Elastic and Adaptive Optical Networks: Possible Adoption Scenarios and Future Standardization Aspects

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Abstract

There is growing recognition that we are rapidly approaching the physical capacity limit of standard optical fiber. It is important to make better use of optical network resources to accommodate the ever-increasing traffic demand. One promising way is to introduce elasticity and adaptation into the optical domain through more flexible spectrum allocation, where the required minimum spectral resources are allocated adaptively based on traffic demand and network conditions. In this article, we discuss elastic and adaptive optical networks from the perspective of future standardization. We first overview the architecture, enabling technologies, and benefits of elastic and adaptive optical networks with the new concept of an optical corridor. We then present possible adoption scenarios from current rigid optical networks to elastic and adaptive optical networks. We discuss some possible study items that are relevant to the future standardization activities. These items include optical transport network architecture, structure and mapping of the optical transport unit, automatically switched optical network/generalized multiprotocol label switching control plane issues, and some physical aspects with possible extension of the current frequency grid.

Introduction

Optical networks have become widespread and have assumed a role as mission-critical infrastructures for our information society. This is due to worldwide intensive R&D activities and continuous initiative by standardization bodies in optical transport network (OTN) and automatically switched optical network (ASON)/generalized multiprotocol label switching (GMPLS) standards. A 10-Tb/s-class transport system that accommodates 100 Gigabit Ethernet (GE) interfaces is under development [1]. Such advanced transport systems will probably employ dual-polarization, quadrature phase shift keying (QPSK) modulation, and powerful digital signal processing, which is associated with sophisticated coherent detection, with a spectral efficiency reaching 2 b/s/Hz. Unfortunately, it is well known that bit loading higher than that for QPSK causes a rapid increase in the optical signal-to-noise ratio (OSNR) penalty, while further increase in the launched signal power results in serious impairment due to nonlinear effects in optical fibers. Therefore, it is becoming widely recognized that we are rapidly approaching the physical capacity limit of conventional optical fiber. Considering the forecasted doubling in the amount of IP traffic every two years, the looming physical limit of optical fibers [2] will lead to a capacity crunch in optical transport systems in the not-so-distant future.

Under these circumstances, there are two foreseeable issues related to the 100GE era and beyond:

- Will the incremental improvement in transmission technology alone still meet the pace of traffic growth?
- Will the electrical aggregation and grooming approach still be feasible in terms of cost, footprint, power consumption, and accommodation inefficiency due to stacked layers?

Considering that the capacity of conventional optical fibers is not limitless as previously thought but rather a precious network resource, a practical strategy for accommodating ever-increasing traffic demands to support the future Internet and services in 2020 is to take advantage of synergetic effects, that is, continuous incremental innovation for higher capacity and spectral-efficiency-conscious networking evolution.

As a promising approach to address these challenges, we recently proposed to introduce elasticity and adaptation into the optical domain through more flexible spectrum allocation, where the required minimum spectral resources are allocated adaptively based on traffic demand and network conditions [3, 4]. The effectiveness of the adaptation approach has been proven in other areas of technology. Link adaptation technology has been employed to increase the spectral efficiency of broadband wireless data

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networks and digital subscriber lines, and virtualization and elastic provisioning of computing resources has been applied to enhance flexibility, scalability, and robustness in emerging super data centers. Facing an impending capacity crunch, the spectral-efficiency-conscious networking approach has attracted growing interest and a number of bandwidth-variable optical network models were investigated [5–9]. The introduction of elasticity and adaptation will be a big leap forward from conventional rigid and fixed optical networks. We therefore believe that early initiatives by the standardization bodies on studying possible extension of the OTN and ASON/GMPLS standards in terms of optical network resource utilization efficiency will greatly support the rapid advance and adoption of more efficient and scalable optical networks. This article is written from the perspective of future standardization. The aim of this article is to clarify which standards should be inherited, which standards should be extended, and which standards should be created as the starting point regarding study of the possible extension of OTN and ASON/GMPLS standards toward spectrally efficient elastic and adaptive optical networks.

The remaining part of this article is organized as follows. We first overview a spectrum-efficient and scalable optical network architecture based on the elastic optical path and optical corridor concepts as keys for addressing the above-mentioned challenges. Next, we present possible adoption scenarios from the current rigid optical networks to elastic and adaptive optical networks. Finally, we discuss potential study items and candidates from a standards viewpoint including network architecture, the structure and mapping of the optical transport unit, control plane issues, and some physical aspects.

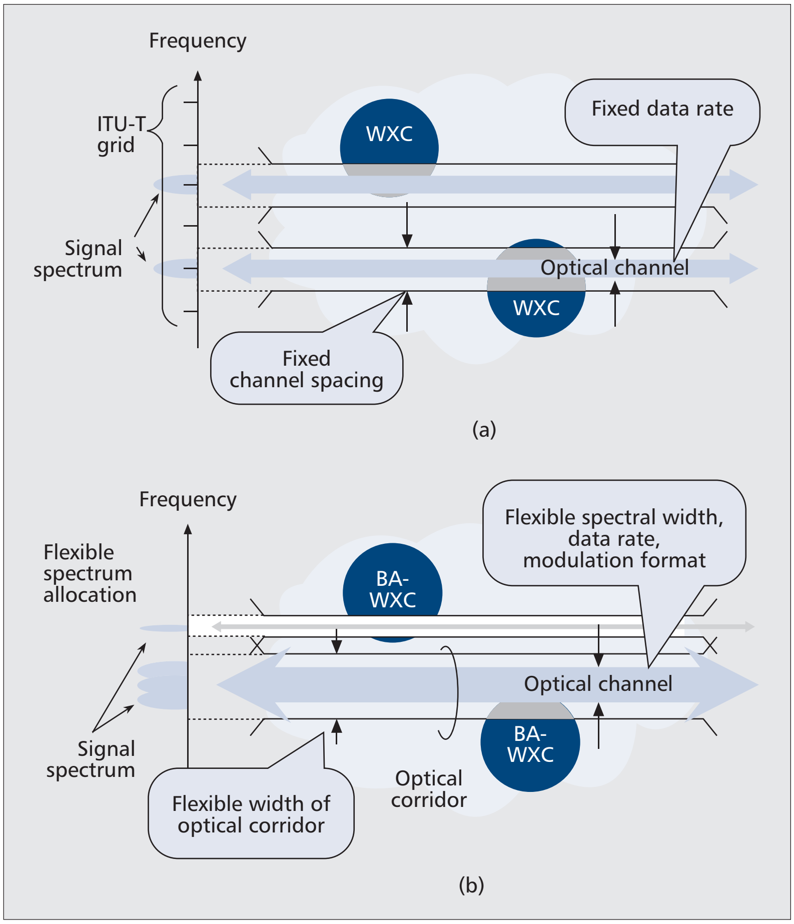

Figure 1. *Elastic and adaptive optical network concept and explicit designation of an optical corridor: a) conventional optical network; b) elastic and adaptive optical network.*

Elastic and Adaptive Optical Network Architecture Overview

Network Architecture Based on Elastic Optical Path Concept

Figure 1 shows the elastic and adaptive optical network with flexible bandwidth and variable channel spacing, in contrast to the conventional rigid optical network with fixed bandwidth and fixed channel spacing. The elastic and adaptive optical network consists of bandwidth-agnostic wavelength crossconnects (WXCs) and bandwidth-agnostic reconfigurable optical add/drop multiplexers (ROADMs) in the network core and rate/modulation-format flexible transponders based on, for example, optical orthogonal frequency-division multiplexing (OFDM) at the network edge. The aim of the elastic and adaptive optical network is to provide spectrally efficient transport of various client data streams through the introduction of flexible granular grooming in the optical domain [3]. In an elastic and adaptive optical network, the required spectral resources on a given route are "sliced off" from the available pool and adaptively allocated to the end-to-end optical path.

It should be emphasized that in elastic and adaptive optical networks, spectral resources allocated on a given route, through which an optical channel is transported, should be specified in an explicit manner. This can be understood as follows. Since channel spacing in conventional optical networks is fixed (Fig. 1a), network operators do not need to distinguish the optical channel itself and the spectral resources allocated on a given route. They only need to specify a center frequency for the optical channel when establishing the end-to-end optical connection. In contrast, the center frequency and the width of the spectral resource allocated to an optical path are variable parameters in elastic and adaptive optical networks, as shown in Fig. 1b. As well as the optical channel itself, network operators need to be aware of the end-to-end spectral resources in elastic optical networks. We hereafter refer to the end-to-end allocated spectral resources as an *optical corridor*, which is specified as a set comprising the center frequency and width, or low-end and high-end frequencies of the optical corridor.

Enabling Technologies for Elasticity and Adaptation

Bandwidth-Agnostic Wavelength Crossconnects — The bandwidth-agnostic WXCs can be established using a continuously bandwidth-variable wavelength selective switch (WSS) as a building block. In a bandwidth-variable WSS, the incoming optical signals with differing optical bandwidths and center frequencies can be routed to any of the output fibers. By using spatial phase modulation technology such as liquid crystal on silicon (LCoS), we can achieve variable optical bandwidth functionality. These technologies allow us to allocate the required bandwidth in nodes along the optical path.

Rate and Format Flexible Transponders — Rate and modulation-format flexible transponders can be achieved, for example, by introducing optical OFDM technology. Optical OFDM is optical multiplexing of orthogonal optical subcarriers that have a frequency spacing equal to the inverse of the symbol duration. The OFDM format allows us to achieve a high level of spectral efficiency and a flexible rate. We can tailor the bandwidth of an optical signal by adjusting the number of subcarriers of the OFDM signal.

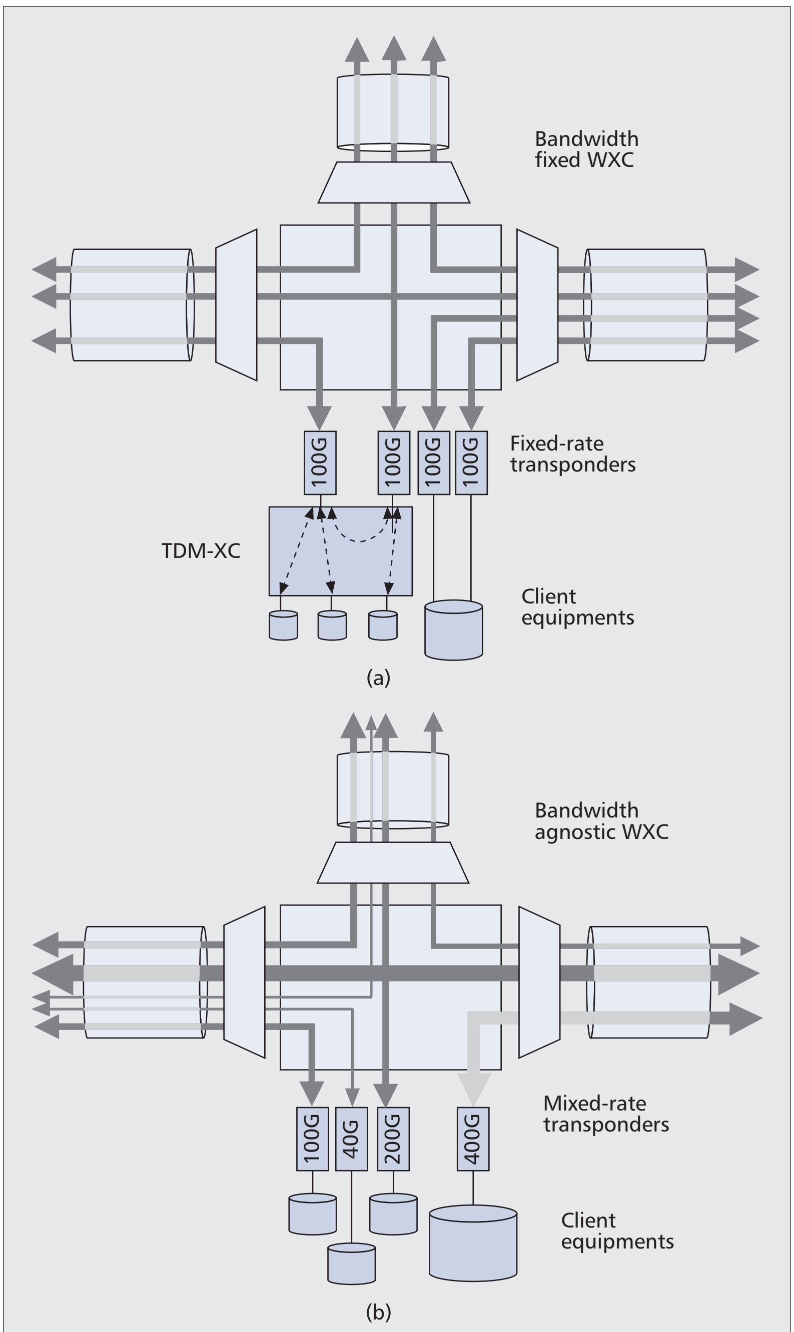

Figure 2. *Rate-adaptive spectrum allocation concept: a) conventional optical network; b) elastic and adaptive optical network.*

Benefits of Introducing Adaptation to the Optical Domain

Rate Adaptive: Adaptation to Actual User Traffic Volume — The network utilization efficiency in conventional optical networks is limited due to the rigid nature of the networks. One limitation originates from the mismatch of granularities between the client layer, which has a broad range of capacity demands with granularities from several to 100 Gb/s or more, and the physical wavelength layer, which has a rigid and large wavelength granularity. For example, bandwidth stranding occurs when the client traffic volume is not sufficient to fill the entire capacity of a wavelength. Current optical networks mitigate the stranded bandwidth issue by aggregating and grooming low-bit-rate data flow with electrical time-division multiplexing (TDM) crossconnects (XCs) or packet transport switches as shown in Fig. 2a. However, such a multilayer approach has drawbacks in terms of extra cost, footprint, and power consumption, especially in the several tens of gigabits per second regions and beyond, as well as accommodation inefficiency and complicated operation due to stacked layers. In contrast, if the requested end-to-end capacity is higher than that of the wavelength, several wavelengths are grouped and allocated according to the request, as shown in Fig. 2a. The adjacent wavelengths in such groups must be separated by a buffer in the spectral domain for wavelength demultiplexing, and this leads to low spectral efficiency.

Elastic and adaptive optical networks mitigate the granularity mismatch problem by dynamically allocating the required minimum spectrum resources in the optical domain, as shown in Fig. 2b. As a result, they provide efficient, scalable, and future-proof accommodation of sub-wavelength and super-wavelength data traffic according to the actual user traffic volume.

We investigated the level to which the rate-adaptive elastic and adaptive optical network provides an increase in network utilization efficiency of an optical link between two nodes [3]. The case of allocation in the rate-adaptive elastic optical network based on OFDM is compared to the cases of the fixed bandwidth optical path of 100 Gb/s and inverse-multiplexing where the path is broken into multiple lower-bit-rate WDM channels. We found that as the average traffic rate is increased, the elastic and adaptive optical network exhibits a large advantage over the case of the inverse multiplexed network. The efficiency of a network employing the fixed optical path approaches that of the rate-adaptive elastic optical network only when the paths are fully utilized.

Distance Adaptive: Adaptation to Physical Conditions on the Route — Another limitation of network efficiency in the current optical network originates from its worst-case design in terms of transmission performance. Such design ensures that the worst-case optical path in the network, which usually is the longest path with multiple hops of linear optical repeaters, ROADMs, and WXCs, can be transmitted with sufficient quality. As a result, most optical paths with path lengths far shorter than that of the worst case have large unused margins in terms of OSNR, nonlinear impairment, and filter clipping at the receiving end.

By introducing distance-adaptive spectrum allocation, such unused margins for shorter connections can be used to conserve spectrum resources, while ensuring a constant data rate. A spectrally efficient but shorter-reach modulation format such as 16-quadrature amplitude modulation (QAM) is utilized for shorter optical paths, while an OSNR-degradation-tolerant but wider-spectrum modulation format such as QPSK is employed for longer optical paths. The distance-adaptive spectrum allocation can conserve spectral resources for shorter paths, thus requiring far fewer spectral resources than the current worst-case spectrum allocation.

We evaluated the network utilization efficiency of a distance-adaptive elastic optical network for ring as well as mesh network topologies [10]. A heuristic routing and spectrum assignment (RSA) algorithm with the spectrum continuity constraint was developed and used in place of the conventional routing and wavelength assignment (RWA) algorithm. We found that the distance-adaptive elastic optical network can conserve the required spectrum resources in excess of 33 percent for a 16-ring network and 50 percent for a 6 × 6 mesh network when compared with the fixed 100 GHz grid scenario.

Availability Adaptive: Adaptation to Available Bandwidth on the Route — Adaptive spectral allocation according to the available bandwidth on the route provides highly survivable restoration through the unique bandwidth variable feature of the elastic optical path [3]. When a link failure occurs and the detour route cannot provide sufficient capacity, we can squeeze the bandwidth of the failed working optical path in order to ensure the minimum connectivity at the expense of the channel bandwidth.

Possible Adoption Scenarios toward Elastic and Adaptive Optical Network

Introducing elasticity and adaptation into the optical domain is expected to yield significant cost savings and enhanced availability associated with the efficient and scalable use of spectral resources in the optical network. One possible adoption scenario for such technology is to be introduced on a step-by-step basis from the link level to the network level and from the static level to dynamic level, most likely led by the development of future higher-bit-rate OTN interfaces as described below. Dynamic spectrum allocation will most likely be introduced at the very last step through maturation of related technologies in both the control and data planes.

Step 1: Spectrally Efficient Accommodation of Future Higher-Rate Data Stream — Future OTN line interfaces should transport client signals having a bit rate higher than 100 Gb/s, for example, 400 Gb/s or even 1 Tb/s. The channel spacing that provides the maximum number of channels at the required channel rate while guaranteeing the required optical reach for future OTN line interfaces may not be aligned on any of the current International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) grids. Introduction of intermediate channel spacing, in which each channel is aligned equally spaced but the channel spacing is set to the minimum by taking into account fiber characteristics and the modulation format, can accommodate future ultra-high-capacity client data streams in a spectrally efficient manner. Figure 3a shows intermediate channel spacing example with a channel spacing of 75 GHz.

Step 2: Mixed-Rate Direct Accommodation in the Optical Domain (Link Level) — The next step is link-level direct accommodation of various data rate client signals in the optical domain through introduction of flexible channel spacing as shown in Fig. 3b. Spectrally flexible dense wavelength-division multiplexing (DWDM) systems achieved by employing bandwidth variable wavelength mux/demux eliminate electrical aggregation of TDM-XCs or packet transport switches at both ends of a DWDM system. We may reach this step by skipping step 1. Flexible-rate transponders based on, for example, OFDM are not indispensable, but they provide intermediate line rates with finer granularity and potentially decrease the total cost of spare transponders.

Step 3: Mixed-Rate Direct Accommodation in the Optical Domain (Network Level) — Once bandwidth-agnostic ROADMs/WXCs are introduced, network-level direct accommodation of various-data-rate client signals in the optical domain can be achieved. Electrical grooming at transit nodes employing TDM-XCs or packet transport switches is no longer required. This step leads to cost-effective and simple network operation achieved through collapsing of layers into a single optical layer.

Step 4: Distance-Adaptive Modulation and Spectrum Allocation — Evolutional change in designing and planning optical networks will be achieved by adopting distance-adaptive modulation and spectrum allocation. This improves the spectral efficiency through significant savings of spectral resources at the network level. Thus, cost-effective accommodation of future Internet traffic and services can be achieved. Once high-speed and high-resolution digital-to-analog converters (DAC) and IQ modulators are introduced, modulation-format-flexible and thus multireach and multirate transponders will be achieved in an economical manner.

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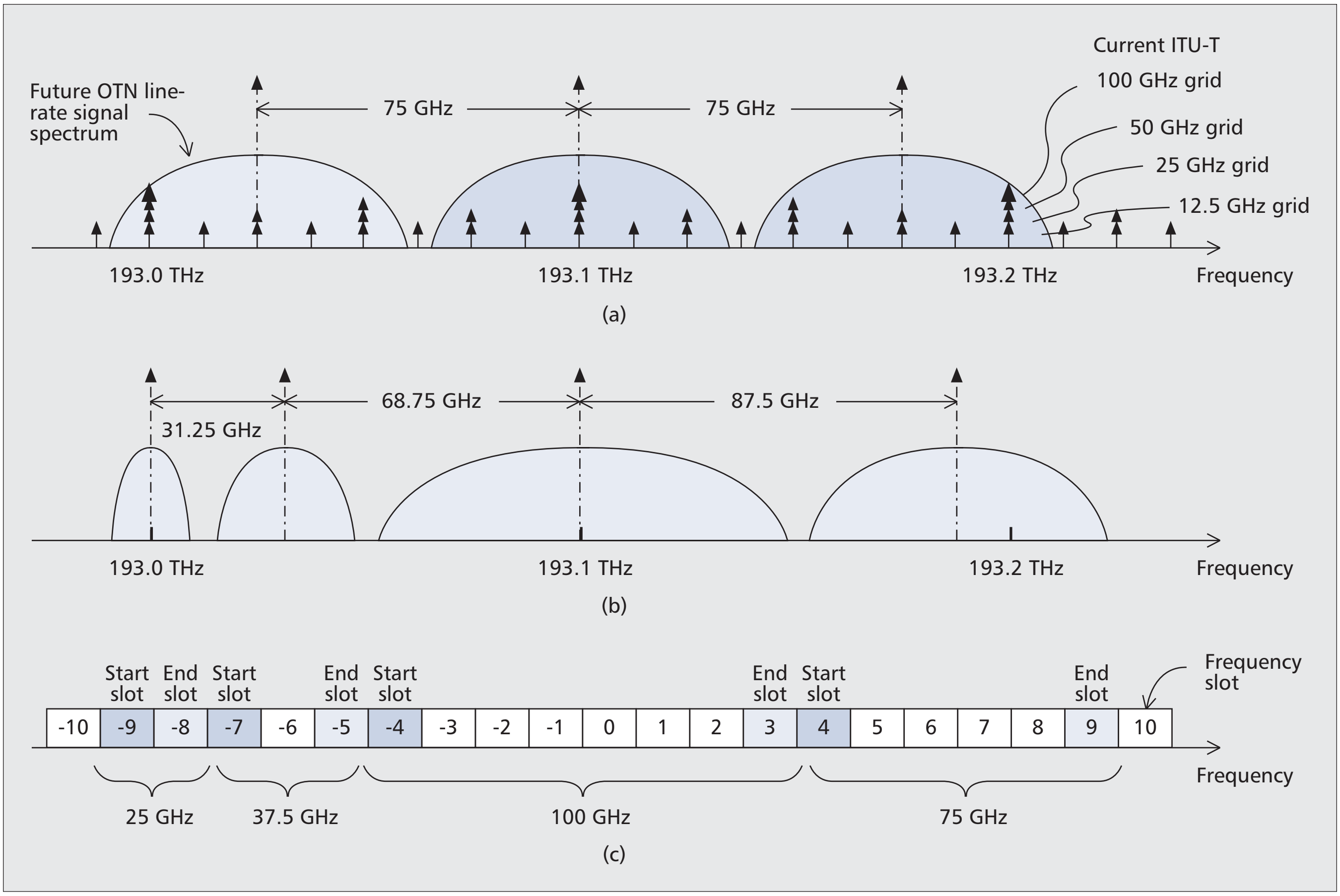

Figure 3. *Channel alignment scheme evolution example: a) intermediate channel spacing (fixed optical corridor width); b) flexible channel spacing (variable optical corridor width); c) frequency slot and slot assignment (slot with 12.5 GHz).*

Step 5: Dynamic Spectrum Allocation — The final step is dynamic spectrum resource allocation. Optical bandwidth-on-demand services and cost-effective high-availability transport services will be achieved through sophisticated operation based on the optical version of the link capacity adjustment scheme (LCAS) and bandwidth-squeezed highly survivable restoration technologies. This can be achieved through maturation of related technologies in the management, control, and data planes.

The other scenario is an earlier adoption scenario to facilitate 100 Gb/s ROADM design. Even employing a spectrally efficient dual-polarization QPSK modulation format, transmitting 100 Gb/s signals over multiple hops of ROADMs on a 50 GHz grid is still a tough task, especially for large-scale networks. One way to relax the system design while keeping reasonable spectral efficiency would be to introduce a non-ITU-T grid or distance adaptive spectral allocation. The distance adaptive spectrum allocation with elastic channel spacing will alleviate 100 Gb/s ROADM design for longer paths, and result in significant spectral savings when compared with the worst-case design on a 100 GHz grid.

Potential Standardization Items

Since the transition from current rigid networks to elastic and adaptive optical networks will be a significant leap forward, the elastic and adaptive optical network concept will bring challenges at both the network and equipment levels, and considerable research effort should be devoted, as discussed in [3]. In addition and equally important, we believe that early initiatives by the standardization bodies will be absolutely indispensable. Clarifying what should be inherited, what should be extended, and what should be created is imperative as the starting point regarding studying the possible extension of OTN and ASON/GMPLS standards in terms of optical network efficiency. In the following, we present potential study items and some candidates from a standards viewpoint.

OTN Network Architecture

ITU-T Recommendation G.872, "Architecture of Optical Transport Networks," specifies the functional architecture of OTN from a network level viewpoint. G.872 defines an optical network layered structure that comprises an optical channel (OCh), optical multiplex section (OMS), and optical transmission section (OTS). Although the data rate, modulation format, and spectral width of an optical path in an elastic and adaptive optical network may change according to user demand and network conditions, an elastic optical path is naturally mapped into the OCh of the current OTN layered structure. We therefore see no significant impact on the current G.872 when introducing the elastic optical path concept.

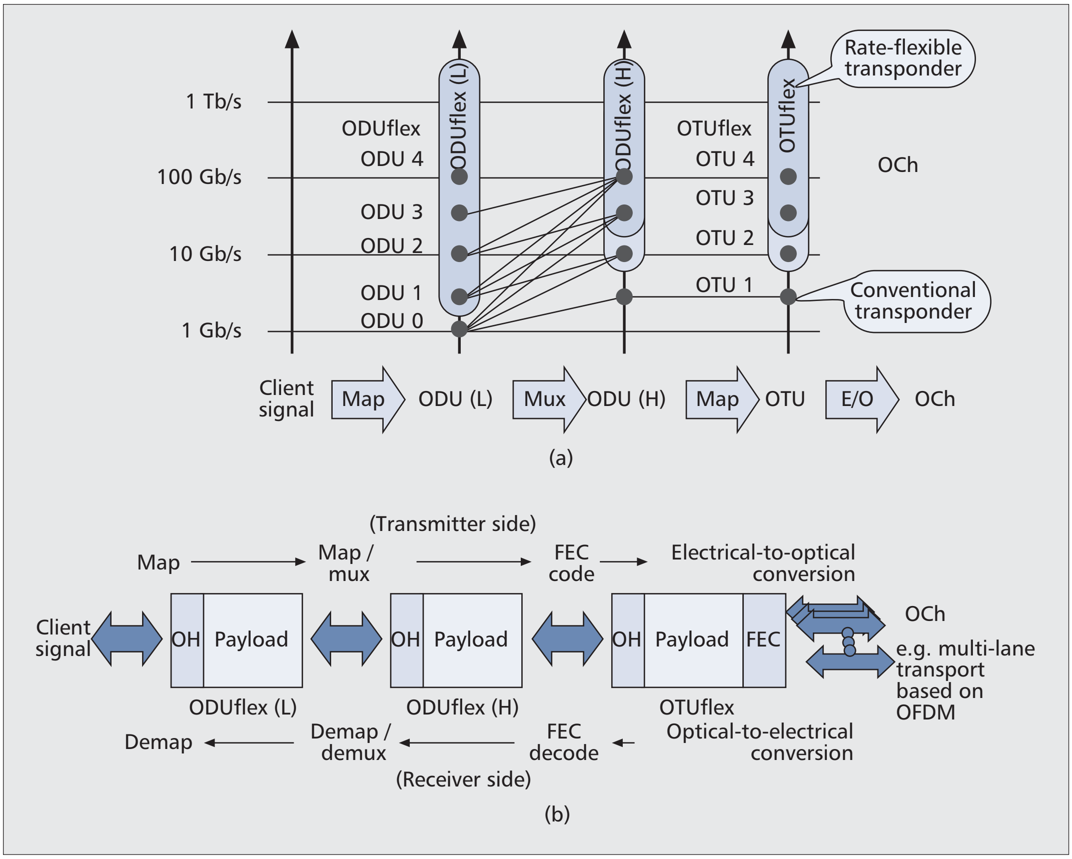

Figure 4. *Structure and mapping of an elastic and adaptive optical network: a) structure of possible extension of OTN; b) mapping and multiplexing into possible OTUflex.*

Although network operators should transport a wide variety of client signals, they must keep the number of kinds of line-interfaces to as few as possible in order to reduce the capital expenditures, which are dominated by line-interface costs.

OTN Mapping and Multiplexing

The interfaces and mappings of OTN are specified in ITU-T Recommendation G.709, "Interfaces for the Optical Transport Network (OTN)." The OTN can accommodate various client signals and transport them over long distances. Originally the OTN specified client signal mapping into optical channel data units (ODUk, k = 1, 2, 3), which have bit rates of approximately 2.5 Gb/s, 10 Gb/s, and 40 Gb/s, and their multiplexing to ODUk with a higher bit rate if necessary. The multiplexed ODUk signal is then transported as an optical channel transport unit (OTUk, k = 1, 2, 3) signal with a forward error correction (FEC) code.

A new ODU was recently specified in G.709 called ODUflex, which can have any bit rate to accommodate any client signal efficiently. ODUflex must be multiplexed into ODUk (k = 1, 2, 3, 4) with higher bit rates. In addition to the specification of ODUflex, the concept of a lower order (LO)/higher order (HO) ODU was introduced. The LO ODU accommodates client signals, and LO ODUs are multiplexed into the HO ODU. Although network operators should transport a wide variety of client signals, they must keep the number of kinds of line interfaces to as few as possible in order to reduce the capital expenditures, which are dominated by line interface costs. The concept of the LO/HO ODUs can address these conflicting requirements. The LO ODU can have many kinds of bit rates in order to accommodate various client signals efficiently. Actually, the LO ODU can have any bit rate because the ODUflex is one of the LO ODUs. On the other hand, the HO ODU has fewer kinds of bit rates. Now four kinds of ODUk (k = 1, 2, 3, 4) are HO ODUs. As a result, the OTU also has four kinds of OTUk (k = 1, 2, 3, 4). The LO ODU offers versatility to accommodate various client signals, and the HO ODU offers simplicity in terms of the physical interfaces.

Once a rate-flexible OCh based on optical OFDM transponders and bandwidth-agnostic ROADMs/WXCs is introduced, cost-effective transport of various client signals will be enabled in the fully optical domain without intermediate electrical multiplexing and grooming processes as described in previous sections. As a natural step toward a rate-flexible OCh, we may need to consider some extension of G.709. One possibility would be to introduce rate-flexible OTUs (OTUflex) as well as rate-flexible HO ODUs (HO ODUflex), as shown in Fig. 4a. The OTUflex and HO ODUflex will be specified in the region of over 10–100 Gb/s depending on the maturity of device technology at the time. Figure 4b shows the client signal transport over OTN with a rate-flexible transponder. On the transmitter side, the client signal is mapped into the LO ODUflex, and then mapped/multiplexed to the HO ODUflex. An FEC code is added to the HO ODUflex to create OTUflex, which is envisioned to be mapped into the optical data stream by using a flexible rate transponder employing, for example, multilane transport based on opti-

> *The ITU-T Recommendations on ASON provide requirements, architecture, and protocol neutral specifications for automatically switched optical networks with a distributed control plane. The goal is not to define new protocols but to provide mappings between abstract protocol specifications and the existing candidate protocols.*

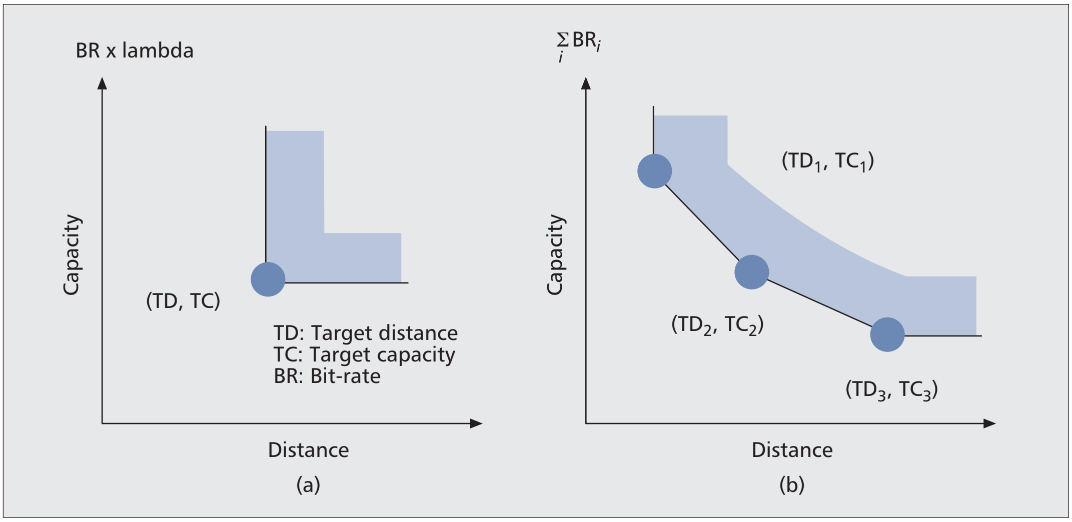

Figure 5. *Possible specification based on longitudinal compatibility: a) conventional optical network; b) elastic and adaptive optical network.*

cal OFDM. On the receiver side, reverse processing is performed to extract the client signal from the OTUflex frame. Another relevant standard that should be investigated for possible extensions is Recommendation G.798, "Functional Characteristics of Optical Networking Equipment," which specifies the details regarding OTN equipment.

PHYSICAL ASPECTS

The current ITU-T frequency grid specified in G.694.1, "Spectral Grids for WDM Applications: DWDM Frequency Grid," is anchored to 193.1 THz, and supports various channel spacings of 12.5 GHz, 25 GHz, 50 GHz, and 100 GHz. In order to fully utilize the spectrally efficient and scalable nature of elastic and adaptive optical networks, we may need to consider some extension of G.694.1 [4, 6]. From a practical viewpoint, one promising way would be to quantize the continuous spectrum into contiguous frequency slots with an appropriate slot width [4]. Figure 3c shows a contiguous frequency slots example with a slot width of 12.5 GHz. In this case, a frequency slot is defined related to the 12.5 GHz frequency grid as a frequency segment between $193.1 + n \times 0.0125$ and $193.1 + (n + 1) \times 0.0125$ (in terahertz), where an integer n is the slot number. Spectral resources of an optical path can be allocated by assigning the necessary number of contiguous frequency slots as shown in Fig. 3c. In contrast to On-the-grid approach in [4], where a frequency grid is defined as a frequency segment on the grid between $193.1 + (n \mp 1/2) \times 0.0125$ (in THz), the illustrated Off-the-grid approach shown in Fig. 3c is able to denote the frequency segment which is implicitly allocated to a channel when a frequency on the grid is designated. This feature may be preferable from a view point of compatibility with the channel plan based on the current ITU-T frequency grid. If we allow any frequency segment with even numbers of 12.5 GHz frequency slot, the central frequency of any channel is aligned on the 12.5-GHz grid.

In order to proceed in specifying other required physical layer specifications, we should pursue the following strategy. In general, physical layer standardization takes one of two approaches: transverse compatibility or longitudinal compatibility. The recommendation supporting multivendor transversal compatibility covers almost all the physical parameters and can usually be achieved when the relevant technologies are sufficiently mature. On the other hand, the recommendation supporting single-vendor longitudinal compatibility requires the minimum number of parameters (e.g. target distance and repeater spacing) as application codes. G.696.1 defines "Longitudinally Compatible Intra-Domain DWDM Applications." For example, application code 40.10G-20L652A(C) indicates a target capacity of a 40-channel system with signals of the 10G payload class, and a target distance of 20 long-haul spans of G.652A fiber.

Considering the advanced functionalities we are trying to achieve, it is natural to start with the longitudinal compatibility approach for physical layer specifications of elastic and adaptive optical networks. Whereas in conventional systems, the target distance and capacity are a fixed set of values as shown in Fig. 5a, in the elastic and adaptive optical network, there can be variable sets of parameters, as shown in Fig. 5b. The sets can be optimized, for example, according to the carrier requirements. This unique feature may bring additional degrees of freedom in defining the physical layer specifications and result in capital expenditure reduction.

ASON/GMPLS CONTROL PLANE

The ITU-T Recommendations on ASON provide requirements, architecture, and protocol neutral specifications for ASONs with a distributed control plane [11]. The goal is not to define new protocols but to provide mappings between abstract protocol specifications and the existing candidate protocols. Development of new protocols such as GMPLS has been tasked by the Internet Engineering Task Force (IETF) and Optical Internetworking Forum (OIF). ITU-

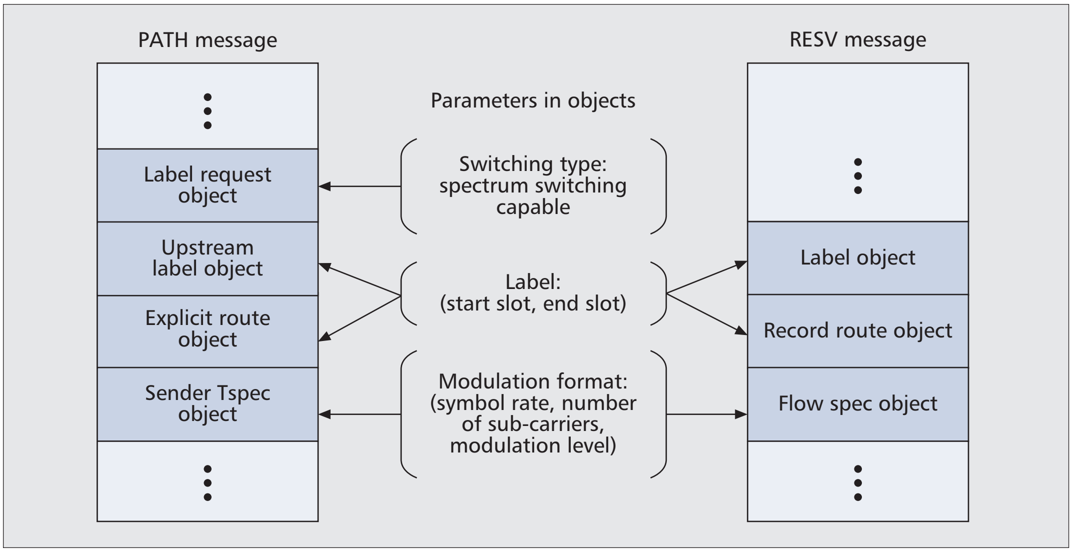

Figure 6. *Possible extension of GMPLS signaling messages.*

As a result of preliminary investigation we consider that there will be no significant impact on the current ASON standards when introducing a distributed control plane into elastic and adaptive optical networks, although further studies are still necessary.

T Recommendation G.8080, "Architecture for the Automatically Switched Optical Network (ASON)," defines fundamental functional components of the control plane. Three major processes in the ASON control plane are call and connection control, path control based on the dissemination of the network state information, and the discovery process for network self-configuration. Their protocol neutral specifications are provided in ITU-T Recommendations G.7713, G.7714, and G.7715, respectively.

The ASON network resource model is based on a generic functional model for transport networks defined in G.805, and functional models for synchronous digital hierarchy (SDH) defined in G.803 and OTN defined in G.872. We have already examined G.872 in the previous subsection; then again, as a result of preliminary investigation, we consider that there will be no significant impact on the current ASON standards when introducing a distributed control plane into elastic and adaptive optical networks, although further studies are still necessary.

As for the technology-specific aspects of routing and signaling in elastic and adaptive optical networks, we should discuss possible extension of GMPLS protocols in the IETF and OIF in close cooperation with the ITU-T. We may define a new switching type, "spectrum switching capable," in GMPLS architecture. In order to establish a necessary optical corridor, a new label, "start slot number and end slot number," in the upstream label, explicit route, label, and record route objects may be specified in the Resource Reservation Protocol — Traffic Engineering (RSVP-TE), as shown in Fig. 6. In addition, we will introduce new parameters, the "symbol rate, number of subcarriers, and modulation level," in the sender TSpec and flow spec objects.

Conclusions

In this article we discuss elastic and adaptive optical networks from the viewpoint of future standardization. We first overview the architecture, enabling technologies, and benefits of the elastic and adaptive optical network where the required minimum spectral resources are adaptively allocated to an optical path based on various network conditions including actual client traffic demand, physical network conditions, and the available bandwidth on the route. As a novel concept for network operators needing to be aware in order to allocate appropriate spectral resources to an end-to-end optical path, we introduced an optical corridor concept, which is an end-to-end spectrum window that is to be open at every WXC on the route.

We present possible adoption scenarios from current rigid optical networks to elastic and adaptive optical networks. One possible scenario is to introduce elasticity and adaptation on a step-by-step basis from the link level to the network level and from the static level to the dynamic level, most likely led by the development of future higher-bit-rate OTN interfaces. An earlier adoption possibility may be the introduction of distance-adaptive spectrum allocation to achieve cost-effective 100-Gb/s-class ROADM systems. We present some possible study items relevant to future standardization activities. As the starting point for studying the possible extension of OTN and ASON/GMPLS standards in terms of optical network efficiency, we present some clarification on what should be inherited, what should be extended, and what should be created. We also discuss some candidates in terms of structure and mapping of the OTU and some physical aspects with possible extension of the current frequency grid.

We hope that this article contributes to future standardizations and revisions, particularly in the context of a more efficient and scalable optical layer as a mission-critical infrastructure to support the future Internet and services.

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Biographies

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Takuya Ohara [M'01] is a research engineer at Photonic Transport Network Laboratory, NTT Network Innovation Laboratories, NTT. He received B.E. and M.E. degrees in electronic engineering from the University of Tokyo in 1998 and 2000, respectively. He joined NTT Network Innovation Laboratories in 2000. His research interests are optical fiber communication, in particular high-speed and large-capacity optical transmission systems, and OTN evolution. He is involved in OTN standardization activities and has been active in ITU-T SG15 since 2006. He was a visiting researcher at AT&T Labs Research, Middletown, New Jersey, from 2007 to 2008, where he was involved with research on an optical path tracing technique. He is a member of IEICE.

Yoshiaki Sone received his B.E. and M.E. degrees in electronics engineering from Tohoku University, Sendai, Japan, in 2001 and 2003, respectively. In 2003 he joined NTT Network Innovation Laboratories and has been engaged in research on control technology of photonic transport networks. His research interest lies in network architecture, resilience schemes, designs of protocols for distributed control such as ASON/GMPLS, and interoperability testing of such protocols. He experimentally provided multiple failure recovery using GMPLS in the photonic transport networks. He is a member of IEICE.

Akira Hirano is a senior research engineer, supervisor, at NTT Network Innovation Laboratories in Japan. He received his B.S. degree in physical chemistry and M.S. degree in astrophysics from Osaka University, Japan. In 1993 he joined NTT working in the high-speed optical communications area. He was a visiting researcher at the University of Illinois at Chicago (2005–2006), where he engaged in research on photonic networking. His main interests are in high-speed optical transport.

Osamu Ishida is a senior research engineer, supervisor, at NTT. He currently leads the photonic networking systems research group in Network Innovation Labs, Yokosuka, Japan, and is responsible for the research on architecture and interfaces of converged packet/optical transport networks. He has over 20 years of experience in research on high-speed Ethernet transport, WDM crossconnect systems, and coherent optical fiber communications. Also, he was involved in developing the IEEE 10/40/100GE standards.

Masahito Tomizawa [M'92] is a senior research engineer, group leader, at NTT. He received his M.S. and Ph.D. in applied physics from Waseda University, Tokyo, in 1992 and 2000, respectively. From 2003 to 2004 he was a visiting scientist at the Massachusetts Institute of Technology. He has been engaged in high-speed optical transmission systems and their deployments, as well as international standardization in ITU-T, and also international carrier-to-carrier collaboration for several years.