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Article

Key Technologies for Beyond 100G Next Generation Passive Optical Network

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Abstract: In order to provide high capacity and universal access of telecommunication networks, this paper reviews and prospects the advanced multiplexing technology, physical layer digital signal processing technology, infrastructure sharing technology, security protection technology, intelligent control management and other key technologies for beyond 100G next generation passive optical network (NG-PON).

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

1. Introduction

At present, the explosive development of bandwidth consuming services such as computing networks, live streaming services, and augmented/virtual reality has stimulated a huge growth in bandwidth demand. The global explosion in the number of Internet usage and connected devices and the emergence of multi-service mobile communications represented by the new sixth generation (6G) have increased the demand for scalable and sustainable telecom network models, placing stringent requirements in terms of network bandwidth/capacity, latency and efficiency. Global data traffic has doubled every 2-3 years for the past 15 years and will continue to grow in the future [1–3]. As one of the transport solutions for high-bandwidth, low-latency services, the new 6G service requirements will enable operators to ensure high availability of 6G services and ubiquitous radio coverage in denser networks with minimal deployment effort. In order to meet the growing demand for service traffic, the all-optical network with optical fiber as the medium has the highest transmission capacity, solving the problem of data transmission capacity and distance from the source to the destination node in the optical domain.

In order to support other applications such as emerging commercial mobile forward, mobile backpass, residential and industrial services, optical fiber to the home (FTTH) deployment has increased rapidly at the optical access end, and the use of passive optical network (PON) technology can provide low-cost broadband access options, connecting antenna sites or users has been widely used in optical access network deployment. It is a promising technology choice. The ITU-T Recommendations for High Speed Passive Optical Networks (HS-PON), published in September 2021, outline industry requirements for the next generation of 50G PONs. The standardization process of NG-PON is shown in Figure 1. In the first PON standard, HS-PON will employ digital signal processing (DSP) to overcome the severe fiber dispersion damage that will be experienced at this line rate. At the same time, beyond-100G PON [4–8] has the characteristics of large capacity, low delay, low cost and high reliability, using various advanced technologies such as coherent detection and flexible rate PON with DSP. The research community has set its eyes on the future single-channel intensity modulation direct detection (IM/DD) system above 100 Gbps to achieve high-speed PON. However, any future IM/DD solution will need to meet the 29 dB PON optical loss budget to support the existing fiber infrastructure already installed by network operators, which is challenging. Therefore, in the process of the development of over 100 Gbps PON, this paper specifically describes the opportunities and challenges faced by many key technologies.

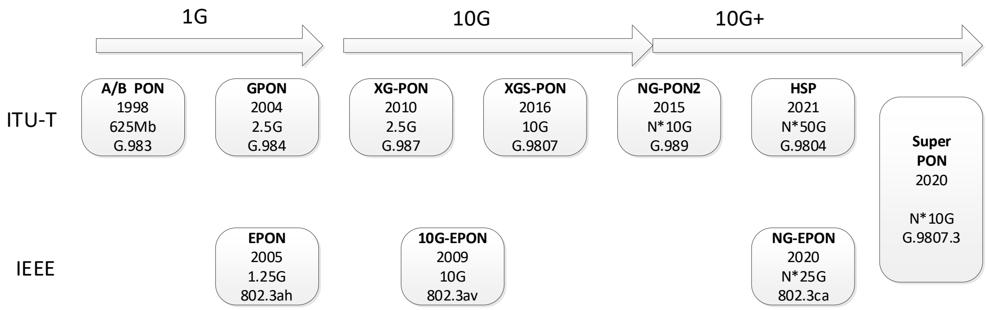

Figure 1. Standardization process of NG-PON.

2. 100G PON Advanced Multiplexing Technology

Next generation passive optical network (NG-PON) system has the characteristics of simplicity and high speed, and is an effective solution for low cost FTTH access network. Its structure is mainly optical line terminal (OLT), optical distribution network (ODN) and multiple optical network units (ONUs) connected through ODN. Multiple OLTs are aggregated upstream by 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 ONU must be supported on the user side. At present, NG-PON is multiplexed. It is mainly divided into time-division multiplexed passive optical networks (TDM-PON), such as ATM PON (APON)/ Broadband PON (BPON), Ethernet passive optical network (EPON), 10GEPON, gigabit passive optical network (GPON), gigabit GPON (gigabit GPON), and 10G symmetric PON (XGS-PON), gigabit Ethernet PON (GE-PON). Among it, the GPON and EPON have been deployed around the world. Future, the 25G/ 50G EPON, the Super PON and the high-speed PON have established relevant standards and are in the process of upgrading. In addition, time wavelength division multiplexing passive optical network (TWDM-PON), wavelength division multiplexing passive optical network (WDM-PON), orthogonal frequency division multiplexing passive optical network (OFDM-PON) and power division multiplexing passive optical network (PDM-PON), space division multiplexing passive optical network (SDM-PON), optical code division multiplexing passive optical network (OCDMA-PON) and other advanced PON formats [9–15]. In recent years, around NG-PON technology, the industry has introduced relevant standards.

In order to meet future PON development needs, different types of NG-PON 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, as shown in Figure 2.

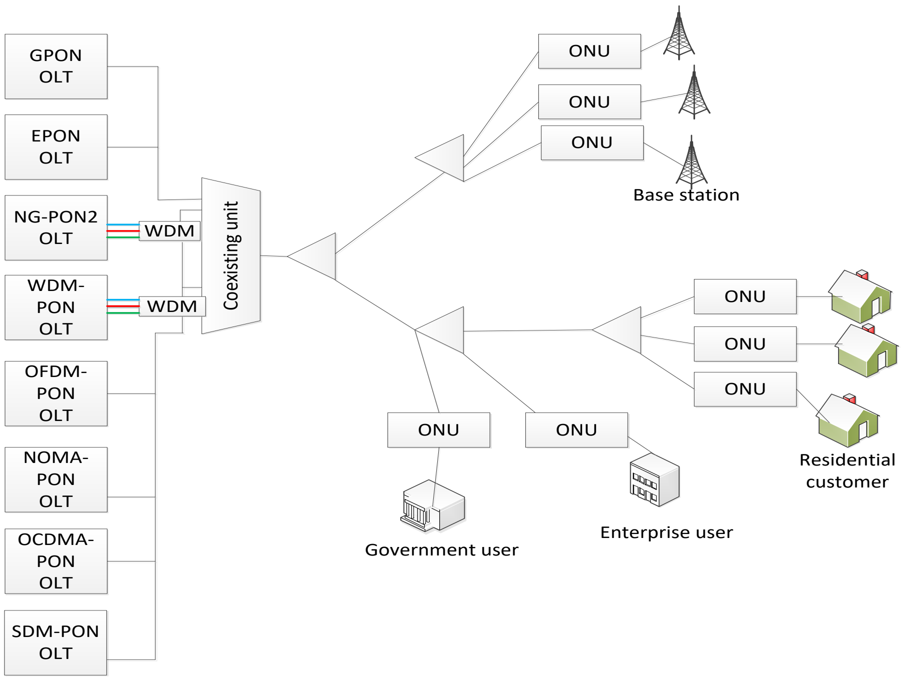

Figure 2. The coexisting process of NG-PON.

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]. In 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 (EFM). In TDM-based EPON, since the physical media is 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 EPON, where the Dynamic Bandwidth allocation (DBA) scheduler via Multi-point Control Protocol (MPCP) plays a key role. In order to further improve the capacity of PON, ITU-T's next generation PON2 (NG-PON2) standard uses wavelength division multiplexing (WDM) technology to superimpose 4 or 8 wavelengths. According to 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. WDM-PON includes coarse wavelength division multiplexing (CWDM), dense wavelength division multiplexing (DWDM) and ultra-dense wavelength division multiplexing (UDWDM) PONs, and broadband optical access based on coherent UDWDM has been proven to be a potential solution to improve spectral efficiency and downstream capacity. In order to achieve low-cost UDWDM-PON, many low-cost simplified coherent receivers have been proposed, especially polarization-independent SCR (PI-SCR) using 3 × 3 couplers, which has aroused widespread research interest, but how to deploy it cost-effectively remains a major challenge for telecom operators.

Scalability remains a major issue for next-generation optical access networks, and to overcome this limitation, the TWDM-PON technology solution, as a TDM-PON upgrade, has been adopted by ITU-T as one of the best architectures for NG-PON2. Take advantage of TWDM in order to strike a balance between coexistence with legacy systems and a gradual migration to pure WDM-PON. PONs adopting new technologies in the future need to meet the coexistence of various PONs. Therefore, there is a strong expectation that WDM-PON can use the existing ODN to implement TDM-PON to provide high access bandwidth at low cost.

In addition, according to the 40 Gbps NG-PON2 and 25 Gbps NG-EPON standard specifications planned by ITU-T and IEEE respectively, OFDM system is an important solution for NG-PON because of its strong dispersion tolerance and high spectral efficiency. However, due to the high complexity of digital signal processing, OFDM-PON is still a long way from commercial use. OCDMA-PON performs encoding and decoding in PON through optical signature codes to allow

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selection of the desired signal so that different users can share the same bandwidth. SDM-PON further increases the capacity of NG-PON by effectively utilizing the latitude of the air separation. However, PON technologies such as TDM-PON, TWDM-PON, WDM-PON, and OFDM-PON must ensure orthogonality in time, wavelength, or frequency dimensions so that user information can be separated to reduce multi-user interference. However, 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. In addition, as one of the key technologies to improve the capacity of 5G networks, non-orthogonal multiple access (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 users, the PON system based on NOMA has been proposed. NOMA-PON supports multiple 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 (SIC) based on multi-user detection technology can successfully distinguish and separate user signals in the receiver according to the difference in user power. Thus, without increasing available resources, NOMA can effectively improve data throughput and spectral efficiency, serving more users at a given time and frequency range. Therefore, the NOMA-PON system is a potential application scenario with limited available resources.

PON is cost-sensitive and the main cost comes from the construction of the ODN. To avoid the cost of rebuilding a new ODN, reuse of the deployed ODN is preferred in PON evolution. This evolution is called smooth evolution. During the evolution of the PON, new PONs are added to the deployed ODN to be shared with the existing PONs. 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. Therefore, the main problem for smooth evolution is the existing ONU dull filter to protect them from the new PON signal in the downstream direction. At present, several methods have been proposed to reduce/ eliminate this crosstalk without changing the existing ONU. Three methods of synchronous pulse interleaving, electric superposition modulation and subcarrier modulation were proposed in literature [22–24]. However, these three methods require expensive components such as high-speed electrical multipliers and pinger transmitters or sacrifice the quality of the new PON signal. A promising smooth evolution technique called spectral shape line coding (SSLC) is proposed [25]. SSLC constructs some line codes that suppress low frequency components and applies them to new PON signals. After encoding, the high-speed new PON signal causes crosstalk to the low-speed traditional PON signal, and SSLC does not degrade the signal of the new PON.

3. Beyond 100G NG-PON Physical Layer Technology

The physical layer solutions of beyond 100G NG-PON can be divided into two categories: the beyond 100G NG-PONs are based on IM/DD [26–30] and coherent technology. Figure 3 shows the physical layer technology of the beyond 100G NG-PONs. For IM/DD NG-PON, compared with non-return-to-zero (NRZ) modulation, four/ high order pulse amplitude modulation (PAM4/M)-ary is a promising solution to meet the increasing demand for optical access network capacity. Although the cost of receiver sensitivity is reduced, the electro-optic bandwidth requirements are reduced. The potential 100 Gbps IM/DD PON solution based on 50 GBaud in high-speed optical access networks is explored. 100 Gbps upstream rate can achieve PAM format and advanced receiver DSP. However, existing NG-PON the system is limited by dispersion (CD) and power fading effect after direct detection, and the increase of 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 dispersion effect in DD systems. For

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example, self-coherence detection based on single sideband (SSB) transmission is often used in combination with krmers-kronig (KK) reception as a way to avoid power fading and overcome signal-to-signal beat interference (SSBI). The application of electric dispersion compensation (EDC) in the transmitter digital signal processing (DSP) of DD system can effectively improve the power loss. In addition, the fundamental challenge associated with direct detection is the disappearance of the phase of the transmitted signal. With the increase of the nonlinear effect of IM/DD, the limited bandwidth and power fading degrade the transmission performance of the system. Moreover, the nonlinear ISI caused by intensity modulation and square law detection will significantly reduce the performance of IM/DD system.

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. Therefore, 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 90 Gbps (25GBaud) -PON under the BER of 10e-11 provides more than 1.5dB encoding gain for soft-decision Low Density Parity Check Codes（LDPC）. In terms of signal shaping methods, there are mainly probabilistic shaping, geometric shaping and super Nyquist (FTN). Advanced modulation formats, in addition to PAM format, mainly such as multi-carrier OFDM, single carrier high order quadrature amplitude modulation (QAM), quadrature phase shift keying (QPSK) and low-cost, low complexity PAM-8 format; DSP-based equalization schemes include Tomlinson-Harashima precoding (THP) at transmitter combined with feed forward equalization (FFE) at receiver, transmitter THP combined with Volterra filter equalization (VFE) , look-table pre-equalization method [31–37], FFE and VFE etc.

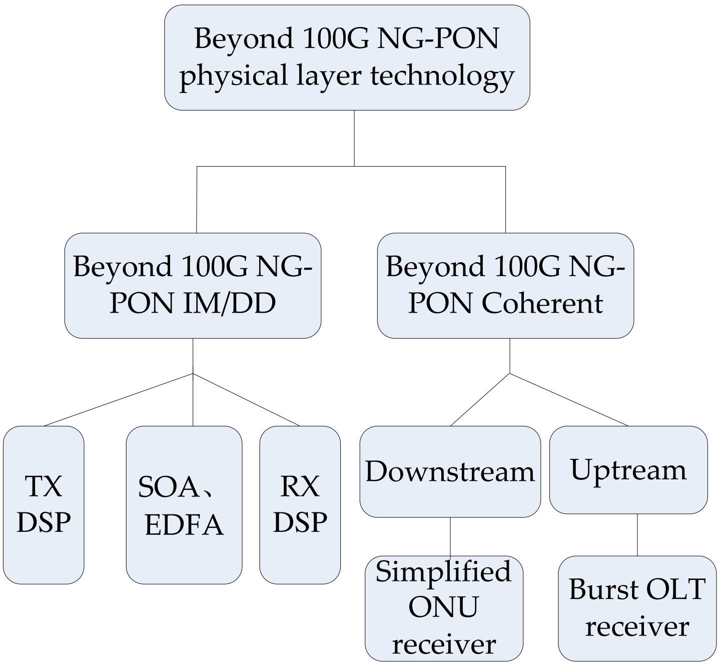

Figure 3. Beyond 100G NG-PON physical layer technology

On the other hand, in order to improve the sensitivity and achieve a 29 dB optical loss budget, a semiconductor optical amplifier (SOA) can be adopted as a receiver preamplifier, and because of its easy integration, it can work in the C and O bands, and the cost is relatively low, which has a wide effect on IM/DD PON. However, the effect of SOA nonlinearity, such as gain saturation, is a problem. Especially in PON upstream transmission, due to the burst-mode PON signaling inherent in the large 19.5 dB dynamic range (DR) [38], in the case of SOA preamplifiers, due to the strict linear requirements of 100G PAM4, the possible implementation of PON can be problematic. Machine learning (ML) based equalization techniques have been proposed in future SOA preamplifier PON scenarios to compensate for expected fiber dispersion and device damage. Current work has focused

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on achieving a 29 dB optical loss budget, for example in [39,40], a recurrent neural network combined with an optical sensor uses an SOA preamplifier to achieve a 30 dB loss budget of 100 Gbps PAM4. However, the challenge of meeting the 19.5 DR requirement has also brought attention to non-machine learning techniques, such as in [41], the authors investigate the sender lookup table pre-compensation technique for the 100 Gbps PAM4 nonlinear Volterra equalizer (VNLE) to overcome the nonlinearity of SOA and achieve up to 18dB DR.

In receivers with higher bit rates, since coherent technology has higher receiver sensitivity than IM/DD technology, it is expected to be used in PON systems of 100 Gbps or higher. Thanks to the rapid development of the latest small-scale DSPS, coherent PON can be expanded to support the next generation high-speed optical access network 100G and above, tens of kilometers of access range power budget. The introduction of customized hardware and efficient signal processing technology for the coherent PON [42–48] system will help to further develop the coherent technology in the PON system. To improve spectral efficiency, coherent transmission can also use advanced modulation formats that can be encoded in all four dimensions of the light field: in-phase and orthogonal in two orthogonal polarization states.

However, such transmission systems require high optoelectronic complexity, typically using at least one photo-detector (PD) and transimpedance amplifier (TIA) per modulation dimension, at least one analog-to-digital converter (ADC) per detection dimension, and at least one external modulator integrated in a nested Mahzindel interference structure per modulation dimension. Coherent systems also require an additional laser receiver as a local phase reference or "local oscillator" (LO). This is comparable to transmission using a directly modulated laser and reception using a single photo - detector. The actual transceivers deployed in optical access networks that modulate and detect only one dimension of the optical field differ greatly. DSP techniques for coherent PON systems include simplified IQ imbalance compensation, adaptive equalization, clock recovery schemes, polarization de-multiplexing, carrier frequency offset and phase offset estimation. In addition, the upstream coherent NG-PON optical communication system has a burst mode of data flow [49–58]. Therefore, burst mode data transmission faces a major challenge in electronic design. Figure 4 shown the coexisting process of IM/DD and coherent for the beyond 100G PON. The downstream of the beyond 100G PON is the continuous mode while the upstream of the beyond 100G PON is the burst mode. In the future, it is necessary to design the structure and software solutions of the burst mode coherent receiver, expand the receiver input dynamic range and make OLT and ONU process the burst data smoothly.

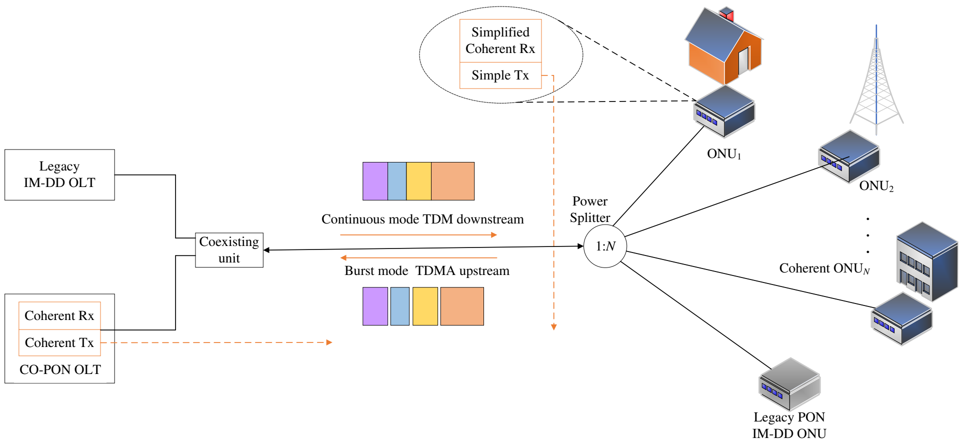

Figure 4. The architecture diagram of the NG-PON with 256 splitter ratio.

4. Beyond 100G NG-PON Infrastructure Sharing Technology

To support high-capacity access, advanced coherent detection is attractive, but its complexity and low power consumption need to be properly addressed. Optical access networks connect end users and carrier networks in the last mile, and because of the scale of their deployment, the access

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portion of the communications network is the most expensive. As a result, the reduction in access costs will have multiple impacts on overall capital expenditure (CAPEX) for 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 will involve more sharing technologies between operators' infrastructure and become the focus of research on NG-PON systems in academia and industry.

In order to get rid of the low research and development efficiency of the traditional optical access system, which has a long development cycle and high initial cost, the architecture based on common components and common software is changing. As virtualization technologies have evolved over the past few years, so have access network management systems. Two typical projects promoted by telecom operators and vendors are Broadband Access to software-defined networks with SDN controllers (SEBA) and Cloud Central Office End (CloudCO) [59–66], which connect coordinators and infrastructure devices using northbound and southbound interfaces (SBI), respectively. In order to accelerate new PON-based services, SEBA uses a classic API to extract different OLT/ ONUs management devices through a single controller. However, the current abstract unit in SEBA only supports ITU-T PON. To support IEEE PON, be sure to consider multiple packet types as well as forward management capabilities. The classic configuration of logical links for ITU-T PON and IEEE PON is to adaptively extract IEEE PON OLT/ ONU by extending the forwarding between operation, management and maintenance. SEBA builds a central office (CO) end with a white box OLT and a common server. It realizes flexible service creation by softwaring the upper functions such as workflow authentication and edge application. In order to create the underlying service flexibly, the hardware of further software OLT is studied. Traditional application-specific networks are provided only in local networks using dedicated systems, and by implementing a specific network within the access segment, edge computing services can be provided that extend a specific network to the access segment, as shown in Figure 5. They provide service providers with lower initial costs for creating new services and simplify system administration.

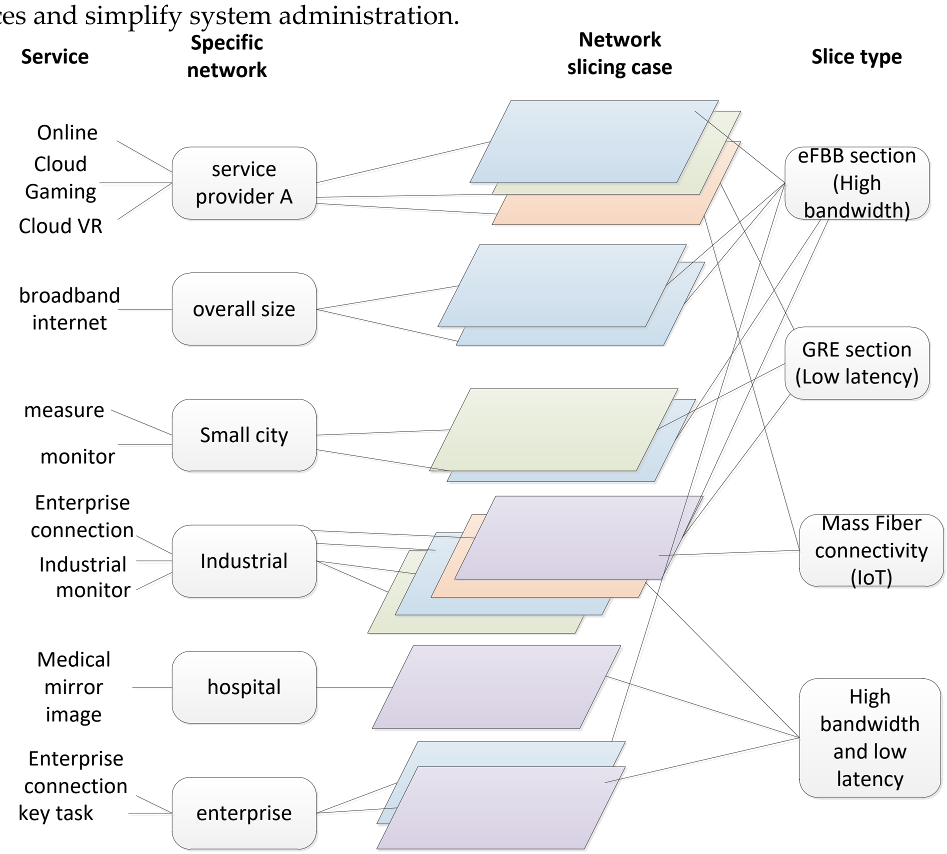

Figure 5. The figure provides network slicing for services that require different slicing types.

In the software-based sharing method, since one of the basic features of PON is to provide burst-level scheduling for upstream transmission of PON, the DBA algorithm [67–71] is responsible for preventing conflicts and providing the required quality of service (QoS) to meet the needs of SLA. Therefore, the DBA scheduler on OLT is one of the important components of the PON control plane that can meet the needs 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 Interleaved polling with adaptive cycle time (IPACT) scheduling scheme better combines simplicity and allocation efficiency. From the theoretical analysis, different scheduling algorithms have their own advantages and disadvantages, but the complete scheduling performance in the actual hardware environment is still lack of 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 TC layer supports the management of traffic on OLT through a single control function at the traffic level. Slicing on OLT collects individual streams into groups called slices and adds control for sharing common resources at the slice level [72–75]. This control function enables a degree of service or virtual network isolation. PON slices are grouped into at least multiple streams on one or more ONUs of OLT. Each slice is processed accordingly by the hierarchical scheduler in the DBA and OLT. Slicing also means that OLT and ONU manage coordination between instances in cases where ONU functionality will be used to handle streams and slice-level streams. The parameters with a set of slice profiles in PON slices need to be further studied in the future. The architecture for controlling PON slicing is considered as follows: Slicing use cases in PON-based optical access include network slicing that supports several different delay limits for application PON, dynamic optimization of PON resource allocation for mobile applications, and slicing in PON systems in multi-operation scenarios.

Figure 5 shows the network slicing configuration for different business QoS requirements and is therefore divided into four slicing types, such as enhanced fixed broadband (eFBB), guaranteed reliable experience (GRE), Internet of Things (IoT) [76–80], 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-Nets has a set of slicing types that need to be supported. For example, residential D-Nets supports 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 services 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.

5. Beyond 100G NG-PON Security Protection Technology

In order to cope with the exponential traffic growth, the large-scale deployment of 100G optical network is developing to 200G/ 400G. In addition, to improve the signal performance and reduce the cost, NG-PON tree topology and it's downstream transmission broadcast characteristics has security risks. Facing serious security challenges, securing the growing amount of confidential information has become a great need. However, the physical layer of optical networks is vulnerable to eavesdropping attacks. Moreover, the encryption algorithms based on mathematical complexity are facing the risk of being cracked by quantum computing. The security of future optical access networks is very important. Many proposals have been made to improve NG-PON security [81–83]. Currently, a variety of NG-PON security protocols have been implemented. Different researchers have proposed different encryption and authentication techniques for future NG-PONs, which usually requiring the provided key only on the downstream channel. For example, 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 channel direction. All of the ONUs behave and act according to a DBA arrangement. The absence of appropriate security measures lead to vulnerabilities in the network and jeopardize 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 to the OLT. Therefore, if one ONU does not transmit in a manner that meets the parameters specified by the standard, threatening will interfere with the other ONUs on the all of the PON's upstream transmissions. This results a disruption of communication. If an ONU is designed, manufactured, and deployed in compliance with the standard, but violates the standard parameters by transmitting optical power from the ONU to the OLT due to design flaws, manufacturing errors, hardware or software malfunctions, environmental or other external influences, it is referred to as a "rogue ONU"[84]. This behavior is not unique to PON systems. However, 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 PON systems, to facilitate the prevention, detection, isolation, and removal of violating ONUs, standard specifications raise awareness of rogues and techniques and tools for system designers and implementers should be provided.

However, to avoid or minimize service disruptions to other ONUs on the PON, the header information or control data encrypted by the upper layer is exposed in the physical layer. Therefore, in recent years, physical layer security protection techniques have been developed to improve the security of the optical access networks. Compared to upper layer security protection, physical layer security provides the transparent encryption for all data. Physical layer security is considered as 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) [85–90], time domain spectral phase encoding (TDSPE) [91–93], chaotic encryption [94–97], and so on. Recently, among many schemes, a number of chaos-based physical layer security schemes have been proposed for the application of joint subcarrier variations in NG-PON, especially in OFDM-PON. However, in practical applications, the stability and key distribution speed of chaotic laser communication are low, and there are problems such as channel interference and parameter matching, which limit the application of chaotic laser communication in practical applications. Chaos includes laser chaos technology and electric chaos technology. Laser chaos technology can improve the security of the physical layer by adjusting the injection strength and feedback strength of the laser in the PON. Electric chaos technology, on the other hand, the processes of signal generation, modulation and error correction are mainly realized in the digital domain. Due to the high flexibility of signal processing in the digital domain, it is easier to employ cryptographic techniques such as digital chaos to improve the security of OFDM-PON systems, such as cubic constellation masking, chaotic and fractional Fourier transforms, segmented chaotic alignment, chaotic IQ encryption, and hybrid chaotic systems.

Table 1. The security protection technology of NG-PON.

Author	Year and publications	Modulation format	Rate [Gbps]	Distance[km]	BER	Scheme	Kinds of PON
Xiao, Y.	JOCN 2018[98]	16 QAM	8.9	100	10e-3	Multi-chaotics	OFDM-PON
Wu, T.	Optics Express 2018[99]	16 QAM	22.06	25.4	10e-3	Three-dimensional Brownian motion and chaos in cell (3DBCC)	OFDM-PON
Wu, T.	IEEE Access 2020[100]	16 QAM	22.06	25	10e-3	Deoxyribonucleic acid (DNA) extension code and Chaotic System	OFDM-PON

Zhang, W.	PTL 2016[101]	16 QAM	11.32	25	10e-3	Joint peak-to-average power ratio (PAPR) and a chaos IQ-encryption	OFDM-PON
Zhang, W.	PTL 2017[102]	16 QAM	36.67	100	10e-3	Brownian Motion Encryption	CO-OFDM-PON
Hu, X.	PTL 2015[103]	16QAM	8.9	20	10e-3	Chaos-Based Partial Transmit Sequence	OFDM-PON
Bi, M.	Photonics Journal (PJ) 2017[104]	16 QAM	10	25	10e-3	Key Space Enhanced Chaotic Encryption Scheme	OFDM-PON
Adnan A. E. Hajomer	Photonics Technology Letters 2017[105]	16-QAM	8.9	20	10e-3	Chaotic Walsh–Hadamard Transform	OFDM-PON
Zhao, J.	Optics Express 2020[106]	16-QAM	16	25	10e-3	4D-hyperchaos and dimension coordination optimization	OFDM-PON
Zhao, J.	PTL 2020[107]	16-ary	20	25	10e-3	Floating Probability Disturbance	CAP-PON
Cui, M.	Optics Express 2021[108]	16QAM	35.29	25	10e-3	Chaotic RNA and DNA	OFDM-WDM-PON
Wu, K.	IEEE Photonics Journal 2022[109]	PAM-8	100	35	3.8e-3	Adjustable Fingerprint with Deep Neural Networks	WDM-PON
Luo, Y.	JLT 2023[110]	16-32- 64-QAM	17.6, 22.1, 26.5	25	3.8e-3	Support Vector Machine	OFDMA-PON.
Liang, X.	JLT 2023[111]	-	35.29	20	3.8e-3	Chaotic Hilbert motion	OFDM-PON
Wei, Z.	JLT 2023[112]	PCS-64-QAM	400	80	3.8e-3	Pseudo-m-QAM Chaotic	WDM-CPON
Xia, W.	Optics Express 2023[113]	Pyraminx-3D-CAP-16	25.5	2	3.8 e-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 fiber-to-the-home (FTTH) architectures. For continuous variable QKD (CV-QKD) and DV-QKD [114–116] protocols, the feasibility of 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 25km WDM-PON network with strong classical channels is reported. However, there is still a large distance from the ideal single photon source. In addition, encrypted probabilistic shaping parameters are another security enhancement scheme for the NG-PON physical layer. All of the above physical layer security enhancement techniques 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 cryptography protocol, also known as Y-00 [117–

128], 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, Therefore, the channel measurement following the principle of randomness is considered a promising solution for secure transmission of optical data in fiber optic networks to achieve a high level of security and suitable for long distance scenarios. 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 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 2e32 [127]. Sun *et al* extended the plaintext type of QAM/QNSC to probabilistic shaped QAM [128]. The experimental results show that the encryption and decryption of QAM/QNSC induce 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 and has received less attention compared to its confidentiality [129]. Therefore, it is necessary to quantitatively analyze the encryption cost of QNSC. Further, endogenous security-based is an important direction for the future development of NG-PON since the seed key does not depend on the generation of external devices but the channel feature. The fiber channel feature extraction, key generation and key quantization, and negotiation of a consistent key, are carried out by exploiting the unique physical layer characteristics of fiber optic channels [130–136].

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

At present, many works have analyzed and studied the importance of introducing software defined network (SDN) [137–140] into 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 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 nes from multiple vendors. Heterogeneous secondary network elements can be provided at the cladding layer and optical layer to provide different services with different features, configurations, and controls with hiding the service characteristics and differences of specific network platforms. The architecture of SDN virtualizes several network function virtualizations (NFVs) using APIs and OpenFlow, NETCONF/YANG, RESTCONF, gRPC, etc protocols [141–147] to communicate between the various hardware and network software that make up the network.

To minimize latency and energy consumption, switching/routing should take place 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 management. 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 with realizing existing optical network economies.

On the other hand, from a strictly functional perspective, management and control in networking refers to a defined set of management and control planes with different functions. The management plane is responsible for the planning, installation, configuration, 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. Business, network, and element hierarchies can be managed based on abstraction and management domains. Currently, artificial intelligence (AI) and ML [148–158] are showing great capabilities in solving tasks in optical network fault management, resource allocation, and quality of transmission optical path (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 make predictions. Digital twin (DT) is a new research field in the field of communication networks [159,160]. 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 machine learning techniques 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 super 100G NG-PON based on a variety of distributed artificial intelligence. For example, considering the characteristics of the future deployment of beyond 100G NG-PON and the characteristics of high energy consumption of NG-PON, how to maximize energy saving while meeting the quality of service, real-time feedback of energy saving and service traffic performance into the network operation decision process and real-time control of PON infrastructure is very important.

7. Conclusion

NG-PON technology is considered as a promising solution for the next generation of large-scale optical access networks due to its high bandwidth and low cost. Aiming at the infrastructure deployment requirements of the next generation of high-capacity, flexible and secure beyond-100G PON system, the key implementation technologies of beyond-100G PON system are proposed to meet the market demand of beyond-high speed and low network cost in the next 5-10 years.

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