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Elastic Optical Path Network Architecture: Framework for Spectrally-Efficient and Scalable Future Optical Networks

Masahiko JINNO†a), ***Senior Member***, **Hidehiko TAKARA**†, **Yoshiaki SONE**†, **Kazushige YONENAGA**†, ***and*** **Akira HIRANO**†, ***Members***

SUMMARY This paper presents an elastic optical path network architecture as a novel networking framework to address the looming capacity crunch problem in internet protocol (IP) and optical networks. The basic idea is to introduce elasticity and adaptation into the optical domain to yield spectrally-efficient optical path accommodation, heightened network scalability through IP traffic offloading to the elastic optical layer, and enhanced survivability for serious disasters.
key words: *optical network, WDM, IP network, elastic optical path, spectrum efficiency*

1. Introduction

Driven by emerging bandwidth-hungry services, interface bit rates for Ethernet and optical transport networks (OTNs) have rapidly increased over the past 10 years as shown in Fig. 1. The IEEE has recently standardized interfaces for 40 G Ethernet and 100 G Ethernet. In close collaboration with the IEEE, the ITU-T has augmented its G.709 OTN standard to transport 100-Gb/s traffic by specifying an optical channel transport unit, OTU4. Figure 2 shows the per-fiber system capacity and spectral efficiency (SE) of commercial systems deployed in Japan. Over the past 30 years, the per-fiber system capacity has increased at an amazing pace, doubling every two years. As a result, a cutting edge 100-Gb/s wavelength transport system employing dual-polarization (DP) and quadrature phase shift keying (QPSK) modulation will have a system capacity and a SE reaching 8–10 Tb/s and 2 b/s/Hz, respectively. Considering that the amount of global Internet traffic will likely continue to grow at an annual rate of approximately 30% over the next several years, if we simply extrapolate the standardization trend for Ethernet interfaces, we see that the next possible Ethernet rate of 400 Gb/s (400 GE) will appear around 2015 and 1 Tb/s (1 TE) around 2020 as indicated in Fig. 1.

Under the traditional flat-rate pricing models for end users, the continuing growth in the volume of internet protocol (IP) traffic and an associated need to accommodate higher rate client Ethernet interfaces will place exacting challenges to network service providers. The first challenge is to evolve the 100-Gb/s OTN interface, which is currently under development, to 400 Gb/s and 1 Tb/s to transport the forthcoming 400 GE and 1 TE traffic while increasing the per-fiber capacity and lowering the per-bit transmission cost. Historically, at a fixed optical amplifier bandwidth of typically 4–5 THz, increases in the per-fiber capacity have been achieved through boosting of the SE by means of increasing the signal bit rate, number of wavelengths, states of polarization, and symbols per bit. Unfortunately, it is well known that bit loading higher than that for QPSK to increase further the channel capacity causes a rapid increase in the signal-to-noise ratio (SNR) penalty. For example, 16-ary quadrature amplitude modulation (QAM) suffers from a 4.0-dB SNR penalty per bit in theory compared to QPSK modulation

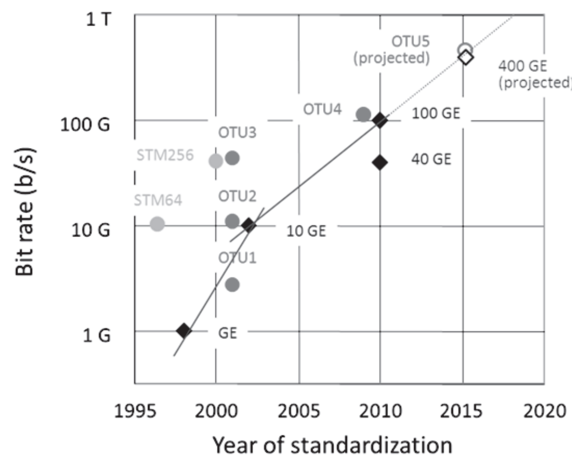

Fig. 1 Standardization trend of interfaces for Ethernet and OTN.

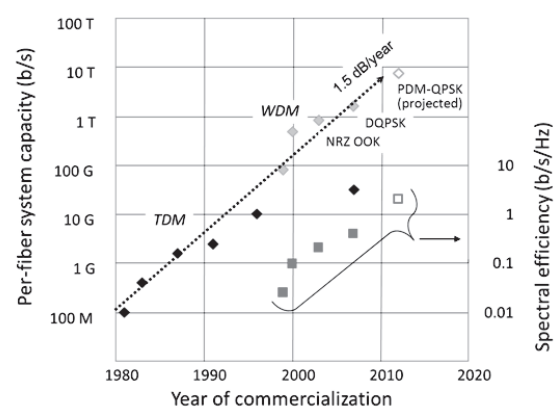

Fig. 2 Trend in per-fiber capacity for transmission systems deployed in Japan.

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†The authors are with NTT Network Innovation Laboratories, NTT Corporation, Yokosuka-shi, 239-0847 Japan.
a) E-mail: jinno.masahiko@lab.ntt.co.jp
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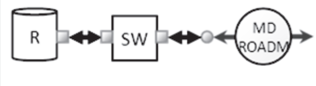
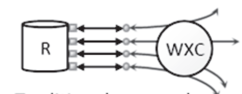
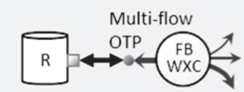
Table 1 Possible IP optical architecture evolution scenario.

	Current	Near term future	Middle term future
Router IF	10 Gb/s	40 Gb/s – 100 Gb/s	400 Gb/s – 1 Tb/s
R to R traffic	100 Mb/s – 1 Gb/s	1 Gb/s – 10 Gb/s	10 Gb/s – 100 Gb/s
Equipment level view			 Traditional approach  Multi-flow OTP and elastic optical network approach

[1]. Considering the limited fiber launched power necessary to avoid excessive nonlinear signal distortion, this SNR penalty results in a shorter optical reach. Due to this, despite the potential for more powerful forward error correction (FEC), efficient digital signal processing (DSP), and a lower-noise optical amplifier, we need to concede that the pace of improvement in the SE will be slowing down in the era beyond 100 Gb/s.

Reducing the overall per-bit transporting cost of IP traffic considering the total network cost from Layer 3 (router) to Layer 0 (WDM) is another challenging problem that the network service providers face. In order to address this challenge, providers are considering offloading IP transit traffic at their core networks to Layer 2 or Layer 1 via emerging new transport technologies such as multi-protocol label switching - transport profile (MPLS-TP) switching and OTN cross-connection, which will yield benefits that are potentially cost-effective and energy-efficient [2], [3] as shown in Table 1. This solution seems reasonable in the near term future when the core router interface rate will be 40 Gb/s or 100 Gb/s and the IP traffic between each end-to-end router pair will range, for example, from 1 Gb/s to 10 Gb/s. Considering the continuing increase in router interface rates, which are likely to operate at around 400 Gb/s and 1 Tb/s in the future Ethernet, we will soon need to achieve much more cost-effective IP core networks.

The third challenge pertains to a service continuity issue. Due to worldwide intensive R&D activities, optical networks have become widely spread and have become mission critical infrastructures for our information society. In our deeply networked society, the higher the per-fiber capacity becomes, the more critical will be the impact of a service disruption due to a fiber-cut or node failure. As mission critical infrastructures, networks should not be only reliable, meaning that they have a low probability of failure, but also resilient, meaning that they can quickly recover to normal function even when multiple failures occur due to a serious and widespread disaster. The challenge is how to achieve network resiliency in an economical manner.

In this paper, we describe the elastic optical path network architecture as a novel networking framework to address the three challenges identified above. The basic idea of the framework is to introduce elasticity and adaptation into the optical domain by taking advantage of emerging digital coherent optical transmission and flexible bandwidth optical switching technologies. The idea of flexible bandwidth has been introduced in reconfigurable optical add drop multiplexer (ROADM) designs [4], [5] based on liquid crystal on silicon (LCoS) or micro electro-mechanical systems (MEMS) technology. However, as far as we know, there have been no prior studies that deal with overall network architecture using flexible bandwidth optical technologies. The framework supports adaptive spectrum resource allocation to an end-to-end optical path according to the client traffic volume and path length. In cooperation with elastic channel spacing, the adaptive spectrum resource allocation will increase the SE at the network level. This in turn will result in significant reduction in the per-bit transmission cost. Advanced higher-order modulation schemes and parallelization in the frequency domain in recent ultra-high-speed long haul transceivers bring a novel degree of freedom to the design of optical transponders with capabilities such as multiple optical flow generation and receiving. Combined with elastic optical path networking this will enable efficient IP traffic offloading to the elastic optical layer and will potentially yield significant savings in terms of capital and operational expenditures in IP based networks. The unique features of adaptive spectral allocation and bandwidth/modulation-format optimization of the elastic optical path network provide highly-survivable optical layer restoration by guaranteeing the minimum connection for high-priority traffic at the expense of bandwidth.

The remaining part of this paper is organized as follows. The next section presents the basic concept and architecture of the elastic optical path network. We then describe enabling technologies for introducing elasticity into the optical domain, i.e., elastic optical transceivers and bandwidth variable ROADMs and wavelength cross-connects (WXCs).

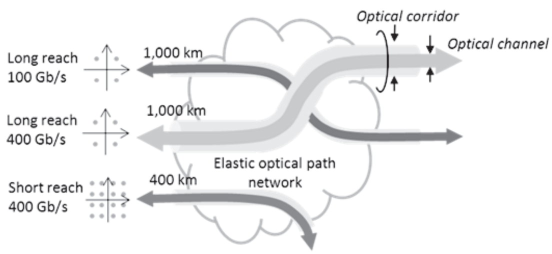


Fig. 3 Elasticity in optical channels and optical corridors.

Finally, we present the benefits of introducing adaptation in terms of efficient optical path accommodation, IP traffic offloading to the elastic optical layer, and highly-survivable optical layer adaptive restoration.

2. Concept of Elastic Optical Path Network

The concept of the elastic optical path network is to introduce elasticity and adaptation into the optical domain to achieve adaptive spectrum resource allocation. In the elastic optical path network, the right-sized optical bandwidth is adaptively allocated to an end-to-end optical path on a given route in the network by "slicing off" the necessary spectral resources from the usable fiber spectral width of roughly 4 THz [6]–[11].

There are two aspects of the elasticity in optical networks. The first aspect is the elasticity of an optical channel that transports client data, and the second aspect is the elasticity of the optical corridor in which the optical channel passes through end to end via ROADMs/WXCs (Fig. 3). In elastic optical path networks, the bit rate, modulation format, and achievable optical reach of the optical channel are not fixed but flexibly changed. In addition, the width of the optical corridor, which is characterized by the filtering and switching window width of ROADMs/WXCs on the route, can be adjusted considering the spectral width that the optical channel is allowed to occupy and the filtering effect caused by cascaded ROADMs/WXCs. An elastic optical path network consists of elastic optical transponders (OTPs) at the network edge and flexible bandwidth ROADMs/WXCs in the network core. Details of enabling technologies for elastic OTPs and flexible bandwidth ROADMs/WXCs are described in the next section.

3. Enabling Technologies for Elasticity

3.1 Multi-rate, Multi-Reach, Multi-Flow Optical Transponder

Intense research efforts toward scaling optical networks to line rates of 400 Gb/s and beyond are being pursued. A superchannel that consists of several tightly-spaced subchannels that are individually generated with arrayed optical modulators driven at a moderate speed is one promising technology [12]. Since a superchannel is transported through ROADMs/WXCs and detected as a single entity, guard bands between subchannels are not required for wavelength routing. This allows us to employ a very tight subchannel spacing that reaches the baud rate of each subchannel, and this results in a high SE. By adjusting the baud rate and the bits-per-symbol of each subchannel and the number of subchannels, we can generate an elastic optical channel with the required data rate and optical reach while minimizing the spectral width [6], [9].

There are two common schemes for achieving a spectrally-efficient superchannel transmitter [12]: optical orthogonal frequency division multiplexing (OFDM) [13] and Nyquist-WDM [14]. Optical OFDM is based on FDM of subchannels aligned with a frequency spacing that is exactly equal to the baud rate to satisfy the orthogonal condition at the receiver. A frequency-locked multi-carrier generator is utilized to generate subcarriers that satisfy the orthogonal condition. Nyquist-WDM is based on WDM of subchannels having an almost rectangular spectrum with a bandwidth close to the Nyquist limit for inter-symbol interference-free transmission, which coincides with the baud rate. Such subchannels are aligned with the frequency spacing close to the baud rate while avoiding inter-subchannel spectral overlap. Since the subcarriers are not required to be frequency locked, individual laser diodes can be used for each subchannel. Sharp roll-off optical filtering, electrical Nyquist filtering, or electrical OFDM can be used to generate a bandwidth-limited almost rectangular spectrum. A superchannel receiver can be achieved by employing a digital coherent receiver array, in which tightly-spaced subchannels are separated with DSP.

Once the superchannel transceiver technology that provides capabilities for multi-rate and multi-reach optical channel generation and receiving has been developed, in which reasonable photonic integration and assembly technology will be employed, the next step will be to introduce individual tunability for each subcarrier over the entire C band or L band in order to achieve multi-flow transceivers. The multi-flow transceiver assigns a different wavelength to each carrier so that each optical flow can be transported to a different destination, or some neighboring carriers can be grouped to form a high SE superchannel optical flow headed to the same destination. The capacity and modulation format of each optical flow is selected according to the amount and source-destination distance of the client data to be transported. Thus, we achieve multi-rate, multi-reach, and multi-flow OTPs based on the superchannel transceiver technology in cooperation with appropriate client data processing functionalities. Possible architectures for multi-flow optical transceivers are described in [15].

3.2 Flexible Bandwidth ROADM/WXC

An elastic optical corridor can be established by using a flexible bandwidth ROADM/WXC that performs self-routing of incoming optical signals to the appropriate outgoing fibers based on the signal wavelength. The optical bandwidth of the self-routing window of the flexible bandwidth

ROADM/WXC is contiguously configured according to the spectral width of the incoming optical signal. A possible architecture for a flexible bandwidth ROADM/WXC is a broadcast-and-select configuration, employing optical splitters at the input and bandwidth-variable wavelength selective switches (WSSs) at the output ports [6], [9] as shown in Fig. 4.

In general, the WSS is a 1xN switch or filter that performs wavelength demultiplexing, multiplexing, and optical switching functions using integrated spatial optics. The light from an input fiber is split into its constituent spectral components using a dispersive element. The spatially separated constituent spectra are focused on a mirror array and redirected to the desired output fiber. The unique feature of a bandwidth variable WSS when compared to the conventional fixed bandwidth WSS is that the mirror array consists of a large number of two-dimensionally arranged pixels and the switching bandwidth can be contiguously changed by adjusting the number of pixels. Such bandwidth variable WSSs can be achieved based on LCoS or digital light processing (DLP) technologies.

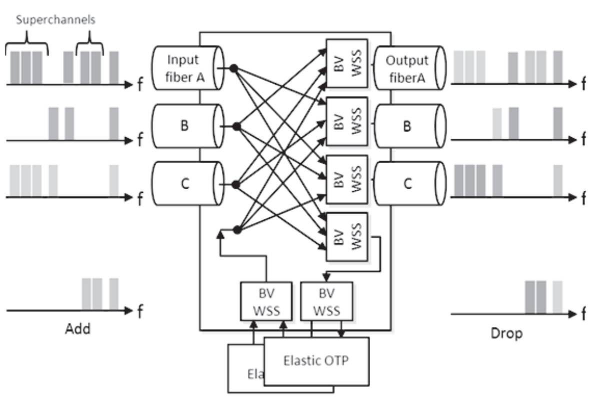


Fig. 4 Possible architecture for a flexible bandwidth WXC.

3.3 Hardware Technologies for Elastic Networking Applications

The ultimate flexible transceiver would be a software-defined multi-rate, multi-reach, and multi-flow transceiver. However, it should be noted that such a fully-equipped functionality is not always necessary. Instead, required functionalities for optoelectronic devices depend on applications for elastic optical path networking that are described in the next section. These applications are determined by considering the cost-performance of functionality consolidation as summarized in Table 2.

For example, let us consider a multi-rate (single flow) OTP that has a capability to support intermediate line rates from 100 Gb/s to 400 Gb/s in steps of 100 Gb/s. If such a multi-rate OTP is operated at a data rate of 200 Gb/s according to the client traffic demand, it might be hard to support the economic justification of the unused 200-Gb/s capacity. Two tightly-spaced 100-Gb/s channels that are generated with two fixed-rate 100-Gb/s OTPs and routed as a single entity may be a cost-effective solution. In contrast, a multi-reach OTP, which has the capability to generate multiple modulation formats while maintaining a data rate, is probably an economical solution to reduce the burden on

Table 2 Hardware technologies required for elastic optical path networking applications.

Elastic optical path networking applications \ Hardware technologies			Wavelength MUX/DEMUX		ROADM/ WXC	OTP (optical transponder)		
			Equal interval, intermediate channel spacing	Bandwidth flexibility	Bandwidth flexibility	Rate flexibility	Reach (format) flexibility	Multi-flow capability
Point-to-point WDM transmission system	Single rate		Must	-	-	-	Not always necessary	-
	Mixed rate		-	Must	-	Not always necessary	Not always necessary	-
Optical network	Optical path provisioning (distance-adaptive, and/or mixed rate)		-	-	Must	Not always necessary	Preferable	-
	IP traffic offloading		-	-	Must	Must	Must	Must
	P2MP optical virtual private line service				Must	Must	Must	Must
	Optical layer restoration	Fixed rate	-	-	Must (directionless/ colorless)	Not always necessary	Preferable	-
		Rate- and reach-adaptive	-	-	Must (directionless/ colorless)	Must	Must	Preferable

the operator inventory of OTPs to cover all of the optical reaches for deployments and spares.

4. Benefits of Adaptation

4.1 Highly-Efficient Optical Path Accommodation

The first benefit that the elastic optical path network yields is highly-efficient optical path accommodation. The resulting spectral savings is achieved by taking advantage of the spectral resources that had not yet been fully utilized. This results in an increase in network capacity. Opportunities for taking advantage of underutilized spectral resources are shown in Fig. 5. Let us consider an example in which we transport mixed-rate traffic. First, let us consider for example three 100-Gb/s optical channels headed for the same destination. We can combine them into a tightly spaced 300-Gb/s superchannel and transport them as a single entity. We can eliminate the unnecessary guard bands between the channels. Second, for client traffic that does not fill the entire capacity of a wavelength, the elastic optical path network provides the right-sized intermediate bandwidth, such as 200 Gb/s. This makes the unused client bandwidth available for use. Third, for shorter optical paths, which suffer from less SNR degradation, we employ a more spectrally-efficient modulation format, such as 16QAM. We utilize the excess transmission margin for shorter optical paths. Finally, combined with elastic channel spacing, where the required minimum guard band for wavelength routing is assigned between channels, we can utilize the excess channel spacing. In this way, elastic optical path networks accommodate a wide range of traffic in a highly spectrally-efficient manner.

There is concern that non-uniform spectral allocation to each optical path might cause unacceptable spectral fragmentation due to the inherent spectral adjacency constraint. Fortunately, stranded spectrum fragments can be reduced to a practically negligible level by employing sophisticated routing and spectrum assignment (RSA) algorithms that consider the spectrum-continuity constraint in the longitudinal direction as well as the spectrum adjacency constraint [11], [16], [17]. We compared provisional network capacities for various network topologies with and without a spectral adjacency constraint. The provisional network capacities are calculated by integrating the provisioned optical path capacity for incremental traffic demands until the first blocking occurs. Individual demands are created by randomly selecting a source/destination pair and randomly choosing a spectral width. The results are normalized with those for the case with no spectral adjacency constraint. As shown in Fig. 6, if we employ RSA algorithms based on, for example, the first fit (FF) [11] algorithm or the maximize common large segment (MCLS) algorithm [16], which are intended to choose carefully the spectral segment assigned to each elastic optical path in order to retain as much as possible contiguous spectra for future utilization, we can minimize the influence of spectral fragmentation to within 4% to 7% based on the spectral adjacency constraint, while receiving the full benefits of spectral savings through the introduction of elastic and adaptive spectral resource allocation as descried in [9] and [11].

4.2 IP Traffic Offloading Using Multi-Flow Optical Transponder

The second benefit that the elastic optical path network yields is efficient IP transit traffic offloading to the elastic optical layer. This results in enhanced IP network scalability [15]. According to general engineering principles, to keep transit traffic at the lowest possible transport layer, the most preferable layer for router bypass would be the optical layer in the coming 400-Gb/s and 1-Tb/s era when IP traffic between each end-to-end router pair will most likely reach 100 Gb/s. However, the traditional router bypass at the optical layer has a drawback. It requires a large number of router interfaces on the client side and a large number of OTPs and ROADM/WXC ports on the network side, which significantly increase the capital and operational expenditures (See Table 1). This is because current optical technologies lack the flexibility provided by MPLS-TP switches and OTN cross-connects in establishing multiple connectivity.

If we achieve multi-flow OTPs that support the capability to identify client data flows and translate them into multiple optical flows, in cooperation with the spectrally-efficient

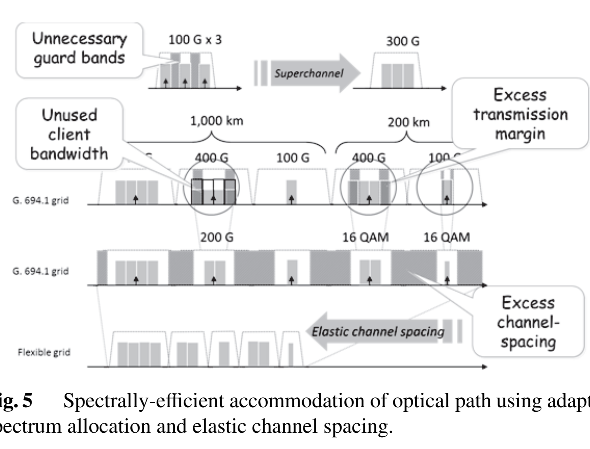


Fig. 5 Spectrally-efficient accommodation of optical path using adaptive spectrum allocation and elastic channel spacing.

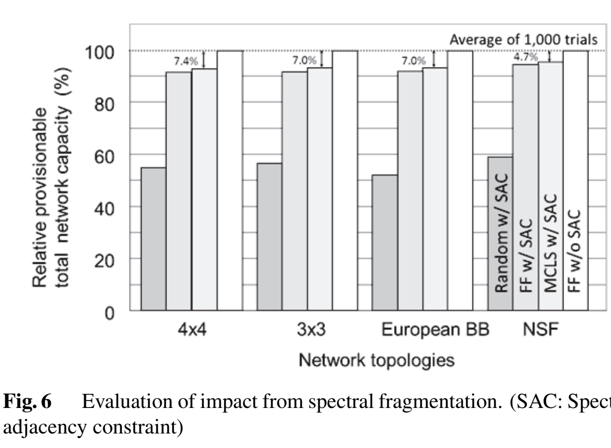


Fig. 6 Evaluation of impact from spectral fragmentation. (SAC: Spectral adjacency constraint)

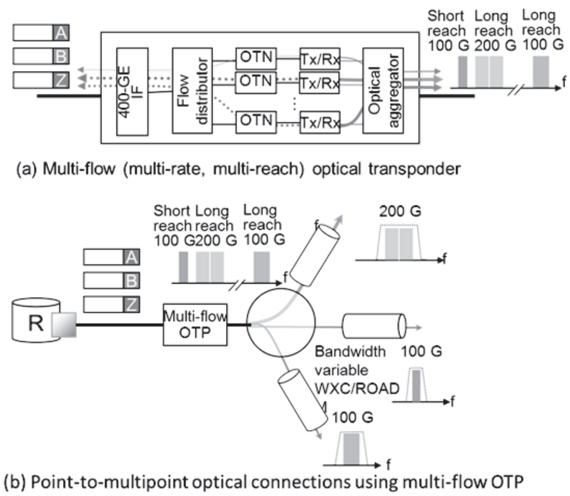


Fig. 7 Example of architecture for multi-flow OTP.

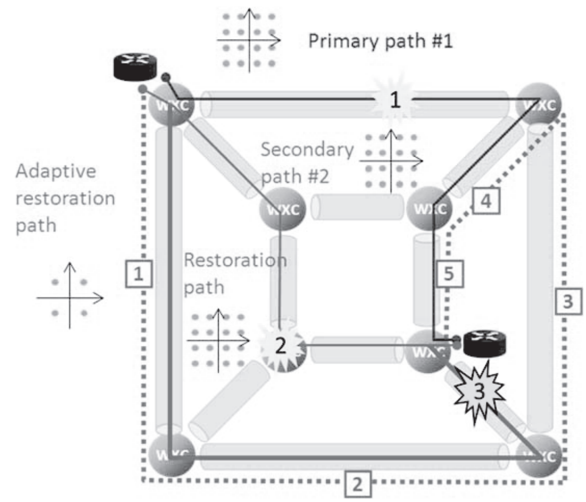


Fig. 8 Optical layer adaptive restoration.

elastic optical path networking technology, multi-flow OTPs can provide multiple optical connections and then enable efficient IP traffic offloading by increasing the number of directly connected router pairs while keeping router-to-WXC interconnections simple. Figure 7 shows an example of the multi-flow optical transponder architecture as well as spectral routing using the flexible bandwidth WXC [6], [9]. Here, we assume that a router is connected to an elastic optical path network via a 400-Gb/s router interface and a 400-Gb/s multi-flow OTP. In this example, a multi-flow OTP translates data traffic into two 100-Gb/s optical flows and one 200-Gb/s optical flow. A flow distributor equipped in the multi-flow OTP identifies data flows to be transported to the same destinations via flow identifiers, e.g., VLAN tags, in order to map them to the appropriate OTUs.

We evaluated the required number of router interfaces for the cases in which 400-Gb/s OTPs are able to generate 1, 4, and 16 optical flows. We assumed that core routers were positioned on a 4×4 mesh topology with uniform IP traffic of 25 Gb/s between end-to-end routers. In this simulation the required number of router interfaces is reduced from 50 to 16 when every router pair is directly connected using 16-flow capable OTPs. Even when the number of optical flows per OTP was 4 due to, for example, the maturity of hardware implementation at the time or the optical reach limitation, we observed considerable reduction in the number of router interfaces to 28 [15].

The multi-flow OTPs will also enable the optical virtual private line (OVPL) service that supports multiple optical connections. By simply connecting each customer site to the provider network via a single access line, the OVPL service will provide multiple optical connections from a single customer site to multiple customer sites with the capability to adjust the capacity [15].

4.3 Highly-Survivable Optical Path Restoration

The third benefit is the optical layer adaptive restoration scheme [11], [18] as shown in Fig. 8. First, let us suppose a conventional pre-planned restoration where a source and destination router pair employs client-side protection and two router interface cards at both routers are connected to the primary and secondary optical paths. When a fiber is cut or a node failure occurs to one or both of the optical paths, WXCs at both ends of the optical paths switch over the failed path to the pre-planned detour route whose route distance is within the optical reach of the original optical channel to ensure the connectivity of the router pair.

Suppose that due to a widespread serious disaster, links along the primary, secondary, and detour routes are simultaneously cut. Thanks to the mesh network topology, there could be surviving detour routes. However, such surviving detour routes may be unable to support sufficient spectral resources to transport the original data rate, and/or the length of the detour route could exceed the optical reach of the original optical signal. The unique features of adaptive spectral allocation and bandwidth/modulation-format optimization of the elastic optical path network guarantee the minimum connection for high-priority traffic at the expense of bandwidth. When a network management system (NMS) detects a fault, the NMS checks the surviving nodes and links, and calculates the detour route. Then the NMS searches the available contiguous spectral resources on the surviving detour route. If no available contiguous spectral resources are found on the route, an alternate route is calculated. Next, the NMS calculates the achievable transmission data rate and selects the modulation format that guarantees a sufficiently long optical reach for the detour route. According to the switch-over request from the NMS, each WXC on the route sets a cross-connection that covers the available spectrum to establish the end-to-end optical corridor. Finally, optical transponders at both ends of the elastic optical path change the bit rate and modulation format to establish an end-to-end optical channel.

5. Conclusion

We presented the elastic optical path network as a novel framework for spectrally-efficient and scalable future optical networks. Introducing elasticity and adaptation into the optical domain brings three major benefits: spectrally-efficient optical path accommodation, heightened network scalability through IP traffic offloading to the elastic optical layer, and enhanced survivability for serious disasters. We showed that sophisticated RSA algorithms reduce the spectral fragmentation for non-uniform spectral allocation to practically a negligible level, and elastic and adaptive spectral allocation yields significant spectral savings that much more than make up for the influence of the spectral fragmentation. Introducing multi-flow OTPs yields efficient IP traffic offloading to the elastic optical layer to scale IP networks in a cost-effective manner. The multi-flow OTPs will also enable the OVPL services that support multiple optical connections from a single customer site to multiple customer sites. We showed that elastic optical path networks enhance the survivability of networks for serious widespread disasters.

While promising various benefits, the elastic optical path network concept brings new challenges toward achieving cost-effective solutions both at the operational and equipment levels. At the operational level, we need to establish a physical transmission design methodology for mixed data rate, mixed format, in other words, the optical reach, and mixed channel spacing DWDM signals. As for the control plane, we need to standardize a new switching type of "spectrum switching capable" and some new parameters, for example the center wavelength and slot width, data rate, and modulation format, in the signaling message. Finally, since the spectral width and optimum per-channel power vary for each channel, we have to achieve cost-effective signal monitoring and control methods for such a wide variety signals. At the equipment level, we need bandwidth variable WSSs with larger port counts, say 20 to 40, for the add/drop side of bandwidth variable ROADMs or WXCs. The ultimate flexible transceiver would be a software-defined multi-rate, multi-format transceiver. However, in order to build solid economic justification for such transceivers, sophisticated photonic integrated circuit technology as well as advanced DSP/DAC technology should be established.

We anticipate that such challenges will be overcome, and the elastic optical path networking technology will provide a more efficient and highly-available optical network infrastructure for the future Internet and services.

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Masahiko Jinno is a Senior Research Engineer, Supervisor, in NTT Network Innovation Laboratories. He received the B.E. and M.E. degrees in electronics engineering from Kanazawa University, Ishikawa, and the Ph.D. degree in engineering from Osaka University, in 1984, 1986, and 1995, respectively. He joined NTT in 1986. He was a guest scientist at the National Institute of Standards and Technology (NIST), Boulder, Colorado, USA, during 1993–1994. He received the Young Engineer's Award in 1993 and the Best Tutorial Paper Award in 2011 from IEICE and Best Paper Awards from the 1997, 1998, and 2007 Optoelectronics and Communications Conferences, and the 2010 ITU-T Kaleidoscope Academic Conference.

Hidehiko Takara received the B.S., M.E., and Ph.D. degrees in electrical engineering from the University of Keio, Kanagawa, Japan, in 1986, 1988, and 1997, respectively. In 1988, he joined Nippon Telegraph and Telephone Corporation (NTT) Transmission Systems Laboratories, Kanagawa, Japan. Currently, he is a Senior Research Engineer in NTT Network Innovation Laboratories, NTT Corporation. His research interests include ultrahigh-speed and large capacity optical transmission systems and optical measurement techniques.

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 the 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, design of protocols for distributed control such as ASON/GMPLS, and interoperability testing of such protocols.

Kazushige Yonenaga received the B.E. and M.E. degrees in electrical engineering from Keio University, Yokohama, Japan, in 1989 and 1991, respectively. In 1991, he joined the Nippon Telephone and Telegraph (NTT) Transmission Systems Laboratories, Yokosuka, Japan, where he has been engaged in research on coherent optical communication and high-speed WDM transmission systems. From 2000 to 2004, he was with NTT Electronics Corporation. He is currently with NTT Network Innovation Laboratories. His current research interests include optical transparent networks and its enabling technologies.

Akira Hirano received the B.S. degree in physical chemistry and the M.S. degree in astrophysics from Osaka University, Osaka, Japan, in 1990 and 1993, respectively. In 1993, he joined the NTT Corporation, Kanagawa, Japan, and is currently with the NTT Network Innovation Laboratories, where he is involved in the lightwave communications area. His main interests are in the high-speed lightwave transport systems, optical signal processing, and ultra-short pulse generation.