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Recent Advances in Elastic Optical Networking

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SUMMARY Many detailed studies ranging from networking to hardware as well as standardization activities over the last few years have advanced the performance of the elastic optical network. Thanks to these intensive works, the elastic optical network has been becoming feasible. This paper reviews the recent advances in the elastic optical network from the aspects of networking technology and hardware design. For the former, we focus on the efficient elastic network design technology related to routing and spectrum assignment (RSA) of elastic optical paths including network optimization or standardization activities, and for the latter, two key enabling technologies are discussed: elastic transponders/regenerators and gridless optical switches. Making closely-dependent networking and hardware technologies work synergistically is the key factor in implementing truly effective elastic optical networks.

key words: *elastic optical network, network design, routing and spectrum assignment, elastic transponder*

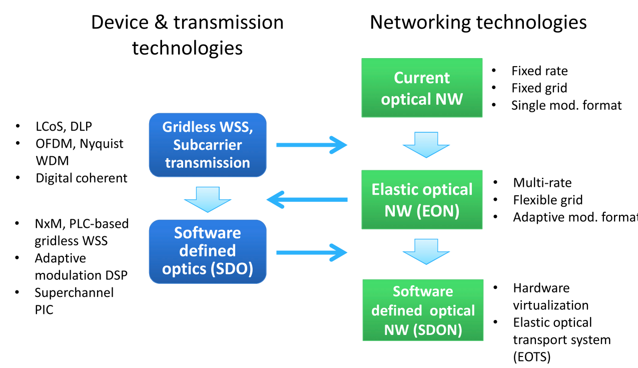

Fig. 1 Optical networking evolution.

1. Introduction

Currently deployed optical networks rely on fixed-rate wavelength-division multiplexing (WDM) signals set on a fixed frequency grid with fixed frequency spacing of, for example, 50 GHz, and employ a single transmission technology regardless of the wide variety of traffic demands. Bandwidth flexible and adaptive optical networking, referred to as elastic optical networking, enables fully flexible, multi-rate optical networks. For example, 50 GHz and 100 GHz spectra are allocated to middle distance and long distance 100 Gb/s channels using different modulation formats such as quadrature phase shift keying (QPSK) and binary phase shift keying (BPSK), respectively; 150 GHz and 100 GHz spectra are allocated to middle distance and short distance 400 Gb/s channels employing QPSK and 16-ary quadrature amplitude modulation (QAM), respectively. Elastic optical networking is expected to significantly improve the spectrum and energy efficiency while supporting the desired quality of service (QoS) levels, all of which are needed in the era beyond 100 Gb/s [1]–[3].

The architecture of elastic optical networks utilizes recent progress in gridless wavelength selective switches (WSSs) and subcarrier transmission based on digital coherent technology. Elastic optical networking is now driving new innovations in optical switch and transponder designs toward software defined optics. These innovations will yield deeply virtualized optical networks leading to software defined optical networks (SDONs), in which elastic optical transport system (EOTS) offers hardware virtualization derived from software defined optics and spectrum resource virtualization derived from elastic optical networking [4]. This interdependent evolution in optical networks between devices, transmission and networking technologies is illustrated in Fig. 1.

This paper reviews recent advances in the elastic optical network from the viewpoints of networking, transceivers, and switches. This paper is organized as follows. Section 2 presents overviews network design issues in the elastic optical network focusing on RSA algorithms, network optimization, network survivability, and multi-layer network design. Recent testbed activities as well as the standardization status of elastic optical networking are also reported. Section 3 reviews hardware design issues in the elastic optical network. We discuss two key enabling technologies; elastic transponders/regenerators and gridless optical switches.

2. Network Design in Elastic Optical Network

The elastic optical network adaptively allocates spectrum resources to an optical channel according to its traffic volume (rate-adaptive) and transmission distance (distance-adaptive). Optical channels with a wide variety of spectrum widths are aligned using the minimum required guard-bands between adjacent channels. Numerical evaluations of the traffic-accommodation efficiency have shown that elastic optical networks with adaptive spectrum allocation offer enhanced spectrum efficiency and better blocking probability

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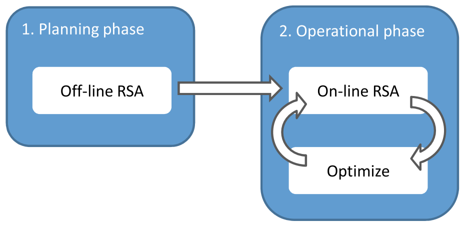

Fig. 2 Network planning and operation process.

than fixed-grid fixed-modulation-format networks [3], [5], [6]. However, the increased complexity created by the parameters needed for realizing flexibility requires a truly sophisticated network design scheme.

This section describes recent network design issues with and approaches to the elastic optical network. The network life cycle generally consists of a planning phase and operational phase as illustrated in Fig. 2. RSA process covers each of them (off-line and on-line RSA), which is described, with solutions, in Sect. 2.1, while the optimization process is detailed in Sect. 2.2. The remaining subsections address items to related optical path assignment: survivability, multi-layer network design, standardization, and network testbeds.

2.1 Routing and Spectrum Assignment

A key problem with fixed-grid networks, which use rigid frequency grids, is the difficulty of assigning routes and wavelengths (center frequency) to optical paths. Referred to as the routing and wavelength assignment (RWA) problem, it is known to be non-deterministic polynomial time (NP) -complete. The problem entails the wavelength continuity constraint that the same center frequency must be used in all links of the route, which means that optical paths must be carried transparently, i.e. no wavelength conversion. For elastic optical networks, the RWA problem evolves into the RSA problem. RSA imposes the additional constraint of spectrum contiguity; frequency slot units (building blocks of frequency slot) [3] assigned to an elastic optical path must be contiguous.

Distance-adaptive modulation [2] is a noteworthy method for efficient spectrum assignment in elastic optical networks. In current fixed-grid based optical networks, the modulation format is determined uniquely in the network so as to assure the transmission quality of the longest optical path in the network. On the other hand, the distance-adaptive elastic optical network adapts transmission parameters such as modulation format and number of carriers to suit the optical reach and maximize the spectral efficiency. This adaptation reduces spectrum requirements and increases fiber resource utilization efficiency. Optical transponders that have bandwidth-tunability such as bandwidth-variable transponder [1] or multi-flow transponder [7] support modification of the transmission parameters. These flexible transponder architectures are detailed in Sect. 3. A basic evaluation showed that distance-adaptive modulation can reduce spectrum resource requirements by more than 45 percent compared to ITU-T 100 GHz fixed grid [2]. Efficient RSA algorithms with distance-adaptive modulation are detailed in [6]. Similar solutions are referred to as routing, modulation level and spectrum assignment (RMLSA) algorithms [5].

2.1.1 Solutions

Integer linear programing (ILP) is a popular technique for designing optical networks [8], [9]. The ILP approach is based on mathematical programming and so yields optimal results from objective and constraint functions. The objective function is usually set to minimize the amount of assigned spectra or equipment cost. If network topology, number of optical path demands, and available spectrum resource are small compared to computing resources, the problem can be solved optimally in reasonable time; otherwise the approach becomes impractical. One way to resolve this issue is to divide the problem into smaller sub-problems and solve them sequentially, such as determining route first and then assigning spectra to the routes [5], [10]. Another way is to adopt LP-relaxation, which solves ILP without demanding integer variables [8].

(Meta-) heuristics is an alternative solution; it is faster than ILP and can find good enough solutions. In addition to large-scale RSA, complicated combinational problems such as traffic grooming, regenerator placement can also be solved in reasonable time by this technique [11]. Following sections mainly focus on heuristic approaches.

2.1.2 Off-Line and On-Line RSA

Several RSA algorithms have been shown so far, but none can cover all situations. They can be categorized into two types according to the operating phases: off-line RSA and on-line RSA.

In the first phase of planning optical networks or in the phase of expanding the network, we need to estimate the required amount of equipment such as transponders and fibers from projected demands. Optical path demands are not given sequentially but are given collectively, so optical paths can be assigned in arbitrary order. Referred to as off-line RSA, it determines optimal network states from static optical path demands which are independent of path assignment order. Both ILP and the heuristic algorithm can be applied.

While operating the transport network, optical path demands are given intermittently as traffic grows and future demands are generally unpredictable. For this we need the on-line RSA algorithm, which determines and then assigns the appropriate route and spectrum for an optical path demand. When optical path demands are given sequentially, the algorithm addresses them in order of arrival. Some situations assume the removal of optical paths because of service termination or link/node failure, which forces the on-line RSA to be even more dynamic. ILP may be not suitable

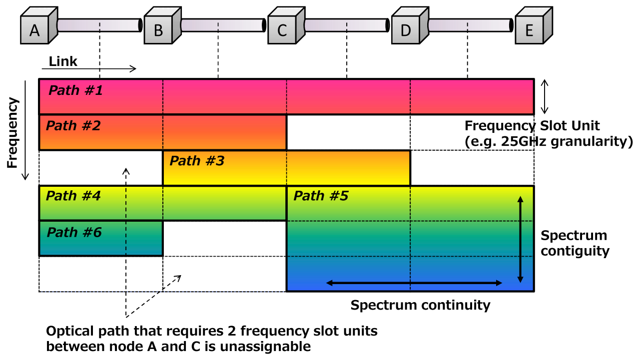

Fig. 3 Spectrum assignment of elastic optical paths.

for the on-line RSA, because ILP does not guarantee optimum solutions [10].

2.1.3 Resource Assignment Criteria

Many proposed on-line RWA algorithms assume a fixed grid, and are mainly differentiated by wavelength assignment policy: random, first-fit, least-used, most-used, for example [12]. The basic concept of these algorithms is also applicable to flexible grid, but many algorithms that exploit the characteristics of elastic optical networks have been proposed and they often outperform traditional algorithms.

The most important factor to be considered is to mitigate the fragmentation of frequency slots, which means that small isolated frequency slot fragments cannot be used by elastic optical paths that require wider frequency slot width or longer route (Fig. 3). The fragmentation in the frequency domain is caused by the spectrum contiguity constraint and that in the spatial (link) domain is caused by the spectrum continuity constraint. The former constraint is characteristic of the elastic optical network, so minimizing the fragmentation is the key factor for efficient resource utilization. However, how to represent the network status quantitatively to counter fragmentation is still a research problem. The maximum common large segment (MCLS) algorithm [13] is one of fragmentation-aware RSA algorithms; it tries to maximize the number of consecutive unused slots on the frequency axis; fragmentation is minimized by comparing frequency slot usage states of adjacent fibers for each frequency slot unit index. Thus it can maximize the success of assigning new elastic optical paths. Evaluation result showed that MCLS statistically provided higher provisionable path capacities compared to other algorithms such as random, first-fit and most-used. Other work [14] proposes utilization entropy (UE), which quantifies the fragmentation level in a link, a path, or a network by counting the utilization status changes between adjacent spectrum slot units. Node handling capacity (NHC) is a node-based evaluation scheme; it introduces a metric to address the relationship among the links connected to a node [15].

Determining the frequency slot granularity that best suits the network condition is also a problem. Reference [16] showed that spectrum utilization is minimized when the slot unit width equals the greatest common factor of the frequency slot widths of all channels in the network, and that fragmentation can be alleviated when the number of slot units of each mixed-rate channel is an integer multiple of the number of slot units of the lowest rate channel.

2.2 Network Optimization

When considering a dynamic network, where elastic optical paths with a wide variety of spectrum widths can be added and removed over time to support, for example, on-demand optical path services, there will be small segments of unoccupied spectra that may not be assignable to other optical paths. In addition to fragmentation-aware RSA, defragmentation, which moves one or more optical paths to other routes or spectra, is also a key challenge for achieving high spectral efficiency. Some defragmentation methods have been proposed and demonstrated.

First is the make-before-break method [17], which establishes an additional connection between the source and destination pair and then switches the path to it. It is a straightforward method and it has high flexibility in that it can switch the path to other routes, but it is costly because additional transponder pairs are needed. The second is referred to as push-pull defragmentation [18] or wavelength sweeping [19]. The method is comprised of three steps: 1) reserve contiguous and unused spectrum slots to be defragmented along the optical path, 2) sweep the nominal central frequency of source and destination transceivers as well as gridless WSSs along the optical path to the target central frequency, and 3) release formerly-used spectrum slots. In the method, re-tunable frequency slot area is restricted to adjacent unused frequency slots in the same route, but it does not require additional transponders or optical path setup/tear-down processes. Another solution adopts wavelength converters [20]. It is a straightforward solution, but the devices are still expensive despite the research efforts expended to date.

2.3 Survivability

2.3.1 Adaptive Modulation for Fault Tolerance

Adaptive modulation technology offers not only high spectral efficiency but also high survivability. Assume that a widespread disaster has simultaneously cut links along primary and secondary routes and the surviving detour route exceeds the optical reach of the original working optical signal as shown in Fig. 4. The original design for the primary and secondary paths, 700 km distance, used 100 Gb/s dual-polarization(DP)-QPSK, but the remaining detour route is 1,400 km. In this case, traditional optical networks would need costly optical to electrical to optical (O-E-O) conversion in an intermediate node on the detour route. On the other hand, the elastic optical transponder of the elastic optical network allows the network operator to increase the spectrum allocated to the detour route to support a more

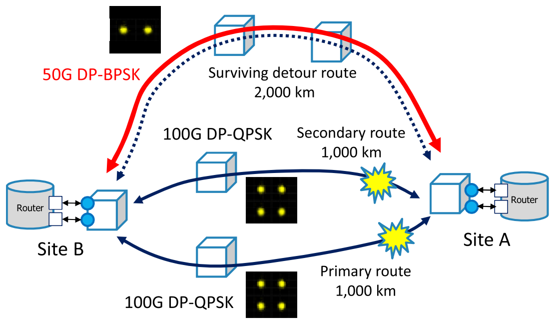

Fig. 4 An example of adaptive modulation.

impairment-tolerant modulation format (50 Gb/s DP-BPSK in Fig. 4), resulting in increased network resiliency. In this case, preserving high priority traffic in cooperation with the client layer network is necessary to prepare for the bitrate decrease. Controlling subcarrier count also contributes to high survivability. The concept of bandwidth squeezed restoration, which controls orthogonal frequency division multiplexing (OFDM) subcarriers in cooperation with service class, is detailed in [21] together with an interworking architecture and control framework.

2.3.2 Protection Algorithms

The protection algorithms of the elastic optical networks use the basic scheme as those in fixed-grid optical networks. However, the impact of fragmentation is expected to be more critical than is true in non-protected networks. For example, when a primary path that requires some frequency slot units is assigned, secondary path assignment fails if just one of the frequency slot units of the secondary path overlapped one of those of the primary path. Therefore, one of the important goals of protection algorithms in elastic optical networks is to find available routes and slots efficiently as the first step.

A dedicated protection algorithm was proposed in [22]. To find primary and secondary path pairs, it created auxiliary graphs, whose links are established if the required set of consecutive frequency slot units is available, for each frequency slot unit index. It then located path pairs by applying traditional algorithms for searching diverse paths to each graph. It showed that introducing flexible grid still reduced required spectrum, power consumption, and network cost even considering survivability.

Shared protection is more complicated. In traditional fixed grid networks, a shared path has binary state in a link: shared or not shared. On the other hand, in the elastic optical network, a shared path has the additional state of partially shared (Fig. 5). Maximizing shared resources for each secondary path is one strategy for achieving efficiency. The efficient shared protection algorithm for static traffic demands proposed in [23] pursued optimal routes and slots by iteratively relocating paths using the metrics of spectrum utilization efficiency (i.e. how many slots are shared) and fragmentation parameters.

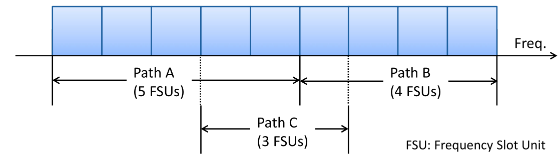

Fig. 5 Partial frequency slot sharing in the shared protection [22].

2.4 Multi-Layer Network Design

If the IP traffic increases continuously at its current rapid pace, directly accommodating client IP traffic in the optical layer will become more likely in the future. Two trends support this: the first is the narrowing bitrate gap between transport layer wide area network (WAN)-based link technology and client layer local area network (LAN)-based link technology. In the past, many low-rate channels were multiplexed into a large transport link, but currently 100 G Ethernet is directly accommodated as Optical channel data unit 4 (ODU4). The second is the emergence of bandwidth-flexible capability in the optical domain, which eliminates electrical switching in the intermediate core node. Therefore, integrated network design of IP layer and elastic optical layer should be considered for cost- and energy-efficient future backbone networks.

Reference [24] proposes a national backbone network architecture that assumes an Internet protocol/multi-protocol label switching (IP/MPLS) layer for metro networks and multi-flow transponder-based elastic optical networking for the core network; it also addresses the metro area partitioning problem. References [25], [26] try to evaluate the performance of IP over elastic as compared to mixed-line-rate, which uses different types of fixed transponders to suit traffic demands, in terms of capital expenditure (CAPEX) and power consumption. They claim that the elastic optical network has no significant benefit other than total number of transponders and spectral efficiency (number of fibers). Their evaluations are reasonable but do not include the multi-flow transponder model. Our previous study addressed an IP over elastic optical network design scheme and compared several models differentiated by transponder architecture [27]. It showed that the elastic network model based on multi-flow transponder needs fewer router line cards (approx. 20% fewer than bandwidth-variable transponder-based elastic optical network), transponders (38–82% fewer) and wavelength selective switches (approx. 20% fewer) because of its feature of bundling multiple optical flows into an optical signal. Its follow-on [28] showed that the network also contributes to CAPEX reduction, even the cost increase of the multi-flow transponder is considered.

2.5 Standardization

International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) introduced a flexible grid option in its G.694.1 recommendation in order to support adaptive spectrum allocation, where the frequency slot concept is introduced as the frequency range that an optical channel is allowed to occupy. The allowed frequency slots have a nominal central frequency defined as 193.1 THz plus/minus an integral multiple of 6.25 GHz and a slot width defined as an integral multiple of 12.5 GHz. ITU-T has recently started discussions on the beyond 100 G optical transport network (OTN). One of major issues is its bit rate. We have two choices for the next optical channel transport unit (OTU) frame. One option is the fixed rate OTU5 with a bit rate of, for example, 400 Gb/s, and the other is the flexible rate OTU with a variable bit rate defined as, for example, an integral multiple of 100 Gb/s.

Standardization efforts for applying the generalized multi-protocol label switching (GMPLS) architecture and protocols to elastic, flexible-grid optical networks have also started in Internet Engineering Task Force (IETF). Such efforts include discussions on a framework and associated control plane requirements for the GMPLS-based control of elastic, flexible-grid optical networks [29], wavelength label extension with additional frequency slot width parameters [30], generalized label for superchannel assignment [31], and routing and signaling protocol extensions.

2.6 Networking Testbeds

Since the first concept-proof demonstration in 2008 [32], a number of elastic optical networking testbeds have been reported. For example, the University of Essex reported a field trial with flexible spectrum switching nodes over 620 km field-installed fiber links [33]. UC Davis demonstrated a real-time, impairment-aware networking testbed with an adaptive control plane [34]. KDDI Laboratories presented dynamic elastic path provisioning using an OpenFlow-based control plane [35].

3. Transponder and Switch for Elastic Optical Network

3.1 Elastic Transponders

Emerging digital coherent technology employing digital to analogue converters, analogue to digital converters (DACs/ADCs), in-phase and quadrature-phase (IQ)-modulators, and DSP has brought a new degree of freedom in designing optical transponders. By adjusting the symbol rate, bits-per-symbol (i.e. modulation format), and number of subcarriers, data-rate and/or modulation-format elastic optical transponders can be achieved [36]. There are two options in modulation-format elastic optical transponder design: constant-capacity/adaptive spectral-occupancy and constant-spectral-occupancy/adaptive capacity. In the former, the symbol rate and bits per symbol are adjusted to minimize spectral occupancy thus saving the spectrum resources in the network while ensuring the required optical reach. On the other hand, in the latter, the symbol

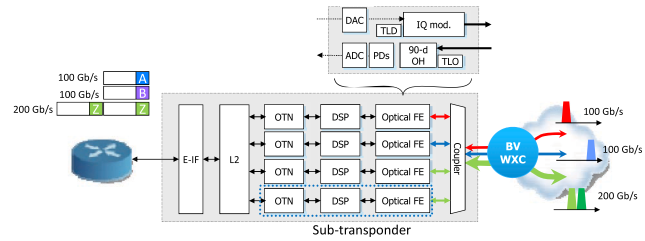

Fig. 6 Multi-flow transponder architecture example.

rate is fixed and the bits-per-symbol is adjusted to maximize the channel capacity while guaranteeing the required optical reach. It should be noted that, in both designs, adjustability originates from engineering the transponders for the maximum symbol rate or the maximum client capacity. This may result in stranded hardware resources when used at lower symbol rate or lower client demands.

One way to balance adjustability against cost-efficiency for heterogeneous traffic demands would be to equip optoelectronic elements as sliceable hardware resources that can be shared with heterogeneous optical channels having a variety of data rates and transmission distances [37]. A multi-flow transponder, where the transponder is sliced into several virtualized sub-transponders that translate client data flows that arrive from a single router interface into optical flows was proposed in [7]. Figure 6 shows a multi-flow transponder architecture example. The multi-flow transponder supports identification of client data flows using packet identifiers, e.g., Virtual LAN (VLAN) tags. Each client data flow is mapped into an appropriate OTU frame according to the size of the flow, and translated into an optical flow with different wavelengths using a shareable optical transceiver front-end and a modulation/demodulation digital signal processor. The optical front-end pool consists of an array of IQ modulators and 90-degree hybrid optical coherent receivers with tunable laser diodes.

A similar architecture can be applied to achieve the sharable elastic regenerator, which consists of an array of spectrum-selective subchannel regenerators that acts as a virtualized regeneration resource pool [37]. Spectrum selectivity can be achieved by using optical coherent detection with wavelength tunable local oscillators. A proof-of-concept real-time demonstration that used 128-Gb/s DP-QPSK transponder prototypes was reported.

A photonic node architecture with shared universal transceivers was proposed by Fujitsu in 2012 [38]. In their architecture, a pool of universal transceivers and client-side cards are connected by an OTU switch. A client card terminates the client signal and maps the signal to an OTU frame. The OTU frame is then distributed to appropriate universal transceivers selected from the sharable transceiver pool through the OTU switch, to suit the client data volume and transmission distance.

3.2 Gridless WSSs

Frequency slot-based, gridless switching can be realized with bandwidth-variable wavelength cross-connects and reconfigurable optical add drop multiplexers (BV-WXCs/ROADMs) that employ gridless WSSs based on, for example, a liquid crystal on silicon (LCoS) spatial light modulator [39]. The LCoS consists of a large number of two-dimensionally arranged pixels. Input optical beams (wavelength-division multiplexed optical channels) with different spectra coming from an input fiber are each imaged via a diffraction grating as a spectrally dispersed line onto the LCoS pixels. LCoS uses phase masks to induce beam tilt to the suit the output port of each beam. The beams traverse the diffraction grating again and are wavelength-division multiplexed. Fourier optics then convents the beam tilts from the LCoS into beam shifts to relay them to the output port. The width of a frequency slot can be contiguously changed by adjusting the number of pixels assigned to each beam.

Since conventional gridless WSSs employ free-space technologies, they demand large installation volumes and the precision assembly of a large number of discrete optics. A monolithic, photonic integrated circuit (PIC) WSS has been demonstrated by Bell Laboratories based on silicon photonics technology to resolve these issues [40]. The size was only 5.5 mm and the switching is gridless with 32 pixels on a pitch of 100 GHz. An N × M gridless WSS is another requirement to provide BV-ROADM nodes with colorless, directionless and contention-less operation. An N × M gridless WSS has been proposed and demonstrated by Bell Laboratories; configured to realize 5 fully connected ports with minimum channel spacing of 50 GHz, it uses essentially the same component building blocks as the conventional 1xN WSSs and has the same footprint [41].

4. Conclusions

We described recent advances in elastic optical networks from the viewpoints of adaptive routing and spectrum assignment of elastic optical paths including network optimization and survivability study, multi-layer network design, standardization activities, elastic transponders and regenerator design, and monolithic and N × M gridless WSSs. Many challenges remain to be addressed for elastic optical networks. Such challenges include elastic network design optimized for evolving hardware architecture, establishing a physical transmission design methodology for heterogeneous DWDM signals, elastic transponders and regenerators with reasonable photonic integration, and management and control plane technology compatible with emerging software defined network (SDN). We anticipate that such challenges will be overcome, and that elastic optical networking will become a widely adopted technology to support the future Internet and services.

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