [42].

Thulium (Tm^{3+})-doped FAs (TDFAs) have been studied to amplify S-band signals. However, the host glass of TDFAs is non-silica glass for S-band amplification, whereas TDFAs operating from 1620 to 2000 nm are based on silica fiber [43]. FOPAs can also operate over a broad band in the low-loss window of the optical fiber by optimizing the dispersion profile of the fiber and pump wavelengths. FOPAs operate unidirectionally, making isolators unnecessary to obtain a high gain. Extremely low-noise PSA operation is also beneficial for cases such as space communication where the incoming signal levels are very low [44]. For efficient FOPAs, highly nonlinear fibers (HNLFs) have been extensively studied and commercialized. FOPAs are also used as optical phase conjugator or wavelength converter for WDM signals [45].

(ii) Integration of optical amplifiers: To date, SOAs have been the only successful OA technology integratable onto PICs by not only monolithic but also heterogeneous integration. For example, SOA-integrated silicon photonic switches have been reported [36]. However, technologies to integrate SOAs onto silicon photonics at a mass-production level have not been widely developed, mostly because of limited demand as well as its technical difficulty to optical alignment, thermal dissipation, and reliability. Recently, wafer-scale heterogeneous integration of active devices on silicon photonics has attracted considerable attention.

Apart from SOAs, research activities have recently been revisited to develop integrated OAs other than SOAs, for instance, those exploiting the parametric gain of periodically poled $LiNbO_3$ (PPLN) [46] and silicon nitride [47]. Silicon nitride waveguides are characterized by low loss and high optical confinement and are suitable for optical amplification purposes that require long interaction lengths. Realizing parametric amplification on a chip is inherently advantageous over FOPAs, considering that the optical phases and states of polarization are considerably more stable on the chip than in the fiber.

Concluding remarks

Optical amplifiers are and will be one of the most important and indispensable building elements for constructing digital infrastructure in modern and future information societies. Owing to the continuous demands of increasing data transfer and processing capacity, optical amplification needs to explore technologies to expand operating bands further and integrate with other optical devices to dramatically improve both system performance and cost–benefit trade-offs.

Acknowledgments

The author would like to thank Mark Pelusi for valuable discussions.

4. Transceiver and DSP hardware

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Status

Optical transceivers are one of the critical building blocks for fiber communication systems. In the past decade, the throughput of deployed long-haul fibers has increased from several Tb/s/fiber to ∼40 Tb/s/fiber [48]. In terms of lab demonstrations, the record per fiber throughput has increased from ∼20 Tb s^{-1} to ∼70 Tb s^{-1} [49]. Such improvement is largely due to the advances in optical transceivers. Around 2010, when coherent technology started to be widely deployed in the field, the available optical transceivers operated at ∼30 Gbaud and carried 100 Gb s^{-1} per wavelength. Now, commercial coherent transceivers operate at >100 Gbaud and carry more than 1 Tb s^{-1} per wavelength [50–53]. The data rate has increased significantly thanks to the progress on complementary metal–oxide–semiconductor (CMOS) technologies, advanced DSP algorithms, and higher-bandwidth analog components such as modulators, photodiodes (PDs), and electrical drivers.

Looking forward, the future of high-speed fiber transmission still relies on the further development of optical transceivers. Besides continuing to develop faster components and more effective DSP, it is also very critical to work on ultra-dense integration, DSP/hardware co-design, and reduced power consumption.

Current and future challenges

One of the major challenges is to sustain traffic growth. We have been observing ∼60% annual traffic growth for the past several decades [48]. There is little evidence suggesting that the growth will be slowing down in the near future. This means the required data rate will double every 1.5 years and become 100 times more in a 10 year span. However, the interface rate of an optical transceiver has been increasing at a steady pace of only ∼20% per year, which, although still very impressive, creates a bigger and bigger gap between what the network needs and what one transceiver can provide.

While the analog parts (modulators, photodiodes, radio-frequency (RF) amplifiers, etc) are going relatively strong in terms of scaling up in the bandwidth, the CMOS-based application-specific integrated circuit (ASIC) for the DSP is one of the major reasons why the transceiver speed is increasing at a limited pace. The first-generation ASIC for coherent optical transceivers was based on 65 nm CMOS, allowing ∼30 Gbaud electrical signal generation. In 2023, optical transceivers are equipped with 7 nm or 5 nm CMOS, supporting >100 Gbaud signal generation [50–53]. This reflects only ∼13% symbol rate increase per year. Furthermore, it is predicted that the CMOS speed may saturate once the node size becomes too small (e.g. <2 nm). This means even the 13% symbol rate increase may not be maintained in the long run.

The other challenge is to manage heat dissipation and power consumption. The 100 Gb s^{-1} coherent transponders can consume several watts per Gb/s. Nowadays a high-end transceiver (e.g. 400 Gb s^{-1} or higher) consumes as little as 0.1 watts per Gb/s. This progress is due to the smaller CMOS nodes as well the integration of electrical and optical components. In general, reducing the form factor helps to reduce power consumption. This is especially true for electrical components. However, optical components may behave differently. For instance, the traveling-wave modulators used today have a tradeoff between length and half-wave voltage (V_π, sometimes referred to as 'driving voltage'). The shorter (smaller) a modulator is, the higher electrical power it requires to drive the modulator. A similar phenomenon happens with PDs. The smaller a PD, the less responsivity it tends to have and therefore needs more photons (higher optical power) to produce the same output voltage. To overcome such size/power tradeoffs, innovations in materials and hardware design are needed.

Advances in science and technology to meet challenges

Great advances have been made in almost all the key components in optical transceivers. For instance, optical modulators become much smaller and more efficient. The 100 Gb s^{-1} coherent transmitters use traditional $LiNbO_3$ modulators, which are typically ∼8 cm long with a half-wave voltage V_π of ∼3.5 V and 3 dB bandwidth of ∼35 GHz [54]. The current generation (800 Gb s^{-1}) transceivers typically use silicon photonics (SiP) or indium phosphide (InP). SiP modulators (more details in section 5) have similar 3 dB bandwidth compared to traditional $LiNbO_3$ ones but significantly smaller sizes [61]. InP modulators can have much higher speed than traditional $LiNbO_3$ modulators, with only a slightly larger form factor compared to SiP ones [55]. Besides the technologies that are made into products, modulators under research show great potential for scaling to even higher speeds. For example, thin-film $LiNbO_3$ modulators can have 100 GHz bandwidth supporting 200-Gbaud signals with a V_π of 2 V or lower [56–58]. The plasmonic modulators can have an extremely small size of only ∼20 μm and an ultra-high 3 dB bandwidth of ∼500 GHz, although they are lossier and require higher V_π than other modulators [59]. Another type of new modulator, the silicon-organic hybrid (SOH) modulator, also features a small size (<1 mm) and low V_π (<1 V) [60]. The stability of the organic material is still under investigation.

In figure 5(a), the bandwidths and modulation efficiencies of new modulator technologies are compared. The modulation efficiency is defined as the product of V_π and its length (the smaller product, the better). The conventional $LiNbO_3$ modulator (marked as a red star) is plotted as a reference. We can see that the new modulators not only have much better modulation efficiency but also significantly higher bandwidth. The other important aspect of modulators is device insertion loss. (Note that the bandwidth of SOH-based Mach–Zehnder modulators (MZMs) is not reported in literatures and therefore not

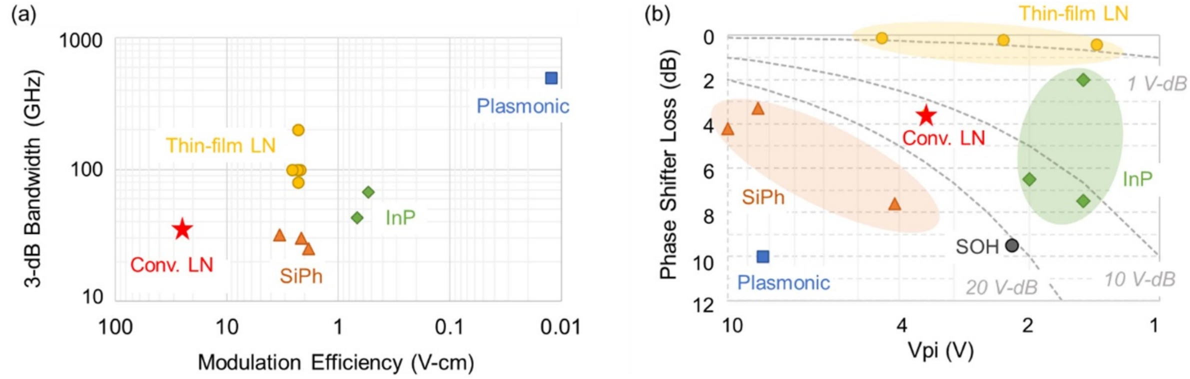

Figure 5. (a) Comparison of MZM's 3-dB bandwidth and modulation efficiency; (b) comparison of device loss and the required driving voltage (V_π). (Due to space limitations, the data points in this figure are not individually referenced. All the data points can be found in [54–61] and references therein.).

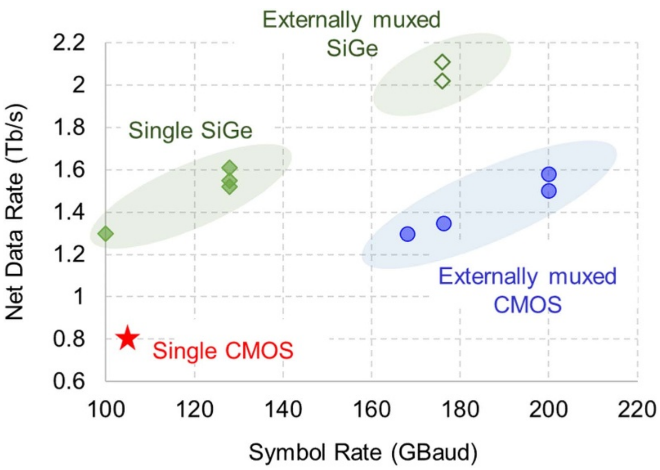

Figure 6. Experimentally demonstrated record net data rates for coherent systems. (Due to length limitation, the data points in this figure are not individually referenced. All the data points can be found in [62–65] and references therein.).

shown in this figure.) figure 5(b) shows a comparison of on-chip loss as a function of V_π. We can see that both thin-film $LiNbO_3$ and InP modulators are less lossy than the conventional $LiNbO_3$ ones.

With the ultra-high-speed modulators available, the speed of the electrical signal becomes the limiting factor for increasing the data rate of a transceiver. As CMOS remains the most suitable platform for DSP but its bandwidth is much lower than optical modulators, externally multiplexing CMOS-generated analog signals can potentially be a good option. Lab demonstrations have shown that multiplexing two or more CMOS signals can result in 222-Gbaud binary signals and up to 200-Gbaud multi-level signals [62–65], and all these ultra-high-speed electrical signals can be modulated into the optical domain with a single modulator. Figure 6 shows an overview of experimentally demonstrated high-symbol-rate single-carrier systems. As shown, the highest data rates from CMOS systems are implemented with external DAC multiplexing. Silicon germanium (SiGe) DACs can achieve even higher data rates, but at the moment it is not clear how SiGe DACs can be integrated with CMOS-based DSP.

The improvements from higher-bandwidth hardware and electrical multiplexing may increase the interface rate by a few times. However, these will likely be insufficient to sustain the continuing 60% annual traffic growth. With other physical dimensions such as quadrature and polarization fully explored, we are left with the single remaining dimension, which is space. This led to the very active research topic of SDM, which is covered in section 6. For transceivers, multiplexing in space means parallel transceivers in one package. Considering the expected 100 times traffic increase in 10 years but the only 6 times speed increase per transceiver (20% annually), we will need to integrate ~20 transceivers into one module. The close integration of multiple transceivers opens up the opportunity to globally optimize the design of DSP, RF components, and optics across transmitters/receivers. Problems that may be difficult or resource-costly to solve in hardware design may be solved in DSP with minimal additional complexity. One example is that one can allow crosstalk among modulator electrodes to save space but pre-compensate such crosstalk in transmitter DSP [66]. It will also be possible to optimize, e.g. the modulation formats and the number of transceivers to achieve the optimal balance among cost, form factor, and power consumption.

Concluding remarks

Future optical transceivers will be more compact, have much higher interface speed, and have a high level of parallelism. To achieve this, it is essential to continue the innovations in materials and hardware, as well as globally design the DSP and the hardware.

5. Photonic integration and silicon photonics

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Status

The economic basis for exponential growth in data rates is in jeopardy—the torrent of data is exhausting our energy resources and is a significant contributor to greenhouse gas emission. Data centers and telecom hubs consume more energy to move bits than we use to move airplanes across the globe. Integration is the key to energy and cost savings.

Addressing these scientific and societal challenges demands best-in-class photonic and electronic functions at nanometer and micrometer scales. We can only accomplish this via advanced manufacturing and characterization capabilities. Building blocks from a wide panoply of material platforms must be integrated and interconnected to realize the full potential of each block as they are brought together to form a system such as that illustrated in figure 7. Daunting integration challenges severely hinder the development of such photonic systems.

To overcome this great hurdle in the technology innovation chain, we must accelerate the development of new components on distinct material platforms and integrate them on high-level assemblies to enhance functionality, shrink power consumption, and catapult data rates. We require a comprehensive hybrid integration strategy that addresses bandwidth density, material compatibility, portability, and complexity. To complement the examples we present, we refer the reader to recent more extensive and focused reports on trends in photonic integrated circuits [67], integration for quantum technologies [68], and optical packaging [69].

Current and future challenges

Integrating electronic integrated circuits and photonic integrated circuits on a single substrate (notably silicon) will allow us to transmit bits via photons at distances ranging from cross-continent to intra-microprocessor [70], all while maximizing bandwidth and minimizing energy consumption. This strategy aligns perfectly with the emerging co-packaged optics (CPO) paradigm [71] in the semiconductor industry to break the data traffic bottleneck in data-center networks and artificial intelligence processors, where the bandwidth density (bits per second per mm^2) is crucial.

Exotic materials with new functionality, electronic and photonic, must be integrated onto a common and mature (most likely silicon) platform [72]. However, manufacturing requirements for these exotic materials (e.g. molecular materials, diamond, etc.) fall outside established industrial processing parameters. Heterogeneous integration provides the required bridge to combine all materials into a functional whole while maintaining optimum performance characteristics.

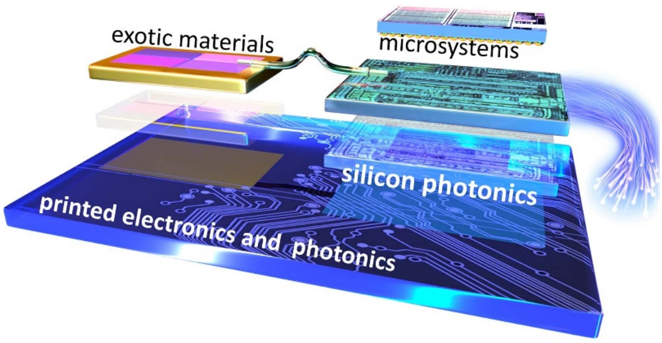

Figure 7. Advanced photonics systems.

Integration relies on efficient and versatile optical-coupling mechanisms and high-density electrical connections. Electrical connection pitch has reached below 10 μm [73], hitting limits in cost, reliability, and crosstalk; photonics must replace electronics to increase signal and processing bandwidth. Beyond traditional telecommunications applications, optical micro-probes, mini scopes, etc. will replace conventional bulk optics to create wearable devices. Electronic integrated circuits can also interface with physical environments and human bodies to incorporate advanced optical probing of the multi-dimensional properties of light [74]. These integrated devices with advanced signal processing (intelligence driven by co-integration of electronics and photonics) enable microsystems with unprecedented functionality and portability.

The complexity of integrated photonic and electronic systems has tracked with growth in data volume, some 30% per year [75]. Research roadmaps in academia and industrial centers must be closely aligned with fabrication infrastructure roadmaps to keep pace, e.g. in terms of materials, 2.5 and three-dimensional (3D) integration strategies (chiplets, interposers, etc), as well as emerging flexible substrates and printed electronics and photonics [76, 77].

Advances in science and technology to meet challenges

To meet the ever-increasing demand for bandwidth, systems must improve a 1000-fold. Researchers are pushing technologies that will scale the capacity of optical communications systems from terabits/s to petabits/s on each link, while reducing the energy consumption from picojoules/bit to femtojoules/bit. To achieve these ambitious goals, researchers are combining the established approach of multiple wavelengths via enhanced integration on silicon and the emergent approach of spatial channels with innovative fibers and multiplexers. Here we will highlight research in integrated high-speed transmitters [78], on-chip multiplexers [79] and multiwavelength sources. Further breakthroughs towards a petabits system require high-accuracy hybrid integration of these electronic and photonic functions side-by-side. When distances between advanced electronic chiplets and high-bandwidth optical transceivers shrink a 100-fold, the

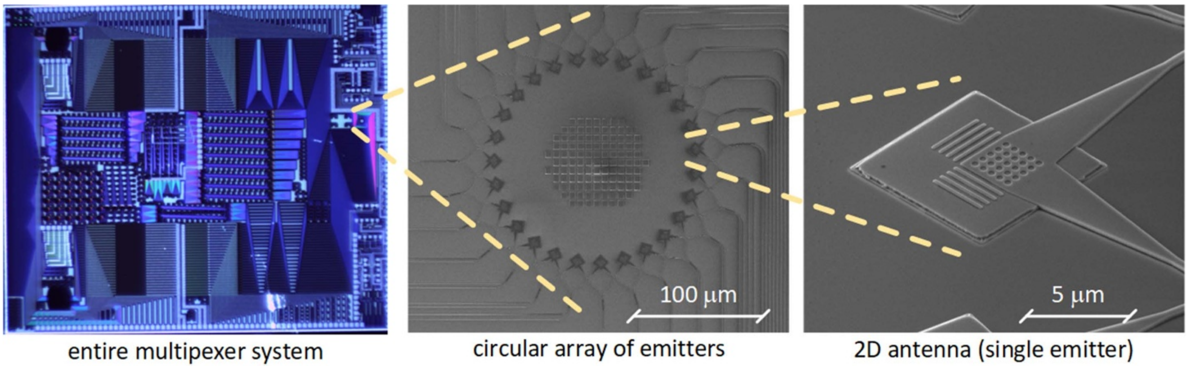

Figure 8. Circular array of 2D emitters in SiP for generation of orbital angular momentum modes.

transmission rate will no longer be subject to compromise, nor will power be squandered.

Integrated silicon transceivers

Silicon has numerous advantages over other material platforms. Chief among them is compatibility with microelectronic fabrication for electronic–photonic co-integration. Optical transceivers on silicon have shown exceptional performance, as we overcome the silicon transmitters' trade-off between efficiency and bandwidth. The backbone of optical communications is the MZM due to its wide wavelength coverage, bandwidth and good efficiency. We can use novel structures, such as segmented modulators and slow-light waveguides, as well as turning towards electronic–photonic co-design to bypass silicon impairments. Work on slow-light modulators [80] results in substantially enhanced efficiency. Combining segmentation and slow-light yields an ultra-low-voltage transmitter with bandwidth beyond 100 GHz. The first high-speed demonstration [69, 70] of an all-silicon MZM exploiting coherent detection achieved a Tb/s line rate on a single wavelength channel. Turning to segmented modulators led to record bandwidth demonstrations greater than 67 GHz [81]. With strategic silicon designs and innovative operating regimes, segments can be used to sculpt performance to favor complexity, bandwidth, or low power consumption. See section 4 for a broader discussion of transceiver technologies.

Parallelism in space and wavelength

For petabit per second rates, researchers are examining spatial multiplexing combined with standard wavelength-division multiplexing [82]. The concentration of data channels will require novel devices and multiplexing techniques for massively integrated interconnects in co-packaged optics. Modal multiplexing can also require special signal generation techniques, for example, orbital angular momentum modes [83]. Ultra-compact devices on silicon, such as that in figure 8, can multiplex these spatial channels and cover multiple wavelength channels [79]. The optical phased array with two-dimensional antennas demonstrates how the silicon substrate supporting transverse electric (TE) modes can be designed for on-chip generation of circularly polarized beams—essential for fiber transmission of orbital angular momentum. Reprogrammable silicon multiplexers that support arbitrary modes are on the horizon. Programmability is key to allow for software-controlled networks using artificial intelligence to dynamically reconfigure signals to maximize network throughput. See section 14 for a broader discussion of software defined networks.

Integrated multi-wavelength sources

These sources are essential for ultra-broadband systems with dense wavelength channels. Several on-chip solutions are being explored, including electro-optic modulation and the micro-resonator Kerr frequency comb. The first silicon electro-optic frequency comb realized 800 Gb/s multi-channel transmission [84]. Micro-resonator Kerr combs solutions have no need for microwave inputs [85]. They rely on third-order optical nonlinearity and require an ultra-high cavity quality factor. A novel heterogeneous integration process of chalcogenide resonators onto the silicon platform achieved a record quality factor [86]. Low-loss silicon nitride waveguides can also be heterogeneously integrated onto silicon at the wafer scale [87]. Researchers are working on architectures of micro-resonator Kerr combs integrated with broadband amplifiers and on-chip tuning mechanisms to improve their flatness and power budget for the multi-channel transceivers.

Concluding remarks

Research into photonic integration and silicon photonics is a mix of theoretical and experimental investigations, involving rigorous electromagnetic simulation, examination of photon–matter interaction, hybrid integration, nano-photonics design and fabrication, electronic–photonic co-design, advanced algorithms, and optical transmission and detection techniques. The benefits of this research will reach beyond information and communications technologies, and contribute to photonics and quantum sciences and technologies as well as advanced sensors.

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6. Space-division multiplexing

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Status

The exponential growth of data services in recent years has driven the photonics research community to explore a range of new optical fibers and related technologies as current systems approach the fundamental capacity limits of conventional fibers. Broadly termed as SDM, this research covers an assortment of technologies supporting the parallel transmission, amplification, and switching of optical signals over spatially distinct optical paths [88–90]. The motivation is both to multiply the information transmission capacity of optical fibers but also to reduce energy consumption and improve efficiency through integration, shared hardware, and joint DSP. Optical fibers for SDM, shown in profile figure 9(a), can be grouped in to two categories that affect how they may be used in SDM systems. Weakly or uncoupled SDM fibers include bundles of SMF and weakly coupled (WC) MCFs, where multiple cores share a common cladding. Coupled SDM fibers include strongly coupled (SC) MCFs, where the core separation is reduced to allow greater coupling between cores, and multi- or few-mode fibers (MMFs, FMFs). Few-mode (FM)-MCFs occupy both coupling regimes with multiple few-mode cores sharing a common cladding. SDM and other optical fiber types are further covered in section 2.

Accessing the individual spatial channels within SDM fibers is achieved with spatial multiplexers. These include fused waveguides and photonics lanterns, 3D laser-inscribed waveguides, and multi-plane light conversion (MPLC) devices with losses as low as 0.5 dB and scaling to over 1000 modes [91]. On-chip mode multiplexing has also been demonstrated [92] as a step towards higher integration.

System experiments, of which hundreds have been summarized in [90], have shown the huge potential for SDM fibers to increase per-fiber data-rates. Figure 9(b) shows the recent increase in per-fiber data-rates using WDM fibers compared to wideband WDM systems. Few-mode multi-core fiber (FM-MCFs) with 114 spatial channels have demonstrated the highest spatial spectral efficiency (SSE) to date and over 20 Pb s^{-1} in a single fiber [16, 93]. Pb/s transmission and trans-oceanic distances have been reached with FMFs and weakly-coupled multicore fiber (WC-MCFs) [90]

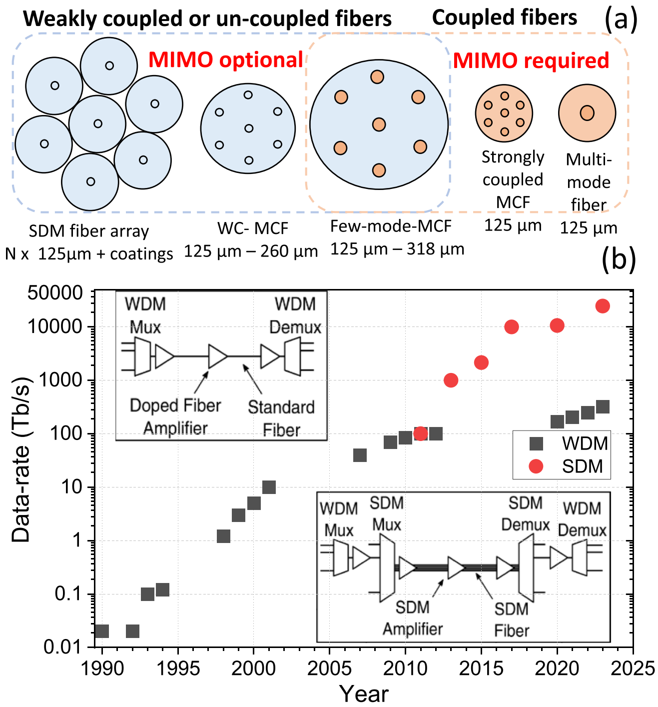

Figure 9. (a) Example profiles of weakly and strongly coupled SDM fibers, (b) evolution of data rate records for WDM systems and SDM systems with generalized WDM system and SDM systems as insets [90]. Reprinted with permission from [90] © 2021 Optical Society of America.

with the number of transmitted modes in a single core reaching 55 [94]. WC-MCFs have thus far offered the highest per-spatial-channel data-rates and are less susceptible to nonuniformity across spatial channels. However, concerns over mechanical reliability, yield, and cabling [95] may mean that cladding diameter and therefore core-count is limited in practical MCFs. Meanwhile, strongly coupled multicore fibers (SC-MCFs) have demonstrated advantages of lower susceptibility to non-linear impairments impairments than SMFs and lower spatial mode dispersion compared to FMFs [96]. 4-core SC-MCF and FMFs with 10 modes have been used with the first real-time MIMO processing demonstrations [97].

Outside of the lab, cabled SDM fibers have been installed in research testbeds enabling more realistic transmission and networking demonstrations [98]. The first submarine fiber cable with shared amplification of SMF bundles has been deployed [99] with plans announced for 2-core MCF technology to be used in submarine cable [100]. Such deployments have been preceded by works on cabling SDM fibers which have included a submarine cable with up to 128 spatial channels based on a 4-core fiber design [101] that has also demonstrated multi-vendor interoperability. Meanwhile standardization of MCFs has been discussed at the International Telecommunication Union (ITU-T) Standardization Sector [102] with the first mass produced MCF announced [103].

Current and future challenges

SDM system research has undoubtedly shown the potential for SDM fibers to increase the information-carrying potential of optical fibers by orders of magnitude over SMFs. However, the techno-economic case for widespread deployment depends on clear demonstration of cost-per-bit savings and a plausible migration path with different fiber choices offering various advantages and disadvantages. In particular, the choice of strong or weak-coupling directly impacts on switching, multiplexing and integration strategies. SMF arrays have the advantage of potentially utilizing existing deployed fibers; however, despite efforts to redesign cables with increasing numbers of fiber pairs [104], it is unlikely to match the number of spatial channels that MCF and FMF can support in the same cable area. Further, relying on SMF will also mean the number of connections increases with the traffic. A crucial advantage of SDM fibers in space-restricted network sites such as data centers is their higher spatial density allowing higher-density connectors [105]. High-density multifiber push-on (MPO)-type connectors have shown up to 256 core connections in a single connector using arrays of WC-MCFs [106]. However, the need to maintain a relatively large core pitch to ensure acceptable crosstalk levels [107] places a limit on the connection density.

Coupled SDM fibers offer both the greatest opportunity for integration and high SSE but also the greatest challenge in achieving it. These systems generally require high-speed electronics to undo crosstalk using MIMO processing, the complexity and cost of which scales with the spatial channel counts [108]. Furthermore, small differences between the propagation characteristics of different cores or modes may lead to mode-dependent loss (MDL), which fundamentally limits the capacity of such systems [109].

A further ongoing challenge for all SDM solutions is realizing the potential of SDM amplifiers for power and components savings. Core-pumped multicore erbium-doped fiber amplifiers (MC-EDFAs) have been demonstrated with transmission characteristics similar to conventional EDFAs [110]. Such amplifiers allow hardware sharing through components such as isolators and pump couplers, but there is no reduction in the number of required pump lasers. The efficiency of cladding pumped MC-EDFAs has been improved through various pump-light recycling techniques [111], but the smaller diameter of coupled SDM fibers are more likely to provide desirable pump conversion efficiencies. The challenge for coupled amplifiers is achieving sufficiently uniform characteristics between spatial channels to prevent capacity reduction from spatial channel gain variation.

In addition to point-to-point links, SDM technologies also offer potential to simplify and increase efficiency in switching and networking. Replacing conventional wavelength switching in WDM networks with highly efficient spatial switching in SDM networks has been proposed and experimentally demonstrated [112, 113], as illustrated schematically in figure 10(b). A growing research area is identifying the optimum networking and control-plane technologies to fully exploit the spatial domain, such as the spatial-bypass shown in figure 10(b).

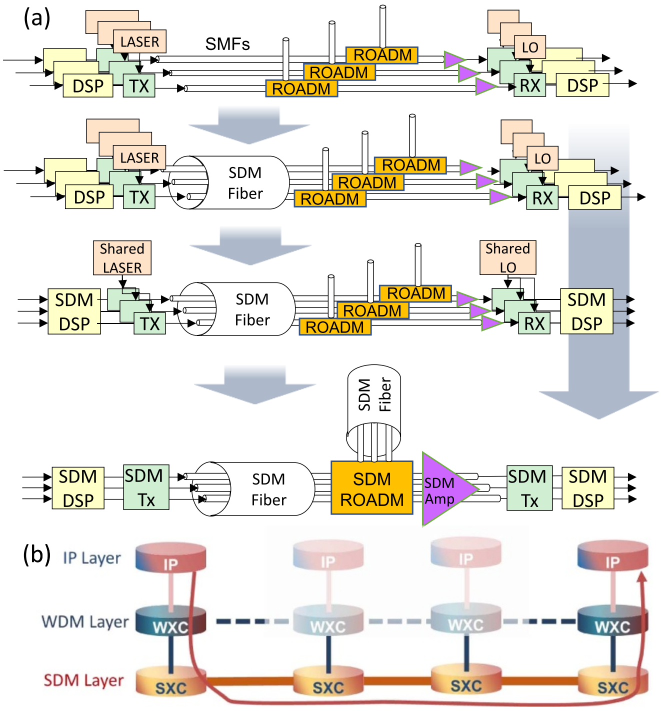

Figure 10. (a) Potential migration paths from parallel fibers to integrated SDM link and (b) example of spatial bypass for network with uncoupled SDF fibers and spatial cross-connect (SXC).

Advances in science and technology to meet challenges

To fulfill their potential as the backbone of future optical transmission systems, SDM technologies must continue to demonstrate clear cost scaling and resource efficiency over conventional approaches. In this respect, technologies such as compact, energy-efficient optical transceiver arrays and amplifiers are crucial targets, but a better understanding of cost and energy efficiency comparison metrics for different SDM solutions is also key.

Amplifier development could particularly benefit from standardized metrics. The optical power-conversion efficiency and the wall-plug efficiency have been used to track improved power efficiency for specific amplifier variants, but direct comparisons of power efficiency between amplifiers with different SDM fibers and pumping schemes are less clear. Whilst it is attractive from an integration point of view to adopt SDM amplifiers that can be connected or spliced to the corresponding transmission fiber, it is also necessary to demonstrate better integration, power saving, and uniformity than low-cost amplifier arrays [114]. Optical amplifiers are further covered in section 3.

With large-scale production only just beginning with 2-core fibers [103], the cost of MCFs relative to SMFs is hard to predict, particularly for advance trench assisted designs. As previously noted [1], it seems likely the cost of large mode-count FMFs can be significantly lower than for an equivalent number of SMFs. However, outside of data centers, fiber costs may be dwarfed by deployment costs, making operation costs and power consumption per spatial channel more critical. At the component level, in addition to low-cost and low-loss multiplexers, couplers and related optical components for performance monitoring of spatial sub-channels are required for nodes and cables.

Coupled SDM systems require further technological advances. Scalable MIMO processing techniques must not only be computationally efficient but also implementable with the prevailing technology. Further, all link components need to be optimized to minimize loss, gain, and delay between spatial channels to match the performance of independent fibers [109].

A further challenge of SDM systems is the migration path and potential for gradual deployment with a plausible economic model that can be built on already deployed and in-service fibers. Figure 10(a) shows how uncoupled SDM solutions offer a relatively simple migration path, but such a migration path for coupled SDM systems is less clear. Further, any migration to SDM technologies will require compatibility with scalable switching technologies and node architectures. This in turn requires new control-plane approaches, taking into account not only the best way to use the additional spatial dimension but also how to manage additional impairments such as crosstalk or delays between spatial channels.

Concluding remarks

SDM technologies remain a solution to meet the demand for increased capacity at lower costs in all optical network regimes with MCF technology on the cusp of commercial adoption in submarine cables. Research continues to identity which fiber flavors are suited to specific applications, with the focus shifting away from escalating hero experiments to investigation of power efficiency, cabling, integration, and the evolution from current systems including tailored networking technologies.

Acknowledgments

Thanks to Ruben Luis and Georg Rademacher for continuous support and discussion on all SDM-related matters.

7. Beyond the C-band

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Status

More than 35 years have passed since the publication of the first experimental demonstration of the erbium-doped fiber amplifier [115]. As already mentioned in section 1, the possibility of simultaneously amplifying channels within approximately 4 THz of optical bandwidth, which came to be known as the C-band (where C stands for conventional) in 1530–1565 nm, an order of magnitude greater than the entire radio spectrum, offered what seemed an inexhaustible communication resource for the future and enabled WDM. However, 37 years on, the exponential growth of bandwidth-hungry internet services including high-definition video streaming, cloud computing, artificial intelligence, Big Data and the Internet of Things urgently needs new advances in optical data transmission technologies to enable ultra-high throughputs with minimal latencies [116]. This applies to all types of networks, from metro, access networks, and inter-data center links through to wide-area terrestrial and ultra-long haul transoceanic systems [48]. The key question is how this ongoing exponential growth in network capacity can be achieved, even with the use of all signaling dimensions, including bandwidth, information spectral density and space. To answer this, all the signaling dimensions, including bandwidth, information spectral density, and space, must be explored.

Under some simplifying assumptions (see section 11), an upper bound on the information rate, or capacity, of a communications link is given by the well-known Shannon–Hartley formula: $C = S \cdot B \cdot ISD \leqslant S \cdot B \cdot \log_2(1 + SNR)$, where S is the number of spatial channels (included in this are the multiplexed spatial modes in each core), B is the channel bandwidth, ISD is the information spectral density per spatial channel and SNR is the signal-to-noise ratio. ISDs approaching the $\log_2(1 + SNR)$ bound are already being achieved using advanced multi-dimensional coded modulation, signal shaping, and Nyquist (or sub-Nyquist) channel spacing, as described in section 11. It has been shown that SNR can be maximized using nonlinearity tailored constellations, low-noise transceivers and amplifiers, and the compensation of linear and nonlinear optical fiber impairments (see section 4 and [117]). To meet the orders of magnitude growth in link capacity demanded by future applications, these near-quantum-limited ISDs must be combined with increased exploitation of the other two signaling dimensions: bandwidth and space. The former requires extending channel bandwidth beyond that of the C-band, both in currently installed fiber links and any future links. This can be combined with space-division multiplexing (SDM), based on multiple fibers (currently installed) or new multi-core/multi-mode fibers as discussed in section 6, making possible link capacities of tens of petabits per second.

The bandwidth of an optical fiber is defined by the low-attenuation window of silica, across the O–U-bands (1260–1675 nm) (figure 11). Despite fibers having over 60 THz of bandwidth, commercial systems have used less than 20% of this [118], while transmission research has explored approximately 60% of this, with most of the developments in the last 12 months [17]. The majority of current systems operate over a relatively narrow bandwidth, limited to 11.4 THz within the C- and L-bands [118]. The current experimental record throughputs per spatial channel over transoceanic distances (see further description of transoceanic system challenges in section 16) are 74.38 Tb s^{-1} over 6300 km [119], 70.4 Tb s^{-1} over 7600 km [120], 51.5 Tb s^{-1} over 17 107 km

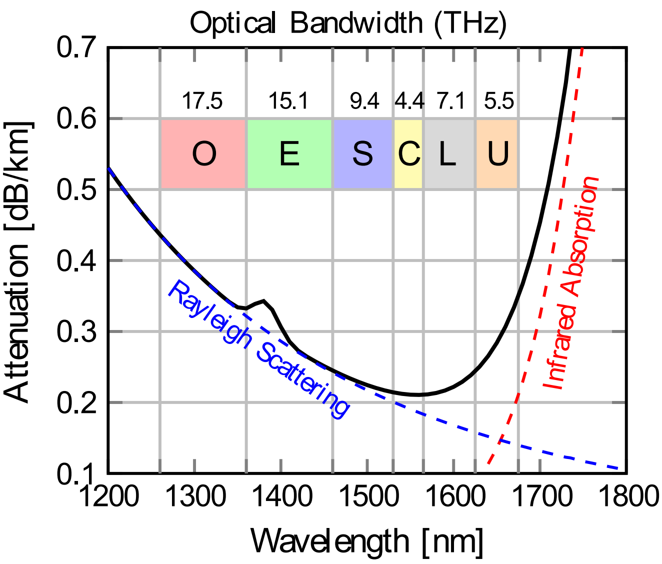

Figure 11. Typical fiber attenuation spectrum for a low-water peak single-mode silica fiber and corresponding transmission bands from O- to U-band.

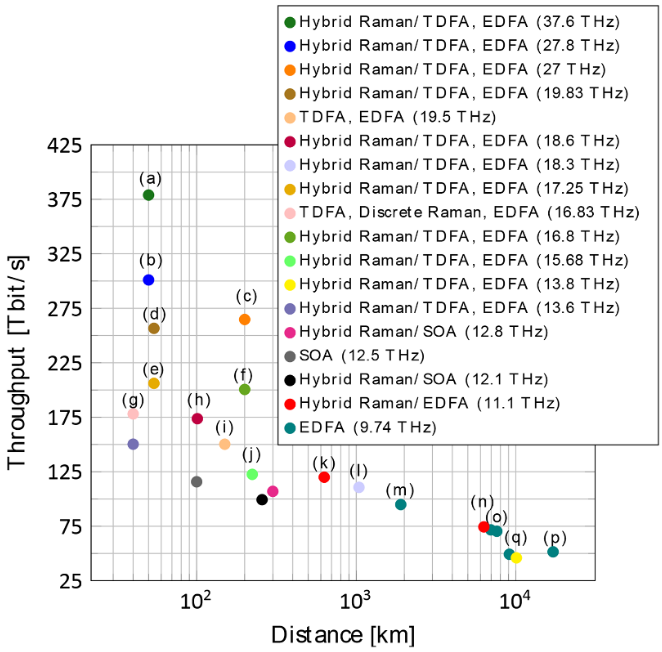

Figure 12. Record data throughput versus distance for single-mode fiber, not including spectral gaps between amplifier gain bandwidths, with the most recent and key results highlighted in the figure: (a) [17] (b) [128] (c) [123] (d) [130] (e) [129] (f) [133]; (g) [127] (h) [134] (i) [135] (j) [136] (k) [124] (l) [125] (m) [126] (n) [119] (o) [120] (p) [121] (q) [122]. Reprinted with permission from [137] © The Optical Society.

[121], and, more recently, 46 Tb s^{-1} over 10 072 km [122], using bandwidths of 11.1 THz, 9.74 THz, 9.74 THz, and 13.8 THz, respectively. The throughput records per core for medium haul (>100 km) currently stand at 264.7 Tb s^{-1} using 27 THz signal bandwidth [123], 120 Tb s^{-1} using 11.4 THz signal bandwidth [124], 110.7 Tb s^{-1} using 18.3 THz signal bandwidth [125], and 94.9 Tb s^{-1} using 9.74 THz signal bandwidth [126], demonstrated experimentally over 200 km, 630 km, 1040 km, and 1900 km, respectively. For short-distance links, the record throughput was achieved using the S-, C-, and L-bands (16.8 THz) to reach 178 Tb s^{-1} over 40 km [127], O-, E-, S-, C-, L- and U-bands (37.6 THz) to reach 378 Tb s^{-1} [17], and E-, S-, C-, and L-bands (27.8 THz) to reach 301 Tb s^{-1} [128], both over 50 km, and over 54 km, throughputs of 206.1 Tb s^{-1} and 256.6 Tb s^{-1} were achieved using 17.25 THz and 19.83 THz signal bandwidth respectively in [129] and [130]. However, the throughput per spatial channel has increased by less than 15% in the last 6 years—constrained by quantum noise, optical amplifier bandwidth, and fiber nonlinearity. These recent transmission record results over standard fiber only, together with other record experiments, are summarized in figure 12. Section 6 describes transmission in multicore fibers. It should be noted that estimates of achievable capacity are not linearly dependent on bandwidth B due the wavelength dependence of the fiber's physical parameters, namely attenuation and dispersion, and thus the understanding and calculation of the systems and network throughputs achievable with increasing bandwidths remain as an open research problem [131, 132].

To successfully utilize the full fiber bandwidth requires fundamental research to solve the problems of increased nonlinearities and approaches to model these over ultrawide bandwidths. New components and sub-systems are also needed, namely sources, amplifiers, and receivers. Some of these challenges have been elegantly summarized in [118], and here two of these key challenges are highlighted.

Increased nonlinearities and modeling. Associated with the increase of bandwidth beyond the C-band is the growth of inter-channel stimulated Raman scattering (ISRS), first experimentally investigated in coherent transmission systems in [138], which manifests itself as power transfer between channels (from short-wavelength channels to those at longer wavelengths) and—unlike other Kerr nonlinearities—grows with increased channel spacing up to approximately 13 THz, reducing sharply beyond 15 THz. It has become widely accepted in the optical fiber community that a simple and effective way to model the distortion due to fiber nonlinearities is to consider it as an additive white Gaussian noise, termed nonlinear interference (NLI). This is captured by the so-called Gaussian noise (GN) model and its extended versions, see section 9 and for example [139, 140]. To enable real-time prediction of the ultrawideband system performance, well beyond the C-band, formulations in closed-form are needed. In particular, for ultra-wideband (UWB) transmission systems, ISRS, must be taken into account in the estimation of the NLI. In addition, these formulations must offer a fast, yet accurate, evaluation of the network characteristics if they are to be useful for transmission link throughput prediction and network optimization. Closed-form equations for the ISRS GN model [140] have been proposed in [141–143], together with techniques to calculate the optimum launch power distribution to mitigate the Raman-induced power transfer, for example, see [137, 144]. The refinement of the modeling to make it more accurate and faster over bandwidths beyond 20 THz remains a challenge and is currently the focus of intensive research.

Amplification. The greatest effort has focused on expanding the amplification bandwidths and investigating the optimal technologies to achieve this (see section 3). A recent review of semiconductor optical amplifiers [37] highlights that a signal bandwidth of 103 nm was used to transmit at a data rate of 107 Tb s^{-1}, using semiconductor amplifiers. However, semiconductor optical amplifiers introduce additional nonlinear distortion of the signal (cross-gain modulation). Raman amplification (either discrete amplification using dedicated gain fibers as the amplification medium or distributed amplification with the gain in the transmission fibers) has the advantage that it can provide gain at almost any wavelength, simply by choosing the wavelength of the pump lasers. Another promising technology is that of rare-earth doped amplifiers, e.g. thulium-doped fiber for the S-band and bismuth-doped fiber for the O- and E-bands [118]. Work in [145] is focused on the use of multi-stage discrete Raman amplification to transmit over the E- to L-bands and BDFA achieving transmission over 25 THz (195 nm), although discrete Raman amplifiers suffer from nonlinear distortion due to the long lengths of gain-fiber required ($\sim$10 km). The widest distributed Raman amplification achieved (see, for example [146]) was 200 nm. However, distributed Raman amplification would be spectrally inefficient as a sole ultrawideband solution, since the pumps and the associated guard bands would occupy a significant fraction of the bandwidth available, and cost and energy considerations place constraints on the number of amplifiers that can be used. The high power consumption of all Raman amplifiers also remains a challenge.

Advances in science and technology to meet challenges

It is expected that key advances will be in three areas:

(i) Ultrawideband amplifiers needed to provide cost effective and energy-efficient continuous gain over the 400 nm or so within the low-loss region of standard single-mode optical fibers and for new fibers being developed.
(ii) New research on ultra-wideband system design: to lead to new systems that will optimally use the combination of new amplifier technologies to maximize system throughput.
(iii) Modeling of the transmission in the ultrawideband regime: Two key developments are needed and expected here. The first step is the development of real-time techniques enabling real-time and accurate modeling of the 60 THz transmission band or even wider for new fiber designs. More challenging is the need to revisit the nonlinear Schrödinger equation, assessing its applicability in the ultrawideband regime, and the development of new methods that stop treating nonlinear distortion simply as additive white Gaussian noise.

Concluding remarks

Although the erbium-doped fiber amplifier revolutionized optical communication and enabled WDM operation, its relatively narrow bandwidth is now constraining capacity increases in optical communications systems. Optical fibers, both existing and new, offer a huge potential source of bandwidth although much exciting work remains to make ultrawideband operation practical. The goal is to exploit the optical fiber bandwidth fully and in a more intelligent manner, rather than treating it as high-capacity plumbing. A further challenge is that of network design—how to translate the impressive achievable point-to-point system gains into network throughput. Advances in artificial intelligence (AI)-aided techniques such as graph neural networks and new graph-generation approaches to train these will help answer questions of whether the fight for bandwidth is justified.

Acknowledgments

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8. Machine learning

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Status

In the past decade, the field of machine learning (ML) has seen a tremendous spike in popularity and has led to transformations in almost every field of science and engineering. This is mostly due to the success of neural networks (NNs) and in particular the technique of deep learning [147]. Deep learning and the accompanying software tools have also found their way into optical communications and are now indispensable tools in the field; ML can nowadays be used in all parts of fiber-optical communication networks [148–150].

ML is widely used for parameter estimation in optical networks, with the goal to configure optical network links. Traditional estimation techniques often rely on complex models and heavy approximations [148]. Examples of parameters that are necessary for optical network configuration include, but are not limited to, optical signal-to-noise ratio (OSNR), bit error rate, chromatic dispersion, polarization mode dispersion, amplifier operating points, but also predicted traffic, prediction of light-path failures and packet loss classification [148]. These parameters can be used in the control plane of the network for network reconfiguration, amplifier control, routing or spectrum management, to just name a few [148]. Due to their property as universal function approximators, ML algorithms and in particular neural networks are also often used in the physical layer to replace (sub-optimal or overly complex) signal processing algorithms in the receiver or transmitter. Examples include, but are not

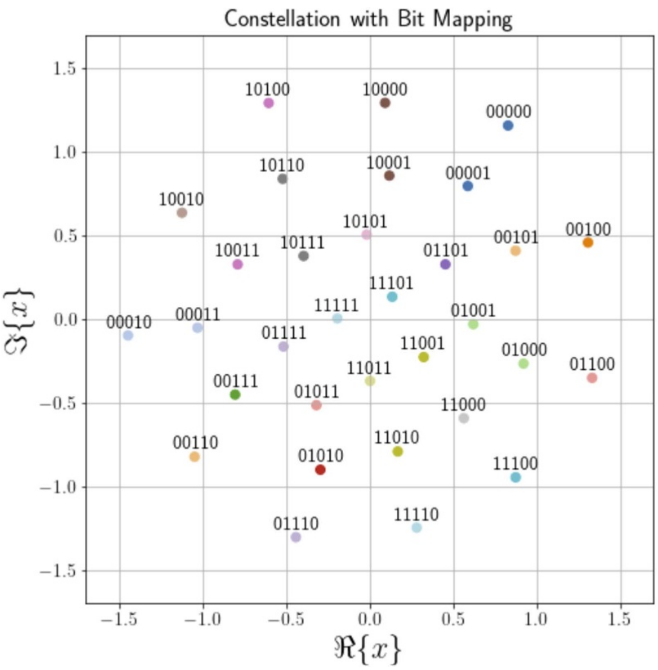

Figure 13. Constellation with 32 points designed for an AWGN channel with residual phase noise using the ML method of auto-encoders. The numbers next to the constellation points indicate the bit pattern assigned to this point. The source code for optimizing the constellation can be found in [156].

limited to, the compensation of (possibly nonlinear) transceiver impairments, equalization [151], nonlinearity compensation by improved backpropagation [152], and many more.

At the core of most ML systems is a versatile optimization framework consisting of an automatic differentiation module and an optimizer based on (stochastic) gradient descent or variants thereof (e.g. the Adam algorithm) [147]. This framework can be essentially used to optimize the parameters of any parameterized computer program. Hence, it can be used to optimize various aspects and parameters of optical communication systems during the system design phase, provided that a simulation software exists [153, 154]. ML has been used to optimize, e.g. Raman amplifiers [155]. Another very common application is the optimization of modulation formats in conjunction with bit mappings, which is a rather hard task using traditional model-based approaches but can be easily numerically carried out using ML. Optimized modulation constellations and bit mappings can enable optical communication systems with larger reach or noise/nonlinearity robustness compared to standard textbook constellations. An example is provided with source code in [156], carrying out the optimization of a modulation constellation for a channel with additive white Gaussian noise and phase noise, as in the setup of [157], modeling a simple coherent communication system. The resulting constellation is shown in figure 13, highlighting how patterns consisting of 5 bit are mapped to 32 complex modulation symbols. The complex modulation symbols are then used to generate, after pulse shaping, the complex baseband transmit signal. ML was the key enabler to bring such optimized constellations together with optimized bit mappings to the field, as the optimization with traditional methods did not yield acceptable results [158].

Despite the already widespread application in the field, we are still only scratching the surface of possibilities that ML offers. Due to the more heuristic nature of ML, we are still unsure about the full potential of ML and need to run extensive numerical assessments. Up to now, ML has been mostly used to improve the system performance with respect to SNR or data rate. An interesting future research direction is the improvement of transceiver energy consumption using ML. Furthermore, the versatility of the numerical optimization framework presents novel opportunities for system design that we cannot yet foresee. We may build upon strong current research activities to develop energy-efficient compute platforms for ML, which may form the basis for future fiber-optic transceivers.

Current and future challenges

Currently, ML algorithms are still not widely deployed in live optical networks and are mostly a research tool. Two applications are most likely to be deployed in the near future: parameter estimation in optical networks and offline optimization of system parameters. Especially in network planning, suboptimal models are often used in conjunction with approximative numerical optimization. Reinforcement learning (RL) [159] is an attractive solution to optimize networks *in situ*, i.e. while being operated. RL can also lead to more efficient networks; however, during the optimization process, the networks' performance may temporarily degrade. Network operators are hesitant to accept a temporary degradation of a live production network; hence, research is needed to avoid temporary degradation during RL or only allow degradations in a virtual, offline version of the network, a so-called digital twin.

The use of ML to replace parts of the transmitter or receiver, e.g. as signal processing algorithms or as nonlinearity compensators, still poses many research challenges, despite the gains we already see. Currently, most such ML systems are treated as 'black boxes,' where it is unclear why and how the ML algorithm works. An important future research challenge will be the explainability and interpretability of ML algorithms: Why does ML outperform classical approaches? Why does the ML-based algorithm require less arithmetic operations than an optimal algorithm while still providing acceptable performance (in case the optimal algorithm, e.g. a maximum-likelihood detector has unacceptably high complexity, in terms of required arithmetic operations, and ML is used to approximate the optimum algorithm with less operations)? What can we learn from an optimized ML algorithm about the design of hand-crafted, low-complexity algorithms or about the system behavior in general? Answering these questions would turn ML from a simple optimization framework into a versatile tool that can actually help us shape and understand fiber-optic communication systems in a much deeper sense, with yet unforeseeable impact.

Due to the enormous data rates at which optical communication systems operate, complexity is a major concern when implementing ML systems. Most modern ML systems employing NNs are not specifically tailored to these high data rates, as the applications driving their development are mostly computer vision (CV) and natural language processing (NLP). However, their structure which leads to simple parallelization makes them attractive for implementation. A future challenge will be the development of ultra-low-complexity hardware platforms with low power dissipation that can be used in highly integrated, high-speed optical transceivers. In particular, it will be important to not only integrate the inference part (which uses the ML model), but also the learning part of the ML systems into a transceiver to enable continuous adaptation to varying conditions.

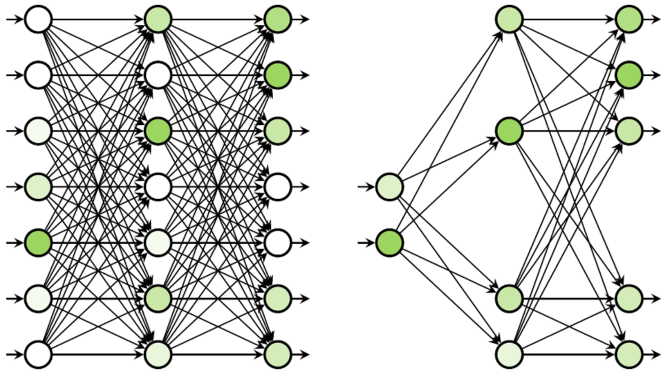

Figure 14. Low-complexity NN based on pruning. (a) Typical NN where each node computes the weighted sum of the incoming edges and applies a nonlinear function. The shade of the node depicts the importance of the node on the final result. (b) Resulting NN after pruning the less important nodes.

Advances in science and technology to meet challenges

To improve explainability and interpretability of ML algorithms in optical communications, and to gain novel knowledge about fiber-optic communications, we need to invent novel ML methods that are specifically tailored to (fiber-optical) communications. Today, the field of ML is mostly driven by applications from the fields of CV and NLP. In these applications, models are often missing, hence the black-box approach to ML is very fruitful. In the field of telecommunications in general, we are often in possession of models that either fully or approximately describe the system behavior. Hence, we may use the knowledge of the underlying physics and the models at our disposal to derive new ML methods that are specifically tailored to communications. A first attempt in doing so has been presented in [152], which introduces a novel ML structure based on the split-step Fourier method to model both nonlinear propagation on the optical fiber and nonlinearity compensation at the receiver. Deriving specifically optimized ML components for telecommunications will need to bring the fields of optical communications, traditionally rooted in physics and the field of ML, rooted in computer science, closer together.

A major challenge that needs to be solved before deploying ML algorithms is the challenge of complexity. Modern ML systems built upon NNs are usually prohibitively complex to be used in optical communication systems, unless specifically optimized. The complexity reduction can be either done algorithmically or by tailored hardware platforms. The algorithmic approach is currently explored in the ML community and has been used in the field of communications in the context of ML-aided forward error-correction decoding [160]. This approach, which is based on pruning NNs, is illustrated in figure 14. ML systems that are specifically tailored to communications will likely need to be built around some complexity optimization.

Besides algorithmic advances, the success of NNs has driven large research efforts to find efficient hardware implementations of NNs. Fiber-optic communications will need either low-complexity digital ML implementations that can be incorporated in the transceiver signal processor or completely novel processing architectures. The latter can be build using either analog hardware or even photonics, which has the potential of integration in a fully photonic integrated circuit. In particular photonic integration of so-called neuromorphic hardware promises unprecedented energy efficiency [161]. Such systems could integrate both inference and learning for constant system adaptability.

Concluding remarks

ML and in particular the application of ML in fiber-optic communications are rapidly growing and evolving fields with widespread applications throughout all the layers of the network. There are many open research and engineering challenges that need to be overcome before ML will be ubiquitously employed in live networks: The application of ML in the physical layer will require novel high-speed, high-throughput ML methods, which are specifically tailored to high-speed fiber-optic communication systems. Additionally, these should be developed in conjunction with novel hardware platforms (so-called neuromorphic processors) implementing the ML schemes. The application of ML in the network will require new learning paradigms, allowing the optimization and adaptation of live networks with novel ML schemes, possibly outperforming the current suboptimal approaches. An already mature application of ML is the use of ML-based optimization tools for offline system design. We have still just scratched the surface of the possibilities of ML, and we expect to see a more holistic, ML-based system design in the future.

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9. Nonlinearity characterization and mitigation

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Status

Nonlinear distortion determines the error floor of an optical fiber communication system and is considered as the performance-limiting factor. The two essential research topics include nonlinearity characterization and mitigation. Figure 15 summarizes the nonlinear impairment sources, including the fiber nonlinear and device nonlinear distortions. The fiber nonlinearity is dominant in long-haul transmission, whereas the device nonlinearity dominates in metro and short-reach transmission.

The fiber nonlinear distortion could be well described using the Manakov equation [162]. The split-step-Fourier method accurately simulates the optical field propagation along a nonlinear fiber with a large computational complexity. The perturbation model was developed to quickly calculate the nonlinear distortion with some penalty of calculation error [163, 164]. To assess the fiber nonlinear distortion, the GN [139] and enhanced GN (EGN) models [165] calculate the nonlinear noise spectrum from the signal spectrum and transmission link parameters.

For the device nonlinearity, there were many research activities in wireless communications [166] and most of them could be used in optical communications. The 'black-box' model, such as the Volterra model, describes the input and output relationships of a nonlinear device. However, it does not consider the actual physical mechanism. Meanwhile, the 'white-box' model employs the actual nonlinear physical mechanism, such as the sinusoidal model of the Mach–Zehnder modulator. Beside the nonlinear behavior model, the nonlinear distortion specification is another import task. Several different methods, such as total harmonic distortion, noise to power ratio (NPR), and orthogonal component have been proposed [167]. In NPR method, a certain frequency component of the input

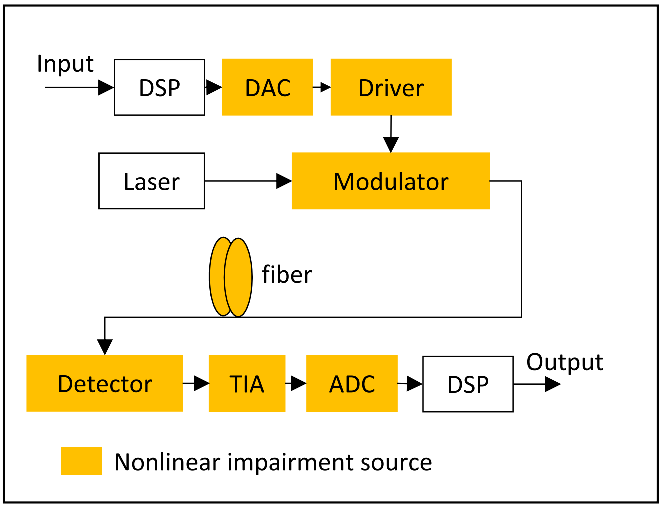

Figure 15. Nonlinear impairment sources in the optical communication system. TIA: Transimpedance amplifier, DAC: Digital-to-analog converter, ADC: Analog-to-digital converter, DSP: Digital signal processing.

signal is notched, and the re-growth component at the nonlinear device output is measured. The ratio between the re-growth component power and the output signal power is the NPR.

There are two different philosophies to mitigate the fiber nonlinear and device nonlinear distortions. The first one selects proper system parameters to reduce the nonlinear impairment or develops a new modulation scheme to tolerate the nonlinear impairment. In general, both the fiber and device nonlinear distortions increase with the signal power, whereas the signal to additive noise ratio also increases. Thus, optimizing the signal power is the most practical mitigation method. In addition, the baud-rate is optimized to reduce the fiber nonlinear distortion. The nonlinear effect of eye skew could be reduced by increasing the bias current of vertical-cavity surface-emitting laser. Multidimensional modulation, constellation shaping, and probabilistic shaping were proposed to increase the tolerance to fiber nonlinear distortion.

The second philosophy first calculates the nonlinear distortion and then cancels it. Nonlinear models with different complexities and different approximation errors are the mathematical basis of such approaches. The back-propagation method compensates for the fiber nonlinear distortion by digitally propagating the received signal backwards to the transmitter using the split-step-Fourier method [168]. The computational complexity is further reduced by perturbation back-propagation [169] and perturbation predistortion [170]. For the device nonlinearity, the look-up-table-based digital predistortion (DPD) first estimates the transmitter nonlinearity perturbation by a training sequence and thereafter cancels it [171]. The Volterra-based nonlinear compensator calculates the inverse function of the nonlinear distortion using the Volterra model and then compensates the nonlinear distortion [172].

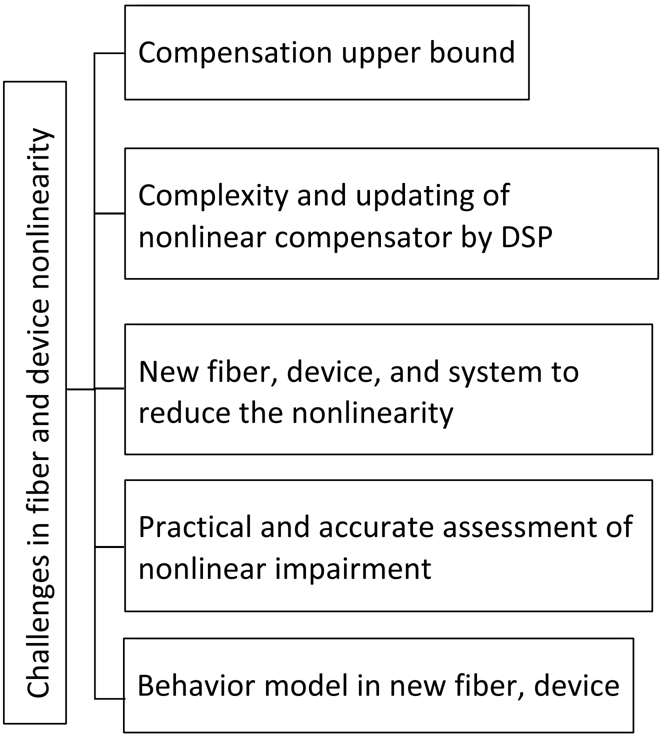

Figure 16. Challenges in the characterization and mitigation of fiber and device nonlinearities.

Current and future challenges

As shown in figure 16, the nonlinearity characterization and mitigation still have many challenges. The nonlinearity characterization in single-mode fiber is relative mature; however, the situation in new fibers, such as the few-mode fiber, is much more complicated. If multi-band transmission is considered, stimulated Raman scattering and frequency-dependent loss should be considered in the GN or EGN model.

The device nonlinearity characterization has much more challenges. One fundamental challenge is that the nonlinear distortion not only depends on the device nonlinear status but also on the input signal characteristics [166]. Thus, the nonlinear distortion measured by a test signal, such as a sinusoidal signal, usually differs from the actual nonlinear distortion in real-world communication [173]. Estimating nonlinear system performance from the device nonlinear characteristics is quite challenging [174]. Counter-intuitively, the nonlinear term cannot be considered as an equivalent nonlinear noise, because the nonlinear term contains information about the input signal. The nonlinear distortion measured by the NPR method is usually not consistent with the actual nonlinear noise in real-world communication, because the notch process changes the signal. The orthogonal component is a good way to describe the equivalent nonlinear noise; however, it is hard to measure.

To mitigate the fiber and device nonlinearities, it is more practical to reduce the nonlinear distortion through a proper selection of system parameters. Nonlinear compensation has two fundamental challenges: high complexity and compensator updating. Additionally, the benefit of practical nonlinear compensation is usually insignificant. For fiber nonlinearity, the cross-phase modulation cannot be compensated if the receiver has no information about the copropagating channels. For device nonlinearity, the effects of high-order nonlinear terms and long memory cannot be compensated by a low-complexity compensator.

The compensator updating is another big challenge, in particular for the device nonlinearity. The dominant device nonlinear distortion occurs in the transmitter. The compensator updating needs a dedicated receiver to calculate the compensation error, which significantly increases the cost.

Finally, most nonlinear compensation algorithms show a trade-off between performance and complexity. Thus, it would be desirable to know an upper bound of the compensation benefit given the complexity limitation. However, it is still unclear how to obtain such a bound.

Advances in science and technology to meet challenges

To solve the above challenges, many new technologies are expected. The nonlinear distortion in the few-mode fiber has been studied in [175]. The stimulated Raman scattering is considered to improve the accuracy of the EGN model [176]. To practically and accurately estimate the nonlinear system performance from the device nonlinear characteristics, a new test signal other than the conventional single-tone or multi-tone signal is expected. For example, the probability-maintained notch method accurately and practically measures the equivalent nonlinear noise [177]. Moreover, new fiber, device, and system designs are still a more practical way to mitigate the nonlinear distortion. For example, the nonlinear distortion in hollow-core fiber is almost zero (see section 2). The thin-film $LiNbO_3$ modulator (see section 4) has a much weaker nonlinear distortion than the silicon-photonics or indium-phosphide modulator. The optical phase sensitive amplifier regenerates the signal during amplification. Machine learning may be useful for nonlinear system identification and nonlinear compensation [178, 179] (see section 8). Many algorithms for compensating device nonlinearities have been developed in wireless communication and automatic control system, such as maximum-likelihood sequence estimation and DPD methods based on iterative learning control, direct learning, and indirect learning. Some of them could be used in optical communication [180, 181]. Phase retrieval could recover the complex optical field from the intensity information obtained from the photodetector [182]. This may facilitate the transmitter-side DPD updating.

Concluding remarks

Nonlinear distortions ultimately limit the transmission performance. Thus, a deep understanding of the nonlinear phenomenon is the basis of nonlinearity characterization and mitigation. A connection between transmission system performance and nonlinear characteristics is necessary for communication system design. Today, the most practical way to mitigate the nonlinear distortion is to select the proper device, system parameters, and modulation schemes to avoid the nonlinear effect. Nonlinear compensation by digital signal processing still faces the challenges of large complexity and dynamic updating. It will be the ultimate solution when nonlinear distortion cannot be avoided.

10. Forward error correction

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Status

FEC is a vital component of virtually all optical communication systems. By adding redundancy (parity bits) to the transmitted data and exploiting that redundancy at the receiver, a transmission link can be engineered to achieve a very low bit error rate (below, say, 10^{-15}), despite the presence of noise, crosstalk, or other stochastic channel impairments present in the link. FEC subsystems are typically designed to operate in concert with an underlying modulation format such as quadrature amplitude modulation (QAM), and may also incorporate probabilistic amplitude shaping schemes that carefully control the relative frequency with which different symbols are transmitted (see section 11).

The decoding problem faced by the FEC subsystem depends on the nature of its interface with the demodulator. The demodulator may make 'hard' symbol-by-symbol decisions, in which case the FEC decoder is presented with a sequence of (possibly erroneous) discrete symbols to decode, a process called *hard-decision* (HD) decoding. Alternatively, the demodulator may augment its hard decisions with information about their reliability, usually in the form of a probability distribution over the symbol alphabet. An FEC decoder that processes such probabilistic information is said to perform *soft-decision* (SD) decoding. SD decoding can provide significantly better performance than HD decoding, but it requires a higher-bandwidth demodulator interface and is generally more computationally intensive and hence power-hungry.

Standardized FEC schemes used in fiber-optic networks typically employ classical error-correcting codes such as Hamming, Bose, Ray-Chaudhuri, Hocquenghem (BCH), and Reed–Solomon codes, often configured as concatenated codes (where an inner code provides an initial level of error control, with residual errors left by the inner code corrected by an outer code) or as product codes or spatially-coupled product-like codes [183, 184]. Modern capacity-approaching codes such as polar codes [185] and irregular low-density parity-check (LDPC) codes [186] are also in use in some proprietary FEC implementations. Table 2 provides a listing of a variety of standardized coding schemes used in optical networks for regional, metro, and long-haul applications. The table lists the coding overhead (OH)—the fraction of parity bits to information bits—and the net coding gain (NCG) at a bit error rate (BER) of 10^{-15}, i.e. the reduction in received SNR needed by the coded system to achieve that BER relative to that required by uncoded transmission, including a penalty term that accounts for the code overhead (thus representing a 'net' coding gain). An excellent and comprehensive overview of the design and use of FEC for optical transponders can be found in [187].

Current and future challenges

The overhead efficiency of all FEC schemes is governed by information-theoretic limits established by Shannon in 1948, as discussed in section 11. Over the past several decades, a number of coding schemes have been developed that, in combination with a suitable modulation format and probabilistic or geometric shaping can, in principle, approach channel capacity [188]. While capacity-approaching codes are in one sense ideal—they minimize the overhead needed to achieve a certain performance level—their excellent performance generally comes at a steep price in decoding complexity and latency. Decoding complexity is of crucial importance in optical communication systems due to their extremely high per-wavelength data rates. At a throughput of 1 Tb s^{-1}, each pJ per decoded bit translates to 1 W of decoder energy consumption, and as the power consumption of the decoder grows, so does the necessity to dissipate heat. The central challenge of FEC design for optical communication systems is therefore not a question of finding a coding scheme with near Shannon-limit performance, but rather one of finding a coding scheme that offers a good balance between *performance, complexity,* and *latency.*

FEC *performance* is usually measured at some fixed reliability level, for example at a bit error rate of 10^{-15}. A fundamental performance measure is the gap to the Shannon limit, with state-of-the-art coding schemes offering performance that comes to within 0.5–2 dB of the Shannon limit, depending on the decoding complexity and latency. The NCG is a less fundamental, but often used, FEC performance measure.

The *complexity* of an FEC scheme is dominated by the implementation of the decoder. The complexity measure of greatest practical interest would be the power consumption of a hardware implementation of the decoder operating at the desired throughput. However, since it is time-consuming and costly to implement decoding circuits, code designers often turn to simpler alternative measures of complexity such as the number of binary operations needed for decoding, or, for iterative message-passing decoders, the edge-complexity of the underlying factor graph multiplied by the number of decoding iterations allowed [189].

Table 2. Standardized FEC schemes.

Scheme	Code	Recommendation	OH%	NCG (dB)
GFEV	RS(HD)	ITU-T G.709, G.975	6.69	6.2
EFEC	BCCH inner (HD), RS outer(HD)	ITU-T G.975.1, Appx. I.4	6.69	8.67
HGFEC	BCH-based stair-case(HD)	ITU-T G.709.2	6.69	9.38
oFEC	BCH-based block-convolutional (SD)	Open ROADM MSA	15.3	11.1 (QPSK), 11.6 (16QAM)
cFEC	Hamming inner (SD), BCH-based staircase outer (HD)	ITU-T G.709.3, OIF 400G ZR	14.8	10.4 (QPSK), 10.8 (16QAM)

End-to-end physical-layer *latency* generally refers to the time difference between when a data bit enters a transmission system at one end of a link and when it is delivered at the other end. Transmitted bits undergo a physical propagation delay, a receiver buffer-fill delay, and an FEC decoding delay, where the latter two terms are proportional to the FEC block length. Assuming an index of refraction near 1.5, light propagates through on optical fiber at about 2×10^8 m s^{-1}; thus a 500 km link induces some 2.5 ms of propagation delay, equivalent, at 400 Gb s^{-1}, to the time it takes to send 10^9 bits. The end-to-end latency of long-haul links is therefore relatively insensitive to the FEC block length, since the buffering and decoding delays induced by even large block lengths on the order of 10^7 bits are dominated by the propagation delay. A 500 m link, on the other hand, induces just 2.5 μs of propagation delay, equivalent to the time it takes to send 10^6 bits at 400 Gb s^{-1}, and thus the end-to-end latency of short-haul links is very sensitive to the choice of FEC block length.

Another key challenge is to design FEC schemes for the actual optical channel, rather than—as is common practice—for a proxy channel such as the additive white Gaussian noise (AWGN) channel. A properly designed FEC scheme should take into consideration increased phase noise due to nonlinear interference noise such as cross-phase modulation, polarization effects such as polarization-dependent loss (PDL), and other effects that cause the channel to deviate from being an AWGN channel. Incorporating knowledge of actual channel noise distributions in the demodulator output can improve FEC performance [190], as can the design of the underlying signal constellation [191].

A final challenge is to design FEC schemes that are flexible, so that that a single decoder can be configured to operate in multiple modes (e.g. low-power low-gain and high-power high-gain) or at multiple code rates. Such flexibility will become particularly important to support the emerging concept of point-to-multipoint optical networks using subcarrier multiplexing [192] in which different subcarriers are used to serve different users. Subcarriers will be aggregated in a variety of configurations to accommodate varying throughput requirements, different subcarriers may encounter different SNR levels that may vary with time, and the reduced effective subcarrier symbol rates may restrict allowable block lengths. Designing an appropriate FEC scheme to support such network-level flexibility will be a challenge.

Advances in science and technology to meet challenges

The design of coded modulation schemes for high-throughput communication systems with optimized performance, complexity, and latency trade-offs continues to be an active area of research, with new developments arising too quickly to properly survey in this brief section (however; see [189] and references therein). The design of shaping schemes that are tolerant to nonlinear interference noise is also an active area; see sections 9 and 11. For channels with PDL, [193] provides a simple interference cancellation scheme that, in conjunction with a universal precoder, transforms the PDL channel into separate scalar AWGN channels, allowing off-the-shelf coding and modulation schemes to approach capacity.

A novel and very energy-efficient hardware architecture for decoding product-like codes such as staircase codes is presented in [194]; the authors report decoder implementations that exceed throughputs of 1 Tb s^{-1} while consuming on the order of just 2 pJ of energy per decoded bit.

Code concatenation continues to be a very promising approach for designing new low-complexity coding schemes, as the inner code (typically with an SD decoder) does not need to correct all channel errors itself, but must merely reduce them to a level where the outer code (typically with an energy-efficient HD decoder) can correct them to the target bit error rate. Various techniques have been proposed to provide effective error-reduction without excessive power consumption, often leveraging the existence of an energy-efficient HD decoder. For example, the cFEC and oFEC schemes of table 2 employ SD decoders that involve HD decoding trials of Hamming or BCH codes for multiple test error patterns (whose selection is guided by the reliability of the individual bit positions as determined by the demodulator output). Combinatorial search methods for the most likely error pattern are also being studied [195]. Another promising way to reduce the complexity of computationally intensive soft-decision decoding is to use error-and-erasure decoding techniques guided by some amount of reliability information; see [196] for an example of this line of work. Figure 17 provides representative performance versus complexity trade-off curves from [189] for complexity-optimized inner LDPC decoders concatenated with outer staircase [184] and zipper [197] codes.

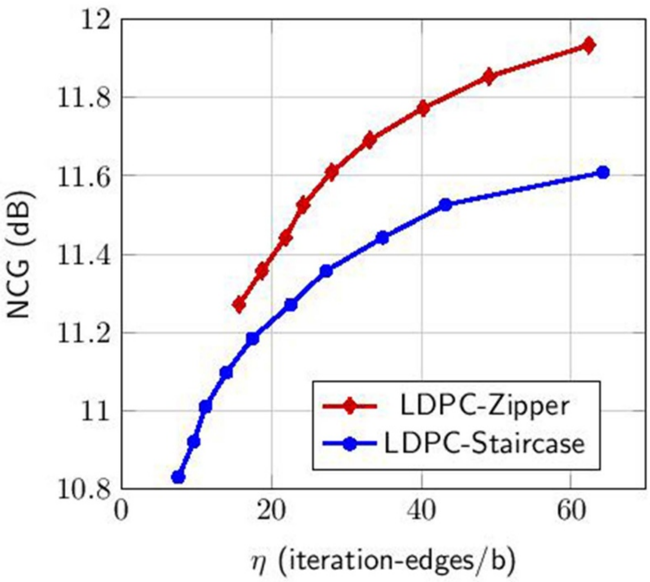

Figure 17. Representative performance versus complexity trade-off for concatenated codes at 20% OH with complexity-optimized inner error-reducing LDPC codes [189]. Outer codes are staircase codes at 6.67% OH [184] or zipper codes [197] at 2% OH. The complexity, measured in iteration-edges per decoded bit, depends on the number of edges in the code graph and the number of allowed iterations.

Concluding remarks

FEC will continue to be an essential element of future high-speed optical communication systems. Future FEC schemes will be carefully optimized to provide the appropriate balance between performance, complexity, and latency for a given application. Codes will be designed so that a single scheme will have the flexibility to be configured to operate at multiple points in this trade-off space, while working in close coordination with other digital signal processing algorithms performing shaping and nonlinearity compensation.

11. Modulation, shaping, and capacity

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Status

C. E. Shannon introduced in 1948 the concept of *channel* capacity, which represents the theoretic maximum amount of information that can be reliably transmitted through a given channel, where *reliable* here means arbitrary low error probability [198]. In practice, a bit error rate of 10^{-15} is often targeted, as discussed in section 10. Shannon's channel capacity guided the design of many wired and wireless communication systems for decades, and reached the fiber-optical communication community only 45 years later [199]. In [199], an optimum launch power maximizing the SNR was shown to exist. This optimum power later on led to the now infamous nonlinear Shannon limit [200, 201], whose estimation, implications, and limitations have been discussed in detail, e.g. in [202–204].

While upper and lower bounds exist, the channel capacity of the optical channel is still unknown. Upper bounds are rare and are often obtained with standard information-theoretic techniques such as duality and Lagrange multipliers [205, 206], maximum entropy and entropy power inequality [207], etc. Lower bounds are often analyzed either using mismatched decoding theory [208] and/or by simply *building* (experimentally or via numerical simulations) systems that achieve low error probability. The channel capacity is still an open question mainly because—although we have excellent models for signal propagation in fibers (see sections 8 and 9)—the resulting problem is a very difficult one, which very quickly gets out of hand. A very good review of the efforts in the direction of computing the channel capacity of the nonlinear optical channel can be found in [209] (see also [206]).

Many works have used an AWGN channel model (or modulation-dependent models like the EGN model) as good and very simple approximations for the coherent fiber-optical channel. These models are certainly good for low and moderate powers where nonlinear effects can be disregarded. However, even for long uncompensated links where the channel *looks like AWGN*, the reality is that nonlinear effects make the channel a non-AWGN one. The nonlinear fiber-optical channel is in fact a channel with multiple sources of noises, not only from amplifiers but also from other electrical and optical components, as well as nonlinear fiber effects. As soon as some of these effects are taken into account, the channel very quickly becomes intractable from an information-theoretic viewpoint. The device nonlinearities discussed in section 9 are particularly challenging in this context, and information-theoretically unexplored.

The so-called achievability results are lower bounds on the capacity of the channel. Lower bounds for high spectral efficiency (SE) systems are obtained by combining nonbinary modulation (e.g. PSK, QAM, or dual-polarized versions thereof) and forward error correction (see section 10), a combination known as coded modulation. Coded modulation using standard modulation formats like QAM works very well in the linear and pseudo-linear regimes; however, a gap to the channel capacity exists. For low powers, where nonlinear effects can be disregarded, the gap to capacity (AWGN capacity in this case) can be as large as 1.53 dB for *dense QAM constellations*. This 'ultimate shaping gap' is unknown for the fiber-optic channel when nonlinear effects are excited. In fact [210], showed that the gap could be even near 2 dB.

Current and future challenges

The first challenge is the calculation of the channel capacity for the nonlinear fiber-optical channel. The gap to capacity is still unknown (because the capacity itself is unknown), nevertheless, finding improved transmission rates is very important, and thus, **the second challenge is try to close**

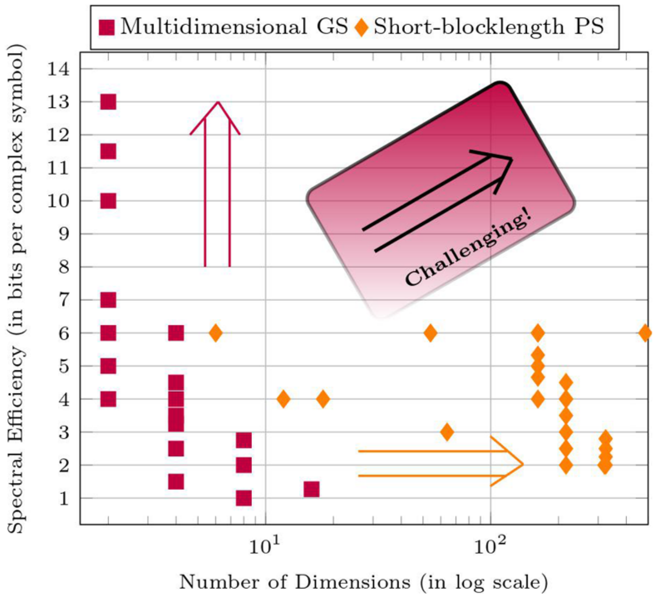

Figure 18. Schematic (and likely incomplete) illustration of available results in the literature for multidimensional GS and short-blocklength PS. Only results for bit-wise decoders are show. Data for GS partly taken from [212]. Data for PS from [213–216].

this capacity gap. Indeed, this is what in recent years the research community has been doing with the help of *signal shaping*. Broadly speaking, there are two flavors: Probabilistic shaping (PS), which targets a good probability distribution of the transmitted symbols, and geometrical shaping (GS), which adjusts the constellation points, moving away from regular (e.g. QAM) constellations. While initially GS targeted two-dimensional (2D) optimized constellations, later works increased the dimensionality to 4D (jointly optimizing constellations over two polarizations), but also to 8D (using for example two time-slots or two WDM channels), etc. These works focus on increasing the constellation cardinality to achieve larger gains at high SE (see, e.g. [211, 212]). This multidimensional GS (MD-GS) approach is shown with purple squares in figure 18, which is an incomplete summary of results available in the literature. Although not shown in figure 18, for a given dimensionality, larger gains are achieved (in general) when the SE is increased (vertical purple arrow).

While PS in principle targets a given input distribution on the transmitted symbols, *short or ultra-short blocklength PS* can in fact be compared to GS with a high number of dimensions: short-blocklength PS can be seen as a special case of MD-GS where only certain sequences are chosen for transmission. The key difference is that PS is restricted to sequences of symbols chosen from regular (e.g. QAM) constellations, while MD-GS has the flexibility to use sequences (MD symbols) that do not come from a regular MD grid. The orange diamonds in figure 18 show short-blocklength PS results with their corresponding SEs. These results are taken from the literature and are based on the probabilistic amplitude shaping (PAS) architecture. Generally speaking, the longer the blocklength (for a given SE), the larger the gains (orange arrow in figure 18). More generally, the results in figure 18 highlight **the third challenge in this area: to operate in the top-right corner of** figure 18, i.e. at high SEs and relatively long blocklengths. Currently almost no results are available in the literature in this regime.

Advances in science and technology to meet challenges

In the optical channel, multiple wavelengths are often transmitted at the same time. Using terminology from the multiuser information theory (MUI) literature, nonlinear effects make the optical channel an *interference channel*. We believe that taking an MUI perspective on nonlinear WDM channels is a promising new research avenue. This is the approach recently taken in [217], where MUI techniques are used for a realistic perturbative model for the nonlinear fiber-optics channel. In MUI, the notion of channel capacity is replaced by a *capacity region*, and lower and upper bounds by *inner and outer bounds*, respectively. In a nutshell, MUI studies the set of feasible jointly achievable rates for all the different users. As such, it captures the contention between the different users accessing the optical transmission resources in terms of the trade-offs between their achievable rates. One could argue that the chances of deriving the MUI capacity region are even smaller than for the point-to-point case; however, an MUI approach has the advantage of looking at the optical channel as a whole, rather than through the eyes of a single user (WDM channel). In this sense, MUI has the ability to study scenarios where, e.g. one or multiple users are sacrificed in favor of other users, or even in favor of the total capacity in the fiber.

To tackle the second challenge, i.e. to operate in the top-right corner of figure 18, one should combine the best of both shaping worlds. On one hand, MD-GS can offer large gains with increased dimensionality (blocklength), but at the same time, it suffers from complex (MD) mappers and demappers. On the other hand, PS can operate at large blocklengths (high dimensionality) because PAS is based on algorithmic ways of generating the required sequences. At the same time, however, the gains of PS are limited by the constraints imposed on the constellation structure (e.g. QAM). This analysis leads us to the almost obvious conclusion that we should be jointly harvesting gains from MD-GS and short-blocklength PS, i.e. by using by doing *hybrid GS and PS*. Naturally, the challenge here is to design low-complexity algorithms (mappers, demappers, shapers, and deshapers) that offer good performance at finite blocklength. In this regard, developments in the area of finite-blocklength information theory are of great importance as well as the development of well-structured MD-GS formats.

Concluding remarks

Finding the channel capacity of the nonlinear fiber-optical channel and harvesting large shaping gains at high spectral efficiencies are still open research problems. Multi-user information theory could help the analysis of the capacity problem by treating the channel as an interference channel, whilst providing trade-offs across users sharing the same fiber (the channel). To solve the second problem, hybrid shaping strategies with low-complexity digital signal processing algorithms are very important. In this context, we believe that the study of finite-blocklength theories—going beyond the traditional asymptotic information-theoretic analyses—could be very important in the coming years.

Acknowledgments

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12. Long-haul and metropolitan networks

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Status

The Internet backbone must regularly evolve and deliver higher bandwidths at lower prices to support growing traffic demands, and optical fibers are the media of choice to transport high volumes of data across long distances as they provide robust, high-bandwidth, and low-latency communication channels, called lightpaths. A long-haul optical network comprises optical nodes interconnected via fibers; and each node comprises optical switches, transceivers, and interfaces to higher-layer networks, e.g. Ethernet and internet protocol (IP)/multiprotocol label switching (MPLS). Optical signals (lightpaths) sent by transmitters (lasers) are coupled using wavelength multiplexers into the fibers. Signals are amplified, when necessary, using EDFAs to maintain signal power and compensate for attenuation. At intermediate nodes, these signals can be added or dropped using reconfigurable optical add-drop multiplexers (ROADMs), which allow wavelengths or spectrum from incoming signals to be switched to different output fibers. A ROADM consists of a wavelength splitter and a wavelength-selective switch (WSS). Recent ROADM architectures provide colorless, directionless, and contentionless (CDC) multiplexing and demultiplexing for greater flexibility [218].

Most fiber-optic systems operate according to the ITU-T based on WDM across the C band (1530–1565 nm) with fixed spectrum spacing of 50 GHz (fixed-grid). To handle the enormous traffic growth, optical-transmission technologies and optical-network architectures are evolving due to enhanced flexibility in optical spectrum and transponders. The new paradigm—elastic optical network (EON)—can maximize utilization of the C-band of SMF by implementing a flexible grid (flex-grid) with finer granularity (e.g. 12.5 GHz) to enhance spectral efficiency over conventional WDM networks [219].

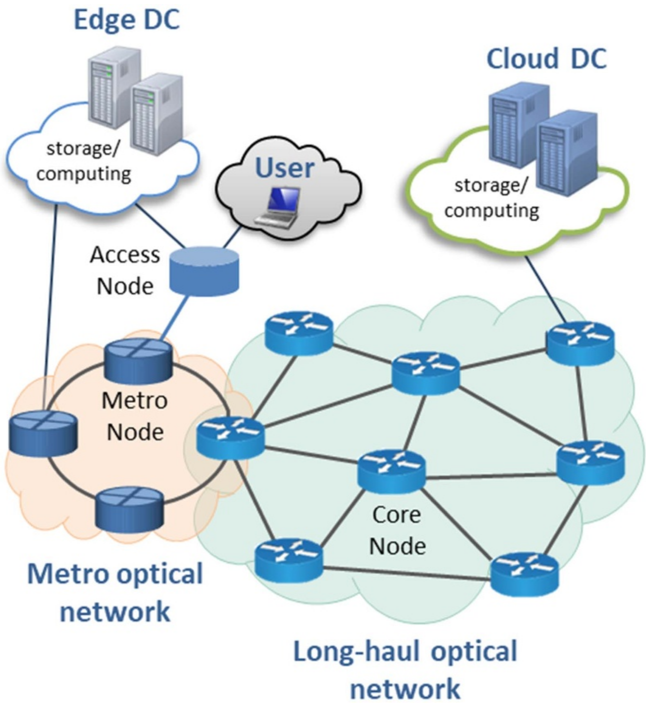

Figure 19. Long-haul (comprising backbone/core nodes), metropolitan (comprising metro nodes), and access (comprising access nodes) optical network segments supporting cloud and edge infrastructures (data centers).

With the emergence of 5G/6G communications, an unprecedented amount of access traffic will load the optical-network segments that aggregate and transport this traffic from metro to long-haul networks and data centers. Metro networks need to evolve from a rigid aggregation infrastructure to a composite network-and-computing ecosystem (see figure 19) to support advanced services with ultra-low-latency and high-reliability requirements (e.g. augmented and virtual reality, autonomous driving, etc.) This evolution is happening in several directions: increased re-configurability and automation enabled by network function virtualization (NFV) and software-defined networking (SDN) (see section 13); integration of optical and wireless access networks; metro nodes becoming edge data centers to process data closer to the user ('edge cloud'); exploiting massive MIMO and 3D beam-forming to enhance data rates; etc. Optical networks play a major role in cloud/edge computing, acting as a substrate for inter-data-center networking. Such evolution needs an end-to-end control-and-management system to ensure robust multilayer traffic management and protection.

Current and future challenges

Optical communication systems flourished around the C-band due to its minimum attenuation; however, with the inevitable exhaustion of C-band, other solutions are needed for capacity enhancement (besides lighting more fibers, called the multifiber (MF) solution), namely multiband (MB), i.e. exploitation of the fiber's remaining low-loss spectrum beyond the C-band (from O to L) (see section 7) and SDM (see section 6) with MF or multicore and/or multimode fiber (MCF/MMF) transmission, the latter for shorter-distance communications. MB transmission allows brownfield deployment through reuse of existing fiber infrastructures (i.e. the widely deployed ITU G.652.D and other optical fibers) by exploiting the entire low-loss spectrum range—encompassing the O, E, S, C, and L bands (see section 7). Migration from C-band-only systems to MB systems can provide 10x higher capacity vs. C-band-only systems [220]; hence, in conjunction with EON-compatible systems, MB can utilize the full potential of standard SMFs. However, new technologies are required to support the usage of the additional bands, the main challenges being low maturity of key components (filters, switches, transponders, amplifiers, etc) and additional complexity in terms of wavelength-dependent fiber parameters such as attenuation and dispersion coefficient, and use of diverse lumped amplification technologies. As MB systems enable co-propagation of many spectral bands, this increase in network capacity comes at the cost of higher NLI due to ISRS along with amplified spontaneous emission (ASE) noise generated by different in-line amplifiers. This limits a lightpath's quality-of-transmission (QoT); hence, we need robust physical-layer models, leveraging ML-based QoT estimation techniques, to accurately predict the OSNR of lightpaths. Other important and intertwined aspects include spectral efficiency, advances in modulation formats that can be supported, baud rates, etc.

On the other hand, SDM solutions with MF or MCF/MMF transmission can attain data rates in Pb/s/fiber [221] (see section 6). However, these solutions require greenfield deployment through rolling out new fibers, lighting up existing dark fibers, or deploying novel types of fibers requiring new transceivers and physical-layer modeling (e.g. considering interference due to inter-core/inter-modal crosstalk). Note that MB and MF transmissions are not mutually exclusive, as MB maximizes per-fiber transmission, which can be combined with SDM by activating additional fibers.

It is imperative that optical networks (long-haul and metro) be resilient against failures and disruptions (e.g. fiber cuts) as their impact can be catastrophic considering the dependence of other networks and services. As shown in figure 20, consumers get services from enterprises (traditionally) and/or cloud service providers (with evolution towards cloud and edge), which host and deliver their services via the supporting carrier backbone optical networks. With networks becoming progressively content or service-centric, metro network resiliency is crucial to ensure connectivity and reliability across the network, so that a link or data-center failure does not cause loss of critical content or service [222]. Regarding long-haul vs. metro links, note that their distances and objectives are different, e.g. the shorter metro links need to provide increased connectivity for edge computing, with low latency requirements, whereas the long-haul links might evolve to point-to-point fat pipes connecting data centers (DCs).

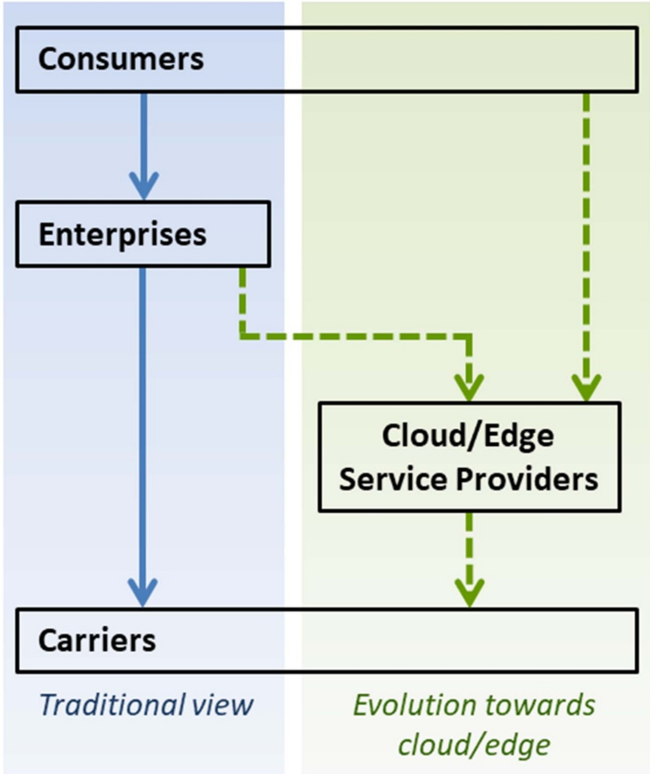

Figure 20. Dependency and relationship of network users (consumers), enterprises, cloud service providers, and carriers.

Advances in science and technology to meet challenges

Recent advances in coherent optical transmission have brought unprecedented elasticity in tuning transponder parameters such as baud-rate, modulation format, forward-error correction overhead, etc. Other emerging technologies such as bandwidth-variable transponders (BVTs) with adaptive baud-rate and modulation format, tuned dynamically to the required transmission distance, and bandwidth-variable optical cross-connects can bring significant benefits to network capacity with a flex-grid [223]. The optical switch architectures should evolve towards fiber switching to handle a large number of fiber inputs, each with dynamically varying spectral utilization.

Towards MB evolution, upgrades of existing C-band systems can benefit from maturing C + L band systems, e.g. by re-use of EDFAs, which can operate across the L band [224]. High performance has also been achieved in case of hybrid EDFA + Raman amplifiers for C + L. Gradual progression from the C band to the L, S, E, and O bands is envisioned as a longer-term solution as technology matures, starting with the L band (or C + L bands) as the next-most promising candidate. Future systems may have a combination of spatial channels and wavelength channels. From a networking perspective, the choice between a spatial channel and wavelength channel to route a connection would come down to the wavelength-continuity and spatial (or spectrum)-continuity constraints, distance traversed by the connection, the bit-error rate it can tolerate (based on the characteristics of the applications the connection is carrying, etc. On a parallel path, HCF shows promise through successful experiments and potential future applications, but HCFs are not yet commercially available (see section 2). HCFs use an air-based core vs. solid glass core of standard optical fibers which allows 50% faster data transmission than traditional fiber, leading to considerable reduction in latency.

In evolution towards cloud or edge, content replication provides intrinsic protection against data loss; however, ensuring availability of a content replica in all disconnected network segments after a failure is essential for service continuity. To maintain users' access to services at times of disaster or failure, content connectivity (i.e. reachability of content from any point of a network) is an important metric for service assurance [225]. Additionally, in case of a resource crunch (caused by failures or traffic surge), degraded service, i.e. reduced amount of resource allocation for a service vs. its regular requirement, is a critical metric to ensure service continuity (with lower but acceptable quality instead of disruption) by exploiting different tolerance levels of services [226].

While content-centric protection is crucial for future services, data security is another important issue. Advances in quantum computing motivate research on quantum key distribution (QKD) to provide security for future optical communication networks, see section 20 and [227]. Moreover, with the advent of network programmability and virtualization, interaction between the network and applications, i.e. application-centric networking, is made possible. Important information about the applications can be utilized to provide better resource allocation, leading to better quality of experience (QoE) for the end-users.

Concluding remarks

As traffic demands continue to grow at nearly 30% annually, optical spectrum is becoming scarce, leading to a 'capacity crunch' which will become more severe in the next 5–10 years. The future network challenge is how to embrace and integrate the advances in optical-fiber technologies towards spectral expansion and flexibility, such as EON, MB, SDM, etc. Advances in optical network equipment (new types of fibers, amplifiers for beyond-C-band, flexible transponders, etc) and in network monitoring and analytics using ML models are paving the way towards next-generation optical networks. With integration of cloud and edge computing, metro networks are evolving into a composite network-and-computing ecosystem to exploit high capacity, while minimizing energy consumption and supporting dynamic traffic with varying bandwidth and reliability requirements. Rapid increases in computing, storage, and transmission bandwidths mean more energy consumption and depletion of the earth's finite pool of energy resources. Fortunately, conducting as many of these activities in the optical domain (rather than in the electronic domain), especially data transmission, can lead to improved energy efficiency.

There will be an equivalent paradigm shift in the network's control and management as well. With the advent of the 5G/6G era, any performance issues in critical services will require careful fault management across multiple layers and planes (data and control), and traditional solutions will not be able to guarantee end-user QoE. Hence, to ensure resiliency and flexibility and to provide seamless and personalized services to end-users, a unified and robust application-aware, network-aware, and optical-layer-aware integrated end-to-end management system is crucial.

13. Software-defined networking

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Status

SDN for optical transport networks has proven effective for a wide range of use cases, yet its continuous development is driven by the need to track advances in optical networking technologies. These include new advances at the data plane level, to exploit the increasing programmability of network elements—e.g. dynamic adaptation of transceivers' operational modes—and to develop automation. SDN has contributed to the softwarization—macroscopically, understood as the increase adoption of software in all aspects of network operation including, but not limited to, control, management, and telemetry—of the network, highlighting the need for open and standard interfaces for interoperability. Its success is partly due to the use of a model-driven development [228] with systematic use of data models, along with open toolchains and reference implementations, focusing on the applications functionality and added-value features [229]. Driven by operators' needs [230], SDN has been applied to closed systems exporting open application programming interfaces (APIs) as well as partially or fully disaggregated systems with different levels of abstraction. Although competing standards do exist, there have been efforts to adopt common (partial) models, maintaining compatibility with fundamental assumptions and underlying core models and frameworks. *Network automation* is key given the requirements of agility and efficiency in service provisioning, yet today it remains limited to a set of well-known aspects and established procedures.

Most efforts regarding SDN for the photonic layer(s) of optical transport networks have focused on fixed/flex-grid ense wavelength-division multiplexing (DWDM) networks (see figure 21) with a certain level of maturity regarding the northbound (NBI) and southbound interfaces (SBI) (e.g. [231], OpenConfig or OpenROADM [232]). Here NBI refers to the interface from the relevant entity towards its clients/consumers

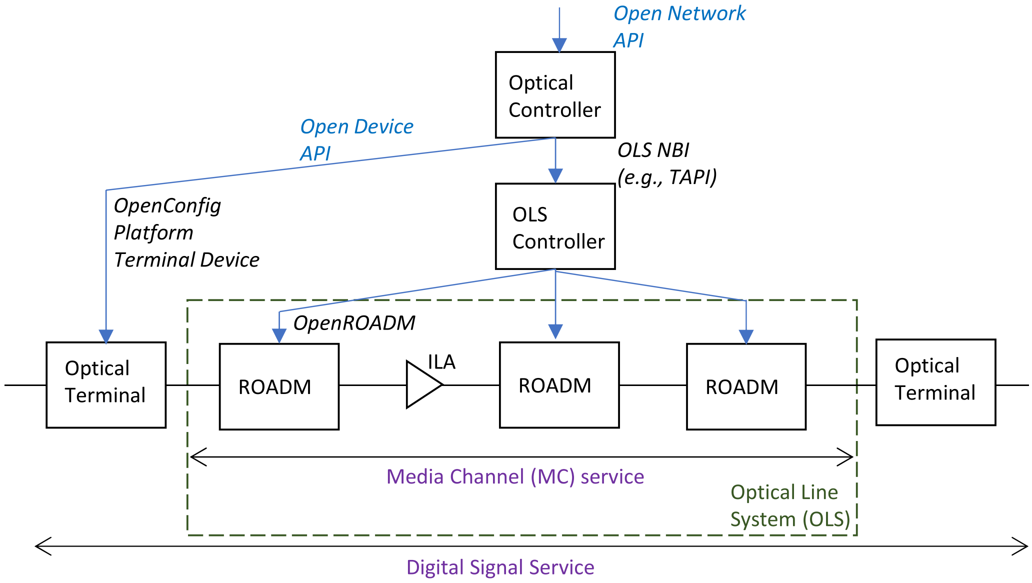

Figure 21. Framework for SDN control of optical networks (see [230, 233]).

and SBI refers to the interface from the relevant entity towards devices or surrogate systems. Interoperability events [233] show a high level of compliance across vendors, covering operations such as device discovery, optical channel configuration and cross-connection management. Path computation mostly addresses scenarios with a few number of layers and constraints. The application to multi-domain and multi-layer networking is also being demonstrated, typically relying on a hierarchical arrangement of controllers e.g. abstraction and control of traffic-engineered networks (ACTN) [234].

Current and future challenges

The evolution towards a generalized software-centric and cloud-native approach for infrastructure operation and service deployment (see figure 22) is a multi-faceted problem with architectural, algorithmic, and modeling specific challenges. The first one is its adoption by network operators, logically tied to the maturity of the underlying technology, applicability to existing workflows, support for fundamental aspects such as provisioning, inventory and alarm management, and availability of guidelines on usage, best practices, and reference implementation agreements.

Arguments for the adoption of SDN include, notably, (i) the ability to automate provisioning services with agile and efficient service provisioning workflows, resulting in tangible savings in operational expenses and (ii) to reduce vendor-interoperability issues and vendor lock-in thanks to the usage of common and standard interfaces. That said, there are also clear drawbacks associated to SDN, such as single point of failure issues or scalability issues. In this sense, SDN architectures need to evolve from monolithic, highly integrated, and highly coupled designs towards more loosely coupled systems, following a *cloudification* of the control plane. This means new designs of entities as composable functions (which can be implemented in terms of components) that are interconnected, via open and standard (internal) interfaces, following a service-oriented architecture and implemented as, e.g. *distributed systems* or *microservices,* benefiting from automated deployment, scaling, and lifetime management [235]. Research is also needed in support of the reliability and security of the control functional elements as critical infrastructure systems, addressing data security and overall system integrity including the use of distributed ledger architectures in support of network control.

Data models, at any level of abstraction, are at the core of transport SDN. A recurring challenge is to extend and refine existing models with additional features, consolidating layer/technology-agnostic concepts and specializing them for specific technologies, adding new layering and constraints while managing flexibility (e.g. a 400G service can use a single optical tributary signal (OTSi) using DP-16QAM at 75 GHz, or a 4 OTSi group using DP-QPSK at 4 × 50 GHz). More challenging research is needed for multi-band/ultra-wideband networking [236] or SDM [237], accounting for heterogeneous optical bands or exploiting the spectral and spatial dimensions by enabling the provisioning of SDM super-channels by exploiting MCF/MMF. In particular, to cope with traffic growth, future systems will exploit a combination of spatial and wavelength/spectral channels. From a software defined networking perspective, resource allocation algorithms will need to be extended to work with such multi-layer networks, addressing the concepts of traffic grooming as well as provisioning connections with different switching paradigms in an integrated way (including media channel/wavelength, waveband, core and/or fiber switching), which will render such SDN control planes significantly more complex to deploy.

A critical aspect across the aforementioned challenges is Physical-layer impairments (PLI), which, given the high data rates, increase nonlinear effects and nonuniform channel behavior. There is a lack of common, mature data models

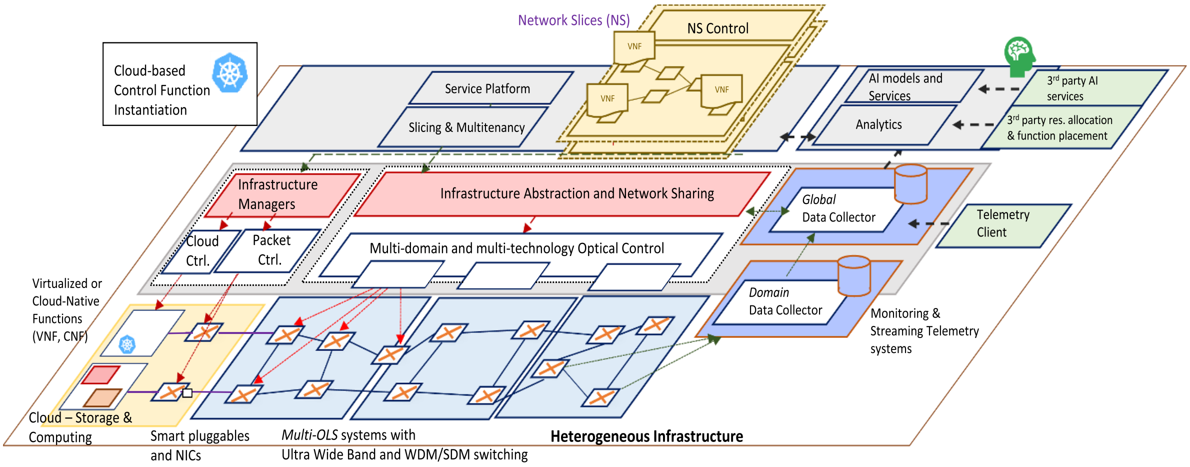

Figure 22. Evolution towards a software-centric, cloud-native control of heterogeneous infrastructure.

and proprietary and costly simulation tools are difficult to integrate. Open-source tools such as GNPy or Net2Plan [238] provide novel algorithms for generalized routing and spectrum assignment or function placement are attracting attention, expected to operate in hybrid off-line/on-line modes, but they require efficient access (in terms of retrieval, storage, and processing) to collected and managed data. The challenge is manifold: first, integrate such tools defining *unified short-term provisioning and long-term network planning* with a single software framework and second, extend current models to account for PLI with a characterization of transceivers (bit/baud-rate, FEC or modulation formats, …), optical fibers, amplifier functions or ROADMs, finding the right model abstraction level that can be applied to a multiplicity of devices from different providers.

Optical monitoring and telemetry are enablers for autonomous/autonomic networking enabling hierarchical closed loops [239]. Open data models are needed for the telemetry data. Specialized and secure protocols and frameworks should provide the required flexibility (cadence-driven telemetry needs to support higher frequencies to identify data patterns and event-driven telemetry shall enable flexible filter definition). Improved platforms are needed for data collection, aggregation, and processing, eventually building on top of open-source projects for database support or visualization.

The extension of SDN to multi-domain networks and technological layers (e.g. spanning multiple optical line systems or the joint control of IP/Optical layers) is complex due to the lack of detailed and global topology visibility. The evolution from discrete optics towards pluggable interfaces is challenging the decoupling of the IP/MPLS and optical control planes [240]. The overarching control of different network segments (wired/wireless access, aggregation/metro and core/long-haul) and their integration in orchestration systems is an open problem, including, e.g. coordinated DBA algorithms, split computing, or network slices with delay constraints in an edge/cloud continuum.

Automation, zero-touch networking, and intent-based networking (IBN) must be further developed to include cross-domain settings. AI/ML solutions in support of network operations should be further developed beyond expert- or rule-based systems, both in single domains and cooperatively across different domains. Specific challenges include: (i) the definition of ML models and reusability of previously used models; (ii) development of use cases and scenarios (e.g. selection of functional splits based on multi-objective problem formulation and dynamic traffic patterns), and (iii) research on distributed self-management control infrastructures based on multi-agent systems, including prediction of network behavior based on potential events and actuations.

Digital Twins (DT)—the concept of using network data to maintain a digital representation of a physical system to improve network operation and decision-making—are increasingly relevant, and DTs being considered for such aspects as soft-failure/anomaly detection; dynamic operation and testing of state changes; root cause analysis or discrete event emulation. In this sense, improved SDN interfaces are needed to support mechanisms for state synchronization between elements [241].

The network slice concept, as a logical set of interconnected functions, forming a logical and contained construct/network tailored and optimized for a (set of) services [242] is being extended to the transport network [243]. Quasi-static partitioning of the network by means of multi-tenant support at the device level or by means of a network hypervisor has been demonstrated, yet traffic isolation guarantees are difficult in the optical domain and enabling soft isolation and resource sharing is an open research problem. Evolved architectures should also empower users with the capability to manage their own services in a multi-tenant environment.

Advances in science and technology to meet challenges

Some of the identified challenges can be met with additional effort in terms of modeling and in-depth use-case development, as part of standardization activities and overall industry adoption. Optical SDN will benefit from architectures developed in the scope of software systems and overall cloudification following a service-oriented architecture, as well as from advances in large-scale, cloud-based, distributed software systems.

Resource-allocation algorithms need to deal with additional complexity and an increasing number of variables, interdependencies, and constraints. In addition to well-known approaches for optimization (e.g. integer linear programming, which may not scale well), new mechanisms are required. AI/ML models in support of network operation, with hierarchical closed loops, need to be developed. Autonomous networks need hierarchical telemetry systems, adopting the same model-driven development.

Current SDN protocols were designed for configuration and basic monitoring operations. New protocols are needed for massive telemetry and state synchronization between entities, and to address increasing security requirements in the exchanges between functional entities. Finally, QKD systems for critical applications need further consolidation.

Concluding remarks

The provisioning of data services (spanning connectivity, computing, and storage resources) needs to be automated. The usage of SDN is clearly a means to this end, regardless of the time scale considered. For a consolidated set of use cases, further standardization work and interoperability events is further required. There is a lot to gain in terms of automation towards truly autonomous networking tied to the consolidation of AI/ML algorithms applied to network operation. Other forward-looking aspects, related to network sharing and multi-domain and multi-layer provisioning and orchestration in complex and heterogeneous scenarios, still require significant research, despite constant advances.

Acknowledgments

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14. Data-center networks

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Status

In the past decade, data centers have become the key technology enabler for internet-based applications. Most of the popular Internet applications today are running in data-center infrastructure. In recent years, machine learning applications and wider adoption of cloud computing have further amplified the importance of such large-scale compute capability.

Data-center networking provides the interconnectivity and scale needed for executing these functions and services [244, 245]. Figure 23 shows a high-level view of Google's data-center network, which is a generic 3-tier architecture with top-of-the-rack (ToR) edge switches, aggregation blocks (ABs), and spine/OCS layer (blocks). For the 3-tier network, the tier 3 layer has evolved from traditional electrical packet switches (EPS) [246] to MEMS-based optical circuit switches (OCS) for directly connecting ABs [247]. Compared to traditional data-center networks, OCS technology holds a number of benefits relative to EPSes, such as being data rate and wavelength agnostic, low latency, and being extremely energy efficient. Also, using OCS instead of EPS as the 'spine' switch greatly reduces network cost because no optical transceivers are required for the OCS spine. As is detailed in [247], with appropriate traffic engineering and topology engineering, using OCS to directly connect the ABs does not degrade the throughput performance for Google's production traffic patterns.

Three types of interconnect technologies have been utilized to optimize the bandwidth cost and energy efficiency: 'direct attach copper' cables used for intra-rack server to ToR connections, with typical reach less than a few meters; parallel MMF-based SR optics or parallel SMF-based parallel single-mode (PSM) optical transceiver technologies for ToR to AB connections, with typical reach up to 100 m; SMF-based coarse wavelength-division multiplexing (CWDM) technology for interconnecting the AB and the EPS-based spine, or AB and AB for OCS-based spines, with 1 km reach.

The evolution of interconnect technology is mainly driven by the need to match the switch electrical I/O speed while improving cost, power, and density [246]. Five generations of optical interconnect technologies [248] have been developed to meet the ever-growing data-center network bandwidth demands, from the first-generation 10 Gb s^{-1} SFP+ using directly modulated lasers, on/off keying pulse-amplitude modulation (PAM2), and analog clock data recovery (CDR) to the latest 800 Gb s^{-1} Octal Small Form Factor Pluggable (OSFP) using externally modulated lasers (EMLs), PAM4, and digital CDR, with bandwidth increased by a factor of 80, energy efficiency improved by a factor of 6, and linear density improved by a factor of 24.

Current and future challenges

Until 2014 with the introduction of 3.2 Tb s^{-1} EPS, the switch ASIC capacity growth was able to match the data-center traffic growth. But due to the slowing of Moore's law as well as the bandwidth-scaling challenges facing the switch I/O, data-center traffic growth has been outstripping switch ASIC capacity growth since then. For example, from 2014 to 2021, Google's data-center traffic has increased by a factor of more than 36 [244], while the switch ASIC capacity only increased by a factor of 8, from 3.2 Tb s^{-1} (128 × 25 Gb s^{-1}) to

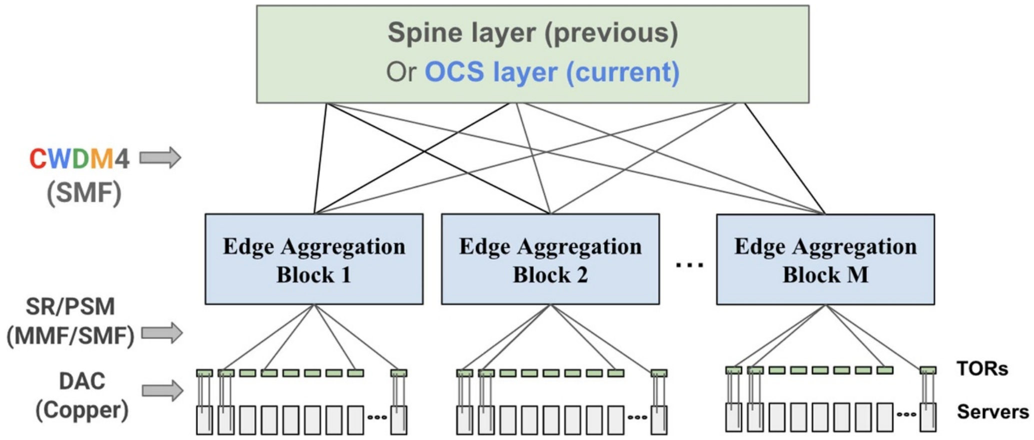

Figure 23. High level view of Google's data-center network. OCS: optical circuit switch; CWDM: coarse-wavelength-division multiplexing.

25.6 Tb s^{-1} (256 × 100 Gb s^{-1}). Two fundamental challenges limit the switch I/O scaling. The first is related to ASIC package size and minimum all grid array (BGA) dimension requirements [249], which determine how many parallel electrical lanes of switch silicon can accommodate. The second is how fast the signal can be transmitted over the chip-to-module (C2M) channels. The achievable lane speed depends on the CMOS serializer/deserializer (SerDes) capability and electrical channel performance. The state-of-the-art switch ASIC has 512 electrical lanes, each operating at 100 Gb s^{-1} using PAM4 and digital CMOS SerDes.

Data-center network interconnects face bandwidth and reach-scaling challenges. Fundamentally, there are only three orthogonal technical axes to scale bandwidth [250]: (1) higher baud-rate; (2) more spectrally efficient modulation formats; and (3) more parallel lanes/dimensions. These three axes have been used to scale the bandwidth, from 10 Gb s^{-1} using 10 Gbaud, non-return-to-zero (NRZ), and a single lane to 800 Gb s^{-1} using 50 Gbaud, PAM4, and 8 lanes. Historically, bandwidth cost reduction in terms of cost per bit was mostly achieved by serial data rate scaling through (1) and/or (2), because only serial data rate scaling allows us to scale bandwidth without increasing optical/electrical component counts. But it is becoming increasingly more challenging to scale the serial data rate to 200 Gb s^{-1} or beyond, because higher-bandwidth components and wider channels are needed to scale the baud-rate, while higher SNR is needed for higher-order modulation formats.

The reach-scaling challenges are illustrated in figure 24. For the direct attach copper channel, the supported reach is reduced from 7 m at 10 Gb s^{-1} lane using PAM2 to only 2 m at 100 Gb s^{-1} lane using PAM4. The reach is expected to be less than 1 m at 200 Gb s^{-1} lane. Fiber chromatic dispersion (CD) will limit the 20 nm-spaced 4-wavelength CWDM4 based IM/DD optics reach to about 1 km at 200 Gb s^{-1} lane and 0.25 km at 400 Gb s^{-1} lane by using PAM4, low-cost (higher chirp) EMLs and low-power linear equalization, although CD-limited reach can be extended by using chirp-managed MZM in combination with more power-hungry nonlinear equalization technologies [251].

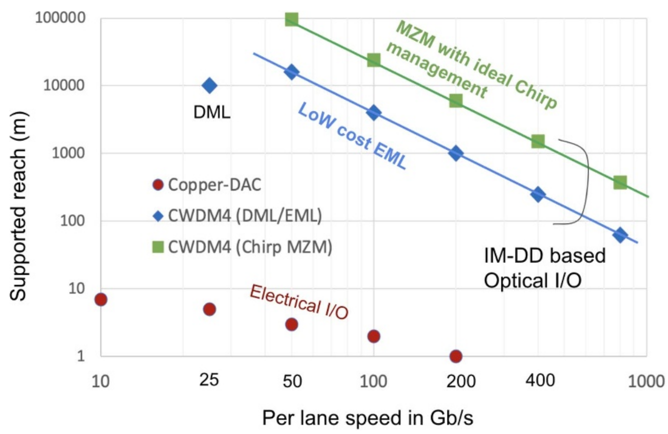

Figure 24. Reach-scaling challenges facing data-center networks (assuming low-power linear equalization). MZM: Mach–Zehnder modulator. IM/DD: intensity modulation-direct detection.

Advances in science and technology to meet challenges

Continual advancement in CMOS technology is critical to scale the switch ASIC capacity with reduced cost and improved energy efficiency. To scale the ASIC switch capacity to 100 Tb s^{-1}, 3 nm or 2 nm CMOS and 200 Gb s^{-1} SerDes technology that can support at least the C2M channel have to be developed. This may require the use of more powerful digital equalization techniques such as maximum-likelihood sequence estimation, floating-tap decision-feedback equalization (DFE) or feedforward equalization (FFE), and the development of more advanced packaging, PCB, and connector technologies. To scale the switching capacity beyond 100 Tb s^{-1}, more disruptive electrical or optical I/O [technologies such as the CMOS compatible high-density parallel optical IO technology [252] may have to be developed.

Network architecture level innovations are also needed to close the gap between the traffic growth and the technology growth. For instance, the hybrid OCS/EPS architecture essentially eliminates the spine EPS capacity-scaling bottleneck. Nevertheless, large-capacity EPS is still needed within an AB, with Clos architecture employed to scale the packet switching capacity.

Intra-rack interconnect technology based on direct attach copper may not be able to scale to 200 Gb s^{-1} lane or beyond. Active copper interconnects, very low-cost VCSEL/MMF- or SiP based PSM optical interconnect technologies have to be developed to support this use case. VCSEL/MMF-based SR optics has been used for ToR to AB connections until 50 Gb s^{-1} lane, but due to the bandwidth limitation of VSEL/MMF, SiP PSM technology has been introduced at 100 Gb s^{-1} lane, in order to support 100m+ reach. Note that VCSEL/MMF based technology can also support 100G lane or even higher, but the supported reach is shorter.

Until 200 Gb s^{-1} lane, PAM4-based CWDM4 IM/DD optics still can support up to 1 km by using low-cost EMLs without powerful DSP, but it could be challenging to scale CWDM4 IM/DD to 400 Gb s^{-1} lane or beyond due to three reasons. First, the required bandwidth of components and E/O interfaces is very high: >110/90 GHz for PAM4/6 at 400 Gb s^{-1} lane. Second, fiber CD limits the reach to ~250 m at 400 Gb s^{-1} with low-cost EMLs. And third, link loss budget could also be a challenge. To continue to scale data-center bandwidth, digital coherent technology may have to be considered to enable multiplexing of orthogonal signal dimensions and reduce the component bandwidth requirement. Coherent optics is also much more tolerant towards fiber CD and other channel impairments such as the very detrimental multi-path interferences, and can support larger link loss budgets [248]. Traditionally, coherent DSP consumes significantly higher power than IM/DD DSPs, but if we fully optimize coherent DSP for data-center reach, DSP power could be significantly reduced.

Concluding remarks

Data-center traffic growth is outstripping switch ASIC and interconnect technology growth. Both network-architecture-level innovation and underlying hardware-technology advancement are needed to meet the ever-growing bandwidth demands. On the architecture side, Google's data-center network has evolved from the EPS-only Clos architecture to a hybrid OCS/EPS architecture, which not only eliminated the spine-block bandwidth-scaling bottleneck but also enabled significant OpEx and CapEx reduction. The interconnect technology has evolved from the first generation's 10 Gb s^{-1} SFP+ to the fifth generation's 800 Gb s^{-1} OSFP, enabled by continual advancements in critical electrical and optical components, plus more advanced modulation, signal processing, and electrical/optical-interfacing technologies.

Both copper and IM/DD-based optical interconnect technologies face significant bandwidth- and reach-scaling challenges. At 200 Gb s^{-1} lane or beyond, IM/DD-based low-cost short-reach optics could replace the copper interconnects for intra-rack connections, while coherent optics may have to be considered for AB to AB connections, especially if the required reach is beyond 1 km. To scale the switch ASIC capacity beyond 100 Tb s^{-1} requires not only continual advancement in CMOS technology; more disruptive electrical or optical I/O technology (to fan-out switch capacity) is also critically important.

Acknowledgments

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15. Optical access

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Status

In addition to the residential and business access use-cases, for example 5G/6G mobile transport and cloud services have become drivers for higher data-rates on the optical access roadmap.

As a result, the peak line-rate of standardized passive optical networks (PONs) have been continuously pushed higher and metrics like latency and jitter have become more important.

In 2016, the ITU-T Standardization Sector approved the symmetrical 10 Gb s^{-1} passive optical network (ITU-T G.9807.1). In 2020, 25 Gb s^{-1} and 2×25 Gb s^{-1} PONs were standardized by the Institute of Electrical and Electronics Engineers (IEEE 802.3ca) and a 25GS-passive optical network (PON) multi-source agreement (MSA) [253] was defined. Most recently, in 2021 a 50 Gb s^{-1} PON was standardized by ITU-T (ITU-T G.9804.1).

Optical access networks are very cost-sensitive, because they have the lowest equipment sharing factor among all networks; the optical network unit (ONU) at the end-user is not shared at all. Therefore, all standardized PONs are based on a passive split single-fiber optical distribution network (ODN), time-division multiplexing (TDM), intensity modulation with direct detection (IM/DD), and simple NRZ or on–off keying (OOK) for lowest cost with optimal performance. Furthermore, a TDM-PON enables a single optical line termination (OLT) transceiver for optimal power consumption and density at the central office. See figure 25 for a conventional IM/DD based TDM-PON architecture.

Another main challenge for PONs is that the same ODN needs to be accommodated for every line-rate upgrade, because installation of the fiber plant is very costly, so operators require that no changes need to be made to it for network upgrades. On the other hand, higher line-rates result in smaller optical power budgets and larger CD penalties, thus making it

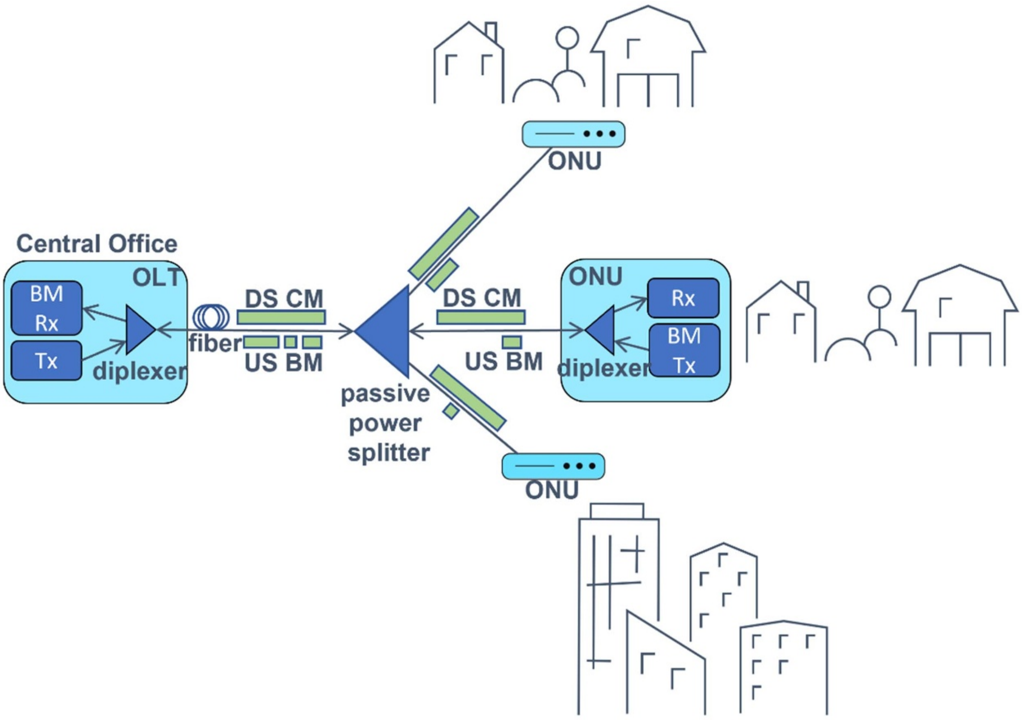

Figure 25. Conventional IM/DD-based TDM-PON architecture. BM = burst mode, CM = continuous mode, Tx = transmitter Rx = receiver, US = upstream, DS = downstream.

more and more difficult to upgrade the line-rate of PON over the same ODN [254].

To enable the upgrade from 10 Gb s^{-1} to 25 Gb s^{-1} and 2 × 25 Gb s^{-1} PON in a cost-effective way, a high-gain FEC code based on a LDPC code replaced the lower gain Reed–Solomon FEC (RS-FEC) code to achieve the optical power budget, and O-band transmission was introduced in both upward and downward direction to avoid high CD penalties. See section 10 about FEC and section 7 about transmission in new bands.

The 50 Gb s^{-1} line-rate PON standard [255] assumes the introduction of DSP and optical amplification in addition to LDPC and bi-directional O-band transmission to enable the stringent >29 dB optical power budget and up to 20 km of standard single-mode fiber (SSMF) reach requirements for a typical ODN. DSP also enables the use of bandwidth-limited 25 Gb s^{-1} grade transceiver components, which can be reused from high-volume data center and short-reach eco-systems for improved cost-effectiveness [254, 256].

Current and future challenges

As stated above, the main challenge for next generations of PON will be accommodating the already installed ODN in a cost-effective way. Until now, transmission technologies for PONs were developed for the worst-case OLT to ONU channel in the PON. However, the point-to-multipoint (P2MP) nature of PON results in a different channel for each ONU, which can be used to effectively relax the worst-case ODN requirement. A flexible-rate IM/DD PON, which optimizes the rate per ONU for higher overall data throughput using same transceiver hardware as used for a fixed rate 50 Gb s^{-1} PON, was analyzed in [257, 258].

A 50 Gb s^{-1} NRZ-OOK PON aligns well with 50 Gbaud 4-level PAM4 transceiver technology from data centers, but there are still challenges. Cost-effective small-form-factor transmitters with high optical modulation launch amplitudes and cost-effective optical pre-amplified receivers for improved receiver sensitivity need to be developed. And to enable receiver DSP in the upstream, a linear burst-mode (BM) receiver and fast converging DSP are needed [254]. Another challenge is the power consumption and real-estate on the OLT side of the PON, which complicates the introduction of the required transceiver technologies. Upstream BM transmission further complicates implementation of these technologies at the OLT.

Coherent PON has been on the research radar for a while, because it can solve several of the challenges that we see in IM/DD, but it is as of now too costly for access. However, it has the potential to enable higher line-rate due to the availability of phase modulation and polarization multiplexing in addition to amplitude/intensity modulation. It can also provide larger optical power budgets due to the coherent gain and CD penalties can be completely mitigated as the optical field is fully recovered.

Unfortunately, coherent detection also introduces new challenges. For example, the P2MP architecture means that the upstream signal from each ONU needs to be aligned to the local oscillator (LO) at the OLT receiver. In addition, the ONU transmitter is typically not wavelength-stable (λ-stable) due to it being bursted [259].

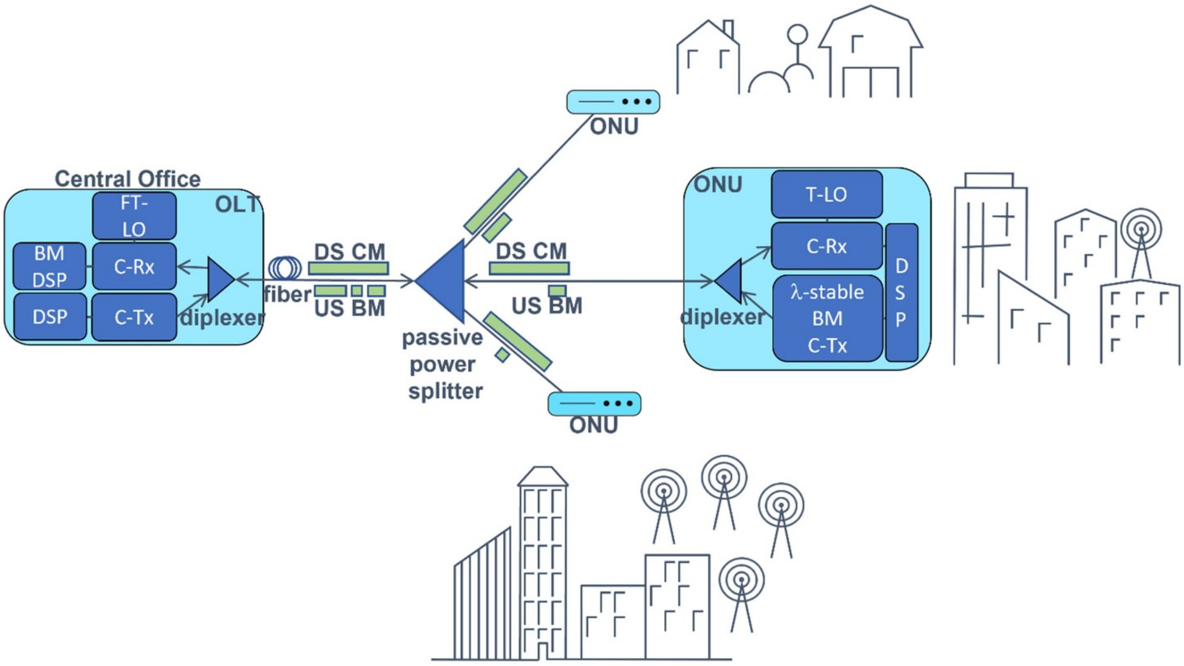

Figure 26. Coherent TDM-PON architecture. C-Tx = coherent transmitter, C-Rx = coherent receiver, FT-LO = fast-tunable local oscillator, T-LO = tunable local oscillator.

The first challenge has been addressed in [260], where a colorless phase-retrieval full-field recovery technique was proposed to avoid the wavelength-alignment requirement at the cost of no coherent amplification. In [261], frequency-comb lasers were proposed to enable quasi-colorless coherent detection but with coherent amplification.

A fast tuneable LO laser at the OLT would be another alternative to colorless coherent detection, but operation of such a solution would likely require wavelength locking of the upstream signals to a fixed wavelength grid, and ONU wavelength drift due to bursting would still need to be mitigated.

Advances in science and technology to meet challenges

In the medium term, the focus will be on developing technology to extend the lifetime of the cost-effective IM/DD PON.

One technology that will be considered to achieve this is flexible multi-rate PON, which effectively relaxes the worst-case ODN limits to extend the usage of low-cost IM/DD technology beyond 50 Gb s^{-1}. PAM-based modulation would be the first choice to enable compatibility with currently standardized single-rate PON, but an alternative flexible-rate PON could also be based on multi-carrier transmission. Multi-carrier transmission has a power budget penalty relative to single-carrier transmission, but it provides higher-density rate resolution, and one could even think about using the subcarriers for media access, which would require mitigation of optical beat interference (OBI) between the ONU transmitters but would eliminate BM transmission.

Another way to extend the usage of IM/DD technology is to stack two or more wavelengths for increasing overall throughput on the PON. In IEEE 802.3ca, this has been already standardized for 50 Gb s^{-1} PON by stacking two 25 Gb s^{-1} wavelengths [262]. Because a doubling of line-rate typically results in a significant excess penalty due to lower-performing transceiver parts at the higher rate, stacking of two wavelengths results in a better optical power budget compared to a single wavelength with doubled line-rate.

In the longer term, a coherent PON needs to be developed to further upgrade the PON bandwidth beyond the capabilities of IM/DD. For cost-effectiveness, reduced coherent DSP complexity compared to DSP for long haul coherent transmission has been proposed for PON in, for example, [263]. A scheme based on Alamouti coding to reduce complexity of a coherent ONU receiver has been proposed in [264]. In [265] an overview is provided of technologies to simplify the ONU in coherent TDM-PON. Moreover, close alignment of coherent PON to coherent technology for data centers is needed for volume. However, alignment with data centers is not guaranteed, as there are principal requirement differences between the two networks; PON architectures are based on single fiber, so bi-directional transmission is needed, which is not the case for dual-fiber data center networks. This complicates sharing of one laser for signal and LO in PON. Also, power-budget requirements for PON are much more stringent than for data-center point-to-point (P2P) networks. Furthermore, the P2MP nature of PON results is additional requirements, as already described above. On top of this, existing coherent technology needs to be adapted to BM transmission. See figure 26 for a coherent TDM-PON architecture.

It is expected that power consumption will play a large role for future generations of PON. Coherent PON technology, but also optical amplification and the application of multiple wavelengths to enable upgrades for IM/DD based PON, are all technologies with relative high consumption. For equipment vendors achieving low power consumption is important to enable higher port densities for cost-effectiveness. Expected rising energy costs make low power consumption of optical access equipment also important for operators. And sustainable use of natural resources dictates us to reduce the power consumption of optical access equipment as much as possible. The access network consumes the most energy from all the networks due to its total volume as this network is shared amongst the fewest end-users.

Finally, developments in optical integration are needed to enable cost-effective premium transceiver technologies that are expected to be required for any future next generation of PON. For example, integration of optical amplifiers as boosters for the transmitters or as pre-amplifiers on the receive side, transceiver arrays for stacked wavelength PONs, and integrated coherent PON transceivers could be enabled.

Concluding remarks

Optical access is all about making the best trade-off between cost and required performance to accommodate the standardized passive power-splitting ODNs.

Until now, an IM/DD-based fixed-line-rate TDM-PON resulted in the most optimal system; the complexity of BM transmission and transceivers capable of line-rates larger than the user-rate, which is needed for TDM-PON, was still more cost-effective than for example the simpler continuous-mode point-to-point network, where each connection runs at the user-rate. But as we get to the limit of the line-rates that can be supported over the typical PON ODN with single-carrier IM/DD technology, we will need to converge to a different optimal solution for access. In medium term, an architecture that extends the use of IM/DD PON via the use of flexible line-rate or wavelength stacking is expected and in longer term, a coherent PON architecture is expected to be needed.

Factors that influence the final optimal architectures are many, like which high-volume technology will be available from other eco-systems like data centers and how well this technology can be reused for PON. A factor is also that the new use-cases for optical access result in more variable ODN requirements. A flexible-rate PON can play an important role here to increase volume for a PON solution suitable for a wider range of use-cases, possibly also in the case of coherent PON [262] further out in the future.

Acknowledgments

The author would like to acknowledge the fixed network colleagues in Murray Hill, Stuttgart, Antwerp, and Ottawa for interesting discussions.

16. Submarine systems

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Status

Over the last several decades, the subsea community has been very successful in growing transmission capacity on a fiber pair exponentially, dating back to 1988 with the first transatlantic fiber-optic cable and a capacity of 280 Mb s^{-1} [266] to 2018 with MAREA and its capacity of 26.2 Tb s^{-1} (on each of 8 fiber pairs) [267]. This growth corresponds to a compound annual growth rate (CAGR) of 47% over three decades, enabled by technology advances like the erbium-doped fiber amplifier, DWDM, FEC and coherent transmission [268] (see figure 27).

The industry then ran into a physics-made boundary, first identified by Claude Shannon, that defines the maximum rate at which information can be transmitted over a noisy channel, also known as the Shannon–Hartley theorem or simply the Shannon limit (see section 11). The SNR is limited on subsea systems due to the enormous length of transoceanic distances and nonlinear effects in fiber [268]. Having exhausted all options to increase capacity by improving the use of the available SNR and having maximized the available bandwidth in erbium-doped fiber amplifiers, only one option remains: increasing the number of spatial channels. This has led to SDM, which has recently allowed the industry to increase capacity beyond the MAREA cable by adding more spatial channels and continuing the exponential growth of capacity on subsea cables. The first system employing this approach went into service in 2020 (Dunant [269]) and was followed by additional cables that have increased capacity even further (Grace Hopper in 2022 [270]).

Current and future challenges

It is interesting to note that over the decades where subsea cable capacity grew exponentially, the price for a new cable remained roughly constant. This is partly because the cost of a new cable was dominated by the marine cost of the cable installation. Equalizing the erbium amplification window to a larger bandwidth, or applying technologies like DWDM, FEC, or coherent transmission, did not fundamentally increase the cost of a new cable. Instead, they helped to decrease cost since tools such as sophisticated dispersion management were no longer necessary. As a consequence, the cost per transported bit dramatically decreased over this time period [271].

In the first instances of SDM, which simply increased the number of fiber pairs in the cable, the industry was able to continue the trend of decreasing cost per bit because marine cost was still dominating [272, 273]. Abandoning the concept

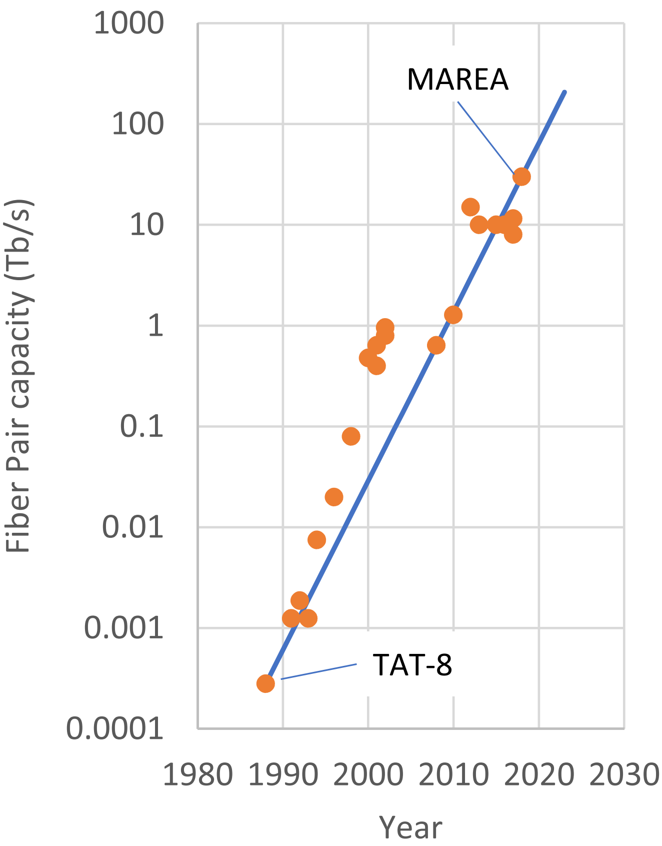

Figure 27. Capacity per fiber pair on transatlantic systems over the last decades showing a compound annual growth rate of 47%.

of complete fiber pair independence and sharing pump power across multiple fiber pairs [274] also brought costs down by decreasing the number of required pumps (laser diodes operating near 980 nm used for inverting the erbium-doped fiber—a key component in subsea systems) in subsea repeaters, while simultaneously increasing system reliability. In modern systems, repeaters are erbium-doped fiber amplifiers, but the legacy term 'repeater' remains from earlier days when the signal was regenerated.

SDM increases the amount of wet plant hardware (number of fiber paths and amplifiers) and, as such, wet plant costs will shift the balance between hardware cost and installation cost, making it a significant challenge for the industry to continue the trend of decreasing cost per bit, especially when also considering the cost of capital.

One other major challenge exists: there is no undersea power grid. Subsea systems are typically powered from shore, limiting the total available power to support the transmission capacity on the cable. The logarithmic nature of the Shannon limit can help in this case. Since capacity only depends logarithmically on signal power, which depends linearly on the cable electrical power, at the power limit we can continue to increase cable capacity by lowering spectral efficiency and increasing the number of spatial paths, i.e. amount of wet plant hardware [275, 276]

Advances in science and technology to meet challenges

Several technology options exist that should enable the industry to continue expanding cable capacity for the next decade. On the terrestrial side, fiber exhaustion on certain routes and shifting ownership patterns have led to major capacity users leasing fiber instead of owning fiber plants, leading to the widespread use of the long wavelength band or L-band. Erbium-doped fiber not only amplifies over the 4.5 THz of bandwidth in the conventional C-band but also, under suitable conditions, on the long wavelength side of the C-band with a similar available bandwidth (see section 7).

The L-band can be considered another spatial path in this case. This technology has been commercialized in subsea systems and first deployed on a 13 000 km transpacific link [277], but widespread penetration into the subsea market is still pending. While the technology can nearly double the available capacity per fiber pair, erbium amplification in the L-band is less power-efficient than in the C-band, compounding potential power limitations for very long and very high-capacity systems.

To improve the powering solutions from shore and provide more power to subsea elements, more capable power feed equipment has been introduced that increases maximum voltage from 15 kV to 18 kV [278]. Since power for a given load depends quadratically on voltage, this increase provides up to 44% higher available power. Of course, more power-efficient repeaters or lower-resistance cable can also mitigate power limitations.

Due to its low resistivity and good processing characteristics, most cable designs today use copper as the main conductor to provide power to the repeaters and other undersea elements. Lower cable resistance can be easily achieved by adding more copper to the cable design, relieving some of the power limitations, albeit while also increasing cable cost. An attractive alternative as a conductor material is aluminum. While aluminum has a higher resistivity than copper, its significantly lower commodity price potentially provides a lower resistance at similar material cost. That lower material cost is offset, however, by the fact that aluminum is more difficult to process and, especially, to weld than copper, thus impacting line speed in volume production. Cable with aluminum as a power conductor is now commercially available in subsea systems [279], but cable with a lower resistance than the copper-based counterpart is still pending.

Cable capacity can also be increased by using smaller-diameter fibers. Standard fiber dimensions are 125 μm glass diameter and 250 μm coating diameter. Fibers with standard glass diameter but reduced coating diameter are now being used in terrestrial applications where duct space is limited. Using fiber with a similar coating diameter in subsea cables can yield an increased fiber count by a factor of 1.5 at constant packing density. Further improvement is possible by optimizing both glass and coating diameter, as much as doubling the fiber count in existing cable designs.

More advanced SDM techniques also exist. MCF with uncoupled or coupled cores [280, 281] and few-mode or multimode fiber will also enable significant increases in cable capacity. Coupled cores and few-mode or multimode fiber will require new or enhanced capabilities in the digital signal processing of coherent modems to remove crosstalk between modes—similar to polarization demultiplexing in coherent transmission on standard single-mode fiber.

Much work has recently been focused on MCF with uncoupled cores. Due to its compatibility with standard coherent modems, the evolution to this type of MCF is relatively straight forward. However, to date the industry is lacking high-performance multicore amplifiers suitable for subsea transmission distances. Up to now, at each repeater, the signals have to be broken out of the MCF into standard single-mode fiber, amplified in single-core amplifiers, and then recombined into MCF for onward transmission. Fan-in and fan-out devices (FIFOs) are used for this purpose, but add cost and attenuation to the transmission path. In addition, crosstalk between cores can penalize transmission performance that is not present in single-core fiber transmission. Counterpropagating signals in two cores lowers this crosstalk but when the core count per fiber increases beyond two, this crosstalk can potentially be significant, because signals on some cores must now be copropagating.

One alternative that must not be overlooked is integration and standardization. If it is going to be difficult to continue the decreasing cost-per-bit trend by growing cable capacity, then another alternative to keep up with the growing capacity demand is to build and deploy more cables. At this point, almost all subsea systems are custom-designed connections. Now that we are close to the Shannon limit, can we standardize on one transmission design and achieve cost reduction by standardization, integration, and higher volume production? Production and installation capacity will have to scale in this case. Added benefits are increased network availability due to route diversification and the enabling of a new network-maintenance and repair paradigm.

Concluding remarks

The technology that can match the required capacity at the lowest cost per bit in the total cost of ownership is the most likely to see wide adoption. This will probably be a combination and evolution of the technologies outlined above, with one example shown in figure 28 for a transatlantic route.

First, we introduce 200 μm coating diameter fiber in the cable. This will increase capacity up to 1 Pb s^{-1} in existing cable designs, possibly with some adjustment to cable resistance. Then we include L-band amplification, nearly doubling the cable capacity again. Next, we introduce uncoupled 4-core fiber to nearly reach 5 Pb s^{-1} cable capacity. Here we assume standard coating diameter on the fiber to mitigate any micro-bend and macro-bend challenges with MCF.

Other technologies may prove disruptive. Semiconductor optical amplifiers have the potential of high integration

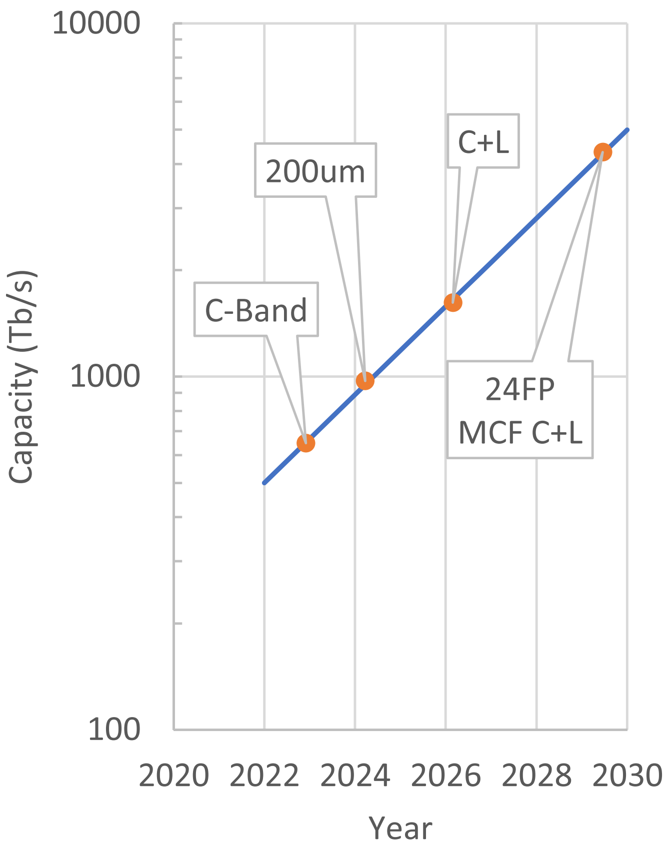

Figure 28. Roadmap to 5 Pb s^{-1} cable capacity. One example of technology evolution yielding a 33% cable capacity compound annual growth rate.

and low cost. However, challenges with reliability and polarization-dependent gain must be overcome [282]. Also, exciting news come from the world of hollow-core fiber, where wide bandwidth, low loss, and low nonlinearity now seem possible (see section 2).

Acknowledgments

The author would like to thank Alexei Pilipetskii and his Forward-Looking Work team at SubCom for their contributions to the work underlying this article. Many thanks also to friends and colleagues in this exciting field for continuing to push the boundaries.

17. Radio-over-fiber communication technology

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Status

Radio-over-fiber (RoF) communication technology has been rapidly evolving over the past four decades to realize effective optical distribution of analog and digital RF signals in wireless networks. In RoF, light is modulated by an RF signal

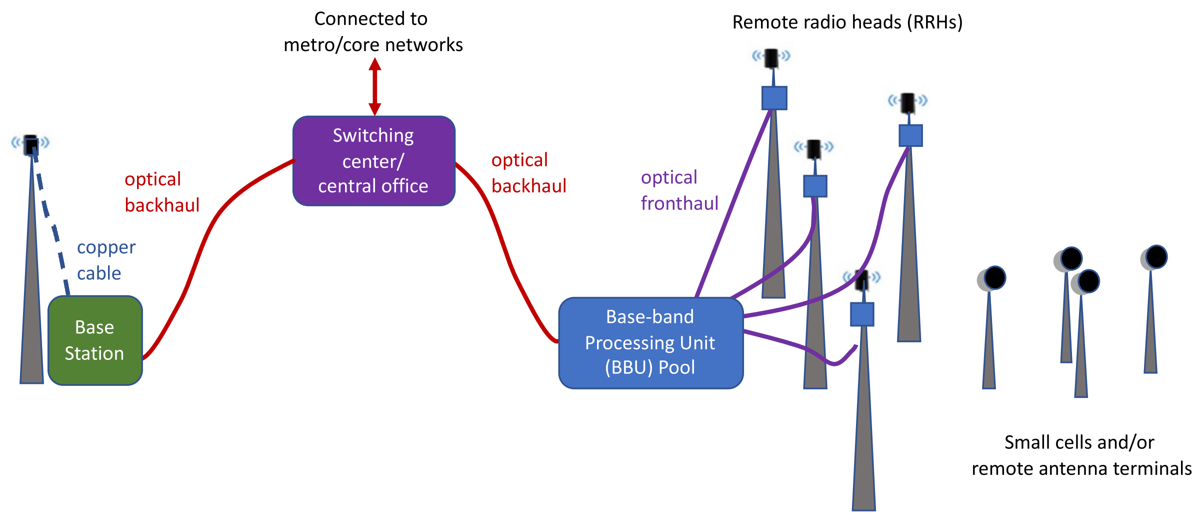

Figure 29. Millimeter-wave radio-over-fiber architecture showing evolution of base station from left to right. [285].

that is transmitted over an optical fiber link, which benefits from high bandwidth, low transmission loss, and immunity to electromagnetic interference. In turn, such advantages allow high-capacity and extended-reach distribution of RF signals to be realized. The initial push for RoF technology development was motivated by the need to address spectral congestion in lower-frequency bands, so that the increasing capacity needs of mobile networks can be met through employing the millimeter-wave (mm-wave) frequency region.

Figure 29 illustrates a mm-wave RoF architecture. On the left, an early RoF deployment shows an optical fiber backhaul to transport ultrabroadband wireless signals in the mm-wave region to a cell site comprising an antenna tower with a base station located at its base. Note that the antenna elements situated atop the tower are connected to the base station via a copper cable. This section of the architecture is known as the fronthaul. With mobile standards pushing towards 5G and beyond mobile systems, which envision the support of higher capacity and lower-latency applications, the mm-wave RoF architecture has evolved into a cloud/centralized radio access network architecture (C-RAN), which is shown on the right of figure 29 [283]. The conventional base station functionality is now split into a baseband unit (BBU) and a geographically separated radio remote head (RRH) or radio unit. In a C-RAN, the cell site comprises only an RRH with an optical fiber connection to the BBU. The segment of the network that forms the BBU, RRH, and the optical fiber connection is thus known as the optical fronthaul. Moreover, the centralized nature of entire architecture lends itself to efficient pooling of BBUs, centralized mm-wave generation, cooperative processing, management, control, and signal distribution, giving rise to effective energy savings for the operators and infrastructure cost-sharing among those users [284].

Current and future challenges

Current optical fronthaul links are based on the Common Public Radio Interface transport protocol, which employs uncompressed digitization for signals up to 24 Gb s^{-1} [286]. In digitized RoF, RF signals are first digitized at a high sampling resolution and then used to directly modulate the optical laser at the transmitter. The optical bandwidth required in digitized RoF is dependent on physical parameters of the antenna at the RRH, specifically the number of antenna ports and the actually wireless bandwidth. With 6G promising an order of magnitude improvement in capacity and device density, and two orders of magnitude of improvement in energy efficiency over 5G, increasingly smaller cell sizes which improve data rates through higher SNR and reduced transmit powers, have been recognized to meet 6G requirements [287]. Further, high counts of antenna ports that support beam-forming and massive MIMO, to support the improvement of performance and energy efficiency [287]. In that respect, the fronthaul link therefore must accordingly be able support optical bandwidths much higher than that of the RF signal, ensuring the ability to scale and future-proof against increasing capacity demands beyond 6G. More Importantly, the factors of increased complexity at the RRHs, unavailability of cost-effective analog/digital and digital/analog converters in the mm-wave frequency region, and high numbers of RRHs to support increasingly small cell sites as mobile networks evolve towards 6G deployments, collectively incentivize the use of analog RoF over digitized RoF [288].

Analog transport of mm-wave signals can be based on RF-over-fiber or intermediate frequency (IF)-over-fiber schemes. In the RoF transport scheme shown in figure 30(a), mm-wave signals at the desired wireless transmission frequency are transmitted directly along the optical fiber. At the cell site, the

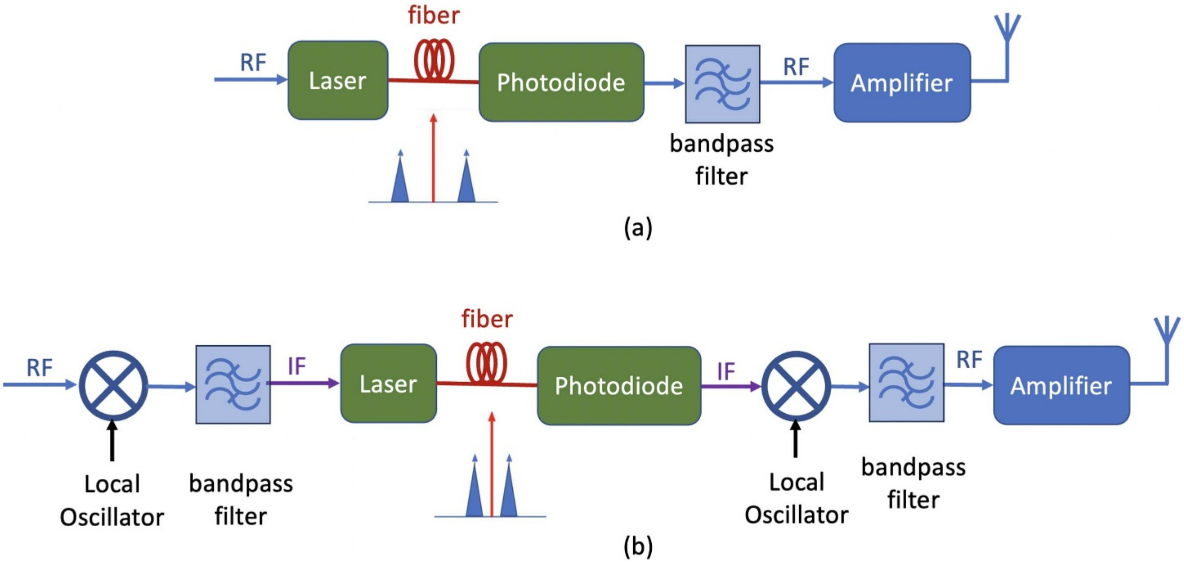

Figure 30. (a) Radio-over-fiber and (b) intermediate frequency over fiber transport schemes.

RRH configuration is straightforward, without requiring frequency up- or down-conversion. In the IF-over-fiber transport scheme, light is modulated by an intermediate frequency radio signal and transported over the optical link. At the cell sites, the configuration is slightly more complex due to the requirement of frequency up/down-conversion. As an example, in the downlink direction, the IF-over-fiber signal is required to be up-converted to RF before wireless transmission. However, as compared to the RoF scheme, IF-over-fiber requires lower-speed optoelectronic devices, which in turn are not as susceptible to fiber chromatic dispersion.

Analog RoF links are not without its challenges. Generally, analog transport of mm-wave signals is susceptible to fiber chromatic dispersion, which degrades transmission performance. When RF signals are optically modulated using optical double-sideband modulation, the two sidebands of the optical carrier will undergo phase shift and phase decorrelation as it propagates along the dispersive fiber medium. This phenomenon results in dispersion-induced RF power fading at the receiver, whose severity depends on transmission length, signal frequency, and fiber dispersion parameter. Furthermore, nonlinearities in the optoelectronic devices in the front-end of an RoF link limit the modulation depth of wireless signals in addition to intermodulation distortion, which in turn causes the wireless signals to be weakly modulated onto the optical carrier.

Advances in science and technology to meet challenges

The motivation to improve analog RoF transmission performance, in the face of inherent impairments, has given rise to innovative mitigation strategies. Among them are proposals of optical single-sideband modulation [289] and optical carrier-suppression modulation [290], using strategically biased dual-electrode MZM and optical filtering using chirped fiber grating [291] to alleviate dispersion-induced RF power fading. As for mitigating nonlinear impairments, proposals include optical feedback, optical feedforward and dual parallel modulation schemes, in addition to predistortion, gain modulation, and, in lieu of the MZM, the use of dual electro-absorption modulators and semiconductor optical amplifiers. Moreover, with the confluence of advanced data acquisition and monitoring capabilities, availability of advanced processing hardware and open-source tools, and the advent of multi-access edge computing, the application of machine intelligence to enhance the performance of RoF links is gaining momentum.

With the IF-over-fiber transport scheme, the need for a mm-wave LOs and correspondingly high-speed mixers limits the upgradability and scalability of the RoF link when additional mm-wave wireless channels are required or when wireless carrier frequencies need to be modified. Innovations involving remote delivery of mm-wave LOs and centrally generated mm-wave LOs, especially for uplink transmission, have been explored using uncooled distributed feedback lasers [292], resonantly enhanced mode-locked lasers [293], and vertical-cavity surface-emitting lasers [294].

In employing digitized RoF, the urgency to overcome the optical fronthaul bottleneck to support significantly higher optical bandwidths than the actual wireless bandwidth has yielded several explorations in the functional split between BBU and RRH. Specifically, the 3rd Generation Partnership Project [295] outlined eight options of functional splits, with each unique functional split defining the required optical bandwidth as well as latency requirements between the two entities, BBU and RRH. As an example, when Option 8 is chosen, more than 800 Gb s^{-1} of bandwidth is expected to be supported by the optical fronthaul, as all the functionalities are placed at the BBU. In contrast, an Option 1 deployment only requires 1 Gb s^{-1} of bandwidth, as all functionalities are placed at the antenna site and only packetized and already processed data are sent to the BBU. In general, high-level functional splits will improve bandwidth utilization but at the expense of decentralizing control and increasing latency [284].

A compromise between analog and digital RoF communication can be provided through sigma-delta-over-fiber (SDoF) modulation albeit at the high cost of oversampling and noise shaping of the signal waveform [296]. With quantization noise minimized in the band-of-interest, SDoF benefits from both the simple implementation of analog RoF and robustness towards optoelectronic nonlinearities and high dynamic range of digitized RoF [297].

Concluding remarks

Today, the use of RoF communication technology to efficiently achieve optical distribution of analog and digital RF signals in wireless networks is well-established. Outdoor cellular networks not withstanding, the fervent investigations of RoF communication technology will continue into the future with applications into a diversity of wireless networks, including indoor and in-building distributed antenna systems and satellite communications.

18. Sensing with transmission fibers

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Status

The potential of optical fibers for sensing has been shown very clearly since the early days of fiber optics [298]. However, this potential did not emerge until recently, when fiber-optic sensing became a practical tool for real-world applications. Many fiber-optic techniques are a fallout of applications in telecommunications, a field that has evolved considerably over the past few decades. This is the case of distributed acoustic sensing (DAS) [299], which is the evolution of coherent time-domain reflectometry that has been developed, and is routinely used, to detect faults in fiber-optic links. DAS is a very promising candidate to deploy a worldwide network of seismic detection because it can potentially make use of the many dark fibers that have been installed over the years. However, DAS requires the use of dedicated equipment and, by relying on Rayleigh backscattering from fiber imperfections, is not compatible with unidirectional erbium-doped fiber amplifiers that are used today and therefore its range is limited to distances of the order of one hundred kilometers.

The fact that many fiber-optic sensing techniques have been inspired by telecommunication applications suggests that practical fiber-optic sensing schemes may be beneficially integrated with existing transmission systems and take advantage of their components. On this regard, it is worth mentioning that optical fiber communications have witnessed over the last two decades a tremendous paradigm shift. While legacy on–off keying systems rely on the presence or absence of a pulse for encoding information, coherent transmission systems, of widespread use today, utilize the full optical field, so that their operation requires that amplitude, phase, and polarization of the transmitted signal is reconstructed at the receiver. Moreover, as the fiber route where the optical field propagates is exposed to all kinds of environmental perturbations, the transition from on–off keying to coherent signaling required the development of DSP techniques able to compensate in real time for the effects of the varying propagation properties of the fiber on the received signal. It comes therefore naturally to use the channel estimation performed by the receiver for the characterization of the mechanical perturbations that affect the fiber along its path, ultimately transforming the optical fiber as a sensing tool for events occurring along the line. This is the idea behind [300] (see [301] for the theoretical aspects), where the polarization of a signal transmitted through 10 500 km of optical fiber lying on the ocean floor for most of its length was reconstructed by the receiver and used to detect events occurring in the depths of the ocean. Several earthquakes were detected, as well as ocean swells affecting the cable in shallow water regions close to the coast.

Alternative techniques for transforming telecommunication equipment into sensing apparatuses have been proposed and demonstrated in [302] and [303]. These works are based on the detection of the perturbations affecting the phase of the field generated by an ultra-narrow linewidth laser that is transmitted over a dedicated channel. In [302], the authors detected the phase of the field transmitted through the fiber, while in [303] they detected the phase of the field backscattered by the transmission fiber and rerouted through the return fiber of a two-way transmission system. This last arrangement allowed the authors to localize various earthquakes occurring along the light path. Obviously, the implementation of these techniques, in principle more sensitive and accurate than those based on the information that can be extracted from a coherent receiver during its operation, does not come for free, because it requires the installation and operation of additional hardware in the transmission system.

A highly promising approach has emerged in a recent publication [304]. Leveraging the Rayleigh backscattered radiation, which is redirected by the high loss loop-back couplers found in each repeater, this study demonstrates that the integration of coherent technology into cable monitoring holds the potential to significantly enhance the sensitivity of a cable monitoring system. A fall out of the deployment of this novel monitoring system would be the capability to localize perturbations acting upon a transoceanic cable with sub-span resolution, turning a transoceanic system into an ultra-long DAS apparatus. This goal would be achieved without affecting the operation of the transmission system and without the use of an ultra-stable laser source.

The sensing capability of transoceanic cables holds immense value due to the limited availability of sensors in oceanic environments. In addition to their application in transoceanic links, terrestrial cables also hold potential for various monitoring purposes. These include traffic surveillance, lightning detection, wind monitoring using aerial cables, and assessing the structural health of bridges. For an in-depth list of references, readers can refer to the comprehensive review provided in [305].

Current and future challenges

A major challenge that can be envisioned in the use of transmission fibers for sensing is exploiting coherent transmission systems for environmental monitoring while the system is in use, extracting the sensing information from the coherent receiver itself. However, a coherent receiver is a fairly complex device [306] and turning it into a sensing apparatus requires careful analysis and appropriate processing of the data that can be extracted from it, as discussed in what follows.

A coherent optical receiver is designed to reconstruct the messages encoded by the transmitter on the x and y polarization of the optical field. After reception and dispersion compensation (see [306] for details), the application of the constant modulus algorithm (CMA) allows the reconstruction of the polarization of a signal transmitted on the x and y polarizations where the information was encoded. Figure 31 shows the representation on the Poincaré sphere [307] of the time-dependent output polarization corresponding to an x-polarized input optical field. The points are the tips of the normalized Stokes vectors obtained using the unitary part of the link Jones matrix extracted from the receiver of the experiment reported in [308], in which a 1 Gbaud signal travelled for about 50 km in two cores of an uncoupled-core four-core fiber installed in an underground tunnel as part of the INCIPICT fiber plan in L'Aquila [98]. The Stokes vectors in figure 31 were collected over a two-hour time window with a sampling time of about 524 μs, and then lowpass filtered and decimated to increase the sampling time by 1000 times. The observed spread is representative of the typical spread expected in the reconstruction and is caused by various transmission nonidealities, including optical nonlinearities (also partially compensated for by the receiver). The reconstruction of the polarization of an optical field transmitted over the x and y polarization does not require the recovery of the common phase and is therefore immune to the phase and frequency noise of the transmit and local-oscillator lasers, nor is it affected by their linewidth and frequency mismatch. This makes the extraction by the receiver of the polarization of an optical field injected over the x or y polarization equivalent to a measurement performed on a polarization interferometer and explains why the measurements of [300] have a very high sensitivity although they were obtained with a system in which transmit and local-oscillator lasers had typical telecom-grade linewidths.

The complete characterization of the polarization of an optical field injected with arbitrary polarization requires the estimation of the full Jones matrix of the fiber, or the equivalent Mueller matrix in Stokes space. It should

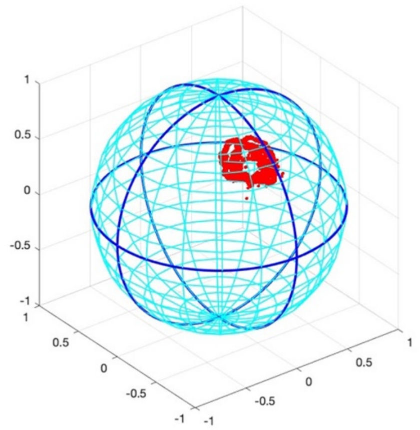

Figure 31. Representation on the Poincaré sphere of the time-dependent output polarization collected over a two-hour time for an x-polarized input optical field (data from the transmission experiment reported in [308]).

be noted that since the transmit laser is common to both polarization-multiplexed channels, its phase noise does not affect the polarization of the optical field. The full characterization of the unitary part of the Jones matrix, or the equivalent Mueller matrix in Stokes space, however, entails the recovery of the phases of the two encoded messages. This is a task that today's receivers perform independently on the two polarization channels in the steps of frequency locking and phase retrieval that follow the implementation of the CMA. These two processes are affected by the phase and frequency noise of the transmit and local oscillator lasers and, as a result, the elements of the Jones/Mueller matrix that depend on this recovery may be less accurate in reproducing the environmental perturbations than the elements that depend on parameters that can be extracted using the CMA alone. The Mueller matrix describes propagation through the fiber link in the form of a rotation of the input Stokes vector [307]. This rotation is fully characterized by a three-dimensional real-valued vector, and it turns out that only two components are, within a good degree of approximation, immune to phase and frequency noise. Figure 32 shows the spectrograms of the three components obtained by processing the Jones matrix extracted, over about 2 h, from the link transfer matrix estimated by the receiver of the experiment in [308]. The vertical stripes in the first two components, the ones immune to laser noise hence sensitive to environmental disturbances, are associated to mechanical perturbations caused by events related to construction works taking place in the downtown area of L'Aquila along the fiber route, whereas the horizontal lines are an artifact of the measurement related to the length of the pseudorandom bit sequences used in the experiment.

This approach to extracting environmental data from the transmission matrix is still in its infancy and much is to be done. An important challenge in this direction is the extraction from the receiver of information that is usually discarded and may require minor, but non-trivial, modifications of the receiver hardware.

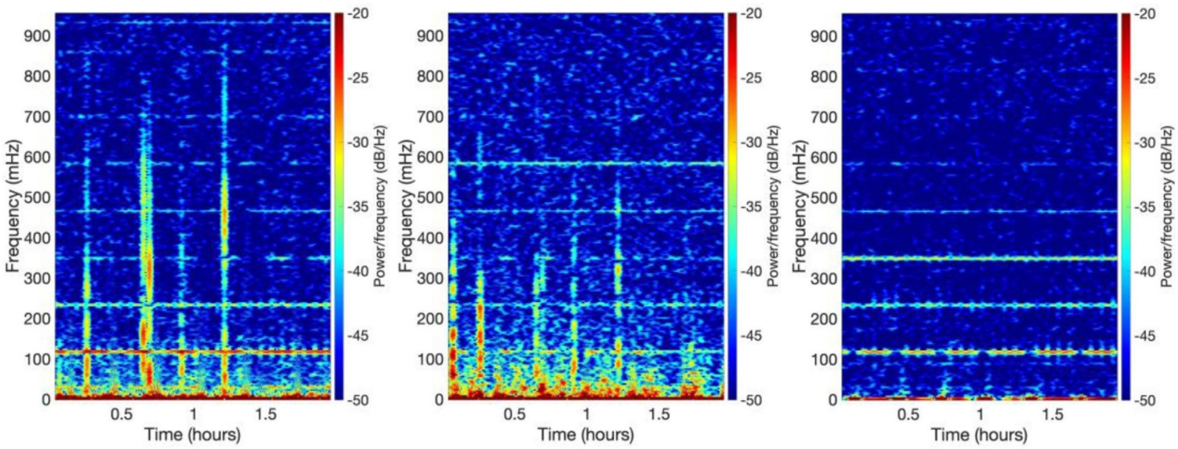

Figure 32. Spectrograms of the three components of the rotation vector of the Mueller matrix extracted from the receiver of the experiment in [308], showing as vertical stripes the effect of mechanical perturbations along the fiber route. Horizontal lines are an artifact of the measurement.

Advances in science and technology to meet challenges

Although coherent receivers are well established devices, they have been designed for reliable and efficient transmission. Very few studies have been devoted to the investigation of the fidelity of the reconstruction of the channel performed by the DSP at the receiver. One of the main challenges for the practical use of a coherent receiver as a sensing device is therefore understanding the dependence of the parameters extracted from the receiver on the external perturbations acting upon the optical cable. For this purpose, it is particularly important to characterize how all the intrinsic sources of noise involved in the signal generation, transmission, and reception (laser noise, linear and nonlinear propagation impairments) affect the reconstruction of the fiber-optic channel performed by the receiver. When polarization is measured, the main propagation nonidealities arise from the fiber random birefringence, and their effect on channel reconstruction have been addressed in [301]. An extension of this study to other transmission impairments would allow a more accurate discrimination of the effects of environmental perturbations from the intrinsic noise sources.

An important aspect of environmental monitoring is localizing the perturbations. While in principle this would be possible performing measurements at more than one frequency, the processing of the information extracted from the receiver of a one-way transmission link does not easily allow localizing a perturbation. For this reason, the potential of coherent receivers has very recently been exploited in a DAS configuration, where a specially designed coherent receiver is used to detect the backscattered radiation from the fiber [309]. In another approach, localization of the perturbation has been demonstrated by cross-correlating the phases extracted from the two receivers of a bidirectional transmission system [310]. Both techniques are based on the extraction of the polarization-averaged phase retrieved by the coherent receiver, which also contains information on the environmental perturbations acting upon the fiber. However, the ability of the cross-correlation method proposed in [310] to localize low-frequency perturbations, such as those caused by earthquakes, is limited. Furthermore, since these techniques are based on the detection of an absolute phase, they require the use of lasers with a linewidth much narrower than that of typical telecom-grade lasers and hence their real-world application would necessitate an upgrade of transmitter and receiver apparatuses. The definitive resolution to the localization issue would be achieved through the deployment of the cable monitoring system demonstrated in [304]. Through the implementation of this monitoring system, a transoceanic cable could effectively transform into an ultra-long DAS system, enabling detection and localization of cable perturbations with a sub-span resolution.

Considering now potential advancements in communication technologies, the adoption of the efficient high-dimensional modulation formats proposed in [311] will necessitate the development of receiver DSP capable of performing joint phase retrieval on the two polarization-multiplexed channels. Such receivers will uncouple the complete reconstruction of the output polarization from the phase and frequency noise of the transmit and local-oscillator lasers, producing a cleaner channel reconstruction and more accurate polarization sensing.

Finally, at a technological level, it is imperative to upgrade the coherent receiver hardware and software, so as to give access to the relevant link parameters. Real-time processing of these parameters will ultimately unlock early-warning functionalities.

Concluding remarks

The operation of a coherent optical transmission system requires that the coherent receiver reconstructs in real time the characteristics of the fiber-optic channel, which is affected by time-varying environmental perturbations. If this information is extracted from the receiver, the fiber can be transformed into a distributed sensing device. As earth is covered with optical fibers, including regions where anthropic perturbations are virtually absent like the depths of the oceans, this can offer an unprecedented opportunity for earth monitoring, which is particularly valuable when applied to hardly accessible regions.

Acknowledgments

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19. Free-space optics for aerial and space communications

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Status

Wireless laser communications or free-space optical (FSO) communication is often presented as superior to conventional RF communication, and also as the ultimate solution to rapidly transfer data in the absence of a hard-wired connection [312]. However, while FSO communication has addressed many of its established challenges and limitations in the past two decades, it still struggles to compete with commercially available RF technologies for terrestrial wireless communications [313]. Key constraints—such as line of sight requirements, susceptibility to weather conditions, and relatively higher costs for manufacturing and maintenance—mean that FSO communication has not yet joined the ranks of the fourth generation (4G) or 5G mobile network ecosystems.

The societal expectation and dependence on connectivity keeps expanding. Many active discussions of beyond 5G and 6G highlight the growing importance of non-terrestrial networks (NTNs) to deliver high-speed connectivity to rural areas, hard-to-reach zones, post-disaster regions, ships at sea, and airplanes in flight. Affordable connectivity can be provided to these far-flung and/or less populated areas by deploying satellites in the backbone network [314]. Alternatively, if the remote location does not require a large footprint, a high-altitude platform station (HAPS) or a swarm/cascade of HAPSs can be suspended in the backbone network at a height of about 18–28 km [315]. These flying platforms can be constructed in the form of gliders [316], airships/aerostats [317], or balloons [318].

In this context, increasing the capacity of telecommunication networks remains limited by bandwidth. All current commercial NTN solutions are based on the conventional RF systems for both feeder and user links operating at the Ku-band (12–18 GHz), the Ka-band (27–40 Ghz), and the Q/V band (40–50 GHz). This still requires many units: for example, around 50 ground stations are required to reach a satellite capacity of 1 Tb s^{-1} with the traditional RF feeder links, and the number of these ground stations increases linearly with the system throughput [319]. Another constraint of RF links is the high risk of frequency overlap with other communication systems, which leads to interference with terrestrial networks as well as undesired interception or jamming. On another front, the requirements for data rate and throughputs are increasing rapidly: now up to several Tb/s.

Use of the fiber-through-the-air (FTTA) concept, implemented via FSO technologies, now underpins any future very high throughput satellite/HAP systems as an attractive alternative to the RF feeder link [320]. Benefits of FTTA include (i) availability of approximately 10 THz bandwidth with no spectrum regulation, (ii) mass/size/power advantage compared to RF components, which is critical for air/space-borne platforms, (iii) extra secrecy advantage of the FSO pencil laser beams, which is further enhanced when combined with quantum key distribution [321], (iv) ability to select propagation paths unobstructed by trees, building, hills, or mountains for ground to/from air/space links, (v) reduced eye-safety concerns, which impose limits on laser transmit powers for these for links between ground and air/space, and (vi) achieved world-record in FSO communications of a few Tb/s in recent years [322, 323]. These benefits underpin a reliance on FSO for feeder links with more than one Tb/s sent via a single optical ground gateway station (OGGS) to the satellite/HAPS: This minimizes the number of ground stations and therefore the cost of the ground network [324, 325]. In addition, the absence of atmospheric turbulence in the stratosphere and in space makes FSO communication the preferred mode of data transmissions for inter-satellite, inter-HAPS, and satellite–HAPS links [326]. This enables air/space-based mesh networking, which reduces end-to-end latency and minimizes the reliance on terrestrial infrastructure, in particular over territories that are not under the sovereignty the NTN operator.

Current and future challenges

A key challenge is associated with weather and related conditions, which can affect FSO system performance, in particular atmospheric turbulence and cloud, fog, and sandstorms. Very high throughput satellites/HAPS, based on FSO feeder-links, are affected by atmospheric turbulence and cloud coverage. Atmospheric turbulence is caused by the variations of the air refractive index that result in strong signal-intensity fluctuations (scintillation), causing optical beam wandering and spreading, which severely degrade the communication system performance. Clouds, which are composed of water droplets and ice crystals, can block the FSO feeder links and introduce atmospheric losses greatly exceeding 3 dB [327].

Orientation is also a consideration. The narrow beamwidth associated with the light signal means that to minimize misalignment losses, it is important for the two terminals to point their apertures in the right direction (towards the location of the receiving terminal and vice versa).

Currently, there is abundant available bandwidth, which means there is not yet a need to adopt coherent detection (and

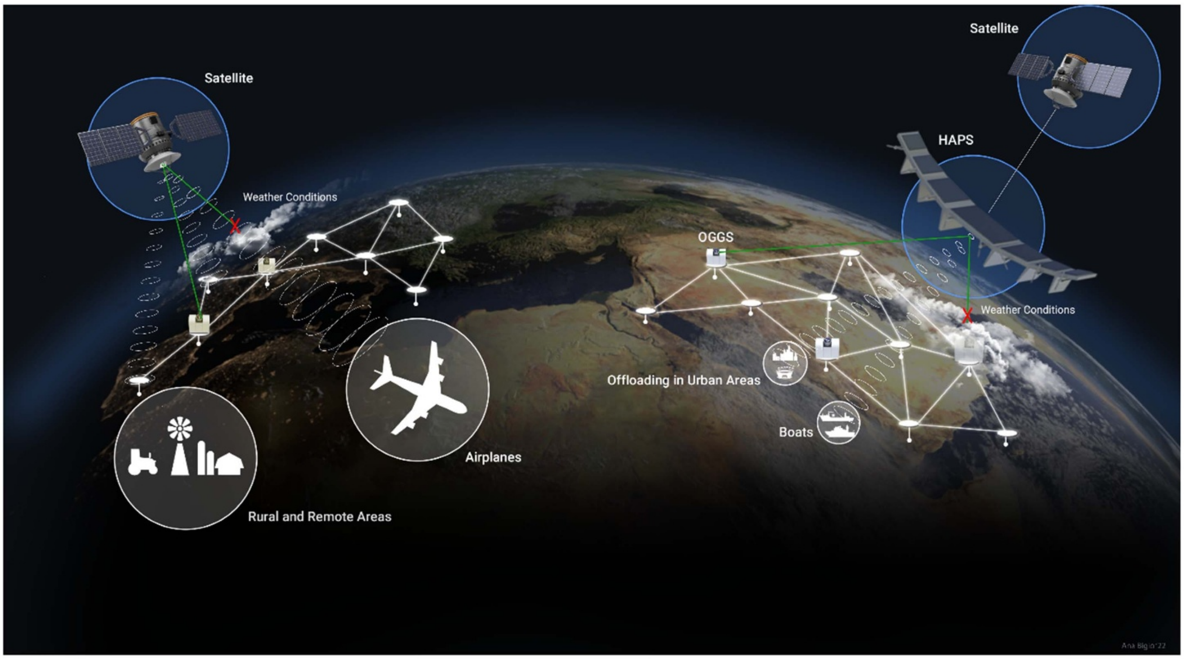

Figure 33. Hybrid very high throughput satellite networks with site diversity and HAPS relaying.

the associated reduction in spectral efficiency when intensity modulation direct detection is used). It remains very complex to implement transceivers, analog-to-digital converters, and digital-to-analog converters with Tb/s digital processing capabilities.

Efficiency and affordability also remain a challenge for FSO adoption and deployment in terms of reducing the cost of manufacturing and maintenance in order to reap the benefits of the economies of scale.

Advances in science and technology to meet challenges

For adaptive optics, recent advances with post-compensation or pre-compensation wavefront correction are shown to effectively mitigate the effect of atmospheric turbulence and so are expected to improve the performance of vertical optical feeder links [328, 329]. This performance can be further enhanced by introducing HAPS with FSO relaying capability to create integrated two-hops ground–air/space links with reduced beam-wandering/spreading effect [330–332].

Other options are emerging to reduce problems associated with weather conditions. RF transmission typically exhibits complementary characteristics to FSO transmission, and so hybrid FSO/RF systems are developed that, with fog or strong cloud attenuation, switch to the RF back-up link when FSO link performance becomes unacceptable [333]. A more practical soft-switching using a dual-FSO threshold can be adopted to reduce the loss of information packets associated with frequent back-and-forth switching between FSO and RF links [334]. In addition, to avoid having a dedicated RF link for each FSO feeder link, a shared backup RF link can be employed by multiple optical users in case a FSO feeder links fails [335]. Site diversity among multiple OGGSs is another effective approach to avoid outages due to fog or cloud obstruction [336]. It relies on state-of-the-art infrared imaging techniques to effectively characterize the type of clouds, in order to both determine and forecast their induced attenuation. This cloud-monitoring/characterization process needs to be done at the beginning of the site survey stage for 'optimal' placement of OGGSs, and then again when the OGGS are operating for optimal traffic scheduling or handover between the various OGGSs.

To ensure that the alignment loss is minimized, modern and practical positioning, acquisition, and tracking (PAT) algorithms—which rely, for example, on an array of highly sensitive avalanche photodiode detectors [337]—need to be implemented. Once the acquisition stage is complete and active tracking is triggered, the receiver array and the transmitter laser beam need to stay 'locked' to each other. Furthermore, if the transmitter's beam position on the array experiences any jitter due to vibrations or beam wandering, the implemented PAT system needs to be intelligent and adaptive enough to track in real-time any error in alignment and use a feedback loop to minimize that error.

To address the interfacing concern with low-complexity Tb/s digital processors, there is a need to design efficient FSO-specific multicarrier waveforms, in order to capitalize on the full potential of the huge available optical bandwidth.

Finally, using off-the-shelf components, which can be internally air/space-qualified, will significantly reduce the cost of deploying these transceivers. Further efficiencies in costs and manufacturing will come from the use of metal optical antennas (i.e. telescopes) rather than more sophisticated and expensive materials.

Concluding remarks

The global dependence on air and space networks is growing rapidly for land, sea, and air end-user terminals deployed in rural, post-disaster, aeronautical/maritime, or urban areas, offloading broadband communication scenarios. This provides an opportunity for FSO communication technology to capitalize on its unique advantages to enter the expected mass market demands for (i) ground to/from air/space and (ii) intra- and inter-orbital point-to-point multi-Tb/s secure links. In this context, progress relies on new or emerging schemes for (i) adaptive optics, (ii) integrated space-air-ground networks, (iii) site and/or RF back-up diversity, (iv) practical low-cost PAT systems, (v) optical waveform design, and (vi) in-house space qualification [338] for standard electronic/photonics. Getting all these elements right will facilitate realizing the holy grail of global, reliable, and affordable broadband connectivity.

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20. Quantum communication

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Status

Defined broadly as the art of transferring quantum states between distant locations [339], the field of quantum communication (QC) constitutes one of the major technological and application pillars of quantum technologies, together with quantum computing, quantum simulation, and quantum sensing and metrology. It offers a radical shift in the way we conceive fundamental phenomena (thanks to the notions of entanglement and non-locality harnessed to enable for instance teleportation) but also applied science (thanks in particular to quantum-cryptographic protocols that are widely considered as the starting point of the quantum communication field).

In QC, information is typically carried by photons, which are transported using optical fiber or free-space (including satellite) links as communication channels. Contrary to classical optical communication, where information can be amplified over suitably chosen channel segments to extend the communication range without restriction, QC is subject to the laws of quantum mechanics, which prohibit cloning the quantum states being transferred or amplifying them without introducing noise that destroys the underlying correlations. This means that the range is inevitably limited by the inherent exponential loss suffered by light in optical fibers. To extend it, quantum repeaters, which crucially rely on quantum memories for synchronization, have to be used. Such quantum-repeater links, together with satellite communication, underpin the general vision of a global quantum communication infrastructure akin to an internet architecture.

It is useful then to think of QC networks as a progressive endeavor, where technological stages encompassing available resources give rise to families of enhanced functionalities or new applications, and as increasingly advanced technology becomes available, this unlocks access to more and more advanced applications [340] (see figure 34). At the earlier stages of such networks, long-distance communication relies on the existence of so-called trusted nodes, where information is released in the classical domain, or on switching. This apparently simple configuration enables notably QKD, which already offers a powerful paradigm shift in cybersecurity. Going further to more advanced stages allows for interconnecting quantum systems of different nature, such as sensors or processors, via entanglement distribution and teleportation. This opens the way to communication with relaxed trust assumptions, multiparty tasks like conference key agreement, and ultimately distributed quantum computing and sensing, among many more applications spanning numerous economic and societal sectors. Reaching such quantum networking capabilities by addressing the challenges on the way will be crucial for exploiting the full potential of QC to drastically enhance our communication and information-processing practices.

Current and future challenges

The operation of QC systems and networks relies on a rich technological toolbox, including high-performance photonic sources and detectors, quantum storage devices and repeaters, networks and software stack, and corresponding interfaces. For the near or medium-term QC network stages, despite significant progress that has enabled milestone implementations, such as the recent deployment of a large-scale network incorporating satellite links [341], several challenges still remain. The key aspect here is integration in all its forms. First, the development of miniaturized and resource-efficient components and systems, relying for instance on photonic integration, will be fundamental for their scalability and wide-scale use. Pushing the performance of PIC based on a variety of platforms and adapted to quantum technologies is in fact a more global challenge [342], and progress directly benefits QC as well. Next, network integration is becoming increasingly important and involves tasks that can ensure the compatibility and coexistence of QC technologies with classical communication and infrastructures, including software-defined networking, by developing the necessary interfaces and multiplexing techniques. Conceiving a more favorable security–cost trade-off for trusted-node networks will also be necessary. Finally, more specifically for quantum-cryptographic applications, integration with post-quantum algorithms to develop full

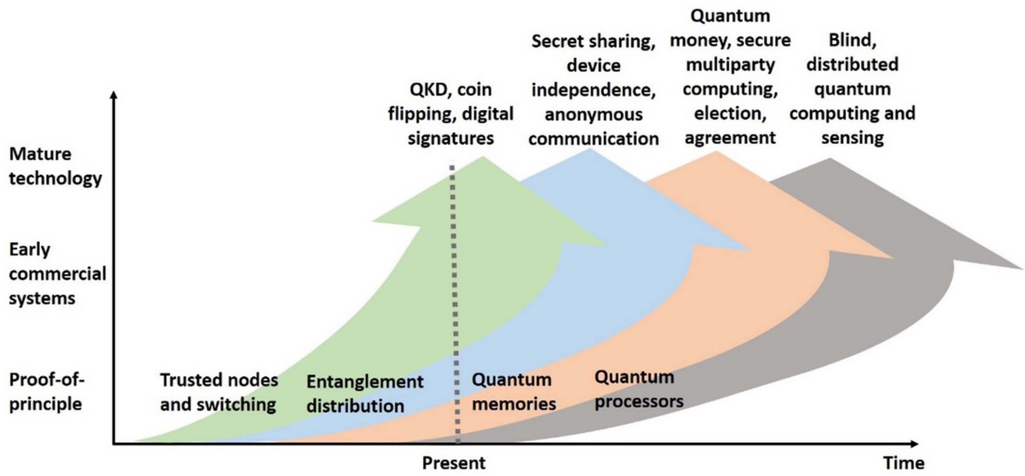

Figure 34. Quantum communication network stages and examples of corresponding functionalities and applications.

cryptographic sequences in a comprehensive manner will open the way to their use in practical application scenarios.

Remaining on the application side, but from a more fundamental angle, although proof-of-principle implementations of QKD achieving so-called device independence (i.e. minimal assumptions on the experimental systems) have succeeded recently (see for instance [343]), it is still a major challenge to realize fully this task with photons. More globally, theoretical developments towards protocols and certification techniques for security models with flexible requirements constitute, together with enabling the practical demonstration of quantum advantage for diverse functionalities such as secure multiparty computing or long-term secure storage, important milestones for the next few years.

Addressing the above challenges will firmly consolidate and significantly expand the maturity and applicability of QC technologies in the near or medium term. However, to materialize the long-term vision of QC networks, arguably the strongest challenge lies in the performance of quantum memories and repeaters. There, years of carefully crafted technological progress using a variety of platforms (such as for instance cold atom clouds or doped crystals) have recently brought exciting results in terms of record-high storage-and-retrieval efficiency with 99% fidelity [344] and elementary quantum-repeater links [345, 346]. Next, it will be necessary to improve the entanglement rate, the range, and tackle the performance benchmark trade-offs in quantum memories, concerning in particular the storage time and efficiency. Targeting a communication rate of a few tens of bit/s over a few tens of kilometers (compared to bit/s over meters achievable today) with a fidelity exceeding 97% appears to be an ambitious but realistic goal for the next few years, and will open brand-new perspectives in the field.

Let us also remark that, although QC is mostly associated with long-distance links, such technologies may in fact also play a central role for shorter communication spans, linking in particular quantum processing units forming a full-scale quantum computer. The issue of interconnecting quantum systems has indeed been recognized as one responding to an imminent bottleneck in quantum information [347], and we expect that QC will open new frontiers in this direction. As the understanding of the underlying needs advances, it is certain that new challenges will emerge and addressing them effectively will be of utmost importance.

Advances in science and technology to meet challenges

The description of some of the most significant challenges mentioned above point to the direction of strongly synergistic efforts that need to be established to be able to bypass the existing barriers. These synergies concern QC with classical optical communication; system, network, and software engineering; PIC design and development; hardware security; classical cryptography; and possibly more. Similar to other quantum technologies, QC will profit from the implementation of hybrid classical–quantum solutions and infrastructures, where it can leverage existing well-established technology and in turn bring quantum-enhanced functionalities and new services. Conceiving and implementing efficient and operational hybrid protocols and systems is actually hard and requires focused efforts, which may depend on the specific configuration or application under study. Some technologies will be more suitable to satisfy some benchmarks and less so for others. For example, encoding information in continuous variables of light enables cryptographic systems that are particularly well adapted to techniques used in classical coherent communication and also amenable to photonic integration, but such systems are in general less performant in terms of communication range.

For quantum memories and repeaters, a major technological advance for all platforms concerns the multimode aspect. Achieving multiplexing in some suitable degree of freedom (spatial or frequency mode, for example) over tens or hundreds of modes will be crucial for boosting their performance. Operation at telecom wavelengths will also be important for smooth integration in standard network infrastructures.

Technological advances in all underlying components, in particular sources and detectors, are also always desirable, so pushing their performance is expected. More specific challenges include achieving the required performance of entangled-photon sources in terms of brightness and qualification for use on-board satellites for global QC networks [348], improving the performance of sources of multiparty entanglement required for advanced tasks, and also the performance of joint measurements that are one of the building blocks of entanglement distribution by teleportation.

Concluding remarks

QC is a rich and diverse field, which lies at the intersection of the other quantum technology pillars, as it provides the connecting links for information transfer between devices, while at the same time offering a broad range of new applications. It is also steadily reaching the age of maturity, with some quantum-enhanced functionalities already commercially available, while more demanding ones may be within experimental reach sooner than expected. As the field progresses, it is important to embrace and expand a synergistic vision encompassing several disciplines that can largely contribute to the overarching goal of a global QC infrastructure. Crucially, widely endorsing a vision of energy-efficient and sustainable technological progress in the field will beyond any doubt also help to propel it to the next phases of development, unlocking its huge potential.

Acknowledgments

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21. Visible light communications

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Status

Visible light communication (VLC) is based on the principle of modulating the intensity of light-emitting diodes (LEDs) without any adverse effects on the illumination levels. The wide availability of LED-based illumination infrastructure gives a unique opportunity to implement high-speed and ubiquitous wireless access solutions. As illustrated in figure 35, VLC converts virtually each LED into an access point and is mainly positioned as a complementary solution to RF counterparts. In addition, VLC brings some distinct advantages such as physical layer security and interference-free operation in unlicensed optical spectrum.

The huge potential of VLC has resulted in a surge of research activities within the last decade, see, e.g. comprehensive surveys [349, 350]. Initial efforts have mostly focused on point-to-point links and physical layer design. Since LEDs are non-coherent light sources, VLC systems build upon IM/DD, where the information is encoded in the intensity of light source and then retrieved by a photodetector via envelope detection. To address the constraints associated with IM/DD, unipolar pulse modulation techniques have been studied. The multipath nature of indoor VLC channels combined with the low-pass frequency response of the LED source however limit the available electrical bandwidth. To increase the spectral efficiency beyond pulse modulation, later works have investigated equalization schemes and optical orthogonal frequency-division multiplexing (O-OFDM). Advanced physical layer techniques such as adaptive transmission, relay-assisted transmission and MIMO communications were further explored in the context of VLC. More recent research works focused on the medium access layer and cross-layer solutions addressing multi-user support, interference management, handover, and resource allocation [351].

The first-generation VLC products are already available from various vendors based on proprietary protocols. In March 2018, Signify (formerly Philips Lighting) became the first major lighting company to offer a VLC product. Various start-up companies in different parts of the world have also launched VLC-based connectivity solutions. These include PureLiFi (UK), Oledcomm (France), VLNComm (USA), Velmenni (Estonia), Lightbee (Spain), and Hyperion Technologies (Turkey) among others. In parallel to the growing industrial interest, international standardization activities have been also initiated. The IEEE 802.11bb standard 'Light Communications' was approved as of June 2023. This standard aims to leverage the OFDM-based physical-layer specifications of IEEE 802.11 (WiFi) to develop VLC systems for light-based wireless access with throughputs up to 9.6 Gb per second.

Current and future challenges

Emerging applications such as extended reality, mobile hologram, and digital twins require data rates in the range of up to 1 Tb per second. Accordingly, hundreds of MHz to tens of GHz bandwidth are required to satisfy the performance requirements of the 6G and beyond networks. While the available optical bandwidth is huge, the bottleneck of a VLC system is the electrical bandwidth of the white light LEDs. There are currently two main approaches to generate the white light. Most white LEDs consist of a blue LED chip with a yellow phosphor coating that absorbs some of the blue light from the LED die. The resulting light is perceived as white by the human eye. Since this coating layer has a slower time response,

Figure 35. VLC is positioned as a complementary wireless access solution to radio-based cellular and WiFi systems, releasing the pressure on highly congested RF spectrum.

this limits the bandwidth of LED to a few MHz. Alternatively, with the RGB method, white light is obtained by combining the outputs from red, green, and blue LEDs. RGB LEDs provide typical bandwidths up to 20 MHz. To position VLC as a part of 6G ecosystem and fully tap its potential, the bandwidth limitations imposed by the conventional light sources need to be addressed.

In addition to indoor deployments, the widespread utilization of LED-based headlights, taillights, streetlights, and traffic lights in vehicles and roadside infrastructures has further prompted investigation of VLC as a potential candidate for vehicular connectivity [352]. In comparison to indoor VLC, vehicular VLC has progressed at a relatively slower pace, due to challenging outdoor environment where adverse weather conditions and solar radiation can significantly affect the link reliability. In addition to environmental conditions, the lack of line-of-sight between distant vehicles and the difficulty of maintaining a VLC link between two mobile vehicles are other major challenges that need to be addressed to realize widespread implementation of vehicular VLC systems.

Convergence with existing and/or emerging technologies is another major challenge. The increasing bandwidth requirements in 6G systems has motivated the wireless researchers to go beyond the conventional sub-6 GHz spectrum and explore the upper parts of the electromagnetic spectrum including millimeter-wave and terahertz (THz) frequencies. To exploit the complementary features of these RF bands and visible light spectrum, the design of radio and lightwave wireless access systems can be pursued [353]. However, several challenges on resource allocation and vertical handover management still need to be addressed for a seamless integration.

Advances in science and technology to meet challenges

Laser-based lighting might provide the platform for VLC technology to realize its full potential. Early examples of laser diode (LD)-empowered white luminaires are already being used in automotive applications [354]. These will likely be deployed in homes and offices, replacing LEDs in the foreseeable future. LD-based white light sources have a much higher electrical bandwidth (up to several GHz) than LED counterparts. Initial experimental works [355] have already demonstrated that tens of Gb/s can be achieved with white light LDs.

The coherent nature of LDs allows the implementation of coherent detection, paving the way for coherent VLC systems [356]. Unlike IM/DD systems, coherent optical systems allow the modulation of amplitude, phase, and frequency of the optical carrier signal. Much higher spectral efficiencies can be therefore realized using multi-level modulation formats, which make use of both amplitude and phase modulation. Coherent systems also have a higher receiver sensitivity and become advantageous to extend the transmission range, which can be advantageous for vehicular VLC systems. Future coherent VLC systems can also leverage advanced DSP techniques, which makes possible the use of digital estimation and correction techniques. In particular, a software-defined system architecture can be envisioned where all core receiver functionalities take place in the DSP domain. Such coherent systems can be further integrated with MIMO techniques and reconfigurable intelligent surface (RIS) assisted transmission for additional performance enhancements in both indoor and outdoor environments.

The physical layer design of future VLC systems (both coherent and IM/DD versions) can also benefit from the recent advances in machine-learning techniques [153, 357], as discussed in section 8. In the traditional approach, the physical layer is split into a chain of multiple blocks, where each block performs an isolated function, e.g. source coding, channel coding, modulation/demodulation, channel estimation, or equalization. These blocks are typically developed and optimized individually, and the overall performance is not guaranteed to be optimal. The use of AI can enable optimization of communication systems for end-to-end performance without the need for splitting transmitter and receiver into blocks. Such an AI-native physical-layer design will be optimally adapted to practical limitations of the optical channel and VLC transceiver hardware, featuring non-linear characteristics. In addition to optimized overall performance, AI-based transceiver implementations are expected to outperform their traditional counterparts in terms of power efficiency, latency, and cost in the foreseeable future, given the latest developments in hardware accelerators.

Concluding remarks

The first-generation VLC modems have already demonstrated the feasibility of building wireless access solutions based on the illumination infrastructure. With appealing features such as inherent physical layer security and robust performance in interference-limited environments, VLC has been considered for various use cases, but a mass market adoption was not yet realized. In the next decade, to position VLC as an integral part of 6G networks, developments in laser-based lightning, coherent communications, and machine learning are needed to push the technology limits and achieve data rates in the order of Tb/s. Future-generation laser-based coherent VLC systems will compete with emerging THz technology solutions to address the needs of ultra-broadband applications such as extended reality, mobile hologram, and digital twins. With their low-cost and simple architectures, LED-based VLC systems will be positioned as an enabler of massive machine-type communications and address the ever-growing device density, realizing the concept of 'Internet of Lights'.

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Data availability statements

The data that support the findings of this study are available upon reasonable request from the authors.

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