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Towards converged, collaborative and co-automatic (3C) optical networks

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Abstract The interconnection of all things is developing a new diagram of future information networks. However, it is difficult to realize future applications with only one single technique. Collaboration between multiple advanced techniques is leading the way for the development of future information networks. Optical communication is an enabling technique to achieve high speed, long reach, and low latency communication, which plays an important role on the transformation of information networks. To achieve these advantages that caters to the characteristics of future information networks, collaboration of multiple advanced techniques with optical, which is called "optical plus X", could realize the vision of "all things connected with networks". In this paper, we focus on the collaboration between optical networks with other techniques, mainly discuss four representative aspects, which are "optical plus IP", "optical plus radio", "optical plus computing", and "optical plus AI". We discuss the challenges, timely works, and developing trends. Finally, we give the future visions for optical network towards a collaborative, converged and co-automatic optical network.

Keywords 5G optical transport networks, edge computing optical networks, IP over optical networks, AI-assisted optical networks, 3C optical networks

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1 Introduction

With the emerging applications such as Internet of things (IoT), massive video, virtual reality, and smart cities, the interconnection of all things leads the development of future communications. Faced with new demands and challenges, there is an urgent need for some important changes in the existing information networks. First of all, a variety of technologies have come into converged. For example, in radio access network (RAN), a typical application mode is mobile fronthaul optical network, which realizes the interconnection between remote radio antennas and baseband processing unit through the optical network. This converged radio and optical networks can effectively increase access capacity and reduce costs. Second, the evolution of computing model triggers changes of access network architecture. A typical application mode for an ultra-low-latency service and IoT is edge computing (a.k.a., fog computing). It decentralizes data computing and storage clusters, and places multiple micro data center nodes on the edge. The micro data centers are typically interconnected by an edge optical network. Third, owing to the complexity of large-scale network and users' behavior, it is difficult to achieve reasonable distribution of

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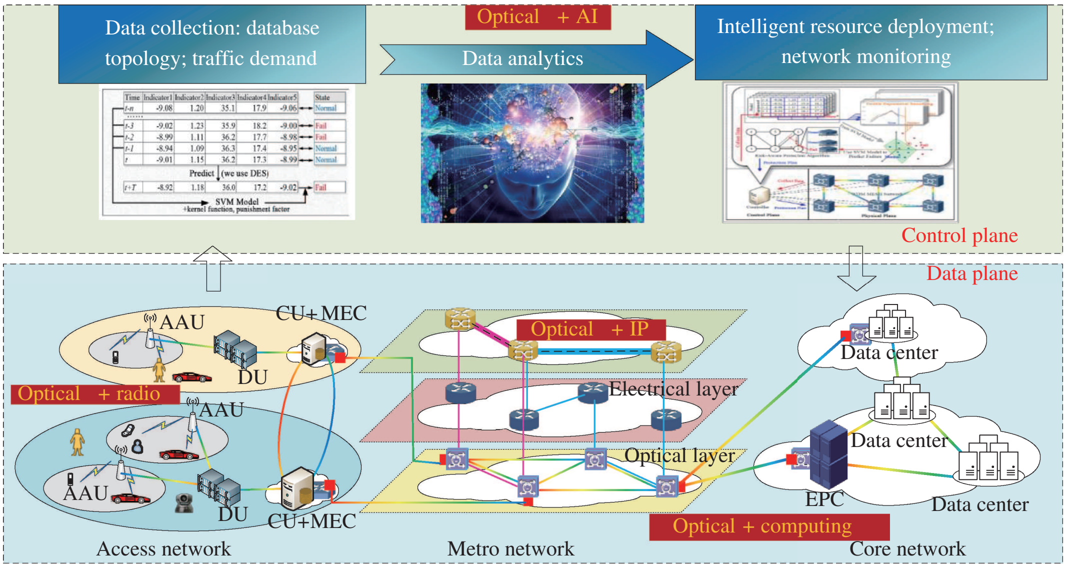

Figure 1 (Color online) An illustration of "optical plus X" with the prospect of 3C.

resources through conventional ways. Therefore, it is necessary to establish an intelligent and automatic learning mechanism. A typical trend is to introduce machine learning (ML) in the network, analyze the user's needs and preferences through a large amount of data. The feedback from learning results can instruct an efficient scheduling action to achieve automatic deployment of network resources and reduce network operating costs.

Optical network is considered as a promising technology to achieve high-speed, long-distance, and low-latency transportation for future network, which plays an important role in network evolution. As shown in Figure 1, this article describes the benefits of "optical plus X" to achieve a converged, collaborative and co-automatic (3C) optical network. We focuses on the background, challenges, and solutions of "optical plus X" that includes "optical plus IP", "optical plus radio", "optical plus computing", and "optical plus AI". In addition, the technical trends for each aspect are summarized in the paper.

2 Optical plus IP-achieve efficient multi-granularity services over large-bandwidth channel

The bottleneck of the traditional transport network is struggle with high-bandwidth provision and bandwidth efficiency. Therefore, the convergence of optical network and IP network is imperative. The IP layer mainly undertakes fine-grained traffic grooming and routing, while the optical layer is responsible for providing large-capacity, low-latency, and long-haul transmission channels. To realize the bandwidth on-demand application, intelligent grooming of traffic demands, and the collaboration of IP and optical is a promising solution, which enables the performances of network capacity, reliability, and service deployment. IP over optical network technology allows IP data streams to enter the optical channel, which helps to fully integrate the advantages of large-capacity optical network technology and IP technology convergence, and provides beneficial ideas for the development of optical networks for data services.

IP network refers to the network based on the TCP/IP protocol as the communication protocol. Among them, the Internet is the most representative type of IP network. IP packet services and circuit switched services based on SDH/SONET or optical transport network (OTN) are traditional optical network bearers. With the widespread adoption of the Internet, a variety of high-bandwidth, real-time services continue to emerge and develop rapidly, and the bandwidth resources of existing IP networks are becoming increasingly intense. With the continuous emergence of new services, the evolution of optical networks has gone through synchronous digital hierarchy (SDH), multiservice transport platform (MSTP), wavelength

Table 1 Literatures on optical plus IP

Research area	References
The convergence costs of IP and optical	Gkamas et al. [3], Tanaka et al. [4], Tucker et al. [5], Lu et al. [6]
Cross-layer controlling and resource scheduling	Qiao et al. [7], Sun et al. [8], Kretsis et al. [9], Melle et al. [10], Autenrieth et al. [11]
Traffic grooming	Zhang et al. [12, 13], Zhang et al. [14], Tang et al. [15]

division multiplexing (WDM), and packet division. Transport network (PTN), automatically switched optical network (ASON) to elastic optical network (EON). At the same time, optical network hardware, such as transponder and switch, should support software programmability [1], and the control circuit was integrated on a chip [2]. From the perspective of evolution, optical networks will continue to develop in the direction of large-capacity, dynamic, flexible, multi-dimensional, and intelligent integration. With the popularization of IP services, the rapid development of high-speed router technology and the extensive adoption of optical network bearer technologies have caused profound changes in the architecture of next-generation networks.

2.1 Research works of IP over optical networks

The recent literatures on IP over optical networks are summarized in Table 1 [3–15], in which the research areas are mainly focused on three parts: the cost of convergence, unified control plane and traffic grooming.

2.1.1 *The costs of convergence of IP over optical networks*

The joint optimization of multi-layer networks in IP over optical networks should consider the costs and benefits of the converged multi-layer networks.

As WDM networks have emerged as a promising candidate for future networks with large capacity, long-haul transmission and low latency. Despite the great strengths of optics as a transmission and switching medium, today's network relies very strongly on electronics. For example, electronic switches, routers, and regenerators are ubiquitous in the network and centrally important to its operation. The dream of an all-optical network, in which data traverses large distances without electronic intervention, still remains a long way from reality. Hence, supporting efficient IP packet transmission in WDM networks becomes eminent. Ref. [3] shows how requirements of low cost and low energy consumption can influence the choice of switching technologies as well as the overall IP over WDM network architecture. The physical technologies in optical network are evolving from fixed grid WDM to a flexible spectrum slots which is called EONs. The integrated multilayer protection planning problem is investigated in IP over elastic optical networks (IP-over-EONs) [4]. A mixed linear programming (MILP) model is also proposed to formulate the backup protection problem, aiming to minimize the total cost of the extra spare capacity in optical-layer and the IP-layer backup lightpaths. The energy optimization is a critical issue for the sustainability of IP over EON. An energy-minimized design of IP over EON is discussed considering jointly the IP and elastic optical layers [5]. A multi-layer network design from network to node equipment level is investigated for the topic on the cost efficiency of IP over EON architectures [6]. Four models of such architecture are evaluated employing different types of transponders, consisting of fixed, mixed-line-rate, bandwidth-variable (BV), and multi-flow (MF) models.

2.1.2 *Cross-layer controlling and resource scheduling*

In this subsection, the routing and bandwidth allocation problems over software-defined based multi-layer optical transport networks are discussed. The IP traffic transportation dependes on the different optical switching patterns, Ref. [7] describes the optical burst switching (OBS) paradigm, and also proposes the use of labeled OBS, or LOBS, as a natural control and provisioning solution under the ubiquitous IP multiprotocol label switching framework. Ref. [8] proposes V-STONES – a data flow-based VLAN tagging and switching technique to increase the connectivity of end host network interfaces in circuit-switched networks. With V-STONES, not only can an IP end host communicate with different remote systems concurrently through bandwidth guaranteed connections, but also protocol entities at different stack layers can talk to their counterparts through dedicated bandwidth pipes.

To improve service velocity, flexibility and lower total cost of ownership for network operators, converging IP and optical network layers are an excellent method. Based on the multi-layer network planning and operation of IP and optical, and software defined network (SDN), and emulation environment for SDN based, multi-layer and flexible IP/Optical networks, called Julius, is proposed [9]. Such environment is useful especially as disruptive changes occur, and minimizing development time to adopt cutting edge technologies. Specifically, enabled with a web-based user interface, the interaction with the users can be solved in the access layer; the creation and management of the emulation environment can be handled in the orchestration layer; and the algorithmic logic of network resource management is decided in the execution layer. The independent control and management of isolated packet and optical networks leads a high cost of expenditures and operations. To address this problem, the integration of control and management of multilayer networks is presented [10, 11]. Enabled with SDN, a dynamic, service-aware, and service-optimized converged packet-optical networks can be realized to improve the efficiency of service provisioning and network resource utilization. A virtual transport link (VTL) based dynamic bandwidth adjustment (VTL-DBA) approach is proposed in the software-defined IP over optical networks, and the feasibility is also experimentally verified.

2.1.3 *Traffic grooming*

The fine-trained IP services should be channeled into coarse-grained optical network pipelines, and different grooming methods are selected according to the attributes and priorities of the services, so as to achieve cost and energy saving.

Traffic grooming is proposed to aggregate multiple electrical channels (packet or circuit flows) to an optical channel in an efficient spectrum utilization manner. Enabled by electrical switching fabric, spectrum efficiency and transponder usage can be achieved by traffic grooming. A dynamic traffic-grooming problem in sliceable bandwidth-variable transponder enabled EON (SBVT-EON) is discussed [12]. A three-layered auxiliary graph (AG) model is presented to solve the electrical and optical traffic grooming under dynamic traffic scenario. A sub-transponder layer in AG is added in order to process the optical and electrical traffic grooming coordination. Two spectrum reservation approaches are also proposed with the goal of improving the transponder's utilization. Energy efficiency of IP-over-optical networks has been widely investigated and traffic grooming is regarded as an effective approach to achieve power consumption saving based on optical-electric-optical (O-E-O) conversion at intermediate nodes. In this paper, an energy-efficient traffic grooming with sliceable transponders is investigated in EONs, considering three types of elastic optical transponder based on their sliceability [13]. An energy-minimized traffic grooming integer linear programming (ILP) models and corresponding heuristic algorithms are proposed. Significant reduction in power consumption is achievable by using sliceable transponders. The relevant research on traffic grooming is reviewed from SDH/SONET to evolutionary flexible-grid and elastic-rate technologies. Enabled with offloading electronic grooming to the optical layer, sliceable optical layer may be impacted on the future grooming paradigm [14]. For mixed channel traffic grooming in shared backup path protected IP over EON, Ref. [15] develops an AG based heuristic algorithm allowing working and protection traffic flows to share common optical channels and shows that the scheme is efficient in greatly improving capacity and transponder utilization. Power-awareness in networking attracts more attention as the trends in the energy consumption of the Internet raise growing concerns about the environmental impacts and sustainability of the network expansion. Building energy efficient equipment is definitely an integral part of the solution. However, such a strategy should be complemented with appropriate network protocols and routing methods to achieve maximum performance. Total power consumption of an optical WDM network is modeled in [16] in terms of the power consumed by individual lightpaths.

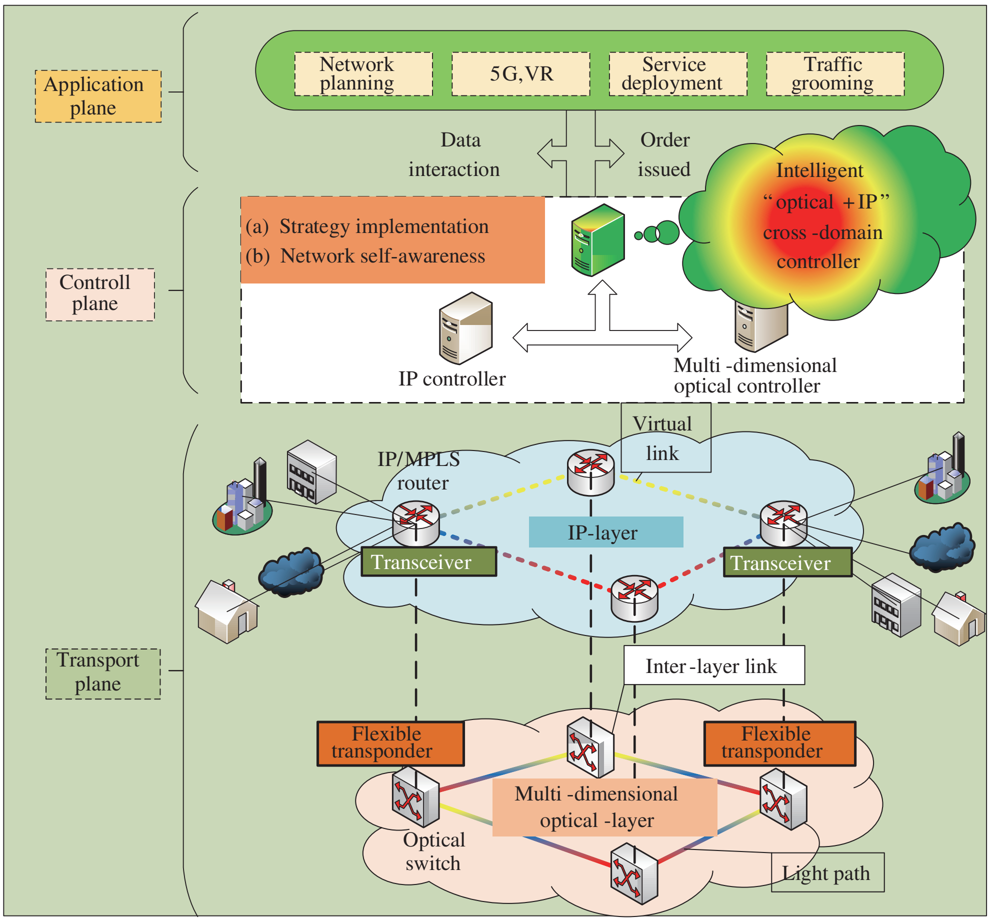

Figure 2 (Color online) Intelligent IP transport over a converged multi-layer optical network.

2.2 Development trends for the future works

In order to achieve rapid upgrade of the bearer network, reduce the network deployment cost, and improve the resource utilization, deep integration and efficient collaboration between the IP and optical layers is imperative. Future developments mainly include: (1) "Optical plus IP" requires intelligent cross-layer management and control technologies. For a long time, independent planning and hierarchical management of the IP layer and the optical layer have led to low utilization of comprehensive resources and high network costs. Therefore, it is necessary to introduce an efficient cross-layer management and control technology, coordinate resource configuration and routing management of the upper and lower layers, so as to provide a more intelligent transmission channel for user services. (2) "Optical plus IP" requires an adaptive traffic grooming mechanism. Adaptive traffic grooming for services with different attributes can improve network performance. For fine-grained services, the traffic grooming in the electrical domain can be considered; for coarse-grained, delay-sensitive services, the priority strategy is to consider the all optical transmission, so as to reducing the extra cost of optical-electrical-optical conversion of the intermediate nodes. (3) "Optical plus IP" requires an enhanced mutual protection mechanism. Since the other party's network status can not be sensed over the IP layer and the optical layer, it is difficult to achieve an effective cooperative protection strategy between the two networks. Therefore, it is necessary to improve the mutual-awareness of the network, and optimize the network collaborative protection measures. Figure 2 illustrates the intelligent IP transport over a converged multi-layer optical network. The intelligent IP over optical transport network is enabled by the SDN technique, in which a multi-layer network (e.g., IP layer, optical layer and other layers between them) is controlled and managed through a software defined manner.

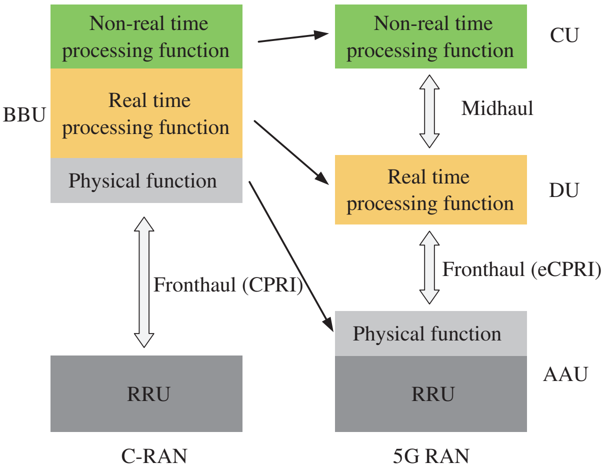

Figure 3 (Color online) Radio access network architecture evolution.

3 Optical plus radio-achieve a converged and flexible radio over fiber networks

With the spreading of virtual reality, mobile online gaming, and other emerging applications concerning about IoT, the fifth generation (5G) mobile communication is heading towards higher data rate, lower end-to-end latency and less power and cost [17]. To achieve these goals, cloud radio access network (C-RAN) has been proposed [18]. A strong motivation of C-RAN is to decouple the baseband processing function, called baseband unit (BBU), from the conventional base station (BS), while making the BS perform radio transmitting/receiving function only, called remote radio unit (RRU). The BBUs are centralized and implemented on a general-purpose platform that can be flexibly configured for better mobility management and cost saving. The RUs are simple, compact and easy manipulating, which can be distributed much closer to mobile users. Mobile fronthaul is a new segment of C-RAN that connects BBUs and RRUs for data transmission. To provide a high bandwidth channel with low latency, optical mobile fronthaul leverages on the strengths of advanced optical technologies to deal with data transmission.

In C-RAN architecture, BBU is responsible for electronic baseband processing, can be moved from the distributed BSs to a BBU cloud at the central office, serving a large group of RRUs, which are simplified as radio-frequency (RF) electronics. The BBU cloud and RRUs are connected by high-speed digital fronthaul links transmitting digitized signals using the common public radio interface (CPRI) [19]. In [20], the authors provide a detailed description for fronthaul requirement in CRAN. First, macro cells typically yield up to 15 RRUs per site. Second, CPRI is a constant bit-rate interface, which requires data rates from 614.4 Mbps up to 24.3 Gbit/s with bit error ratio on the fronthaul link lower than 10^{-12}. Third, the baseband processing at BBU should be less than 1 ms. The round-trip time dedicated to fronthaul and to the optical network segment should be less than 500 µs.

In order to release the pressure of high bandwidth of fronthaul and increase the flexibility of network, the next-generation RAN based on functional split has been proposed which also adopts a baseband processing pooling structure. However, unlike C-RAN, it divides the BBU processing functions into several layers and forms different split options to re-partition RRU and BBU's respective functions. The 5G RAN will evolve from the BBU-RRU two-level structure of the 4G/LTE network to the CU-DU-AAU three-level structure as shown in Figure 3. The real-time processing part of the original BBU will be segmented and redefined as CU (centralized unit). Some of the physical layer functions of the BBU are combined with the RRU as an active antenna unit (AAU). The remaining functions of the BBU are redefined as DU (distribute unit) responsible for processing physical layer protocols and real-time services. The interface protocol of the fronthaul evolves from CPRI to eCPRI/NGFI[1] interface based

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[1] eCPRI 1.0 specification. http://www.cpri.info/spec.html.

Table 2 Literatures on optical plus radio

Research area	References
High-bandwidth provision	Zou et al. [24], Diallo et al. [25], Tayq et al. [26], Yoshima et al. [27], Kondepu et al. [28], Llorente et al. [29]
Low-latency guarantee	Kobayashi et al. [30], Takahashi et al. [31], Tashiro et al. [32], Hatta et al. [33], Anthapadmanabhan et al. [34], Hatta et al. [35], Zhou et al. [36], Xu et al. [37], Chitimalla et al. [38], Chang et al. [39], Chang et al. [40]
The flexibility of optical fronthaul network	Zhang et al. [23, 41–44], Wang et al [45, 46], Carapellese et al. [47]

on functional split options. Therefore elastic lightpath provision with adaptive modulation format was proposed by [21, 22] to achieve flexible fronthaul.

The evolution of the mobile fronthaul network can be divided into two phases. The first stage is a point-to-point fixed connection pattern based on CPRI interface. In this stage, the connections between the BBUs and the RRUs are fixed, the data rate in the fronthaul has been defined in CPRI specification and does not vary with traffic demand of cell sites; the second stage is an any-any connection pattern based on the eCPRI/NGFI which enhances the flexibility of fronthaul. On the one hand, the strong correlation between the number of antennas on the RRU and the fronthaul interface rate is removed, so that the rate of fronthaul interface can be dynamically changed according to the actual user traffic. In addition, some baseband processing functions belonging to original BBU are transferred to the RRU side to relieve the pressure of the transmission bandwidth of the fronthaul network. On the other hand, the cloudized BBU pool can be efficiently and flexibly shared among different RRUs, and achieve statistical multiplexing of baseband processing resources.

The RAN connects the user equipment to the core network through the BS, and the transport network between the mobile core network and the BS is the mobile backhaul networks. Backhaul establishes a secure and reliable connections between the core network and the BS through various physical media. In the long term evolution (LTE) era, backhaul network accounts for data transmission between the eNodeB and the EPC. The core network part mainly completes the functions of authentication, authentication and connection to the Internet for mobile services. At present, there are mainly three technologies for the mobile backhaul: MSTP, PTN, and IP RAN.

The biggest difference between 5G and 3G/4G is that 5G not only has a large bandwidth requirement, but also has clear requirements for multiple scenarios such as ultra-high reliability, low latency communication, and massive machine communication. 5G CU-DU-AAU architecture, mobile edge computing (MEC) function sinking, network slicing and virtualization will call for changes in 5G transport networks. Simply upgrading or expanding PTN, IP RAN, or OTN will not meet future demands. With the further evolution of the 5G transport network architecture, the transport network in the future will be further divided into three parts: fronthaul, mid-haul and backhaul. How to construct the midhaul and backhaul networks is a key issue that needs to be solved.

3.1 Research studies of optical and radio converged technologies

The recent studies on optical plus radio are summarized in Table 2 [23–47], in which the research area are mainly focused on the fronthaul technologies. Large-capacity, low-latency, and high-flexibility are three requirements for optical fronthaul networks.

3.1.1 *High-bandwidth provision*

There is no doubt that high capacity is an ever-lasting goal for any communication system and architecture. Different radio configurations have different CPRI rate levels which go from 614.4 Mbit/s up to 24.3 Gbit/s. Although the eCPRI reliefs the bandwidth pressure, the growing radio frequency band (e.g., 200 MHz) and number of antennas (e.g., 32×32 massive MIMO) still result in huge fronthaul bandwidth demand. Optical technologies with advanced modulation format and multi-dimensional multiplexing [23] are promising solutions for building a high-capacity fronthaul. For example, WDM technology with huge capacity can flexibly provision opical frouthaul [24]. The WDM technology is designed to deliver a wavelength-based P2P connectivity between BBUs and RRHs with each wavelength achieving bit rates up to 10 Gbps over a transmission distance of 20 km. Ref. [25] verifies the compatibility of a self-seeded DWDM solution with the most critical fronthaul requirements with regard of the data rate, the bit error rate, the jitter, the round trip delay and the radio frequency accuracy budget. In [26], experiments were performed on a fronthaul link measuring performances in terms of Ethernet frame loss on the CPRI data transport in a wavelength division multiplexing-passive optical network (WDM-PON)-based fronthaul networks. Beside 100 Gb/s coherent WDM-PON system can also be applied in mobile fronthaul [27]. To reduce the cost of deployment of optical transceivers, flexible VCSEL-based WDM fronthaul is also proposed in [28] and the author experimentally demonstrate that stringent delay and bandwidth requirements in this architecture can be satisfied. Recently, spatial division multiplexing (SDM) is widely studied and discussed. SDM-based fronthaul network is proposed and experimentally demonstrated in [29]. A radio-over-multicore fiber system for fronthaul connectivity is evaluated with full standard 3GPP LTE-advanced signals. It points out that multicore fiber spatial multiplexing and MIMO processing can be used to multiply the data rate with 4×4 MIMO LTE-A.

3.1.2 *Low-latency guarantee*

Some novel application such as automatic drive will be emerging in 5G era, which requires a low latency fronthaul. However, wireless protocol exchanging between BBU and RRU (e.g., hybrid automatic repeat request, HARQ) transmitting over fronthaul will cause significant delay. So optical fronthaul should be re-designed from both radio and optical perspectives to support 5G latency requirement. When applying time division multiplexing-passive optical network (TDM-PON) into fronthaul, the latency due to dynamic bandwidth allocation (DBA) for upstream transmission in TDM-PON, now of the order of milliseconds, is much larger than the 5G expected requirement of 1 ms. In [30, 31], the authors propose a low-delay DBA scheduling mechanism based on simple statistical traffic and demonstrate TDM-PON based fronthaul with small delay variation and low latency. A novel mobile-DBA (M-DBA) scheme [32] with low-latency for a TDM-PON based mobile fronthaul is proposed by the cooperation between OLT and BBU, which can reduce the latency to about 1/20 of conventional one. During the allocation of bandwidth in uplink transmission, Ref. [33] also considers the priority of traffic demand. By allocating less bandwidth for each ONU according to priority information, this method can achieves an ultra-low delay of 60 μs. An optimized TDM-PON with minimal latency for transport of constant bit rate fronthaul traffic was proposed using queuing theory [34], and it proves that latency less than 250 μs can be achieved in the TDM-PON fronthaul mathematical derivation. Also, authors in [35] propose a bandwidth allocation method with adaptive polling period which is a simple three-step allocation: the first two steps are based on the method proposed in [33], and the third step is to shorten the corresponding DBA cycle. This method can automatically adjust the DBA cycle according to the wireless service load conditions, thereby improving the bandwidth utilization while achieving fronthaul latency less than 60 μs. Ref. [36] proposes a mobile front-end network architecture with high bandwidth efficiency and low processing delay, namely mobile-PON. This architecture reconstructs the original TDM-PON function based on the physical layer functional partition and defines a mobile scheduler with unified scheduling function. Besides dynamic bandwidth scheduling, flexible frame structure can also reduce the scheduling latency efficiently. Ref. [37] proposes a PON network architecture based on flexible frame, which separates some functions from the existing PON architecture which can increase the flexibility and response speed of existing PON systems supporting delay-sensitive wireless services and fixed services.

Compared with CPRI over TDM-PON, CPRI over Ethernet has more flexibility in frame scheduling. Ref. [38] gives a latency and jitter studies of CPRI over Ethernet in fronthaul. Based on the idea of functional spilt, Ref. [39] analyzes the effect of different functional partitioning schemes on the fronthaul bandwidth, and analyzed the influence of different packet encapsulation methods on the bandwidth utilization and delay in the fronthaul network. The research results show that there is a close relationship between the overhead of the frame blocking and the delay. Selecting the proper frame blocking method under the determined function partitioning scheme can effectively reduce the network delay and improve the bandwidth utilization. On the basis of [39], Ref. [40] focuses on the study of the frame-blocking method under different functional split schemes and proposes a scheduling algorithm for frame-sealing. This paper studies the effect of different packet scheduling strategies on the statistical multiplexing gain at the RRU gateway. The results show that the LRB (least remaining bit) scheduling strategy incorporating multiple frame blocking techniques can provide the largest statistical multiplexing gain.

3.1.3 *The flexibility of optical front-haul network*

In general, BBUs and RRUs are virtualized in the CRAN. Distributed virtual network functions (virtual BBU and virtual RRU) need to be connected over fronthaul links to form a customized service (network slice) for each individual client. To support this, fronthaul need to exhibit a high degree of flexibility for the connections between BBUs and RRUs. In addition, the NGFI rate is user-dependent that varies with mobile traffic. The tidal-effect mobile users require fronthaul to have elastic resource allocation. Optical networks with programmable optical switches will improve the flexibility of fronthaul. Through the flexible lightpath reconfiguration in the fronthaul network, the performance of the wireless service is improved so as to better satisfy the user experience quality. In [41], the author proposed an AG based lightpath reconfiguration scheme, which exploits the minimum-cut graph to deal with the BBU-RRU mapping problem. The proposed scheme can maximize the intra-BBU CoMP as well as minimize the data migration. In [43], BBU aggregation is proposed which refers to BBU load compaction that is to compact many low-utilized DUs into few BBUs or less by reconfiguring the lightpaths between BBUs and RRUs for energy saving. In [43], based on [42], lightpath reconfiguration is experimentally. In [45,46], the authors proposed TWDM-enabled fronthaul architecture to explore the potential of allocation of time and wavelength under the mobile traffic demand and a virtual PON concept was proposed to dynamically create wavelength channel associating several cells, which can promote wireless performance. In [46], the author proposes an energy-efficient WDM aggregation network, and we formally define the BBU placement optimization problem, whose objective is to minimize the defined aggregation infrastructure power (AIP). Ref. [47] introduces a novel BBU-placement optimization problem for C-RAN deployment over a WDM aggregation network and formalize it by ILP, the results show a tradeoff between the number of BBU-hotels (BBU consolidation), the fronthaul latency and network-capacity utilization.

3.2 Development trends for future works

The reconfiguration of the baseband function and 5G E2E network slicing is the trend of the future RAN, since the baseband processing function is further divided into DU and CU. The structure (Figure 4) requires the deep integration of radio and optical resource, future developments mainly include flexible mapping of wireless resources, dynamic adaptation to mobile services, and efficient connections to virtual functions. For example, more flexible mapping between DUs and CUs through flexible fronthaul network interfaces should be discussed. Also, the currently fixed fronthaul/midhaul service adaptation mode cannot meet future development requirements. A more flexible service configuration model needs to be designed based on service requirements. On the other hand, from the past to the current 4G networks, mobile networks mainly serve mobile phones. However, in the 5G era, mobile networks need to serve various types of equipment. There are more application scenarios including mobile broadband, large-scale IoT, and mission-critical IoT. Different applications need different types of networks with different requirements in terms of mobility, billing, security, policy control, latency, and reliability. How to build a network which can satisfy so many applications with various requirements. We can create multiple logical networks on a physical network through network slicing technology which is a very cost-effective approach. The introduction of network functions virtualization (NFV) technology can improve the overall network operation performance and enable all resources to be flexibly shared. However, it is necessary to cascade or deploy different virtualized functional modules through an effective resource allocation strategy so as to realize diversified mobile services under different network conditions. An end-to-end 5G RAN slicing

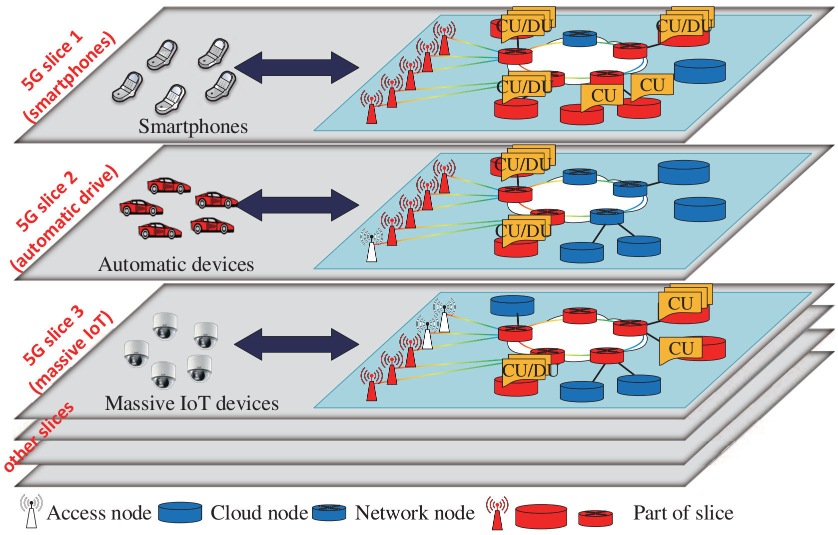

Figure 4 (Color online) End-to-end 5G RAN slicing in a converged radio and optical access networks.

in a converged radio and optical access networks is illustrated in Figure 4 based on the NFV technology. For each slice in Figure 4, the topology and the bandwidth of each link may be different from others. For example, CU/DU will be placed at the site close to RRU for automatic devices scenario. On the other side, CU/DU will be place far away from RRU for massive IoT scenario, since the latency may not the important thing that should be considered firstly.

4 Optical plus computing-achieve collaboration between edge computing with optical networks

With the advancements in IoT, billions of devices are expected to generate a huge amount of data that need to be processed and analyzing in a centralized manner for the cost efficiency and capacity improvement, which is called cloud computing. Data centers consisting of many servers handle a large amount of computing task and cooperate with each other for the more complicated applications through an optical transport network, which is called data center optical interconnection. Nowadays, the explosion of mobile traffic not only inundates the communication networks but may also lead to ineffectiveness of conventional computing paradigms for analysis. The conventional computing approaches require transporting data from source devices over a network, storing it on centralized servers, and then performing analysis. The increase in volume elevates the complexity and costs of transporting and storing the data, and time required to analyze the data. To mitigate these issues, edge computing has been introduced that aims to bring the cloud resources and services closer to data sources. The arrival of edge computing facilitates analyzing the IoT data closer to the sources which is achieved by multiple micro data centers, making applications more responsive to dramatically changing local conditions while avoiding communication bottlenecks of wide area networks. Therefore, frequent data migration and interaction between micro data centers and cloud data center is unavoidable. The use of optical access interconnections is an effective means for achieving efficient collaboration among distributed micro data centers. Reconfigurable optical add and drop multiplexer (ROADM) is a promising device to realize dynamic lightpath provision in the datacenter networks [48].

Cloud computing [49] is an information technology (IT) paradigm that enables ubiquitous access to shared pools of configurable system resources and higher-level services that can be rapidly provisioned with minimal management effort, often over the Internet. It is the delivery of computing services-to-servers, storage, databases, networking, software, analytics and more-over the Internet (“the cloud”). Companies offering these computing services are called cloud providers and typically charge for cloud computing services based on usage, similar to how you are billed for water or electricity at home. In

Table 3 Literatures on optical plus radio

Research area	References
Completion time optimization	Hu et al. [51], Hung et al. [52], Chen et al. [53], Yao et al. [54, 55], Li et al. [56], Wang et al. [57], Liu et al. [58]
Joint optimization of spectrum and computing resource	Gharbaoui et al. [59], Takita et al. [60], Liu et al. [61], Fang et al. [62]

the aspect of cost, cloud computing eliminates the capital expense of buying hardware and software and setting up and running on-site datacenters-the racks of servers, the round-the-clock electricity for power and cooling, the IT experts for managing the infrastructure. Cloud computing makes data backup, disaster recovery and business continuity easier and less expensive, because data can be mirrored at multiple redundant sites on the cloud provider's network. Network virtualization is the key to the current and future success of cloud computing2). It turns out that computer networking itself has to be virtualized.

MEC [50] is a network architecture concept that enables cloud computing capabilities and an IT service environment at the edge of the cellular networks. The basic idea behind MEC is that by running applications and performing related processing tasks closer to the cellular customer, network congestion is reduced and applications perform better. MEC technology is designed to be implemented at the cellular BSs, and enables flexible and rapid deployment of new applications and services for customers. Combining elements of IT and telecommunications networking, MEC also allows cellular operators to open their RAN to authorized third-parties, such as application developers and content providers3).

4.1 Research studies of edge computing enabled optical networks

The recent studies on MEC over optical networks are mainly focused on job completion time optimization and joint optimization of spectrum and computing resources, which are summarized in Table 3 [51–62].

4.1.1 *Completion time optimization*

A number of research studies have been carried out to optimize completion time. By considering both route allocation and bandwidth allocation, the average batch data transmission time is minimized on the basis of improving network resource utilization. The authors in [53] propose to reduce the response time of the user request by jointly optimizing the location and path of the target data center considering data calculation and processing. Disaster recovery based on disaster awareness in multiple data center systems across different geographical locations is also investigated [54] in terms of backup time. Ref. [55] uses minimum-maximum fair design to optimize multiple batch data transmission scheduling algorithms. Ref. [56] proposes a delay-optimized traffic routing scheme for optimization of large data traffic across geographically distant data centers.

According to the request's explicit division of delay sensitivity, an optimal path is selected for different requirements to achieve large data flow and the delay in transmission is the lowest. They focused on non-real-time data backup and migration and rescued unutilized bandwidth across core data centers (DCs). The scheduling of multiple jobs were not studied. Because the processing capacity and storage capacity of the micro-datacenter are limited. So, the sequence of multiple parallel processing tasks needs to be decided. In [63], an optimization target data center selection algorithm for a task (a task containing only multiple associated subtasks) across different data center environments is proposed by determining the optimal task processing. The target data center minimizes task data transmission in the network, thereby reducing the completion time of a single task. But in general, the data required by users may be stored in multiple geo-distributed DCs. Therefore, the characteristic of job model with multiple related tasks were considered. Ref. [51] proposes an optimization algorithm for scheduling tasks in the data

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2) https://en.wikipedia.org/wiki/Cloud_computing.

3) https://en.wikipedia.org/wiki/Mobile_edge_computing.

center according to the task's processing time in the data center, and a task scheduling algorithm that minimizes task completion time. Ref. [52] also proposes that in a multi-data center network distributed across different locations, tasks can be allocated to the optimal data center by optimizing the position of task processing, so that the average completion time of multiple tasks can be minimized. In [55], in a multi-data center network distributed across different locations, both the bandwidth utilization and the user's delay requirement are taken into account. The sum of the reciprocals of the bandwidth utilization and the user delay is minimized by using the Nash equilibrium.

4.1.2 *Joint optimization of spectrum and computing resource*

In the data backup, data migration or cooperative task operation, data need to be routed from one micro data center to other data center through the optical transport networks which requires optimized routing and spectrum allocation schemes. In [58], the author investigates the data path allocation policies to select a proper inter-DC network path, and accordingly a destination server, to allow VM migration data to experience adequate delay performance. To provide dynamic and reconfigurable services in order to adapt to the dynamicity of cloud traffic as well as to maintain the optimality of resource utilization, the author proposed a re-optimization process which can minimize connection disruption by determining migration order [59]. The joint optimization of optical spectrum resources and IT resources can reduce the consumption of spectrum and computing resources, thereby reducing the blocking rate of service requests [60]. In [61], a network reconfiguration scheme that considers the controllability of multi-dimensional resources in a joint manner is proposed in the data center interconnected EON for the joint fragmentation reorganization of spectrum resources and computing resources, which not only changes the optical path routing and spectrum resources, but also changed the computing resources in the data center. Ref. [62] proposes an optimization algorithm for effective virtual network function service chain configuration by jointly considering optical spectrum resources and computing resources, thereby reducing the consumption of spectrum resources and reducing the blocking rate of data transmission.

4.2 Development trends for future works

The cooperation between multiple micro data centers is the trend of edge computing in the future. Optical communication is an important means of interconnecting and interoperating data centers and an effective method for efficient data calculation and processing. The future topics mainly include the following aspects. First, for the characteristics of high burstiness and high dynamicity of the traffic in the micro-data center interconnected optical network, it is necessary to achieve adaptive routing, modulation format and spectrum slot allocation. Second, for the heterogeneity features of the micro data center, coordinating the data calculation and processing resources of each micro data center through the optimal configuration of optical networks. Third, to achieve efficient and efficient spectrum allocation for both the network and IT resources that affect the characteristics of both operators and content providers. The joint optimization of IT resources to complete the optimal allocation of resources. Elastic edge optical networks under the micro-DC interconnection is shown in Figure 5. The edge computing nodes are placed at the RRU sites or at the metro network. Elastic optical network is a promising technology to provide adaptive bandwidth and modulation format. Then the transport bandwidth between the edge computing nodes could be flexible with deadline of each jobs.

5 Optical plus AI- achieve co-automatic control and manipulate of optical networks

With the advent of the IoT, a variety of heterogeneous networks are intertwined, and a variety of information technologies are integrated with each other, resulting in a substantial increase in the scale of optical network equipment, and an increasing complexity of network. Relying on network management control and manual intervention, it is unable to meet the evolutionary needs of the future flexible network. Moreover, the network management or human intervention easily fall into a partial optimization

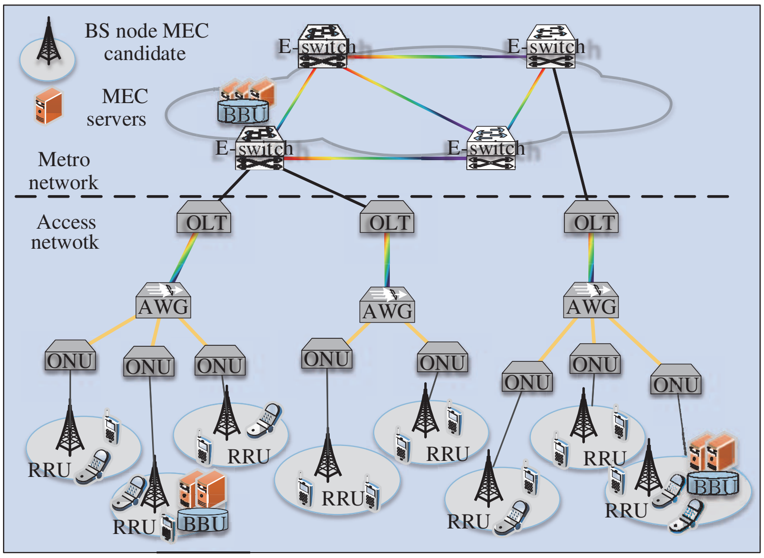

Figure 5 (Color online) Edge computing architecture with a collaborative edge optical network.

Table 4 Literatures on optical plus AI

Research area	References
Optical signal detection and nonlinear compensation	Maor et al. [64], Liu et al. [65], Liu et al. [66], Rafique et al. [67], Ekanayake et al. [68], Lau et al. [69], Napoli et al. [70], Wang et al. [71], Lin [72], Huang et al. [73], Zhang et al. [74], Takagi et al. [75], Cugini et al. [76]
Optical system condition monitoring	Mo et al. [77], Samadi et al. [78], Dikbiyik et al. [79], Hou et al. [80, 81], Huang et al. [82], Li et al. [83], Wang et al. [84], Christodoulopoulos et al. [85], Barletta et al. [86]
Optical network resource optimization	Chen et al. [87, 88], Ohba et al. [89], Box et al. [90], Ohba et al. [91]

trap in a complex environment, which requires more flexible and intelligent optical networks. Therefore, co-automatic optical networks with artificial intelligence (AI) will become the main trend of the next generation optical network evolution.

In broad terms, ML is a study of how a computer simulates or implements human learning behavior to acquire new knowledge or skills, and reorganizes an existing knowledge structure to continuously improve its performance. It is the core of AI, and it is the fundamental way to make computers intelligent. Its application covers all areas of AI. It mainly uses induction, synthesis rather than interpretation. Over the past decade, ML has helped us to automate the driving of cars, effective voice recognition, effective web search, and greatly improved human genome awareness. In this paper, we mainly investigate the application of ML into optical networks and explore how ML can benefit the researching fields of optical signal detection and non-linear compensation, optical system condition monitoring, and optical resource optimization.

5.1 Research studies of optical and AI technologies

Optical communication enhanced by AI technologies is a hot topic in recent years. From optical physical layer to network layer, ML supports optical communication in many aspects, the research area are summarized in Table 4 [64–91].

5.1.1 *Optical signal detection and non-linear compensation*

AI approaches such as neural networks are used to detect the optical layer signal and compensate for its nonlinear effects, which greatly improves the accuracy of signal detection and compensation. The related AI-assisted works on predicting the traffic fluctuation to avoid future cascaded failures of the sudden congestion, automated fault detection, mitigating nonlinear phase noise (NLPN), and compensating for the pose-EDFA discrepancy without the data given in advance, are reviewed in the following.

As the ever-growing IP applications and frequent service interruptions in an IP-over-EON, to ensure a survivable IP over EONs, effective cross-layer orchestration, and centralized network control and management, it is necessary to investigate SDN enabled multi-layer restoration (MLR). Moreover, distributed and centralized new frameworks, such as SDN, are able to enhance the performance of network programmability. However, since IP traffic is dynamic and bursty, conventional studies [64, 65] only re-establish new routes for the affected flows based on the current network status, which may not be efficient to avoid future cascaded failures triggered by the congestion of the sudden increase of certain flows? data-rates. With the prediction of the traffic fluctuation, AI assisted MLR based on the deep learning presents more effective and intelligent to avoid future congestions [66]. Besides, typical network management approaches bring a variety of negative costs of underutilization of network resources, unpredictable condition, increasing network complexity. To investigate network assurance involving automated fault detection, a transport SDN (TSDN)-integrated cognitive fault detection architecture, incorporating data analytics based on advanced ML methods have been proposed [67]. To mitigate NLPN [68], commonly used conventional approaches are the maximum likehood estimation (MLE) [69] and digital back-propagation (DBP) algorithms [70]. These approaches depend on the fixed fiber link information, which are not efficient in dynamic and reconfigurable optical network conditions. To address these problems and mitigate the NPLN in a more efficient and optimal way, a machine-learning based classifier, named support vector machine (SVM) algorithm into the M-PSK based coherent optical transmission system is proposed [71]. Furthermore, no information is required in advance, which can be learned from the training data by SVM. The ML approach can also compensate for the post-EDFA discrepancy [72] at automatic and dynamic adjustments of pre-EDFA power levels [73]. The channel-dependence of power excursions for three defragmentation methods of hop [74], make-before-break [75], and sweep [76], are characterized, and an adaptive strategy for automatic power adjustments is proposed during the defragmentation process.

5.1.2 *Optical system condition monitoring*

For the signal-to-noise ratio of the optical link and the performance of the optical system equipment, the improvement of the SNR and the effective prediction of the system equipment can be achieved through ML methods. The related studies with AI approaches on the quality of transmission (QoT) prediction, optical signal to noise ratio (OSNR) estimation, predicting optical network equipment failure, compensating physical layer impairments, and predicting the probability of bit-error-rate (BER) are reviewed in the following.

Compared with the existing Q-factor and OSNR prediction model, an artificial neural network (ANN) based transfer learning scheme can achieve higher accuracy QoT prediction in various networks with different system configuration in a high accuracy in real time mixed line-rate systems. Besides, ANN model is not required to re-train from scratch [77]. The experimental setup for mix line-rate QoT prediction using ANN-based transfer learning with an SDN controller is also presented. The estimation of QoT before establishing the lightpath in dynamic and agile network is necessary. Due to the conventional OSNR analytical models estimate QoT showing inefficient performances, such as requiring component specifications of network, over provisioning with increasing margins and resource under-utilization, dependent to the accuracy of the modeling, and inaccurate model, it is necessary to propose a novel cognitive method to achieve more optimal OSNR estimation [78]. Neural network with the ML engine could address this problem with no prior network knowledge requirements, which is scalable to large size networks, high accuracy, and adjusting the dynamic condition of network.

In addition, the disaster/attack scenarios occur more frequently. However, traditional risk models

[79–83] focus on switching the services or establishing a backup protection scheme to solve optical network failure problems. A method of predicting optical network equipment failure based on a method combining double-exponential smoothing (DES) and a specific SVM is proposed [84]. For the efficient resource optimization problem, the existing research predicts the QoT of unestablished lightpaths through optical performance monitors (OPMs) installed at the receiver side based on the field data [85]. Based on the history data of traffic requests, the modulation format, the lightpath total length, the length of its longest link and lightpath link number, a ML based classifier is proposed to predict the probability of BER of lightpath [86].

5.1.3 *Optical resource optimization*

Through monitoring the status and traffic demands, setting reasonable optimization goals, and autonomous learning based resource deployment strategies, the intelligent control is achieved, the congestion rate of access network is reduced, and user service experience is improved. The related studies on AI-assisted RMSA (routing, modulation and spectrum allocation) in dynamic networks, virtual network reconfiguration framework are reviewed in the following.

RMSA is one of the critical topics in EONs. Although a lot of in-depth RMSA research has been discussed, these existing heuristic algorithms or theoretical models are fixed and not flexible to solve more complicated RMSA schemes. Specifically, as time-varing traffic demands arrive at the dynamic networks, these proposed approaches are not adaptive to solve the RMSA problem in the complicated environment. A deep reinforcement learning based self-learning RMSA is proposed in dynamic EONs [87]. According to different EON conditions and dynamic and bursty service requests, a deep Q-network consisting of multiple convolution and fully connected layers, is constructed to learn the RMSA policies. Compared with the basement RMSA algorithm, proposed cognitive and autonomous RMSA has been verified its significant superiority in different aspects. Besides, deep learning approach makes some breakthroughs to intelligently improve the inefficient resource utilization. In [88], a deep learning knowledge-based autonomous service provisioning framework is proposed for broker-based multi-domain SD-EONs. According to the predicted traffic, an autonomous and intelligent traffic engineering is discussed using a deep neural network (DNN) based traffic estimator, and an inner-domain RMSA, which performs high accurate traffic prediction and effective blocking rates reduction. Furthermore, driven by the dynamical nature of the network virtualization, and inspired by human's recognition and decision-making, a VN reconfiguration framework based on the Bayesian inference is developed. Moreover, the current traffic situation is inferred from the Bayesian attractor model [89]. A concept of Bayesian inference is utilized to identify the traffic situation from easily available information in a dynamic environment [90]. A noise-induced VN reconfiguration method incorporating proposed VN framework is presented to reconfigure a VN no matter the identification succeeds or fails [91].

5.2 Future development trends of “optical plus AI”

In order to achieve highly reliable transmission, high effective resource deployment, and low operation and maintenance complexity, the integration of optical and AI is imperative. Future developments mainly include the following aspects. First, intellisense and prediction of the optical transport layer. Whether it is optical signal processing or network state awareness, it is ultimately an accurate and rapid processing of transmission system information, and the integration of optical and AI can overcome the problems of the existing systems and time complexity, and play a good role in the foundation of efficient network maintenance and management. Second, automatic deployment of optical network resources. The increase in the complexity of the access network makes the deployment of its resources more difficult. Relying on traditional manual and semi-intelligent deployment strategies cannot meet the flexible and dynamic network requirements in the future. The automated deployment of optical plus AI overcomes this drawback by actively learning to adapt to a flexible and flexible network environment, enabling efficient and flexible deployment of system resources. AI-assisted co-automatic and intelligent optical network is illustrated in Figure 6. Massive information are collected through a south bound interface (SBI) of SDN, and the

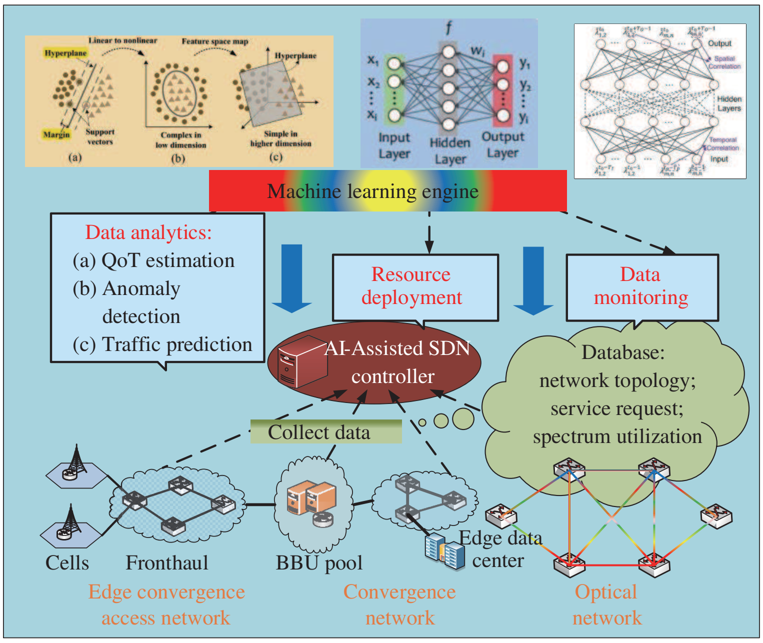

Figure 6 (Color online) AI-assisted co-automatic and intelligent optical network.

information is processed with ML. An ML based engine is embedded in the SDN controller. After the learning process is finished, the controller can deploy network resources automatically.

6 Conclusion

As a key technology of information networks, optical communication plays an irreplaceable role in its evolution and development. This paper discussed the benefits of "optical plus X" to achieve a converged, collaborative and co-automatic (3C) optical network. We reviewed on the background, challenges, and solutions of "optical plus X" that includes "optical plus IP", "optical plus radio", "optical plus computing", and "optical plus AI". The inevitable trends and bright future for the development of optical networks with different technologies were also introduced.

In summary, to deal with the increasing number of things that are connected to the Internet, optical networks should be moved to the edge of the network, and converged with the mobile network to provide high-capacity and low-latency service for the mobile users. In addition, RAN transport networks with optical technology influence the edge computing significantly, where the placement of micro datacenter should be close to the RAN transport network (e.g., midhaul or backhaul). The joint resources allocation in optical plus IP, optical plus radio, and optical plus computing should be assisted by AI to realize an automatic and intelligent deployment.

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