Spectrum-Efficient and Scalable Elastic Optical Path Network: Architecture, Benefits, and Enabling Technologies

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ABSTRACT

The sustained growth of data traffic volume calls for an introduction of an efficient and scalable transport platform for links of 100 Gb/s and beyond in the future optical network. In this article, after briefly reviewing the existing major technology options, we propose a novel, spectrum-efficient, and scalable optical transport network architecture called SLICE. The SLICE architecture enables sub-wavelength, super-wavelength, and multiple-rate data traffic accommodation in a highly spectrum-efficient manner, thereby providing a fractional bandwidth service. Dynamic bandwidth variation of elastic optical paths provides network operators with new business opportunities offering cost-effective and highly available connectivity services through time-dependent bandwidth sharing, energy-efficient network operation, and highly survivable restoration with bandwidth squeezing. We also discuss an optical orthogonal frequency-division multiplexing-based flexible-rate transponder and a bandwidth-variable wavelength cross-connect as the enabling technologies of SLICE concept. Finally, we present the performance evaluation and technical challenges that arise in this new network architecture.

INTRODUCTION

Driven by high-definition video distribution services and high-speed broadband penetration, the consumer IP traffic is expected to double approximately every two years through 2012 [1]. The emerging interactive, real-time video communications will likely maintain the growth rate even after 2012. On the hardware side, the innovative server technologies including multicore processing, virtualization, network storage, and I/O convergence are becoming the driving forces behind the standardization process of 40 and 100 Gb/s higher speed Ethernet for the enterprise computing and communication environments. These advances will help to support a new generation of e-science and grid applications emerging with high-end computers, clustered data storages, scalable adaptive graphic environment, and scientific instruments almost certainly generating data flows of 10 Gb/s up to terabit level. These flows will need to be connected via hundred-gigabit per second class high-speed optical paths. The probable consequence is that in the near future network operators will need to transport a wide variety of traffic ranging from several tens of gigabits up to terabits per second in a cost-effective and scalable manner.

Following the growing demand for traffic-carrying capacity, recent innovations in optical communication systems achieved through the introduction of phase and multi-level modulation formats, polarization-division multiplexing, coherent detection, and digital equalization in electrical domain together with the advanced optical amplification have enabled long-distance dense wavelength-division multiplexed (DWDM) transmission with per-channel bandwidth of 100 Gb/s. Aside from the increased per-wavelength bit rate and the total system capacity, an important benefit of these innovations is the expansion of the optical reach. The extended distance an optical signal can travel through multiple DWDM links and wavelength cross-connects (WXCs) without undergoing optical-electrical-optical (OEO) regeneration has made the optically routed transparent mesh networks feasible.

The optically routed transparent mesh networking has obvious advantages, such as the elimination of costly, power- and space-consuming OEO regenerators and automated remote provisioning of optical paths. However, it still has a drawback with respect to the stranded bandwidth due to its rigid large granularity. Needless to say, the efficient utilization of the deployed network capacity is one of the network operators' major concerns. In spite of that, current wavelength-routed optical path networks require full allocation of wavelength capacity to an optical path between an end-node pair even when the traffic between the nodes is not sufficient to fill the entire capacity of wavelength. Being able to allocate resources with granularity finer than a wavelength, namely to create a sub-wavelength, would certainly provide an economic

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advantage. Another important challenge of a network operator is to accommodate the super-wavelength data traffic for cutting edge enterprise and scientific customers in a cost-effective and scalable manner. Several approaches such as optical packet switching (OPS) [2], waveband switching [3], or optical virtual concatenation (OVC) [4] have been proposed to meet the above mentioned demands offering sub- and super-wavelength traffic accommodation. However, their enabling technologies are still in the primary development stage, or these techniques lead to inefficiencies in bandwidth allocation.

In this article, we present a novel spectrum efficient and scalable optical transport network architecture called spectrum-sliced *elastic optical path* network (SLICE). SLICE alleviates the stranded bandwidth issue of current wavelength-routed optical path networks. It provides the support of various data rates including the possible future ones in a highly spectrum-efficient manner. Since SLICE offers a coarser granularity than OPS, we consider it as a middle-term alternative to the yet immature OPS technology. We employ the frequency-domain approach instead of the time-domain approach to provide efficiency and flexibility for wavelength routed optical transport networks. The remaining part of the article is organized as follows. First, we discuss the existing major scalable optical network technology options and present their strengths as well as weaknesses. Next, we describe the concept and architecture of SLICE enabling of accommodation of sub-wavelength, super-wavelength, and multiple rate data traffic. We then move on to the bandwidth-variable transponders and WXCs as the enabling technologies for SLICE. Subsequently, we discuss the benefits of SLICE in terms of efficiency and present the elastic bandwidth variation for efficient utilization of network resources, enhanced survivability, as well as future-proof, efficient accommodation of a variety of new possible data rates and modulation formats. Finally, we conclude the article with an outline of topics which need to be investigated in this new optical networking area.

Scalable Optical Networks

Several approaches have been proposed to provide the sub-wavelength and super-wavelength data transport in the optical domain. One of them is the optical packet switching (OPS). Significant research efforts have been focused on introducing the packet transport concepts such as multi-protocol label switching (MPLS) and provider backbone bridge (PBB) into the optical domain in order to take advantages of optical transparency, high efficiency due to statistical multiplexing and fine, sub-wavelength granularity [2]. All-optical packet switching is, however, not ready and seems to be a long term solution due to not only the lack of a practical optical buffering technique but also the limited transmission performance for backbone networks.

On the other hand, OVC was proposed for high-end applications in order to provide an end-to-end capacity much higher than that of the currently standardized interfaces, namely a super-wavelength. OVC is the optical domain analogy of the synchronous optical network/synchronous digital hierarchy (SONET/SDH) virtual concatenation (VCAT). In the OVC, several wavelengths are grouped and allocated end-to-end according to the application request for bandwidth-intensive and latency-sensitive cutting-edge applications [4]. OVC is also capable of providing the sub-wavelength data transport if original data traffic is inverse-multiplexed into lower rate data streams and transported with grouped lower rate wavelengths. Waveband switching [3] can be applied to reduce the port count of optical cross-connects by switching the grouped wavelengths together as a band using a single cross-connect port. Accordingly, a non-uniform waveband was proposed for an efficient accommodation of a wide range of traffic [5]. However, in the waveband approach the adjacent wavelengths have to be separated by a buffer in the spectral domain for wavelength demultiplexing, which leads to low spectral efficiency. This is true regardless of whether the grouped wavelengths are allocated contiguously or discretely.

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Concept of SLICE

The aim of SLICE is to address the issues of the existing scalable networks by providing spectrum-efficient and scalable transport of 100 Gb/s services and beyond through the introduction of flexible granular grooming in the optical frequency domain. SLICE is the analogy of SONET/SDH contiguous concatenation (CCAT). Unlike the SONET/SDH CCAT, SLICE provides arbitrary contiguous concatenation of optical spectrum that allows creation of custom-size bandwidth. The concept of SLICE is to allocate appropriate-sized, as opposed to fixed-sized, optical bandwidth to an end-to-end optical path. The allocation is performed according to the traffic volume or user request in a highly spectrum-efficient and scalable manner. However, it should be noted that in comparison to VCAT which concatenates the temporally scattered virtual containers, SLICE cannot aggregate the resources scattered in the spectral domain. In SLICE, the necessary spectral resources on a given route are *sliced off* and allocated to the end-to-end optical path. Unlike the *rigid* bandwidth of the conventional fixed-bandwidth optical path, an optical path in SLICE *expands and contracts* according to the traffic volume and user request, if necessary. The name elastic optical path of the optical paths in SLICE stems from their ability to expand and contract in contrast to the conventional rigid optical path.

The unique features of SLICE in terms of segmentation and aggregation of spectral resources, efficient accommodation of multiple data rates, as well as elastic variation of allocated resources are illustrated in Fig. 1. The following concepts are discussed in more detail in the remainder of the article

Sub-wavelength accommodation: As described in the previous sections, current wavelength-routed optical path networks require full allocation of wavelength capacity to an optical path between an end-node pair. SLICE provides

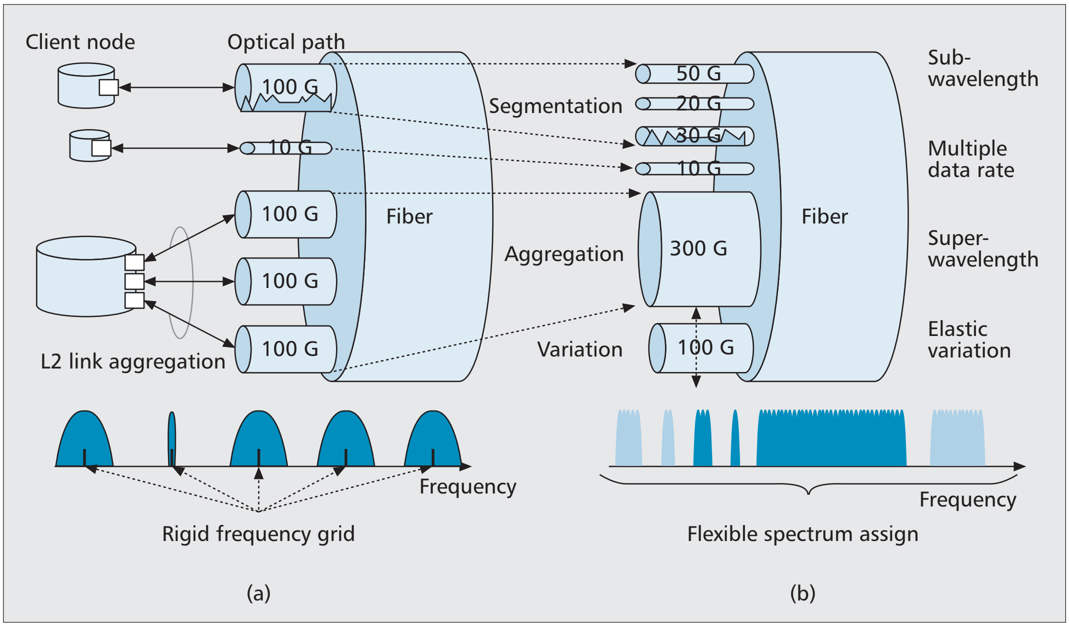

Figure 1. *Spectrum assignment in SLICE: a) conventional optical path network; b) SLICE.*

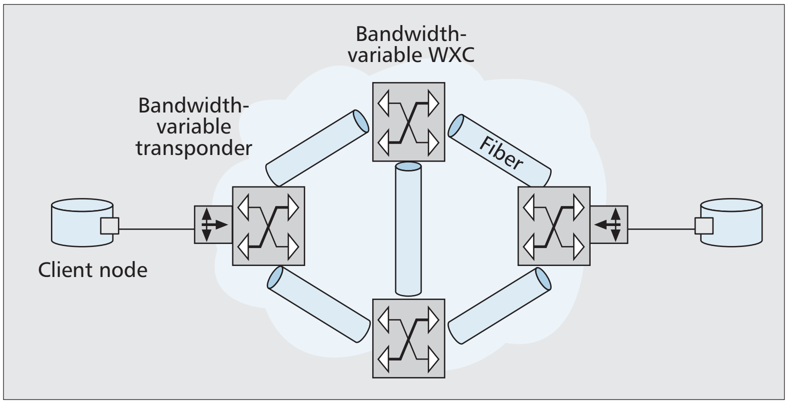

Figure 2. *SLICE network model.*

a new mechanism for cost-effective sub-wavelength (in other words, fractional bandwidth) connectivity service. When the 100 Gb/s Ethernet technology becomes standardized and popularized, the customers will be able to attach to the optical transport network with an inexpensive, short-reach 100 GbE interface. If only a fractional of bandwidth is required, SLICE can allocate just enough optical bandwidth to accommodate the client traffic, as shown in Fig. 1. At the same time, every node on the route of the optical path allocates a cross-connection with the appropriate spectrum bandwidth to create an appropriate-sized end-to-end optical path. The efficient use of network resources will allow the cost-effective provisioning of fractional bandwidth service.

Super-wavelength accommodation: Link aggregation is a packet networking technology standardized in IEEE 802.3 which combines multiple physical ports/links in a switch/router into a single logical port/link to enable incremental growth of link speed as the traffic demand increases beyond the limits of any one single port/link. Similarly, SLICE enables the creation of a super-wavelength optical path contiguously combined in the optical domain, thus ensuring high utilization of spectral resources, as shown in Fig. 1b. This unique feature, here called *layer one* (L1) *link aggregation*, can be realized by the optical orthogonal frequency-division multiplexed (OFDM) SLICE transponders, as will be discussed in the following sections.

Multiple data rate accommodation: As shown in Fig. 1, SLICE enables spectrally-efficient direct accommodation of mixed data bit rates in the optical domain because of the flexible assignment of spectrum [6, 7]. By contrast, current optical networks with fixed grid can lead to stranding of the optical bandwidth due to the excess frequency spacing for lower bit rate signals.

Network and Node Architecture of SLICE0

Figure 2 shows the SLICE network model. SLICE consists of bandwidth-variable transponders at the network edge and bandwidth-variable WXCs in the network core. In order to achieve the high spectral resource utilization in wavelength-routed optical path networks, the bandwidth-variable transponder generates an optical signal using just enough spectral resource to transmit the client signal while minimizing the separation between adjacent optical paths. At the same time, every WXC on the route of the optical path allocates a cross-connection with the corresponding, spectrum bandwidth to create an appropriate-sized end-to-end optical path. When the utilization increases, the transmitter increases the line capacity and every WXC on the route expands the switching window, raising the bandwidth of the elastic optical path. The use of optical orthogonal frequency division multiplexing (OFDM) as a highly spec-

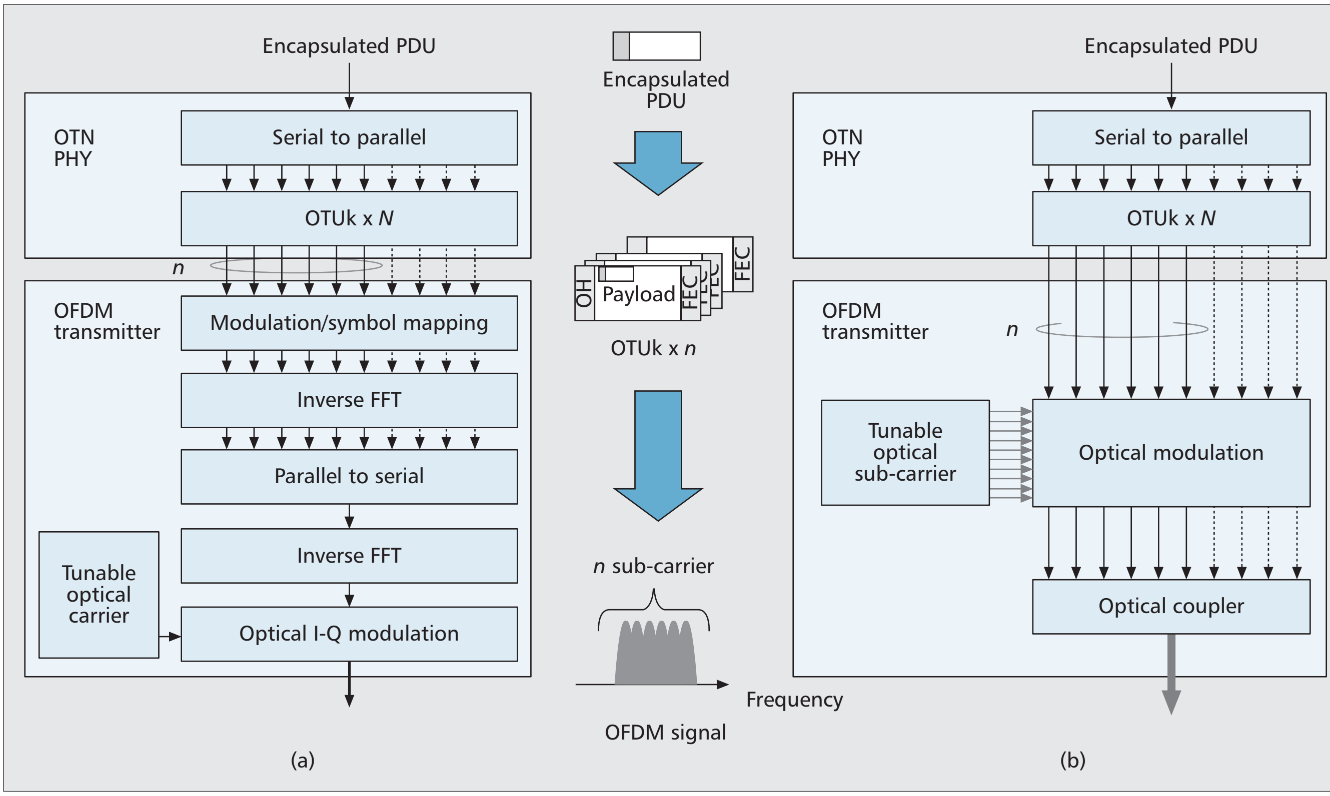

Figure 3. *Implementation examples of OTN PHY and OFDM optics: a) electrical approach; b) optical approach.*

trally-efficient, bandwidth-variable modulation format as well as the continuously bandwidth-variable wavelength-selective switch (WSS) as a building block of the WXC enables increasing the overall spectral efficiency of the network when compared to the conventional, fixed-bandwidth WDM network.

SLICE Transponder Model

Similar to the case of Ethernet transport over SONET/SDH or optical transport network (OTN), a SLICE transponder would work in one of three operational modes, i.e., frame-mapped, transparent-mapped, or direct-mapped operational modes. Client protocol data units (PDUs) in the incoming client signal are extracted via client-specific physical coding sublayer (PCS) and media access controller (MAC) layer. The all-idle client signals (e.g., inter-frame byte) are removed for efficient utilization of network bandwidth. In the case of a fractional rate service, traffic policing or shaping is applied to drop or smoothen the traffic that exceeds the configured maximum rate. The PDUs are then encapsulated using, e.g., generic framing procedure (GFP), mapped onto the International Telecommunication Union — Telecommunications Standardization Sector (ITU-T) G.709 OTN frame, and transformed to the optical OFDM signal. The tailoring of spectral width is achieved by allocating the appropriate number of optical subcarriers in the optical signal. The transparent-mapped and the direct-mapped operational modes, which offer less complexity of hardware and less-intrusive transport of client signal, may only require monitoring of the client-specific MAC and PCS.

Figure 3 shows the implementation examples of OTN PHY and OFDM optics in the SLICE transmitter. The encapsulated PDUs are mapped onto *n* out of *N* OTUk channels in OTN PHY. OTUk is an optical transport unit defined in ITU-T G.709 standard containing an overhead to manage optical transport network layer and a forward error correction (FEC) byte. The suffix *k* corresponds to the supported data rate of approximately 2.5 Gb/s ($k = 1$), 10.3 Gb/s ($k = 2$), 43 Gb/s ($k = 3$), and 112 Gb/s ($k = 4$, currently under standardization). By adjusting n (the number of OTUk channels) according to the client traffic volume or request, the necessary logical bandwidth can be allocated to the client signal. Accordingly, *n* OTUk channels are sent to the OFDM transmitter block. In order to support the unique bandwidth-adjustable feature of SLICE, an extension of G.709 OTU frame structure standard covering more efficient transport of fractional data rate with less complicated hardware would be desirable; however, this topic is beyond the scope of this article.

The application of OFDM technology enables transmitting the data over multiple orthogonal subcarriers with a frequency spacing of the inverse symbol duration. This technology has been widely implemented in various digital communication systems, such as wireless local area network (LAN) and asymmetric digital subscriber line (ADSL). Recently, extensive research efforts have been made to develop an optical version of the OFDM in order to overcome the impairments due to chromatic dispersion (CD) and polarization mode dispersion (PMD) in high-capacity long-haul fiber transmission [8, 9]. Besides the advantage of lower symbol rate of

The application of OFDM technology enables the L1 link aggregation. It can be realized by feeding frequency-locked optical multi-carriers to SLICE transponders and combining the OFDM signals in the optical domain without any spectral gap.

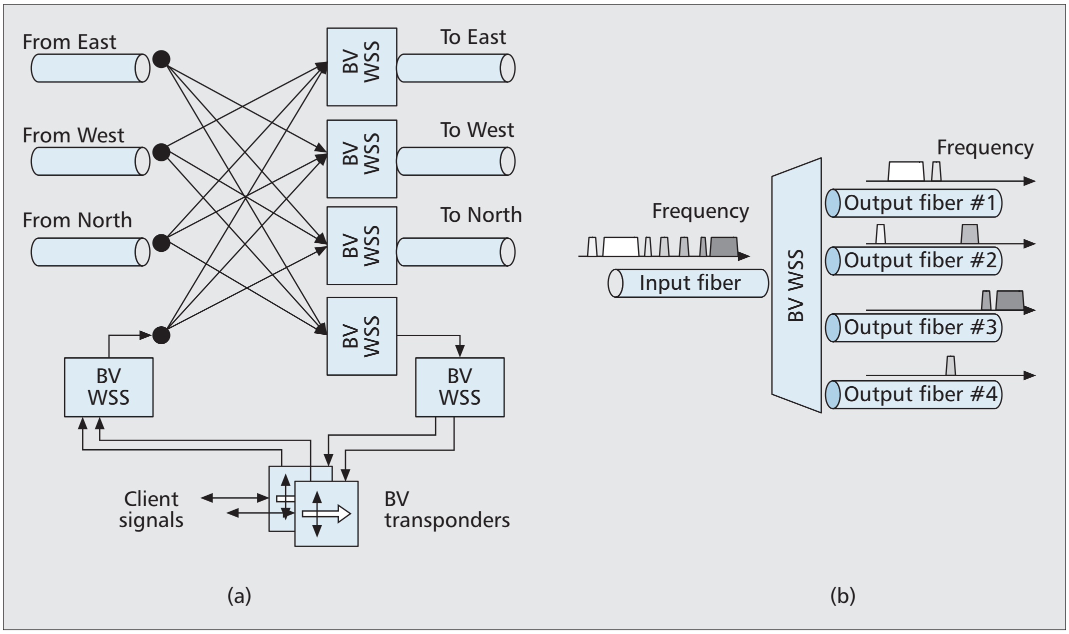

Figure 4. *SLICE node model: a) bandwidth variable WXC; b) bandwidth variable WSS.*

each subcarrier which mitigates the CD and PMD impairments, the introduction of OFDM format brings unique benefits in terms of high spectral efficiency due to the partially overlapping subcarriers and adaptive data rate modification which can be realized by changing the number of subcarriers.

As shown in Fig. 3, there are two possible approaches to implementing OFDM in optics. In the electrical approach, data bits of *n* OTUk channels are mapped onto individual subcarrier symbols and converted to the time series baseband OFDM signal through inverse fast Fourier transform (IFFT) and digital-to-analog conversion. An optical OFDM signal is generated by linearly upconverting the baseband OFDM signal to the optical carrier frequency fed by a wavelength-tunable laser using an optical in-phase/quadrature (I/Q) modulator [8]. Conversely, in the optical approach, an optical OFDM signal is directly generated through modulating individual optical subcarriers [9] using the data bits of each OTUk channel. The subcarriers are subsequently combined with an optical coupler. In each case, the optical frequency tuning and spectral bandwidth adjustment of the optical OFDM signal are achieved by changing the carrier laser optical frequency and adjusting the number of subcarriers, respectively. An electrical/optical hybrid approach is also possible.

The application of OFDM technology enables the L1 link aggregation, described in the previous sections. It can be realized by feeding frequency-locked optical multi-carriers to SLICE transponders and combining the OFDM signals in the optical domain without any spectral gap.

SLICE Node Model

The SLICE node performs self-routing of the incoming optical signal to the appropriate outgoing fibers based on the signal wavelength. The unique feature of the SLICE node when compared to the conventional WXC is that the optical bandwidth of the self-routing window is contiguously configured according to the spectral width of the incoming optical signal. An implementation example of such a bandwidth-variable WXC is shown in Fig. 4a, where bandwidth-variable WSSs (BV WSS) are utilized in broadcast-and-select configuration to provide an add-and-drop function for local signals as well as grooming and routing function for transit signals. In general, a WSS 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 one-dimensional mirror array and redirected to the desired output fiber. A mirror array may, for example, employ the micro-electro-mechanical systems (MEMS) or spatial phase modulator technology such as liquid crystal on silicon (LCoS). Since the LCoS is based on phased array beam steering utilizing a large number of pixels, LCoS-based WSSs can easily provide variable optical bandwidth functionality [6]. As shown in Fig. 4b, the incoming optical signals with differing optical bandwidths and center frequencies can be routed to any of the output fibers. A bandwidth-variable WSS has also been realized by high resolution and high fill factor MEMS-based WSS [7].

Benefits of SLICE

The analytical performance evaluation of SLICE architecture for fractional traffic accommodation is shown in Fig. 5. We consider the allocation of the entire L-band with optical paths carrying traffic of bit rates determined by log-normal distribution. The average traffic bit rate is shown in the horizontal axis. The plot shows the spectral efficiency of the link considering three traffic allocation technologies. The performance of SLICE is compared to the cases of inverse multiplexing (traffic allocated to DWDM channels) and fixed-bandwidth optical path (100 Gb/s path employing the same OFDM transmission technology). Assuming that the entire usable spectrum is occupied, the evaluation shows that the SLICE's fractional traffic accommodation scheme significantly increases the utilization efficiency, especially for paths with relatively low bit rate. Only in the case of high average traffic bit rates the fixed bandwidth path approaches the level of spectral efficiency of SLICE, whereas the inverse multiplexing scheme remains at a constant, low spectral efficiency level.

ELASTIC BANDWIDTH VARIATION

Expansion and contraction of an elastic optical path is one of the major unique features of SLICE. We present three examples which underline the benefits of the elastic optical path. These are the time-dependent elastic bandwidth sharing, energy efficient network operation, and bandwidth squeezed restoration:

Time-Dependent Elastic Bandwidth Sharing — In SLICE, the allocated optical bandwidth can be shared between the customers with time-dependent complementary demands. For example, a large amount of inter-office traffic of enterprises is transported during the business hours; on the other hand, a great deal of data between data centers is sent for data back-up or workload adjustment at nighttime. In such situations, the same link bandwidth can be allocated to different customers in a time-based manner by adjusting the spectral bandwidth according to the complementary time-dependent demands.

Energy Efficient Network Operation — Energy consumption and efficiency is becoming a major concern for network operators. During the periods of low link utilization, for example during the nighttime or weekend, SLICE transponders may partially turn off the electrical drivers through decreasing the number of OTUk channels and OFDM subcarriers. Also, the optical pumping power of the optical amplifiers on the route may be reduced to an appropriate level for supporting the client traffic. Both approaches will reduce the overall power consumption.

Bandwidth Squeezed Restoration — In the case of link failure, in current fixed-bandwidth optical networks, a failed optical path cannot be recovered unless the available bandwidth on the detour route equals or exceeds the original path bandwidth. This situation is illustrated in Fig. 6a. By contrast, in SLICE even if the available bandwidth on the detour route is not sufficient, the bandwidth of the failed working optical path is squeezed using the elastic feature of SLICE in order to ensure the minimum connectivity. Using this approach, shown in Fig. 6b, ensures a highly survivable restoration.

In order to realize elastic bandwidth variation, protocols coordinating the transitions to and from a lower level of bandwidth will be required. For example, no frames in transit shall be dropped or corrupted during the transition of bandwidth adjustment, except in the case of link failure. Therefore, a protocol similar to that used in SONET/SDH link capacity adjustment scheme (LCAS) will be required.

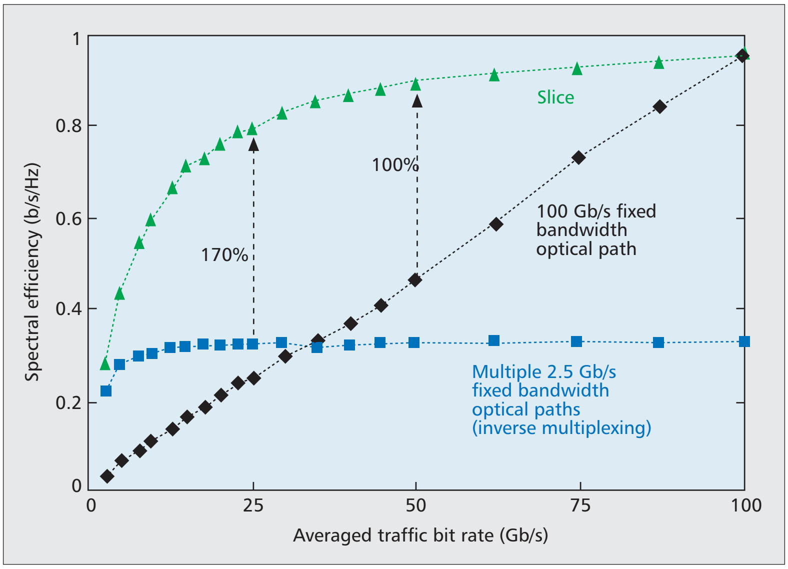

Figure 5. *Spectrum efficiency evaluation.*

FUTURE PROOF MULTI-SERVICE ACCOMMODATION

Since the deployment of DWDM and ROADM, the pressure on introducing larger system capacity has been accelerating the move towards the higher per-channel capacity on a narrower grid. Alignment to 200 GHz grid has been reduced to 50 GHz. In the latest experimental reports employing the quadrature phase-shift keying (QPSK) modulation format and polarization-division multiplexing, 100 Gb/s DWDM channels were transmitted with spectrum efficiency as high as 2 bit/s/Hz. Introduction of OFDM format or multilevel modulation (e.g., 8PSK, 16QAM) may further increase the spectrum efficiency, however at a cost of receiver sensitivity. Further improvements in spectrum efficiency may require a breakthrough innovation. However, any form of fixed grid (e.g., 50 GHz, 100 GHz) is too limiting for accommodating future ultra-high capacity client signals beyond 100 Gb/s. Consequently, a flexible spectrum allocation based on SLICE technology may be a viable and future-proof solution.

TECHNOLOGY CHALLENGES

While promising high spectrum efficiency and scalability for future optical transport networks, the SLICE concept presents new challenges. On the network level, flexible spectrum allocation scheme, routing and non-uniform spectrum allocation algorithm, network control and management scheme, etc. have to be explored. In particular, new bandwidth allocation scheme needs to be considered. Instead of the currently used fixed allocation to the ITU-T frequency grid, the allocation of bandwidth in SLICE can be carried out for example on a frequency slot basis. Moreover, in addition to the wavelength

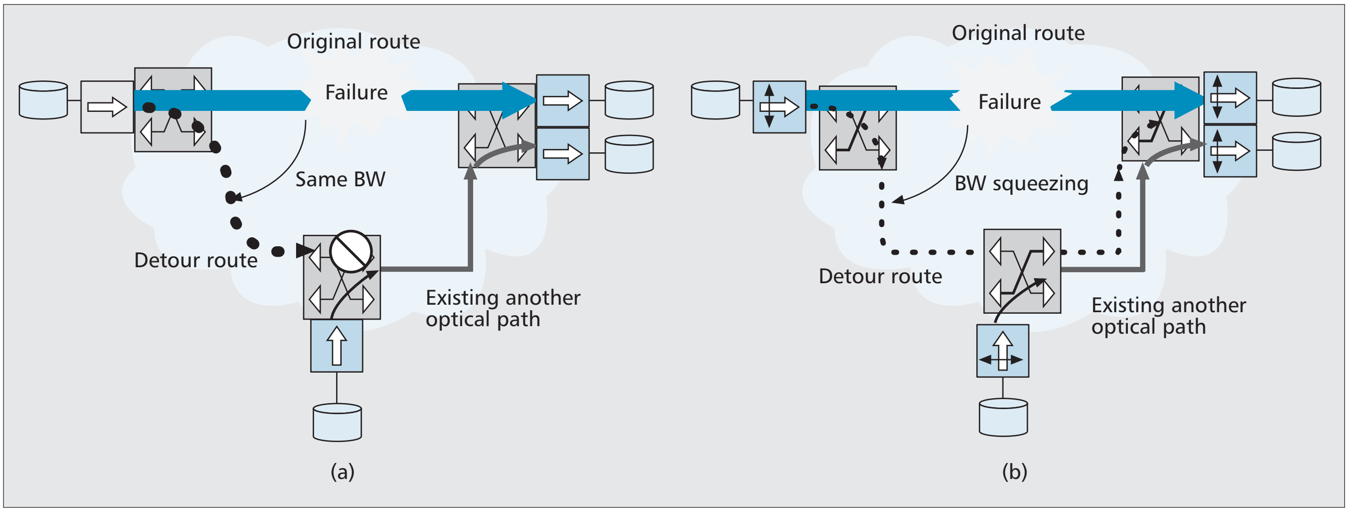

Figure 6. *Highly survivable restoration with bandwidth squeezing: a) conventional optical path network; b) SLICE.*

continuity constraint of the current routing and wavelength assignment (RWA) algorithms, spectrum continuity has to be incorporated.

On the node level, novel optical switching and filtering element providing high resolution and steep filtering performance, efficient client PDU mapping procedure, optimum modulation format for bandwidth variability and higher nonlinear impairment tolerance, etc. should be developed. A particular challenge is posed by the design of a new bandwidth-variable transponder. However, we expect that with the proliferation of the 100 Gb/s OFDM transponders, the technology will be adapted to scale to lower bit rates, thereby allowing the same device to provide fractional-bandwidth services. Such technology may find compact and cost-effective implementation using the optical integrated circuits. Similarly, the need for multiple temperature-stabilized, frequency controlled lasers can be alleviated by phase-locked carrier generation form a single laser source. Solutions to some of the challenges are presented in our latest report of preliminary experimental demonstration of SLICE concept with the per-channel variable capacity of 40 Gb/s to over 400 Gb/s [10].

Conclusions

In this article, we proposed the novel spectrum-efficient optical transport network architecture, SLICE, based on elastic optical paths. SLICE realizes the promise of efficient transport by using OFDM flexible-rate transponders and bandwidth-variable WXCs. The proposed architecture enables sub-wavelength, super-wavelength, and multiple-rate data traffic accommodations in highly spectrum-effective manner, as well as provides cost-effective fractional bandwidth service. Dynamic bandwidth variation of elastic optical path creates new business opportunities for network operators offering cost-effective and highly-available connectivity service through time-dependent bandwidth sharing, energy efficient network operation, and highly survivable restoration with bandwidth squeezing.

We believe that SLICE will introduce a new degree of freedom and open up a more significant role for optics in future transport networks.

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