photonics

Review

Key Technologies for a Beyond-100G Next-Generation Passive Optical Network

Nan Feng [1,2,*], Mingyi Ma [1,2], Yinsong Zhang [1,2], Xiaochuan Tan [1,2], Zhe Li [1,2] and Shaobo Li [1,2]

1 The 54th Research Institute of CETC, Shijiazhuang 050081, China
2 Hebei Key Laboratory of Photonic Information Technology and Application, Shijiazhuang 050081, China
* Correspondence: fengnan65@163.com

Abstract: The explosive development of emerging telecommunication services has stimulated a huge growth in bandwidth demand as people seek universal access to telecommunication networks. In addition, the kinds of services of an existing optical access network are becoming more flexible. In order to provide higher capacity and meet higher transmission performance requirements, it is necessary to further explore the application of the beyond-100G passive optical network (PON). This paper offers a comprehensive review and outline of the prospects of technologies for bringing a beyond-100G PON to practical applications in the future. We review the current existing technologies, mainly in terms of the physical layer and higher media access control layer. These key technologies for the beyond-100G PON, which plays an increasingly significant role, include the advanced multiplexing technology, physical layer digital signal processing technology, infrastructure-sharing technology, security protection technology, and intelligent control management key technologies. Finally, open issues and new challenges for the next-generation PON are focused upon.

Keywords: next-generation passive optical networks; beyond-100G; digital signal processing; infrastructure-sharing technology; intelligent control management

check for updates

Citation: Feng, N.; Ma, M.; Zhang, Y.; Tan, X.; Li, Z.; Li, S. Key Technologies for a Beyond-100G Next-Generation Passive Optical Network. *Photonics* **2023**, *10*, 1128. https://doi.org/10.3390/photonics10101128

Received: 14 August 2023
Revised: 5 September 2023
Accepted: 18 September 2023
Published: 8 October 2023

1. Introduction

With the vigorous development of emerging telecommunication services such as cloud computing, the Internet of Things (IoT), the next-generation Internet, and beyond (e.g., the fifth generation (B5G)/sixth generation (6G), with 4K/8K high-definition (HD) video [1–4]), a "new infrastructure" of information construction and optical fiber to the home (FTTH) (as the "last kilometer" connecting people, things, and the cloud) is the "cornerstone" of consolidating high-quality economic and social development. The trend is of improvements in the capacity (higher speed and wider coverage) and flexibility of an optical broadband access network [5–8]. In order to support these more flexible broadband services and ensure the low cost and low delay of a B5G/6G network, the use of passive optical network (PON) technology is a promising access technology option, which places higher transmission performance requirements on both the physical (PHY) layer and higher media access control (MAC) layer.

Recently, the standardization of the single-channel next generation of 50G PONs has been completed. The ITU-T Recommendations for high-speed PON (HS-PON), published in September 2021, outline the industry requirements for the promising 50G PON. In the first PON standard, HS-PONs must employ digital signal processing (DSP) [9,10] to overcome the severe fiber dispersion and other impairments that can be experienced at this line rate. Given its characteristics of a large capacity, low delay, low cost, and high reliability, the beyond-100G PON [11–14] using DSP could be developed into an NG-PON in the future by using various advanced key technologies.

First, in terms of the PHY, research communities have focused on new multiple access multiplexing technologies, which can form different PONs in optical access networks. For the different high-speed beyond-100G PONs, in this article, we carefully consider both the future single-channel intensity modulation/direct detection (IM/DD) and coherent detection systems. All of the IM/DD solutions need to meet the 29 dB PON optical power/loss budget to support the existing fiber infrastructure already installed by network operators, which is challenging. Consequently, in the process of the development of a beyond-100 Gbp PON, this paper specifically describes the opportunities and challenges faced with many key technologies in terms of the new modulation and demodulation advanced algorithms.

In addition, from the comprehensive high-MAC-layer perspective, the shared co-existence, security, control, and management functions must be considered to abstract various flexible-rate PONs over the high-speed 100 Gbps. In order to give the solutions and achieve high performance, for the first time, this paper further explores the profiles of the infrastructure-sharing technology, security protection technology, and intelligent control management key technologies for the beyond-100G PON application.

In sum, the motivation of the paper is to give a comprehensive overview of the beyond-100G PON technologies that may be involved in making beyond-100G PON real for practical applications in the future. To the best of our knowledge, this review is the first to survey the high-speed 100 Gbp next-generation passive optical network (NG-PON). The insights from this review can benefit the development of the high performance and low power of the NG-PON.

Our contributions can be summarized as follows:

(1) We introduce the concept of a coexisting process to fully support the beyond-100G PON vision in the coming years; in addition, we summarize the limitations of the NG-PONs and review the PHY DSP for both the IM/DD and coherent detection system.

(2) In order to ensure that heterogeneous services can be properly, reliably, and intelligently transported over the beyond-100G PON, we discuss the latest developments of the virtual PON sharing scheme, describe the security technologies, and identify the main challenges regarding the intelligence for future NG-PON developments.

This article is organized as follows. In Section 2, the related work on 100G PON advanced multiplexing technologies is described. Then, in Section 3, we focus our attention on beyond-100G NG-PON physical layer key technologies in transceivers. Section 4 provides insights on the beyond-100G NG-PON infrastructure-sharing technology. In Section 5, the different security protection technologies for beyond-100G NG-PON are described. Section 6 describes the intelligent control and management technologies. Finally, Section 7 offers the conclusion, which gives challenges as well as some open research problems for NG-PON. The outline of this paper is shown in Figure 1. Meanwhile, Table 1 lists the acronyms in this paper.

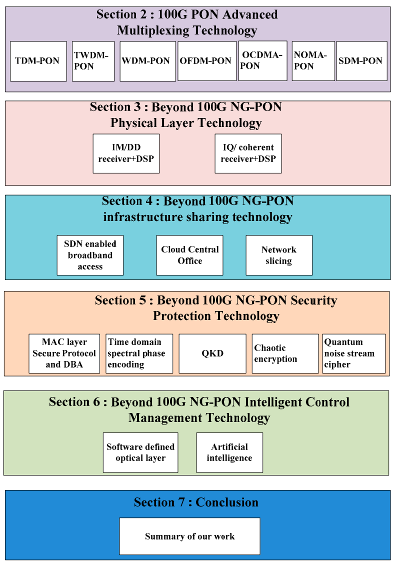

Figure 1. Outline of paper.

Table 1. List of acronyms.

Fifth generation	B5G
Sixth generation	6G
High definition	HD
Fiber to the home	FTTH
Passive optical network	PON
Physical	PHY
Media access control	MAC
High-speed PONs	HS-PONs
Digital signal processing	DSP
Intensity modulation direct detection	IM/DD
Next-generation PON	NG-PON
Optical line terminal	OLT
Optical distribution network	ODN
Optical network units	ONUs
Broadband network gateway	BNG
Time-division multiplexed PON	TDM-PON
Asynchronous transfer mode	ATM
Broadband PON	BPON
Ethernet PON	EPON
Gigabit PON	GPON
Gigabit ethernet PON	GE-PON
Time wavelength division multiplexing	TWDM
Wavelength division multiplexing	WDM
Orthogonal frequency division multiplexing	OFDM
Power division multiplexing	PDM
Space division multiplexing	SDM
Optical code division multiplexing	OCDM
Institute of Electrical and Electronics Engineers	IEEE
International Telecommunication Union	ITU
Multi-point control protocol	MPCP
Dynamic bandwidth allocation	DBA
Ultra-dense wavelength division multiplexing	UDWDM
Non-orthogonal multiple access	NOMA
Spectral shape line coding	SSLC
Non-return-to-zero	NRZ
Pulse amplitude modulation	PAM
Chromatic dispersion	CD
Quadrature amplitude modulation	QAM
Feed forward equalization	FFE
Volterra filter equalization	VFE
Semiconductor optical amplifier	SOA
Erbium-doped optical fiber amplifier	EDFA

Table 1. *Cont.*

Application programming interface	API
Photo-detector	PD
Transimpedance amplifier	TIA
Enhanced fixed broadband	EFB
Guaranteed reliable experience	GRE
Multiple private networks	D-Nets
Quantum noise stream cipher	QNSC
Quality of transmission	QoT
Optical signal-to-noise ratio	OSNR
Analog-to-digital converter	ADC
Local oscillator	LO
SDN-enabled broadband access	SEBA
Cloud central office end	CloudCO
Central office	CO
Quality of service	QoS
Quantum key distribution	QKD)
Intensity modulation-based QNSC	IM/QNSC
Phase-shift modulation-based QNSC	PSK/QNSC
QAM-based QNSC	QAM/QNSC
Software-defined network	SDN
Bit error rate	BER
Quantum key distribution	QKD
Network function virtualizations	NFVs
Advanced Encryption Standard	AES
Continuous variable QKD	CV-QKD
Artificial intelligence	AI
Machine learning	ML
Digital twin	DT

2. Beyond-100G PON Advanced Multiplexing Technology

This section introduces the standardization process and research trends of the different kinds of NG-PON systems, which have the characteristics of simplicity and high speed and make an effective solution for a low-cost FTTH access network. Traditionally, the NG-PON structure is mainly an optical line terminal (OLT), optical distribution network (ODN), and multiple optical network units (ONUs) connected through an ODN. Multiple OLTs are aggregated upstream by using an Ethernet aggregation switch. The Ethernet aggregation switch sends Layer 2 traffic of OLTs to the broadband network gateway (BNG). The BNG is essentially a dedicated Layer 3 router for managing user services. The ODN is usually composed of 1×32 or 1×64 shunt passive splitters. A large number of ONUs must be supported on the user side. At present, NG-PON is multiplexed. It is mainly divided into time-division multiplexed PONs (TDM-PONs), such as asynchronous transfer mode (ATM) PON (APON)/broadband PON (BPON), ethernet passive optical network (EPON), 10G EPON, gigabit PON (GPON), 10G symmetric PON (XGS-PON), and gigabit ethernet PON (GE-PON). Among them, the GPON and EPON have been deployed around the world. Considering those with most relevance for the future, for the 25G/50G EPON, the Super PON, and the high-speed PON, relevant standards have been established and they are in the process of being upgraded. In addition, the time wavelength division multiplexing PON (TWDM-PON), wavelength division multiplexing PON (WDM-PON), orthogonal frequency division multiplexing PON (OFDM-PON), power division non-orthogonal multiple access (NOMA-PON), space division multiplexing PON (SDM-PON), optical code division multiplexing PON (OCDMA-PON), and another advanced PON formats [15–19] have been researched. In recent years, around NG-PON technology, the industry has introduced relevant standards. At present, the two main standardization bodies that develop PON standards are the Institute of Electrical and Electronics Engineers (IEEE) and the International Telecommunication Union (ITU) [16–21]. For the TDM-PON, the OLT allocates time slots for TDM to a single ONU end. In November 2000, the IEEE 802.3 Study Group proposed extending ethernet to the user access area, called Ethernet in the First Mile. In order to further improve the capacity of the PON, ITU-T's next generation PON2 (NG-PON2) standard uses WDM technology to superimpose four or eight wavelengths. According to the ITU-T G.989.1 recommendation, point-to-point WDM systems are widely considered to be a strong candidate technology for future NG-PON3 access networks. The standardization process of NG-PON is shown in Figure 2.

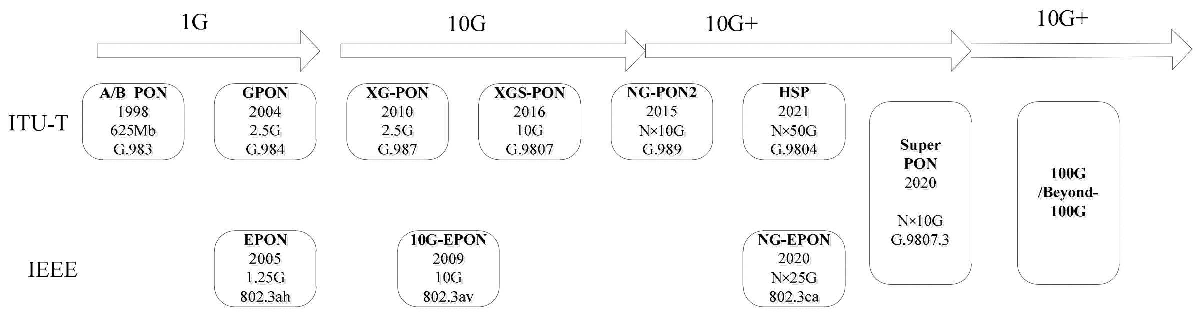

Figure 2. Standardization process of NG-PONs.

In order to meet future PON development needs, different types of NG-PONs differ in data rate, wavelength, and frame format used by PON, but it is important to improve the cost, data rate, and latency by following the same architecture and improving the NG-PON architecture for transmitters and receivers. Figure 3 shows the coexisting process of different PONs for the beyond-100G PON. With the TDM-based PON, since the physical media are shared and the same PON deployment is shared among the maximum number of users, the total bandwidth must be shared among all users while guaranteeing the maximum bandwidth per user. This leads to the primary bandwidth limitation of PON, where the dynamic bandwidth allocation (DBA) scheduler via multi-point control protocol (MPCP) plays a key role. The category WDM-PON includes coarse WDM, dense wavelength division multiplexing, and ultra-dense wavelength division multiplexing (UDWDM) PONs. The broadband optical access based on a coherent UDWDM has been proven to be a potential solution to improve spectral efficiency and downstream capacity. However, deploying it cost-effectively remains a major challenge for telecom operators. In addition, in order to overcome the scalability limitation, which remains a major issue for next-generation optical access networks, as one of the best architectures for NG-PON2, the TWDM-PON technology solution has been adopted by ITU-T as a TDM-PON upgrade. The TWDM can be utilized in order to strike a balance between coexistence with legacy systems and a gradual migration to a pure WDM-PON. PONs adopting new technologies in the future need to be designed for the coexistence of various PONs. Consequently, there is a strong expectation that the WDM-PON will be utilized in order to use the existing ODN to implement a TDM-PON that provides high access bandwidth at a low cost.

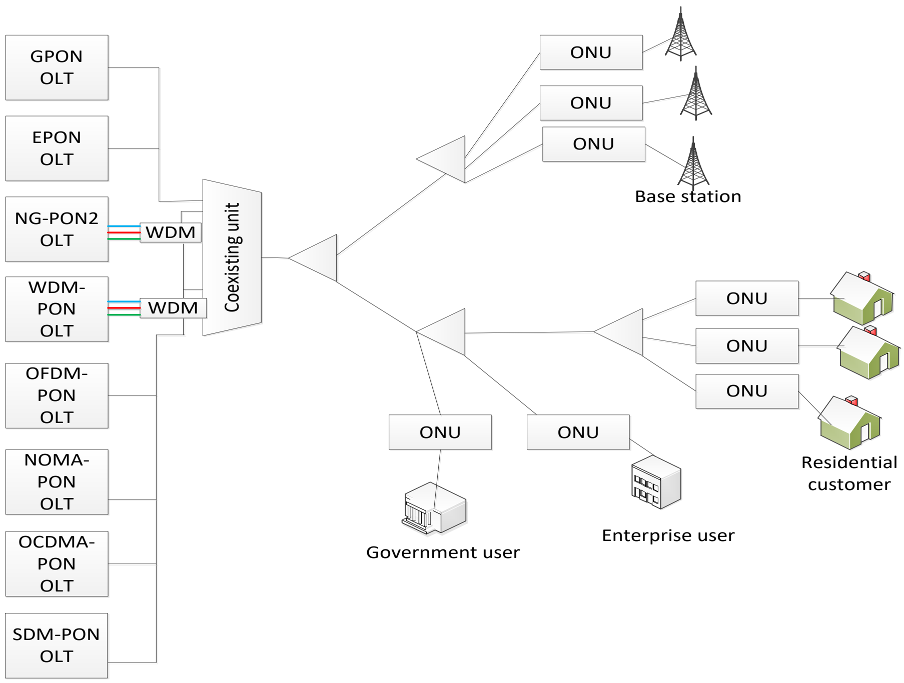

Figure 3. The coexisting process of the NG-PONs.

In addition, according to the 40 Gbp NG-PON2 and 25 Gbp NG-EPON standard specifications planned by ITU-T and IEEE, respectively, the OFDM system is an important solution for the NG-PON because of its strong dispersion tolerance and high spectral efficiency. However, due to the high complexity of digital signal processing, the OFDM-PON is still a long way from commercial use. The OCDMA-PON performs encoding and decoding in a PON through optical signature codes to allow the selection of the desired signal so that different ONU users can share the same bandwidth. Furthermore, the SDM-PON increases the capacity of the NG-PON by effectively utilizing the latitude of the air separation. However, PON technologies such as the TDM-PON, TWDM-PON, WDM-PON, and OFDM-PON must ensure orthogonality in time, wavelength, or frequency dimensions so that ONU user information can be separated to reduce multi-ONU user interference. With that said, due to strict orthogonality, it seems impossible to use limited system resources such as time and frequency to transmit multiple parallel signals at the same time. Consequently, as one of the key technologies to improve the capacity of 5G networks, NOMA, unlike orthogonal access schemes, has received great attention from the industry and academia. In recent years, in order to improve the spectral efficiency and the number of ONU users, the NOMA-PON systems have been proposed. The NOMA-PON supports multiple ONU users sharing the same simultaneous frequency resources to transmit signals with different power weights, resulting in overlapping signals in the time domain and frequency domain and multiplexing in the power domain. Successive interference cancellation based on multi-user detection technology can successfully distinguish and separate user signals in the receiver according to the difference in user power. Consequently, without increasing available resources (as those are cost-sensitive and the NOMA-PON system is a potential application scenario with limited available resources), this can effectively improve data throughput and spectral efficiency, serving more users at a given time and frequency range. To avoid the cost of rebuilding a new ODN, the reuse of the deployed ODN is preferred in PON evolution. This evolution is called smooth evolution. During the evolution of the PON, the new NG-PONs are added to the deployed ODN to share with the existing PONs [22–25]. However, this coexistence causes crosstalk between the two PON signals. Typically, conventional PONs and new PONs are assigned different wavelengths to carry their signals. The new PON link uses an optical filter to filter out the traditional PON signal. However, traditional PON links usually do not have such optical filters. Adding optical filters to traditional PON links will bring retrofit costs. If additional filtering is required, it is best to do so in an OLT with easier access, rather than an ONU, to avoid the impact. Consequently, the main problem for smooth evolution is the existing ONU dull filter to protect from the new PON signal in the downstream direction. At present, in the literature, three methods have been proposed to reduce/eliminate this crosstalk without changing the existing ONU—synchronous pulse interleaving, electric superposition modulation, and subcarrier modulation [26–28]. However, these three methods require expensive components such as high-speed electrical multiplier transmitters or sacrifice the quality of the new PON signal. A promising smooth evolution technique called spectral shape line coding (SSLC) is proposed [29]. SSLC constructs some line codes that suppress low-frequency components and applies them to new PON signals. After encoding, the new high-speed PON signal causes crosstalk with the traditional low-speed PON signal, but SSLC does not degrade the signal of the new PON.

3. Beyond-100G NG-PON Physical Layer Technology

In this section, the physical layer solutions of beyond-100G NG-PONs are described and discussed. The beyond-100G NG-PONs can be divided into two categories: the IM/DD technology and the coherent technology [30–34]. Figure 4 shows the physical layer technology of the beyond-100G NG-PONs. Firstly, for IM/DD NG-PON, compared with the non-return-to-zero (NRZ) modulation, the four/high-order pulse amplitude modulation (PAM4/M) is a promising solution to meet the increasing demand for optical access network capacity. In addition to the low-cost and low-complexity PAM format, other advanced modulation formats mainly include multi-carrier OFDM, single-carrier quadrature phase shift keying (QPSK), and high-order quadrature amplitude modulation (QAM). The potential and achieved 100 Gbp IM/DD PON solutions based on a 50GBaud PAM4 format and advanced receiver DSP in high-speed optical access networks have been explored. However, the existing NG-PON system is limited by chromatic dispersion (CD) and the power fading effect after direct detection, and the increase in transmission distance leads to significant performance degradation. The direct way to minimize the CD effect is to transmit in the O-band, but even in this case, the channel of the PON system is affected by the associated dispersion effect due to the chirp of the modulator. There are several proven methods to overcome the CD effect in DD systems. For instance, as a way to avoid power fading and overcome signal-to-signal beat interference, self-coherence detection based on single sideband transmission is often used in combination with the Kramers–Kronig reception. In order to keep the overhead requirements of hardware low, the bit rate PON of over 100 Gbps per channel based on IM/DD is physically limited to its development. Consequently, in the future wideband access network transmitter, it is necessary to design new coding methods, signal forming methods, modulation formats, and equalization methods. For example, in the new encoding mode, the record performance of a 90 Gbp (25GBaud) PON under the BER of 10×10^{-11} provides more than 1.5 dB encoding gain for soft-decision low-density parity check codes (LDPCs). In terms of signal shaping methods, there are mainly probabilistic shaping, geometric shaping, and faster Nyquist. The fundamental challenge associated with direct detection is the disappearance of the phase of the transmitted signal. With the increase in the nonlinear effect of IM/DD, the limited bandwidth and power fading degrade the transmission performance of the system. Moreover, the nonlinear Inter-Symbol Interference caused by intensity modulation and square law detection will significantly reduce the performance of the IM/DD system. Consequently, the application of DSP-based equalization schemes of the DD system can effectively improve the different undesirable factors. For instance, electronic dispersion compensation such as Tomlinson–Harashima precoding (THP) and the lookup table pre-equalization method in the transmitter's DSP, feed forward equalization (FFE), decision feedback equalization (DFE), Volterra filter equalization (VFE), etc., at the receiver's DSP [35–41] can effectively contribute to impairment mitigation. The transmitter's and receiver's DSPs can be combined to suppress undesirable factors.

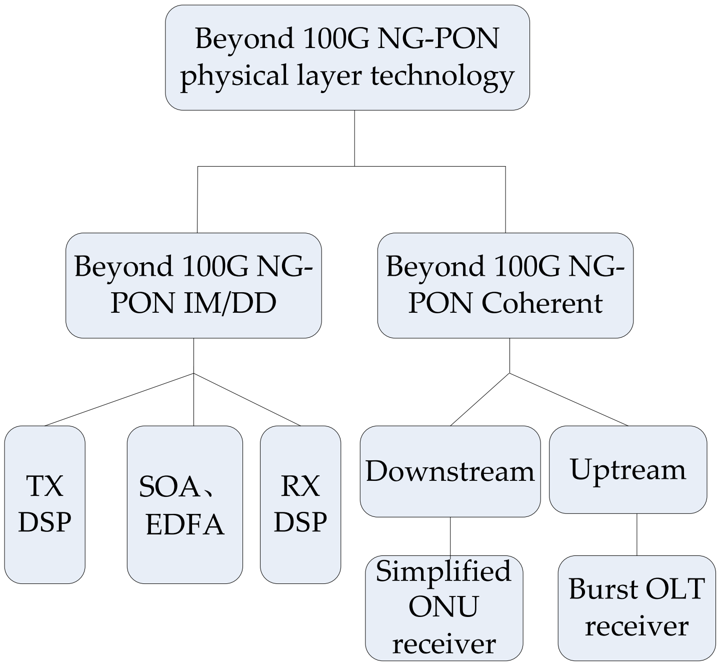

Figure 4. Beyond-100G NG-PON physical layer technology.

On the other hand, in order to improve the sensitivity and achieve a 29 dB optical loss budget, a semiconductor optical amplifier (SOA) and erbium-doped optical fiber amplifier (EDFA) can be adopted as a receiver preamplifier. Among them, the SOA can work in the C and O bands, which has a wide effect on the NG-PON because of its easy integration and relatively low cost. However, the effect of SOA nonlinearity, such as gain saturation, is a significant issue. Figure 5 shows an architecture diagram of the NG-PON with N splitter ratio. The downstream of the beyond-100G PON is the continuous mode while the upstream of the beyond-100G PON is the burst mode. The different colors in the figure represent different services for ONUs.

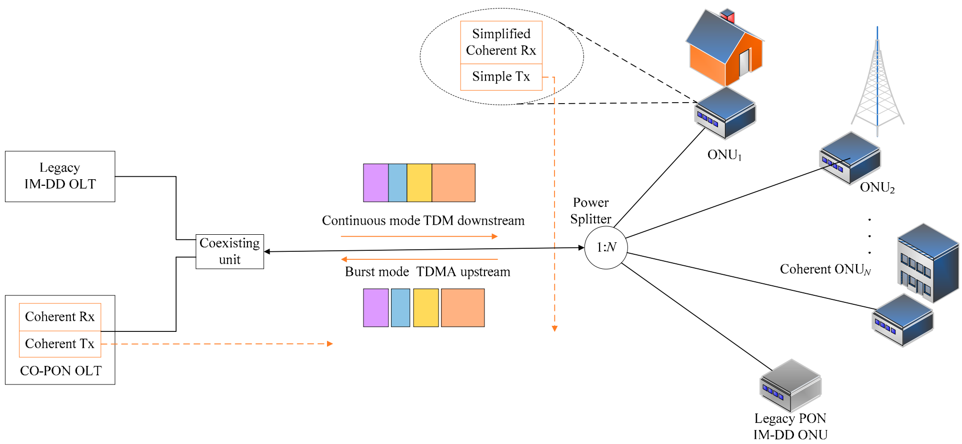

Figure 5. Architectural diagram of the NG-PON with N splitter ratio.

In receivers with higher bit rates, it is expected to be used in PON systems of 100 Gbps or higher since coherent technology has higher receiver sensitivity than IM/DD technology. Thanks to the rapid development of the latest small-scale DSPs, coherent PON can be expanded to support the next generation beyond high-speed 100G optical access networks, with tens of kilometers of access range. The introduction of customized hardware and efficient DSP technology for the coherent PON [42–44] system helps to further develop it. To improve the spectral efficiency, coherent transmission also uses advanced modulation formats that can be encoded in all four dimensions of the light field: in-phase and orthogonal in the two orthogonal polarization states.

However, such beyond-100G PON transmission systems require high optoelectronic complexity, typically using at least one photo-detector (PD) and trans-impedance amplifier (TIA) per modulation dimension, at least one analog-to-digital converter (ADC) per detection dimension, and at least one external modulator integrated into a nested Mahzindel interference structure per modulation dimension. Coherent systems also require an additional laser receiver as a "local oscillator" (LO). This is comparable to transmission using a directly modulated laser and reception using a single PD. The actual transceivers deployed in beyond-100G PONs that modulate and detect only one dimension of the optical field differ greatly. In the downstream direction, in order to achieve a low-cost coherent PON, many low-cost simplified coherent receivers have been proposed. For instance, there are the polarization-independent coherent receivers using 3×3 couplers, which have aroused widespread research interest. DSP technologies for coherent PON systems include simplified IQ imbalance compensation, adaptive equalization, clock recovery, polarization de-multiplexing, carrier frequency offset, and phase offset estimation schemes. In addition, in the upstream direction, the data flow of the coherent NG-PON system has a burst mode [45–54]. Particularly in the NG-PON with SOA transmission, the inherent large dynamic range (DR) of the burst-mode signaling is 19.5 dB [55]. In the case of SOA preamplifiers of beyond 100G, the linear requirement is very strict. The possible implementation beyond 100G can be problematic. Consequently, machine learning (ML)-based equalization technologies have been proposed in future SOA preamplifier PON scenarios to compensate for expected fiber dispersion and device damage. The current works have focused on achieving a 29 dB optical loss budget; for example, in [56,57], a recurrent neural network combined with an optical sensor uses an SOA preamplifier to achieve a 30 dB loss budget of 100 Gbp PAM4. However, the challenge of meeting the 19.5 DR requirement has also brought attention to non-ML technologies, such as in [58], where the authors investigate the transmitter's lookup table pre-compensation technique with a nonlinear Volterra equalizer (VNLE) to overcome the nonlinearity of SOA and achieve up to 18 dB DR for the 100 Gbp PAM4 format. Consequently, burst mode data transmission faces a major challenge in electronic design. In the future, it is necessary to design the structure and software solutions of the burst mode coherent receiver [59–62], expand the receiver input dynamic range, and make the OLT and ONU process the burst data smoothly.

4. Beyond-100G NG-PON Infrastructure-Sharing Technology

This section discusses the beyond-100G NG-PON infrastructure-sharing technology and its potential to bring benefits by considering the end-to-end dynamic slice. The optical access networks connect end ONU users and carrier networks in the last mile. The access portion of the communications network is the most expensive due to the scale of deployment. As a result, the reduction of access costs has multiple impacts on overall capital expenditure (CAPEX) for the network deployment. Infrastructure/resource sharing has the potential to reduce capital and operational expenditure for network operators. As the cost of market entry decreases, this involves technologies for sharing between the operators' infrastructures.

In order to improve on the low development efficiency of the traditional optical access system, which has a long development cycle and high initial cost, the sharing architecture based on common hardware of components and software is developing. Over the past few years, virtualization technologies have been evolved to access network management systems that connect coordinators and infrastructure devices using northbound and southbound interfaces (SBIs). Two typical projects promoted by telecom operators and vendors are SDN-enabled broadband access (SEBA) and cloud central office (CloudCO), which provide virtualization and cloudification [63–70], respectively. In order to accelerate new PON-based services, SEBA uses a classic application programming interface (API) to extract different OLT/ONU management devices through a single controller. SEBA builds a CO end with a white box OLT and a common server. It realizes flexible service creation via software for the upper functions such as workflow authentication and edge application. However, the current abstract unit in SEBA only supports the ITU-T PON. To support the IEEE PON, multiple packet types as well as forward management capabilities should be considered. The classic configuration of logical links for the ITU-T PON and IEEE PON extract IEEE PON OLT/ONU adaptively by extending the forwarding between operation, management, and maintenance. In order to flexibly create the underlying service, the hardware of further software OLT has been studied. Traditional application-specific networks are provided only in local networks by using dedicated systems. In addition, edge computing services can be provided by implementing a specific network within the access segment. They provide service providers with lower initial costs for creating new services and simplify system administration.

In the software-based sharing method, since one of the basic features of the PON is to provide burst-level scheduling for upstream transmission, the DBA algorithm [71–75] is responsible for preventing conflicts and providing the required quality of service (QoS) to meet the needs of service-level agreement. Consequently, the DBA scheduler on OLT is one of the important components of the PON control plane that can meet the demands of users. According to the MPCP defined in the IEEE 802.3ah standards group, the DBA scheduler manages the entire bandwidth allocation process. Taking into account the bandwidth requirements of registered EPON users and the maximum allowed upstream latency, the available bandwidth is allocated to the individual ONUs. Various DBA schedulers have been proposed in the literature. Among them, the most classic, the interleaved polling with adaptive cycle time (IPACT) scheduling scheme, better combines simplicity and allocation efficiency. From the theoretical analysis, we can surmise that different scheduling algorithms have their own advantages and disadvantages. However the complete scheduling performance in the actual hardware environment still lacks analysis.

Furthermore, traditional PON systems can support multiple services through associated service isolation, QoS control, and connectivity configurations. The existing PON standard recommendation ITU-T G.9804.2 defines that the transmission converge layer supports the management of traffic on OLT through a single control function at the traffic level. Slicing on the OLT collects individual streams into groups called slices and adds a control for sharing common resources at the slice level [76–79]. This control function enables a degree of service or virtual network isolation. The PON slices are grouped into at least multiple streams on one or more ONUs of the OLT. Each slice is processed accordingly via the hierarchical scheduler in the DBA of the OLT. Slicing also means that the OLT and ONU manage coordination between instances in cases where ONU functionality will be used to handle streams and slice-level streams. In the future, the parameters with a set of slice profiles in PON slices need to be further studied. The architecture for controlling PON slicing is considered as follows: slicing use cases in the beyond-100G NG-PON include network slicing that supports several different delay limits, dynamic optimization of resource allocation for mobile applications, and slicing in multi-operation scenarios.

Figure 6 shows the network slicing configuration for different business QoS requirements. The different colors in the figure represent different slicing types, such as enhanced fixed broadband (eFBB), guaranteed reliable experience (GRE), IoT [80–84], and vertical/industrial applications. Multiple private networks (D-Nets) serve specific market segments, such as residential, wholesale, smart city, industrial, hospital, or any other enterprise-oriented segment. Each D-Net has a set of slicing types that need to be supported. For example, residential D-Nets support eFBB, GRE, and IoT slicing types to provide traditional broadband, cloud virtual reality (VR), cloud gaming, and smart home services. By sorting all network slicing instances according to their slicing types, all service types can be effectively supported to meet their corresponding QoS requirements. A network operator may group one or more services into one or more network slices of the same or different types.

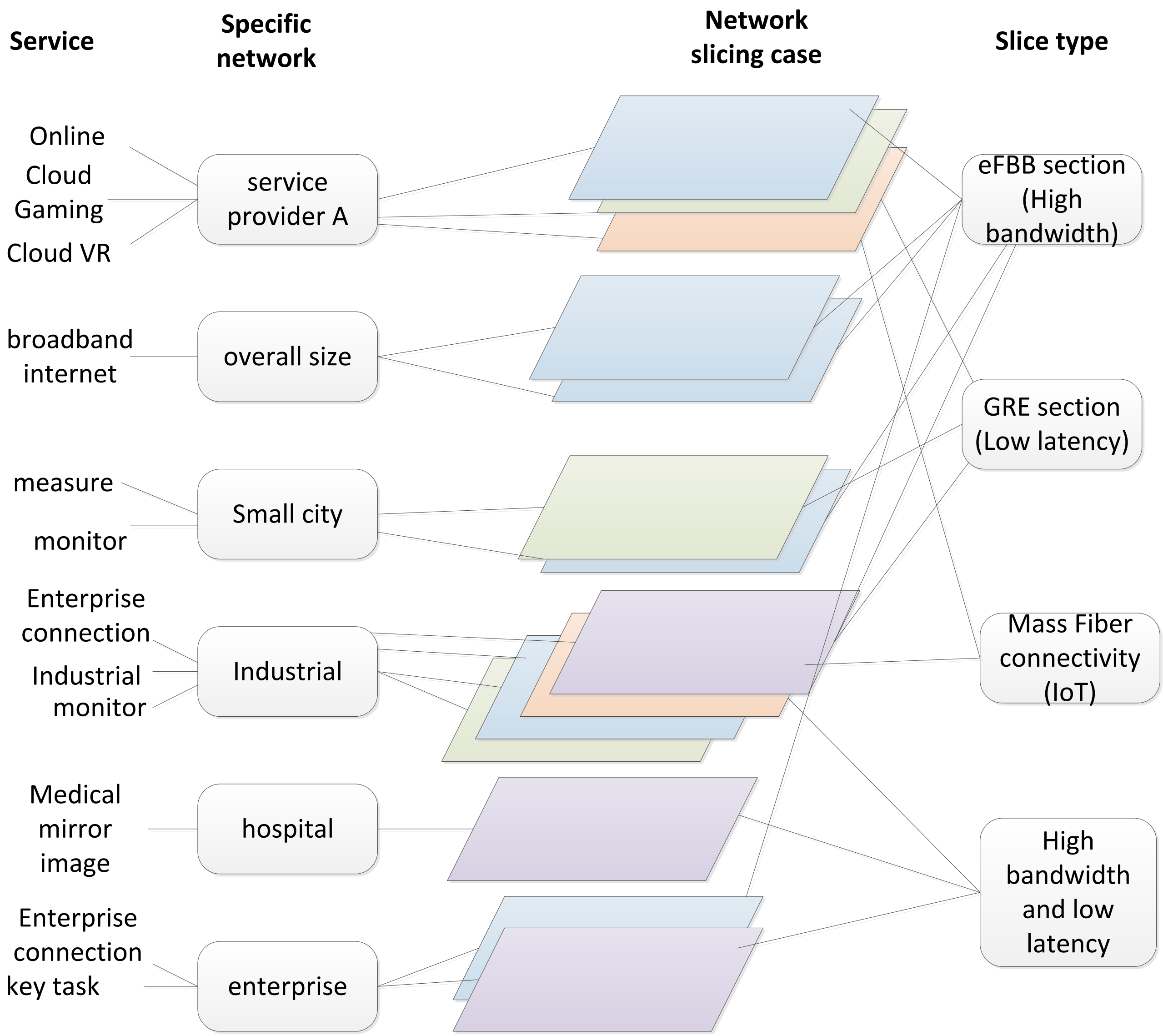

Figure 6. Network slicing for services that require different slicing types.

5. Beyond-100G NG-PON Security Protection Technology

In order to cope with the exponential traffic growth, the large-scale deployment of 100G optical networks is developing into 200G/400G. However, in seeking to improve the signal performance and reduce the cost, the high speed NG-PON tree topology and its downstream transmission broadcast characteristics have taken on security risks. In the current scenario where we are facing serious security challenges, securing the growing amount of confidential information has become a great need. However, the physical layer of a beyond-100G NG-PON is vulnerable to eavesdropping attacks. Moreover, the encryption algorithms based on mathematical complexity are facing the risk of being cracked via the use of quantum computing. The security of future optical access networks is very important. Many proposals have been made to improve the NG-PON security [85–87]. Currently, a variety of NG-PON security protocols have been implemented. Different researchers have proposed different encryption and authentication technologies for the future NG-PONs, which usually require the provided key only on the downstream channel. For example, the GPON provides security features such as data encryption, authentication, and key establishment. However, encryption is supported by the plain text key exchange that occurs during the setup.

In addition, currently, the NG-PON has a shared medium in the upstream direction. All of the ONUs behave and act according to the DBA arrangement. The absence of appropriate security measures leads to vulnerabilities in the network and jeopardizes the security of the DBA mechanism itself, which is essential in PONs. Degradation attacks occur during the DBA process at the expense of other bandwidths rather than destroying the entire NG-PON. The passive ODN combines all ONU outputs with the OLT. Consequently, if an ONU does not transmit in a manner that meets the parameters specified by the standard, threats will interfere with the other ONUs on all of the PON's upstream transmissions. Those results in a disruption of communication that is designed, manufactured, and deployed in compliance with the standard. If an ONU is violated due to design flaws, for instance, the change in standard parameters of transmitting optical power from the ONU to the OLT, manufacturing errors, hardware or software malfunctions, and environmental or other external influences, it is referred to as a "rogue ONU" [88]. This behavior is not unique to NG-PON systems; it can exist in any communication system using the same shared channel scheme, resulting in a single rogue device that can affect other devices or disrupt the operation of the entire system. Diagnosing and isolating the offending device can be difficult because the affected device is not always the one causing the outage. In the context of beyond-100G NG-PON systems, to facilitate the prevention, detection, isolation, and removal of violating ONUs, standard specifications raise awareness of rogues, and technologies and tools for system designers and implementers should be provided.

To avoid or minimize the service disruptions to other ONUs on the beyond-100G NG-PON, the header information or control data encrypted with the upper layer is exposed in the physical layer. Accordingly, in recent years, physical layer security protection technologies have been developed to improve the security of the optical access networks. Compared to upper-layer security protection, physical layer security, which provides transparent encryption for all the data, is considered a promising solution to exploit the inherent randomness of optical access networks. So far, researchers have proposed many physical layer security methods such as quantum noise stream cipher (QNSC) [89–94], time domain spectral phase encoding [95–97], chaotic encryption [98–101], and so on. Recently, among those schemes, a number of chaos-based physical layer security schemes have been proposed for the application of joint subcarrier variations in the NG-PON, especially in the OFDM-PON. However, in practical applications, the stability and key distribution speed of chaotic laser communication are low, and there are issues such as channel interference and parameter matching, which limit the application of chaotic laser communication in practical applications. Chaos includes optical chaos and electric chaos technology. Optical chaos technology improves the physical layer's security by adjusting the injection strength and feedback strength of the laser in the PON. Meanwhile, electric chaos technology mainly realizes the processes of signal generation, modulation, and error correction in the digital domain. Due to the high flexibility of DSP in the digital domain, it is easier to employ cryptographic technologies such as digital chaos cubic constellation masking, chaotic and fractional Fourier transforms, segmented chaotic alignment, chaotic IQ encryption, and hybrid chaotic systems to improve the security of OFDM-PON systems. Table 2 shows the security protection key technologies of the NG-PON.

Table 2. Security protection key technologies of NG-PON.

Author	Year and Publication	Modulation Format	Rate [Gbps]	Distance [km]	BER	Scheme	Kind of PON
Xiao, Y.	JOCN 2018 [102]	16 QAM	8.9	100	10×10^{-3}	Multi-chaotics	OFDM-PON
Wu, T.	Optics Express 2018 [103]	16 QAM	22.06	25.4	10×10^{-3}	Three-dimensional Brownian motion and chaos in cell (3DBCC)	OFDM-PON
Wu, T.	IEEE Access 2020 [104]	16 QAM	22.06	25	10×10^{-3}	Deoxyribonucleic acid (DNA) extension code and chaotic System	OFDM-PON

Table 2. *Cont.*

Author	Year and Publication	Modulation Format	Rate [Gbps]	Distance [km]	BER	Scheme	Kind of PON
Zhang, W.	PTL 2016 [105]	16 QAM	11.32	25	10×10^{-3}	Joint peak-to-average power ratio (PAPR) and a chaos IQ encryption	OFDM-PON
Zhang, W.	PTL 2017 [106]	16 QAM	36.67	100	10×10^{-3}	Brownian motion encryption	CO-OFDM-PON
Hu, X.	PTL 2015 [107]	16 QAM	8.9	20	10×10^{-3}	Chaos-based partial transmit sequence	OFDM-PON
Bi, M.	Photonics Journal (PJ) 2017 [108]	16 QAM	10	25	10×10^{-3}	Key space enhanced chaotic encryption scheme	OFDM-PON
Adnan A. E. Hajomer	Photonics Technology Letters 2017 [109]	16 QAM	8.9	20	10×10^{-3}	Chaotic Walsh–Hadamard transform	OFDM-PON
Zhao, J.	Optics Express 2020 [110]	16 QAM	16	25	10×10^{-3}	4D-hyperchaos and dimension coordination optimization	OFDM-PON
Zhao, J.	PTL 2020 [111]	16-ary	20	25	10×10^{-3}	Floating probability disturbance	CAP-PON
Cui, M.	Optics Express 2021 [112]	16 QAM	35.29	25	10×10^{-3}	Chaotic RNA and DNA	OFDM-WDM-PON
Wu, K.	IEEE Photonics Journal 2022 [113]	PAM-8	100	35	3.8×10^{-3}	Adjustable fingerprint with deep neural networks	WDM-PON
Luo, Y.	JLT 2023 [114]	16-32-64 QAM	17.6, 22.1, 26.5	25	3.8×10^{-3}	Support vector machine	OFDMA-PON
Liang, X.	JLT 2023 [115]	-	35.29	20	3.8×10^{-3}	Chaotic Hilbert motion	OFDM-PON
Wei, Z.	JLT 2023 [116]	PCS-64 QAM	400	80	3.8×10^{-3}	Pseudo-m-QAM chaotic	WDM-CPON
Xia, W.	Optics Express 2023 [117]	Pyraminx-3D-CAP-16	25.5	2	3.8×10^{-3}	Pyramid constellation design for 7-core fiber	3D CAP

In addition, quantum key distribution (QKD) is theoretically considered to be absolutely secure. To achieve provably secure communication in NG-PON topology, multiplexing of weak quantum channels with classical data channels has been proposed to allow fast updating of Advanced Encryption Standard (AES) encryption keys. Constraints on the QKD concept for practical deployment have also been proposed in existing FTTH architectures. For continuous variable QKD (CV-QKD) and DV-QKD [118–120] protocols, the feasibility of the coexistence of quantum and classical channels over the same optical fiber using C-band DWDM technology has been investigated. Recently, the integration of a CV-QKD scheme for a 25 km WDM-PON network with strong classical channels has been reported. However, there is still a long distance from the ideal single-photon source. In addition, encrypted probabilistic shaping parameters are another security enhancement scheme for the beyond-100G NG-PON physical layer. All of the above physical layer security enhancement technologies are realized at the symbol level in the time or frequency domain and lack flexibility at the bit level. While bits are the basic form of data in the physical layer of optical networks, encryption at the bit level can better enhance the security of optical communication systems. To address this problem, quantum noise flow based a cryptography protocol, also known as Y-00 [121–132], is a symmetric encryption method that hides the encrypted higher-order signals in quantum noise. Due to the quantum mechanical nature of the coherent state of light, fluctuations in photocurrent caused by photoelectric transitions are unavoidable, which is known as quantum noise or bulk noise. If the spacing of neighboring symbols is less than the quantum noise, the masking effect of the quantum noise prevents the eavesdropper from determining the correct cipher. The channel for signal transmission is subject to various random noise interferences and physical effects. Consequently, given that it is suitable for long-distance scenarios, the channel measurement following the principle of randomness is considered a promising solution for the secure transmission of optical data in fiber optic networks to achieve a high level of security. Currently, different QNSC schemes have been proposed in the industry, such as intensity modulation-based QNSC (IM/QNSC), phase-shift modulation-based

QNSC (PSK/QNSC), and quadrature amplitude modulation-based QNSC (QAM/QNSC). Compared to the IM/QNSC or PSK/QNSC, the QAM/QNSC not only significantly improves the level of security but is also suitable for different modulation formats used in optical networks. Using wavelength-division multiplexing, Masato et al. demonstrated a 10 Tbit/s 128QAM/QNSC transmission over 160 km. By introducing cascaded modulators, the highest encryption order of the reported QAM/QNSC reached 2×10^{32} [131]. Sun et al. extended the plaintext type of QAM/QNSC to probabilistic shaped QAM [132]. The experimental results showed that the encryption and decryption of QAM/QNSC induced additional optical signal-to-noise ratio (OSNR) loss, i.e., the difference between the bit error rate (BER) curve of the cipher and that of the reference code curve for the same OSNR. However, in the actual deployment of QAM/QNSC systems, this part of the cryptographic cost is not negligible but has received less attention compared to its confidentiality [133]. Consequently, it is necessary to quantitatively analyze the encryption cost of QNSC. Furthermore, endogenous security-based work is an important direction for the future development of the NG-PON since the seed key does not depend on the generation of external devices but on the channel feature. The fiber channel feature extraction, key generation and quantization, and negotiation of a consistent key are carried out by exploiting the unique physical layer characteristics of fiber optic channels [134–140].

6. Beyond-100G NG-PON Intelligent Control and Management Technology

At present, many works have analyzed and studied the importance of introducing a software-defined network (SDN) [141–144] into the NG-PON. This combination enables the programmable NG-PON to dynamically adjust its operation based on the decision of the SDN controller. Open software and white box hardware are explored as practical ways to scale fiber access networks, enabling integration into software-defined network control environments while transitioning from a vertically integrated model with black box PON solutions. An application can request resources from the network through a north interface to the control plane. Through this interface, applications can dynamically request network resources or network information that may span different technologies. The application layer can dynamically request and obtain network resources at the message flow, circuit, and even optical layer as required. Meanwhile, the principle of SDN is to abstract the centralized control plane from the data plane. That is, the control plane is separated from the network switching plane. The switching plane can be composed of network elements from multiple vendors. Heterogeneous secondary network elements can be provided at the optical layer to provide different services with different features, configurations, and controls while hiding the service characteristics and differences in specific network platforms. The architecture of the SDN produces several network function virtualizations (NFVs) using APIs and OpenFlow, NETCONF/YANG, RESTCONF, gRPC, etc., protocols [145–151] to communicate between the various hardware and software that make up the network.

To minimize the latency and energy consumption, switching/routing should be conducted on the lowest network layer possible. This means that the optical layer should participate in the SDN process, making it possible for optical technology to move from high-speed transmission to dynamic, energy-efficient exchange. However, this approach has the potential to include lower latency (through multi-layer cutting) and optical bandwidth benefits on demand. The SDN controller must be able to understand the key functions of the optical layer. Without this kind of thinking, whether the controller can really match network resources and applications in an optimal way without complicating the network is questionable. One concrete way to achieve this is to extend the adopted SDN language to a standardized, concise set of parameters. For example, by extending the L2-L4 OpenFlow matching rules to include L0 parameters (e.g., light wavelength, modulation format, etc.), an application-aware on-demand wavelength circuit configuration can be introduced. This is especially important for optical access/photo polymerization. Dynamic L0 circuits can be used to rapidly deploy networks for new services (e.g., mobile backhaul, desktop mobile, enterprise, data center/cloud, etc.) and to better leverage large existing PON infrastructures while realizing existing optical network economies.

On the other hand, from a strictly functional perspective, management and control in networking refer to a defined set of management and control planes with different functions. The management plane is responsible for the planning, installation, configuration, and supervision of network infrastructure to ensure the coordinated operation and ensure that network functions run as efficiently and smoothly as possible according to user requirements. Network management consists of a set of management activities and processes with specific objectives. Application, network, and element hierarchies can be managed based on abstraction and management domains. Currently, artificial intelligence (AI) and ML [152–162] are showing great capabilities in solving tasks in optical network fault management, resource allocation, and optical path quality of transmission (QoT) estimation. However, the focus of the research community has been on the predictive power of ML models, neglecting aspects related to model understanding, that is, explaining how to make predictions. Digital twin (DT) is a new research field in communication networks [163,164]. DT can bridge the real world and the virtual world, making a significant contribution to the optimal operation of the network. In addition, management operations are typically deployed over time in a centralized approach across different layers of the management system and rely on manual configuration by human operators. However, automation and advanced ML technologies can significantly improve efficiency. The control plane is mainly responsible for learning and updating the network topology and deciding how to handle incoming packets or connection requests from the source to the destination node. In the virtual connection-oriented network, control plane operation is essentially automated, and it is necessary to design intelligent control management of a beyond-100G NG-PON based on a variety of distributed artificial intelligence. For example, considering the high energy consumption characteristics of the future beyond-100G NG-PON, it is very important to consider how to maximize energy saving while meeting the quality of service, incorporate real-time feedback on energy saving and service traffic performance into the network operation decision process, and take real-time control of the PON infrastructure.

7. Conclusions

Focusing on the impact of the emerging telecommunications services, associated with a huge growth of the bandwidth demand of optical access networks, the optical access system is developing in the direction of faster rates, wider coverage, lower costs, and greater flexibility. By focusing on the infrastructure deployment and market requirements of the next-generation beyond-100G PON system, this paper differs from the existing mentioned work because (i) we consider a wide range of alternatives for the PHY layer implementation and MAC layer technological enabler modes, and (ii) our focus is more comprehensive with regard to the current key technologies of the beyond-100G NG-PON access, which have the potential to become research targets and promising solutions for the optical access network.

However, another avenue or study would be to review potential solutions (and problems involved) to the open challenge facing the single-channel beyond-100G PON, which has become the fundamental driving force of development work. For instance, the standardization of thecoherent PON, the advancement of technologies for the next-generation industrial PON, as well as evolution of the considered low-latency, time-sensitive services of the 6G mobile network should be explored in terms of contributions both from academia and industry. Looking to the future, in the next 5–10 years, it remains to be seen whether the key implementation technology systems will meet the demands of large open-source and integration projects in terms of the community of vendors, operators, and system integrators.

Author Contributions: Conceptualization, N.F. and M.M.; methodology, N.F.; software, M.M.; validation, N.F., M.M. and Y.Z.; formal analysis, X.T.; investigation, Z.L.; resources, S.L.; data curation, N.F.; writing—original draft preparation, N.F.; writing—review and editing, N.F. and M.M.; visualization,

N.F. and M.M.; supervision, X.T.; project administration, S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Development of the 34th Research Institute of CETC (Q134002022S601).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data in this paper are not publicly available at this time.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hu, W.; Zhu, Y. 100G and Beyond for PON and Short Reach Optical Networks. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; Th3G.5 IEEE. pp. 1–3.
2. Jiang, W.; Huang, L.; Xu, Y.; He, Z.; Hu, W.; Yi, L. Real-Time Deployment of Simplified Volterra Nonlinear Equalizer in High-Speed PON. *IEEE Photonics Technol. Lett.* **2023**, *35*, 1067–1070. [CrossRef]
3. Zhou, J.; Xing, Z.; Wang, H.; Zhang, K.; Chen, X.; Feng, Q.; Zheng, K.; Zhao, Y.; Dong, Z.; Gui, T.; et al. Flexible Coherent Optical Access: Architectures, Algorithms, and Demonstrations. *arXiv* **2023**, arXiv:2308.01046.
4. Campos, L.A.; Jia, Z.; Zhang, H.; Xu, M. Coherent optics for access from P2P to P2MP. *J. Opt. Commun. Netw.* **2023**, *15*, A114–A123. [CrossRef]
5. Houtsma, V.; van Veen, D. Optical strategies for economical next generation 50 and 100G PON. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 3–7 March 2019; M2B-1. pp. 1–3.
6. Effenberger, F.J.; Mukai, H.; Park, S.; Pfeiffer, T. Next-generation PON-part II: Candidate systems for next-generation PON. *IEEE Commun Mag.* **2009**, *47*, 50–57. [CrossRef]
7. Simon, G.; Saliou, F.; Chanclou, P.; Neto, L.A.; Elwan, H.H. 50 Gbps TDM PON Digital signal processing challenges: Mining current G-PON field data to assist higher speed PON. In Proceedings of the 2020 European Conference on Optical Communications (ECOC), Brussels, Belgium, 6–10 December 2020; pp. 1–4.
8. Simon, G.; Potet, J.; Saliou, F.; Chanclou, P.; Blache, F.; Charbonnier, P.; Duval, B.; Caillaud, C.; Mallecot, F. Real-Time 58, 2 Gbps Equalization-Free NRZ Mode Burst Transmission for Upstream HS-PON and beyond with Monolithically Integrated SOA-UTC Receiver. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 6–10 March 2022; Optica Publishing Group: Washington, DC, USA, 2022. M3G-2. pp. 1–3.
9. Saliou, F.; Potet, J.; Foch, F.; Bramerie, L.; Gay, M.; Simon, G.; Chanclou, P. DSP-free and Shared SOA for HS-PON Transmissions with up to 30 dB Optical Budget and 15 dB dynamic range. In Proceedings of the 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, 13–16 September 2021; pp. 1–4.
10. Simon, G.; Saliou, F.; Potet, J.; Chanclou, P.; Rosales, R.; Cano, I.N.; Nesset, D. 50 Gbps real-time transmissions with upstream burst-mode for 50G-PON using a common SOA pre-amplifier/booster at the OLT. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 6–10 March 2022; Optica Publishing Group: Washington, DC, USA, 2022; p. M3G-3.
11. Simon, G.; Sampaio, F.N.; Saliou, F.; Potet, J.; Gaillard, G.; Chanclou, P. Equalizer Convergence for various Transmission Channels and Multi-Rate Upstream 50G-PON. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
12. Hraghi, A.; Rizzelli, G.; Pagano, A.; Ferrero, V.; Gaudino, R. Analysis and experiments on C band 200G coherent PON based on Alamouti polarization-insensitive receivers. *Opt. Express* **2022**, *30*, 46782–46797. [CrossRef] [PubMed]
13. Li, F.; Yin, M.; Luo, Z.; Wang, X.; Rong, L.; Li, Z. Architecture and key digital signal processing techniques of a next-generation passive optical network. *J. Opt. Commun. Netw.* **2023**, *15*, A82–A91. [CrossRef]
14. Cao, P.; Hu, X.; Zhuang, Z.; Zhang, L.; Chang, Q.; Yang, Q.; Hu, R.; Su, Y. Power margin improvement for OFDMA-PON using hierarchical modulation. *Opt. Express* **2013**, *21*, 8261–8268. [CrossRef]
15. Poudel, B.; Oshima, J.; Kobayashi, H.; Iwashita, K. Passive optical delivering network using conventional graded-index multi-mode fiber with mode division multiplexing and sub-carrier multiplexing. *J. Opt. Commun. Netw.* **2018**, *10*, 252–259. [CrossRef]
16. Guan, K.; Cho, J.; Winzer, P.J. Physical layer security in fiber-optic MIMO-SDM systems: An overview. *Opt. Commun.* **2018**, *408*, 31–41. [CrossRef]
17. Gao, W.; Cvijetic, M. Allocation of spectral and spatial modes in multidimensional metro-access optical networks. *Opt. Commun.* **2018**, *413*, 80–86. [CrossRef]
18. Bao, F.; Morioka, T.; Oxenløwe, L.K.; Hu, H. 300 Gbps IM/DD based SDM-WDM-PON with laserless ONUs. *Opt. Express* **2018**, *26*, 7949–7954. [CrossRef] [PubMed]
19. Kumari, M.; Arya, V. Investigation of high-speed hybrid WDM-OCDMA-PON system incorporating integrated fiber-FSO link under distinct climate conditions. *Opt. Quantum Electron.* **2022**, *54*, 775. [CrossRef]
20. Roberts, H. Status of ITU-T Q2/15: New higher speed PON projects. *IEEE Commun. Stand. Mag.* **2020**, *4*, 57–59. [CrossRef]

21. Zhang, D.; Liu, D.; Wu, X.; Nesset, D. Progress of ITU-T higher speed passive optical network (50G-PON) standardization. *J. Opt. Commun. Netw.* **2020**, *12*, D99–D108. [CrossRef]
22. Bonk, R.; Geng, D.; Khotimsky, D.; Liu, D.; Liu, X.; Luo, Y.; Nesset, D.; Oksman, V.; Strobel, R.; Van Hoof, W.; et al. 50G-PON: The first ITU-T higher-speed PON system. *IEEE Commun. Mag.* **2022**, *60*, 48–54. [CrossRef]
23. Wey, J.S.; Luo, Y.; Pfeiffer, T. 5G wireless transport in a PON context: An overview. *IEEE Commun. Stand. Mag.* **2020**, *4*, 50–56. [CrossRef]
24. Wey, J.S. The outlook for PON standardization: A tutorial. *J. Light. Technol.* **2019**, *38*, 31–42. [CrossRef]
25. Saliou, F.; Gaillard, G.; Simon, G.; Le Huérou, S.; Potet, J.; Chanclou, P. Triple Coexistence of PON Technologies: Experimentation of G-PON, XGS-PON and 50G (S)-PON over a Class C+ ODN. In Proceedings of the 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 18–22 September 2022; pp. 1–4.
26. Luo, Y.; Shen, A.; Effenberger, F. PON Coexistence Interference Avoidance with Cross-Layer Design. In Proceedings of the 2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC), Toyama, Japan, 3–6 July 2022; pp. 1–3.
27. Kani, J.I.; Bourgart, F.; Cui, A.; Rafel, A.; Campbell, M.; Davey, R.; Rodrigues, S. Next-generation PON-part I: Technology roadmap and general requirements. *IEEE Commun Mag.* **2009**, *47*, 43–49. [CrossRef]
28. Cao, L.; Lu, Y.; Xu, K.; Li, X.; Zhai, Y.; Bi, M. A smooth PON evolution on one single wavelength based on mark ratio modulation. *Opt. Fiber Technol.* **2022**, *71*, 102906. [CrossRef]
29. Lu, Y.; Cao, L.; Wu, S.; Mi, X.; Jiang, L.; Zhai, Y.; Bi, M. A novel smooth evolution to TWDM PON based on wavelength complement coding. *Opt. Fiber Technol.* **2022**, *74*, 103053. [CrossRef]
30. Jin, J.; Zhang, D.; Li, Q.; Jiang, M. First Demonstration of 50G TDM-PON Prototype in Compliance with ITU-T G. 9804.3 Standard N1 ODN Class 29-dB. In Proceedings of the 2022 IEEE 8th International Conference on Computer and Communications (ICCC), Chengdu, China, 9–12 December 2022; pp. 236–240.
31. Molina-Luna, J.; Gutiérrez-Castrejón, R.; Ceballos-Herrera, D.E. Alternative to Super-PON downstream transmitter using a directly-modulated SOA. *Opt. Quantum Electron.* **2022**, *54*, 830. [CrossRef]
32. Reza, A.G.; Troncoso-Costas, M.; Browning, C.; O'Duill, S.; Barry, L.P. Mitigation of SOA-Induced Nonlinearities with Recurrent Neural Networks in 75 Gbit/s/λ PAM-4 IM/DD WDM-PON Transmission Systems. *J. Light. Technol.* **2023**, *41*, 3967–3975. [CrossRef]
33. DeSanti, C.; Du, L.; Guarin, J.; Bone, J.; Lam, C.F. Super-PON: An evolution for access networks. *J. Opt. Commun. Netw.* **2020**, *12*, D66–D77. [CrossRef]
34. Sampaio FA, N. Study of Digital Compensation Techniques for 50G-PON Optical Access Networks. Ph.D. Thesis, Ecole Nationale Supérieure Mines-Télécom Atlantique, tenue à Plouzané, IMT Atlantique, Paris, France, 2023.
35. Wang, N.; Li, J.; Zhang, D.; Li, H.; Cheng, J.; Chen, W.; Mikhailov, V.; Inniss, D.; Chen, Y.; Duan, X.; et al. Real-Time 50 Gbps Upstream Transmission in TDM-PON with Class E1 Power Budget Using Ge/Si Avalanche Photodiode and Bismuth-Doped Fiber as Preamplifier. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
36. Suzuki, N.; Miura, H.; Mochizuki, K.; Matsuda, K. Beyond-100G PON Systems for Integrated Access and Metro Networks in the B5G/6G Era. In *Signal Processing in Photonic Communications*; Optica Publishing Group: Washington, DC, USA, 2023; p. SpM3D-4.
37. Houtsma, V.; van Veen, D. Reusing Data Center Optics and Solutions for Beyond 25 Gbps PON: Is the Gap Really Bridged? In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 5–9 March 2023; Optica Publishing Group: Washington, DC, USA, 2023. W1I-1. pp. 1–3.
38. Bonk, R.; Harstead, E.; Borkowski, R.; Houtsma, V.; Lefevre, Y.; Mahadevan, A.; van Veen, D.; Verplaetse, M.; Walklin, S. Perspectives on and the road towards 100 Gbps TDM PON with intensity-modulation and direct-detection. *J. Opt. Commun. Netw.* **2023**, *15*, 518–526. [CrossRef]
39. Kaur, H.; Singh, S.; Kaur, R.; Kaur, R. 50G-next generation passive optical networks stage 2 using millimeter wave over fiber technique under the ITU-T G. 9804 standardization. *Opt. Quantum Electron.* **2023**, *55*, 449. [CrossRef]
40. Nesset, D. Next Generation PON Technologies: 50G PON and Beyond. In Proceedings of the 2023 International Conference on Optical Network Design and Modeling (ONDM), Coimbra, Portugal, 8–11 May 2023; pp. 1–6.
41. Gaillard, G.; Saliou, F.; Potet, J.; Simon, G.; Chanclou, P.; Duran-Valdeiglesias, E.; Neto, L.A.; Morvan, M.; Fracasso, B. Real Time Assessments of DML and EML with 25G-class APD for Higher Speed PONs. In Proceedings of the 2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Gothenburg, Sweden, 6–9 June 2023; pp. 335–340.
42. Xing, Z.; Zhang, K.; Chen, X.; Feng, Q.; Zheng, K.; Zhao, Y.; Dong, Z.; Zhou, J.; Gui, T.; Ye, Z.; et al. First Real-time Demonstration of 200G TFDMA Coherent PON using Ultra-simple ONUs. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
43. Zhang, J.; Li, G.; Xing, S.; Chi, N. Flexible and adaptive coherent PON for next-generation optical access network. *Opt. Fiber Technol.* **2023**, *75*, 103190. [CrossRef]
44. Zhang, J.; Xing, S.; Li, G.; Chi, N. High-Performance and Robust Burst Reception in Coherent PON. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.

45. Casasco, M.; Rizzelli, G.; Pagano, A.; Mercinelli, R.; Valvo, M.; Ferrero, V.; Gaudino, R. Experimental Demonstration of a 400 Gbps Full Coherent Transmission in an in-field Metro-Access scenario. In Proceedings of the 2023 23rd International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania, 2–6 July 2023; pp. 1–4.
46. Kovacs, I.B.; Faruk, M.S.; Savory, S.J. 200 Gbps/λ Upstream PON using Polarization Multiplexed PAM4 with Coherent Detection. *IEEE Photonics Technol. Lett.* **2023**, *35*, 1014–1017. [CrossRef]
47. Kovacs, I.B.; Faruk, M.S.; Savory, S.J. A Minimal Coherent Receiver for 200 Gbps/λ PON Downstream With Measured 29 dB Power Budget. *IEEE Photonics Technol. Lett.* **2023**, *35*, 257–260. [CrossRef]
48. Wang, H.; Zhou, J.; Xing, Z.; Feng, Q.; Zhang, K.; Zheng, K.; Chen, X.; Gui, T.; Li, L.; Zeng, J.; et al. Fast-Convergence Digital Signal Processing for Coherent PON using Digital SCM. *J. Light. Technol.* **2023**, *41*, 4635–4643. [CrossRef]
49. Li, F.; Wang, W.; Li, Z. Beyond-100G signal transmission in optical short reach for mobile fronthaul. In Proceedings of the Broadband Access Communication Technologies XIV, San Francisco, CA, USA, 31 January 2020; Volume 11307, pp. 7–14.
50. Shen, W.; Xing, S.; Li, G.; Li, Z.; Yan, A.; Wang, J.; Zhang, J.; Chi, N. Demonstration of Beyond-100G Three-Dimensional Flexible Coherent PON in Downstream with Time, Frequency and Power Resource Allocation Capability. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
51. Suzuki, N.; Miura, H.; Mochizuki, K.; Matsuda, K. Digital Coherent based PON Technologies and Beyond-100G Optical Access Systems. In Proceedings of the 2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC), Toyama, Japan, 3–6 July 2022; pp. 1–3.
52. Suzuki, N.; Miura, H.; Mochizuki, K.; Matsuda, K. Simplified digital coherent technologies for beyond-100G optical access systems in the B5G/6G era. In Proceedings of the Optical Fiber Communication Conference, San Francisco, CA, USA, 6–10 June 2021; Optica Publishing Group: Washington, DC, USA, 2021. Th5I-5. pp. 1–3.
53. Suzuki, N.; Miura, H.; Mochizuki, K.; Matsuda, K. Simplified digital coherent-based beyond-100G optical access systems for B5G/6G. *J. Opt. Commun. Netw.* **2022**, *14*, A1–A10. [CrossRef]
54. Wang, H.; Zhou, J.; Yang, J.; Zeng, J.; Liu, W.; Yu, C.; Li, F.; Li, Z. Non-Integer-Oversampling Digital Signal Processing for Coherent Passive Optical Networks. *arXiv* **2023**, arXiv:2306.11325.
55. Murphy, S.; Townsend, P.D.; Antony, C. Recurrent neural network equalizer to extend input power dynamic range of SOA in 100 Gbps/λ PON. In Proceedings of the 2022 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 15–20 May 2022; pp. 1–2.
56. Murphy, S.; Jamai, F.; Townsend, P.D.; Antony, C. High dynamic range 100 Gbit/s PAM4 PON with SOA preamplifier using Gated Recurrent Neural Network equaliser. In Proceedings of the European Conference and Exhibition on Optical Communication, Basel, Switzerland, 18–22 September 2022; Optica Publishing Group: Washington, DC, USA, 2022. Th1C-6. pp. 1–3.
57. Xue, L.; Yi, L.; Lin, R.; Huang, L.; Chen, J. SOA pattern effect mitigation by neural network based pre-equalizer for 50G PON. *Optics Express* **2021**, *29*, 24714–24722. [CrossRef] [PubMed]
58. Li, Z.; Li, Y.; Luo, S.; Yin, F.; Wang, Y.; Song, Y. SOA Amplified 100 Gbps/λ PAM-4 TDM-PON Supporting PR-30 Power Budget with> 18 dB Dynamic Range. *Micromachines* **2022**, *13*, 342. [CrossRef] [PubMed]
59. Murphy, S.L.; Jamali, F.; Townsend, P.D.; Antony, C. High Dynamic Range 100G PON Enabled by SOA Preamplifier and Recurrent Neural Networks. *J. Light. Technol.* **2023**, *41*, 3522–3532. [CrossRef]
60. Zhang, D.; Hu, X.; Huang, X.; Zhang, K. Experimental demonstration of 200 Gbps/λ coherent PON with a low-complexity receiver and a multi-purpose neural network. In Proceedings of the 2022 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 6–10 March 2022; pp. 1–3.
61. Lam, C.F.; Yin, S. Evolution of Fiber Access Networks. In *Optical Fiber Telecommunications VII*; Academic Press: Cambridge, MA, USA, 2020; pp. 827–865.
62. Xu, M.; Jia, Z.; Zhang, H.; Campos, L.A.; Knittle, C. Intelligent burst receiving control in 100G coherent PON with 4× 25G TFDM upstream transmission. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 6–10 March 2022; Th3E-2. pp. 1–3.
63. Simon, G.; Chanclou, P.; Wang, M.; Abgrall, D.; Minodier, D. Optical access evolutions towards SDN and disaggregated hardware: An operator perspective. *J. Opt. Commun. Netw.* **2022**, *14*, C57–C69. [CrossRef]
64. Montalvo, J.; Torrijos, J.; Cortes, D.; Chundury, R.; Peter, M.S. Journey toward software-defined passive optical networks with multi-PON technology: An industry view. *J. Opt. Commun. Netw.* **2021**, *13*, D22–D31. [CrossRef]
65. Lin, S.C.; Lin, C.H.; Chu, L.C.; Lien, S.Y. Enabling Resilient Access Equality for 6G LEO Satellite Swarm Networks. *IEEE Internet Things Mag.* **2023**, *6*, 38–43. [CrossRef]
66. Suzuki, T.; Koyasako, Y.; Nishimoto, K.; Asaka, K.; Yamada, T.; Kani, J.I.; Shimada, T.; Yoshida, T. Zero touch provisioning compliant with authentications of IEEE PON packages A and B for SDN-enabled broadband access. *J. Opt. Commun. Netw.* **2021**, *13*, 244–252. [CrossRef]
67. Suzuki, T.; Kim, S.Y.; Kani, J.I.; Yoshida, T. Virtualized PON based on abstraction, softwarization, and service chaining for flexible and agile service creations. *J. Opt. Commun. Netw.* **2023**, *15*, A39–A48. [CrossRef]
68. Suzuki, T.; Koyasako, Y.; Kim, S.Y.; Kani, J.I.; Yoshida, T. Demonstration of industrial network applications by PHY softwarization for fully virtualized access networks. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.

69. Suzuki, T.; Kim, S.Y.; Kani, J.I.; Yoshida, T. Low-latency PON PHY implementation on GPUs for fully software-defined access networks. *IEEE Netw.* **2022**, *36*, 108–114. [CrossRef]
70. Hatano, T.; Kani, J.I.; Maeda, Y. Standardization and technology trends in optical, wireless and virtualized access systems. *IEICE Trans. Commun.* **2019**, *102*, 1263–1269. [CrossRef]
71. Bonk, R.; Pfeiffer, T. New use cases for PONs beyond residential services. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 6–10 March 2022; Optica Publishing Group: Washington, DC, USA, 2022. Tu2G-1. pp. 1–3.
72. Bonk, R. The future of passive optical networks. In Proceedings of the 2021 International Conference on Optical Network Design and Modeling (ONDM), Gothenburg, Sweden, 28 June–1 July 2021; pp. 1–3.
73. Effenberger, F.J. Recent progress in optical access and home networking standards. In Proceedings of the 2023 32nd Wireless and Optical Communications Conference (WOCC), Newark, NJ, USA, 5–6 May 2023; pp. 1–5.
74. Zhang, D.; Luo, Y.; Jin, J. Highspeed 50 Gbps Passive Optical Network (50G-PON) Applications in Industrial Networks. In Proceedings of the 2022 IEEE 23rd International Conference on High Performance Switching and Routing (HPSR), Taicang, China, 6–8 June 2022; pp. 113–118.
75. Nesset, D. The progress of higher speed passive optical network standardisation in ITU-T. In Proceedings of the 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, 13–16 September 2021; pp. 1–4.
76. Uzawa, H.; Honda, K.; Nakamura, H.; Hirano, Y.; Nakura, K.; Kozaki, S.; Okamura, A.; Terada, J. First demonstration of bandwidth-allocation scheme for network-slicing-based TDM-PON toward 5G and IoT era. In Proceedings of the Optical Fiber Communication Conference, San Diego, CA, USA, 3–7 March 2019; Optica Publishing Group: Washington, DC, USA, 2019. W3J-2. pp. 1–3.
77. Uzawa, H.; Honda, K.; Nakamura, H.; Hirano, Y.; Nakura, K.I.; Kozaki, S.; Terada, J. Dynamic bandwidth allocation scheme for network-slicing-based TDM-PON toward the beyond-5G era. *J. Opt. Commun. Netw.* **2020**, *12*, A135–A143. [CrossRef]
78. Das, S.; Ruffini, M. Optimal virtual PON slicing to support ultra-low latency mesh traffic pattern in MEC-based Cloud-RAN. In Proceedings of the 2021 International Conference on Optical Network Design and Modeling (ONDM), Gothenburg, Sweden, 28 June–1 July 2021; pp. 1–5.
79. Das, S.; Slyne, F.; Ruffini, M. Optimal slicing of virtualized passive optical networks to support dense deployment of cloud-RAN and multi-access edge computing. *IEEE Netw.* **2022**, *36*, 131–138. [CrossRef]
80. Tian, Q.; Li, S.; Wang, F.; Tang, X.; Sun, D.; Yao, H.; Tian, F.; Zhang, Q.; Xin, X. A Dynamic Restructuring Algorithm Based on Flexible PON Slices. *Photonics* **2023**, *10*, 614. [CrossRef]
81. Ra, Y.; Park, C.; Hwang, K.; Doo, K.H.; Kim, K.O.; Lee, H.H.; Cheung, T.; Shin, J.; Chung, H.S. Field Trial of Remotely Controlled Smart Factory based on PON Slicing and Disaggregated OLT. In Proceedings of the 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 18–22 September 2022; pp. 1–3.
82. Centofanti, C.; Marotta, A.; Cassioli, D.; Graziosi, F.; Sambo, N.; Valcarenghi, L.; Bernard, C.; Roberts, H. Slice Management in SDN PON Supporting Low-Latency Services. In Proceedings of the European Conference and Exhibition on Optical Communication, Basel, Switzerland, 18–22 September 2022; Optica Publishing Group: Washington, DC, USA, 2022. Tu5-64. pp. 1–3.
83. Luo, Y.; Jiang, M.; Zhang, D.; Effenberger, F. Field Trial of Network Slicing in 5G and PON-Enabled Industrial Networks. *IEEE Wirel. Commun.* **2023**, *30*, 78–85. [CrossRef]
84. Centofanti, C.; Marotta, A.; Cassioli, D.; Graziosi, F.; Gudepu, V.; Kondepu, K. End-to-End Slicing via O-RAN and Software Defined Optical Access. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
85. Gong, X.; Zhang, Q.; Zhang, X.; Xuan, R.; Guo, L. Security issues and possible solutions of future-oriented optical access networks for 5g and beyond. *IEEE Commun. Mag.* **2021**, *59*, 112–118. [CrossRef]
86. Wang, G.; Song, P.; Pan, Y.Y.; Chan, C.K.; Chen, L.K. Secure OFDM-PON Bandwidth-limited System Precoded by Chaotic Frank Sequence-Based Circulant Matrix. In Proceedings of the CLEO: Science and Innovations, San Jose, CA, USA, 7–12 May 2023; SF2M-5. pp. 1–3.
87. Shen, J.; Liu, B.; Mao, Y.; Ullah, R.; Ren, J.; Zhao, J.; Chen, S. Enhancing the reliability and security of OFDM-PON using modified Lorenz chaos based on the linear properties of FFT. *J. Light. Technol.* **2021**, *39*, 4294–4299. [CrossRef]
88. Horvath, T.; Munster, P.; Oujezsky, V.; Vojtech, J.; Holik, M.; Dejdar, P.; Latal, M. GPON network with simulated rogue ONU. In Proceedings of the 2019 International Conference on Software, Telecommunications and Computer Networks (SoftCOM), Split, Croatia, 19–21 September 2019; pp. 1–5.
89. Yang, X.; Zhang, J.; Li, Y.; Zhao, Y.; Gao, G.; Zhang, H. DFTs-OFDM based quantum noise stream cipher system. *Opt. Fiber Technol.* **2019**, *52*, 101939. [CrossRef]
90. Zhang, M.; Li, Y.; Song, H.; Wang, B.; Zhao, Y.; Zhang, J. Security analysis of quantum noise stream cipher under fast correlation attack. In Proceedings of the Optical Fiber Communication Conference, San Francisco, CA, USA, 6–10 June 2021; Optica Publishing Group: Washington, DC, USA, 2021. Th1A-5. pp. 1–3.
91. Futami, F.; Tanizawa, K.; Kato, K. Experimental demonstration of quantum deliberate signal randomization for Y-00 quantum noise stream cipher. In Proceedings of the CLEO: QELS_Fundamental Science, San Jose, CA, USA, 15–20 May 2022; Optica Publishing Group: Washington, DC, USA, 2022. JW3B-107. pp. 1–3.
92. Wang, K.; Zhang, J.; Li, Y.; Zhao, Y.; Zhang, H. Multi-bit mapping based on constellation rotation in Quantum Noise Stream Cipher. *Opt. Commun.* **2019**, *446*, 147–155. [CrossRef]

93. Yu, Q.; Wang, Y.; Li, D.; Song, H.; Fu, Y.; Jiang, X.; Huang, L.; Cheng, M.; Liu, D.; Deng, L. Secure 100 Gbps IMDD transmission over 100 km SSMF enabled by quantum noise stream cipher and sparse RLS-Volterra equalizer. *IEEE Access* **2020**, *8*, 63585–63594. [CrossRef]
94. Zhu, H.; Liu, Z.; Chen, S.; Xu, X.; Li, F. Optical stealth communication based on quantum noise stream ciphered amplified spontaneous emission light. *Opt. Express* **2023**, *31*, 3595–3605. [CrossRef] [PubMed]
95. Wang, X.; Wada, N. Spectral phase encoding of ultra-short optical pulse in time domain for OCDMA application. *Opt. Express* **2007**, *15*, 7319–7326. [CrossRef] [PubMed]
96. Wang, X.; Gao, Z.; Kataoka, N.; Wada, N. Time domain spectral phase encoding/DPSK data modulation using single phase modulator for OCDMA application. *Opt. Express* **2010**, *18*, 9879–9890. [CrossRef] [PubMed]
97. Gao, Z.; Wang, X.; Kataoka, N.; Wada, N. Stealth transmission of time-domain spectral phase encoded OCDMA signal over WDM network. *IEEE Photonics Technol. Lett.* **2010**, *22*, 993–995. [CrossRef]
98. Song, P.; Hu, Z.; Chan, C.K. Multi-band chaotic non-orthogonal matrix-based encryption for physical-layer security enhancement in OFDM-PONs. *J. Opt. Commun. Netw.* **2023**, *15*, C120–C128. [CrossRef]
99. Ren, J.; Jiang, L.; Zhang, J.; Zhao, J. High-security multi-slot chaos encryption with dynamic probability for 16-CAP PON. *IEEE Photonics J.* **2020**, *12*, 1–10. [CrossRef]
100. Wei, H.; Zhang, C.; Wu, T.; Huang, H.; Qiu, K. Chaotic multilevel separated encryption for security enhancement of OFDM-PON. *IEEE Access* **2019**, *7*, 124452–124460. [CrossRef]
101. Wei, H.; Cui, M.; Zhang, C.; Wu, T.; Wen, H.; Zhang, Z.; Chen, Y.; Qiu, K. Chaotic key generation and application in OFDM-PON using QAM constellation points. *Opt. Commun.* **2021**, *490*, 126911. [CrossRef]
102. Xiao, Y.; Wang, Z.; Cao, J.; Deng, R.; Liu, Y.; He, J.; Chen, L. Time–frequency domain encryption with SLM scheme for physical-layer security in an OFDM-PON system. *J. Opt. Commun. Netw.* **2018**, *10*, 46–51. [CrossRef]
103. Wu, T.; Zhang, C.; Chen, C.; Hou, H.; Wei, H.; Hu, S.; Qiu, K. Security enhancement for OFDM-PON using Brownian motion and chaos in cell. *Opt. Express* **2018**, *26*, 22857–22865. [CrossRef]
104. Wu, T.; Zhang, C.; Huang, H.; Zhang, Z.; Wei, H.; Wen, H.; Qiu, K. Security improvement for OFDM-PON via DNA extension code and chaotic systems. *IEEE Access* **2020**, *8*, 75119–75126. [CrossRef]
105. Zhang, W.; Zhang, C.; Chen, C.; Jin, W.; Qiu, K. Joint PAPR reduction and physical layer security enhancement in OFDMA-PON. *IEEE Photonics Technol. Lett.* **2016**, *28*, 998–1001. [CrossRef]
106. Zhang, W.; Zhang, C.; Chen, C.; Zhang, H.; Qiu, K. Brownian motion encryption for physical-layer security improvement in CO-OFDM-PON. *IEEE Photonics Technol. Lett.* **2017**, *29*, 1023–1026. [CrossRef]
107. Hu, X.; Yang, X.; Shen, Z.; He, H.; Hu, W.; Bai, C. Chaos-based partial transmit sequence technique for physical layer security in OFDM-PON. *IEEE Photonics Technol. Lett.* **2015**, *27*, 2429–2432. [CrossRef]
108. Bi, M.; Fu, X.; Zhou, X.; Zhang, L.; Yang, G.; Yang, X.; Xiao, S.; Hu, W. A key space enhanced chaotic encryption scheme for physical layer security in OFDM-PON. *IEEE Photonics J.* **2017**, *9*, 1–10. [CrossRef]
109. Hajomer, A.A.; Yang, X.; Hu, W. Chaotic Walsh–Hadamard transform for physical layer security in OFDM-PON. *IEEE Photonics Technol. Lett.* **2017**, *29*, 527–530. [CrossRef]
110. Zhao, J.; Liu, B.; Mao, Y.; Ullah, R.; Ren, J.; Chen, S.; Jiang, L.; Han, S.; Zhang, J.; Shen, J. High security OFDM-PON with a physical layer encryption based on 4D-hyperchaos and dimension coordination optimization. *Opt. Express* **2020**, *28*, 21236–21246. [CrossRef]
111. Zhao, J.; Liu, B.; Mao, Y.; Ren, J.; Xu, X.; Wu, X.; Jiang, L.; Han, S.; Zhang, J. High-security physical layer in CAP-PON system based on floating probability disturbance. *IEEE Photonics Technol. Lett.* **2020**, *32*, 367–370. [CrossRef]
112. Cui, M.; Chen, Y.; Zhang, C.; Liang, X.; Wu, T.; Liu, S.; Wen, H.; Qiu, K. Chaotic RNA and DNA for security OFDM-WDM-PON and dynamic key agreement. *Opt. Express* **2021**, *29*, 25552–25569. [CrossRef]
113. Wu, K.; Wang, H.; Ji, Y. Channel Characteristics Based Adjustable Fingerprint for Identity Authentication in WDM-PON With Deep Neural Networks. *IEEE Photonics J.* **2022**, *14*, 1–11. [CrossRef]
114. Luo, Y.; Zhang, C.; Wang, X.; Liang, X.; Qiu, K. Robust Key Update with Controllable Accuracy Using Support Vector Machine for Secure OFDMA-PON. *J. Light. Technol.* **2023**, *41*, 4663–4671. [CrossRef]
115. Liang, X.; Zhang, C.; Luo, Y.; Wang, X.; Qiu, K. Secure Encryption and Key Management for OFDM-PON Based on Chaotic Hilbert Motion. *J. Light. Technol.* **2023**, *41*, 1619–1625. [CrossRef]
116. Wei, Z.; Zhang, J.; Li, W.; Plant, D.V. 400-Gbps/80-km Rate-Flexible PCS-64-QAM WDM-CPON With Pseudo-m-QAM Chaotic Physical Layer Encryption. *J. Light. Technol.* **2023**, *41*, 2413–2424. [CrossRef]
117. Xia, W.; Liu, B.; Ren, J.; Ullah, R.; Wu, X.; Mao, Y.; Ma, Y.; Chen, S.; Wan, Y.; Zhong, Q.; et al. High-security 3D CAP modulation scheme based on a pyramid constellation design for 7-core fiber. *Opt. Express* **2023**, *31*, 6659–6674. [CrossRef] [PubMed]
118. Choi, I.; Young, R.J.; Townsend, P.D. Quantum key distribution on a 10 Gbps WDM-PON. *Opt. Express* **2010**, *18*, 9600–9612. [CrossRef] [PubMed]
119. Vokić, N.; Milovančev, D.; Schrenk, B.; Hentschel, M.; Hübel, H. Differential phase-shift QKD in a 2: 16-split lit PON with 19 carrier-grade channels. *IEEE J. Sel. Top. Quantum Electron.* **2020**, *26*, 1–9. [CrossRef]
120. Yunlu, W.; Hao, W.; Zhihua, J.; Shuhuai, L. A novel WDM-PON based on quantum key distribution FPGA controller. *Int. J. Embed. Syst.* **2017**, *9*, 241–249. [CrossRef]

121. Chen, Y.; Jiao, H.; Zhou, H.; Zheng, J.; Pu, T. Security analysis of QAM quantum-noise randomized cipher system. *IEEE Photonics J.* **2020**, *12*, 1–14. [CrossRef]
122. Zhu, K.; Zhang, J.; Li, Y.; Wang, W.; Liu, X.; Zhao, Y. Experimental demonstration of error-free key distribution without an external random source or device over a 300-km optical fiber. *Opt. Lett.* **2022**, *47*, 2570–2573. [CrossRef]
123. Tan, Y.; Pu, T.; Zheng, J.; Zhou, H.; Su, G.; Zhu, H. A novel realization of PSK quantum-noise randomized cipher system based on series structure of multiple phase modulators. In Proceedings of the 2020 International Conference on Wireless Communications and Signal Processing (WCSP), Nanjing, China, 21–23 October 2020; pp. 316–320.
124. Futami, F.; Tanizawa, K.; Kato, K. Y-00 quantum-noise randomized stream cipher using intensity modulation signals for physical layer security of optical communications. *J. Light. Technol.* **2020**, *38*, 2774–2781. [CrossRef]
125. Sun, J.; Jiang, L.; Yi, A.; Feng, J.; Deng, X.; Pan, W.; Yan, L. Experimental demonstration of 201.6-Gbit/s coherent probabilistic shaping QAM transmission with quantum noise stream cipher over a 1200-km standard single mode fiber. *Opt. Express* **2023**, *31*, 11344–11353. [CrossRef] [PubMed]
126. Zhu, H.; Liu, Z.; Xiang, P.; Chen, S.; Li, F.; Xu, X. Quantum noise ciphered optical stealth communication based on equivalent spectral encoding. *Opt. Express* **2022**, *30*, 38128–38138. [CrossRef] [PubMed]
127. Shi, H.; Pu, T.; Zheng, J.; Tan, Y.; Chen, Y. Research on the key expansion module of quantum noise random stream cipher. *Chin. J. Quantum Electron.* **2020**, *37*, 196.
128. Wang, K.; Li, Y.; Zhao, Y.; Yu, H.; Li, Z.; Zhang, J. A multi-ring BPSK mapping in quantum noise stream cipher. In Proceedings of the 2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC), Fukuoka, Japan, 7–11 July 2019; pp. 1–3.
129. Wang, Y.; Li, H.; Cheng, M.; Liu, D.; Deng, L. Experimental demonstration of secure 100 Gbps IMDD transmission over a 50 km SSMF using a quantum noise stream cipher and optical coarse-to-fine modulation. *Opt. Express* **2021**, *29*, 5475–5486. [CrossRef] [PubMed]
130. Mao, W.; Gao, G.; Xu, C.; Liu, H.; Shen, Y.; Zhang, J.; Guo, Y. Long distance IM/DD transmission with OFDM-QAM Based quantum noise stream cipher. In Proceedings of the 2019 18th International Conference on Optical Communications and Networks (ICOCN), Huangshan, China, 5–8 August 2019; pp. 1–3.
131. Yoshida, M.; Kan, T.; Kasai, K.; Hirooka, T.; Nakazawa, M. 10 Tbit/s QAM quantum noise stream cipher coherent transmission over 160 km. *J. Light. Technol.* **2020**, *39*, 1056–1063. [CrossRef]
132. Sun, J.; Jiang, L.; Yan, L.; Yi, A.; Feng, J.; Pan, W.; Luo, B. High-speed Long-hual Probabilistic Shaped QAM Quantum Noise Stream Cipher Transmission. In Proceedings of the Novel Optical Materials and Applications, Maastricht, The Netherlands, 24–28 July 2022; Optica Publishing Group: Washington, DC, USA, 2022. JW3A-37.
133. Wei, S.; Liu, S.; Lei, C.; Li, Y.; Wang, W.; Zhao, Y.; Li, Y.; Zhang, D.; Yang, H.; Li, H.; et al. Basis Precoding Based on Probabilistic Constellation Shaping in QAM/QNSC. In Proceedings of the 2023 International Conference on Optical Network Design and Modeling (ONDM), Coimbra, Portugal, 8–11 May 2023; pp. 1–3.
134. Li, S.; Cheng, M.; Chen, Y.; Deng, L.; Zhang, M.; Fu, S.; Shum, P.; Liu, D. Enhancing the security of OFDM-PONs with machine learning based device fingerprint identification. In Proceedings of the 45th European Conference on Optical Communication (ECOC 2019), Dublin, Ireland, 22–26 September 2019; IET: Stevenage, UK, 2019; pp. 1–4.
135. Li, S.; Cheng, M.; Chen, Y.; Fan, C.; Deng, L.; Zhang, M.; Fu, S.; Tang, M.; Shum, P.P.; Liu, D. Enhancing the physical layer security of OFDM-PONs with hardware fingerprint authentication: A machine learning approach. *J. Light. Technol.* **2020**, *38*, 3238–3245. [CrossRef]
136. Li, Y.; Hua, N.; Zhao, C.; Wang, H.; Luo, R.; Zheng, X. Real-time rogue ONU identification with 1D-CNN-based optical spectrum analysis for secure PON. In Proceedings of the 2019 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 3–7 March 2019; pp. 1–3.
137. Fan, C.; Gong, H.; Cheng, M.; Ye, B.; Deng, L.; Yang, Q.; Liu, D. Identify the device fingerprint of OFDM-PONs with a noise-model-assisted CNN for enhancing security. *IEEE Photonics J.* **2021**, *13*, 1–4. [CrossRef]
138. Gao, W.; Fan, C.; Dai, X.; Wang, Y.; Lu, W.; Cheng, M.; Deng, L.; Yang, Q.; Liu, D. A machine learning assisted device fingerprint identification technique for TDM-PON system. In Proceedings of the Optoelectronics and Communications Conference, Hong Kong, China, 3–7 July 2021; Optica Publishing Group: Washington, DC, USA, 2021; p. W4A-4.
139. Shi, H.; Pu, T.; Mou, W.; Chen, Y. NIST randomness tests on the extended key of quantum noise random stream cipher. In Proceedings of the 2019 18th International Conference on Optical Communications and Networks (ICOCN), Huangshan, China, 5–8 August 2019; pp. 1–3.
140. Tanizawa, K.; Futami, F. Quantum noise-assisted coherent radio-over-fiber cipher system for secure optical fronthaul and microwave wireless links. *J. Light. Technol.* **2020**, *38*, 4244–4249. [CrossRef]
141. Das, S. From CORD to SDN enabled broadband access (SEBA) [Invited Tutorial]. *J. Opt. Commun. Netw.* **2021**, *13*, A88–A99. [CrossRef]
142. McGettrick, S.; Slyne, F.; Kitsuwan, N.; Payne, D.B.; Ruffini, M. Experimental end-to-end demonstration of shared N: M dual-homed protection in SDN-controlled long-reach PON and pan-European core. *J. Light. Technol.* **2016**, *34*, 4205–4213.
143. Hwang, I.S.; Rianto, A.; Pakpahan, A.F. Peer-to-peer file sharing architecture for software-defined TWDM-PON. *J. Internet Technol.* **2020**, *21*, 23–32.
144. Ratkoceri, J. Software-Defined Passive Optical Network Evolution. *SSRN Electron. J.* **2022**. [CrossRef]

145. Jiang, M.; Luo, Y.; Zhang, D.; Effenberger, F.; Jin, J.; Ansari, N. Enabling Next Generation Industrial Networks with Industrial PON. *IEEE Commun. Mag.* **2023**, *61*, 129–135. [CrossRef]
146. Mohammadani, K.H.; Butt, R.A.; Nawaz, W.; Faizullah, S.; Dayo, Z.A. Energy-Efficient Sleep-Aware Slicing-Based Scheduler (SA-SBS) for Multi-Operators Virtualized Passive Optical Networks. *IEEE Access* **2023**, *11*, 48841–48859. [CrossRef]
147. Effenberger, F.J.; Zhang, D. Wdm-pon for 5G wireless fronthaul. *IEEE Wirel. Commun.* **2022**, *29*, 94–99. [CrossRef]
148. Das, S.; Ruffini, M. Enhanced PON Architectures for Converged Access Networks for 5G and Beyond. Ph.D. Thesis, Trinity College Dublin, School of Computer Science & Statistics, Dublin, Ireland, 2022.
149. Pesando, L.; Fischer, J.K.; Shariati, B.; Freund, R.; Cananao, J.; Li, H.; Lin, Y.; Ferveur, O.; Jiang, M.; Jin, J.; et al. Standardization of the 5th Generation Fixed Network for Enabling End-to-End Network Slicing and Quality-Assured Services. *IEEE Commun. Stand. Mag.* **2022**, *6*, 96–103. [CrossRef]
150. Suzuki, T.; Koyasako, Y.; Kim, S.Y.; Kani, J.I.; Yoshida, T. Real-time demonstration of industrial protocol applications by PHY softwarization for fully virtualized access networks. *J. Opt. Commun. Netw.* **2023**, *15*, 449–456. [CrossRef]
151. Suzuki, T.; Koyasako, Y.; Nishimoto, K.; Asaka, K.; Yamada, T.; Kani, J.I.; Shimada, T.; Yoshida, T. Demonstration of IEEE PON abstraction for SDN enabled broadband access (SEBA). *J. Light. Technol.* **2021**, *39*, 6434–6442. [CrossRef]
152. Chen, A.; Law, J.; Aibin, M. A survey on traffic prediction techniques using artificial intelligence for communication networks. *Telecom* **2021**, *2*, 518–535. [CrossRef]
153. Mikaeil, A.M.; Hu, W.; Hussain, S.B. A low-latency traffic estimation based TDM-PON mobile front-haul for small cell cloud-RAN employing feed-forward artificial neural network. In Proceedings of the 2018 20th International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania, 1–5 July 2018; pp. 1–4.
154. Tang, Z.; Gao, J.; Yang, T.; Liu, D.; Dai, G. Smart OLT equipment of optical access network. *Optoelectron. Lett.* **2023**, *19*, 159–163. [CrossRef]
155. Mikaeil, A.M.; Hu, W.; Hussain, S.B.; Sultan, A. Traffic-estimation-based low-latency XGS-PON mobile front-haul for small-cell C-RAN based on an adaptive learning neural network. *Appl. Sci.* **2018**, *8*, 1097. [CrossRef]
156. Das, S.; Slyne, F.; Kilper, D.; Ruffini, M. Schedulers synchronization supporting ultra reliable low latency communications (URLLC) in cloud-RAN over virtualised mesh PON. In Proceedings of the 2022 European Conference on Optical Communication (ECOC), Basel, Switzerland, 18–22 September 2022; pp. 1–4.
157. Chung, H.; Lee, H.H.; Kim, K.O.; Doo, K.H.; Ra, Y.; Park, C. TDM-PON-based optical access network for Tactile Internet, 5G, and beyond. *IEEE Netw.* **2022**, *36*, 76–81. [CrossRef]
158. Fathallah, H.; Rad, M.M.; Rusch, L.A. PON monitoring: Periodic encoders with low capital and operational cost. *IEEE Photonics Technol. Lett.* **2008**, *20*, 2039–2041. [CrossRef]
159. Yi, L.; Liao, T.; Huang, L.; Xue, L.; Li, P.; Hu, W. Machine learning for 100 Gb/s/λ passive optical network. *J. Light. Technol.* **2019**, *37*, 1621–1630. [CrossRef]
160. Abdelli, K.; Tropschug, C.; Griesser, H.; Pachnicke, S. Faulty branch identification in passive optical networks using machine learning. *J. Opt. Commun. Netw.* **2023**, *15*, 187–196. [CrossRef]
161. Abdelli, K.; Tropschug, C.; Griesser, H.; Pachnicke, S. Fault Monitoring in Passive Optical Networks using Machine Learning Techniques. In Proceedings of the 2023 23rd International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania, 2–6 July 2023; pp. 1–5.
162. Brügge, M.; Müller, J.; Patri, S.K.; Jansen, S.; Zou, J.; Althoff, S.; Förster, K.T. Live Demonstration of ML-based PON Characterization and Monitoring. In Proceedings of the 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 5–9 March 2023; pp. 1–3.
163. Pg, D.S.N.A.B.; Newaz, S.S.; Rahman, F.H.; Au, T.W.; Nafi, N.S.; Patchmuthu, R.K.; Al-Hazemi, F. Digital-twin-assisted Software-defined PON: A Cognition-driven Framework for Energy Conservation. In Proceedings of the 2021 31st International Telecommunication Networks and Applications Conference (ITNAC), Sydney, Australia, 24–26 November 2021; pp. 166–177.
164. He, Y.; Yang, M.; He, Z.; Guizani, M. Resource allocation based on digital twin-enabled federated learning framework in heterogeneous cellular network. *IEEE Trans. Veh. Technol.* **2022**, *72*, 1149–1158. [CrossRef]