Optical Networking Technologies That Will Create Future Bandwidth-Abundant Networks [Invited]

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***Abstract*—The transport network paradigm is moving toward next-generation networks that aim at IP convergence, while architectures and technologies are diversifying. Video technologies including ultrahigh-definition TV (more than 33M pixels) continue to advance, and future communication networks will become video-centric. The inefficiencies of current IP technologies, in particular, the energy consumption and throughput limitations of IP routers, will become pressing problems. Harnessing the full power of light will resolve these problems and spur the creation of future video-centric networks. Extension of optical layer technologies and coordination with new transport protocols will be critical; hierarchical optical path technologies and optical circuit/path switching will play key roles. Recent technical advances in these fields are presented.**

***Index Terms*—Wavelength routing; Networks, circuit-switched; Switching, circuit; Optical communications; Networks; WDM; Waveband; Wavelength path; Optical path; Optical cross-connect**.

I. Introduction

Broadband access including ADSL and FTTH is being rapidly adopted throughout the world and, as a result, traffic is continually increasing by around 50% every year in North America and Japan. The number of FTTH subscribers exceeded thirteen million in Japan and three million in the USA in 2008. In order to cope with the traffic increase, optical transmission and node technologies are being extensively developed. The maximum number of WDM wavelengths per fiber exceeds one hundred, and WDM transmission systems with a channel speed of 40 Gbits/s are now being introduced in some countries. The key to enhancing node throughput while simultaneously reducing node cost is optical path technology [1,2] based on wavelength routing. Wavelength routing using reconfigurable optical add/drop multiplexers (ROADMs) has recently been introduced, and large-scale deployment is being conducted in North America and Japan. GMPLS-controlled optical cross-connects have also been used to create nationwide testbed networks [3].

Video technologies including IP TV and high-definition and ultrahigh-definition TV (more than 33M pixels) are advancing [4], and they will induce further traffic expansion in the near future; future communication network services will become video-centric. More advanced video applications that include 3D TV [5] and cutting-edge applications including e-science, all of which need enormous bandwidth, have also been conceived. The inefficiencies of the present TCP/IP protocol will become more tangible given the above service advances. The power consumption and throughput limitations of IP routers are expected to limit the scale of Internet expansion in terms of bandwidth and the number of users [6,7], and the approach of relying on only IP convergence will not be the best in creating future bandwidth-abundant networks [8].

This paper first discusses the bottlenecks of present IP network technologies. They include the scalability limitation of IP routers and the protocol bottleneck. We then clarify the requirements for future optical networks where the reconfigurability or agility of optical networks is expected to play a key role. It is shown that the one important approach that can resolve these problems is the enhancement of photonic networking capabilities [9]. Future networks must offer a greatly increased number of wavelength paths and hence optical node throughput. The enhancement of optical path benefits and the introduction of new protocols including fast optical circuit switching will play key roles. This paper shows that, to realize the future networks needed, wavebands (WBs, bundles of optical paths) and hierarchical optical path cross-connects need to be adopted as the basic transport technologies. The merits and technology issues of in-

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troducing higher-order optical paths are elucidated. The introduction of WBs substantially reduces optical switch size at cross-connects, which mitigates one of the major barriers to the implementation of large throughput optical path cross-connect systems. Finally, recent advances in hierarchical optical path network realization technologies are introduced. They include network design algorithms, network reliability enhancement with WB and wavelength path protection, enhanced network control protocols, and some key component technologies for creating the hierarchical optical path cross-connects; a WB-selective switch (WBSS) and hierarchical optical cross-connect architectures. The hierarchical optical path network will be implemented in the not so distant future when traffic volumes warrant it.

II. Bottlenecks of Present IP Network Technologies

A. Power Consumption Bottlenecks

Energy consumption by information and communication technologies is expected to become a pressing issue in the near future [10–12]. Figure 1 shows the increase in electrical power consumption by one of the major carriers in Japan [13]. The power consumption in fiscal year 2003 was 7.4 TW h [14], which corresponds to almost 1% of total electric power purchased in Japan. It is estimated that the typical European carrier consumes 1.2–2.2 TW h [15], which corresponds to almost 1% of total electric power purchased in each country [16]. The power consumption continues to increase due to recent broadband service penetration. Of particular note, the power consumption of electrical routers will become more and more significant. The present largest throughput IP/MPLS router consumes about 13.6 kW per rack [17], and the largest expected multirack architecture (an 80 rack structure) consumes more than 1 MW, which is not really practical. Actually, in Japan, if traffic keeps increasing continuously at the rate of 40% every year, then total router power consumption in the year 2020 is expected to reach at 450 TW h/yr, which corresponds to about 50% of all electrical power produced in Japan at present [18]. Different evaluations [6] show that if 33% the people in the world were to subscribe to broadband access with the rate of 10 Mbits/s, the total electrical power consumed by the Internet would be estimated to be 58% of the world's power supply in 2007. Of course, advances in semiconductor device technologies, in particular, drive voltage reduction of large-scale integrated circuits and will mitigate these problems [18]; however, this will be one of the major bottlenecks in the IP-converged router-based networks expected.

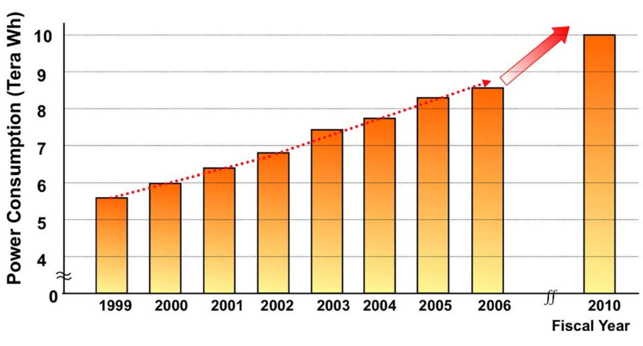


Fig. 1. (Color online) Consumption of electricity by telecommunication carrier in Japan.

B. Divergence in Service Attributes

Originally the IP protocol was designed and developed for computer communications, not human-related communication. The quality expected, best effort, is acceptable for web browsing and most non-real-time services such as e-mail and file transfer via TCP. As the Internet has become so popular, IP has been recognized as a major transport mechanism that should be utilized for providing universal services, including real-time services such as VoIP and video streaming service. The next-generation network [19] that promotes IP convergence is now recognized as the next step in network evolution. For real-time services, large delay is not acceptable, and so the UDP (User Datagram Protocol) is most commonly used. The acceptable packet loss rate for real-time services is, therefore, relatively tight, 10^{-3} for VoIP, and is very stringent for high-quality video streaming service, 10^{-5}, which is standardized in ITU-T as a provisional quality of service class for IP video transmission [20]. VoIP is a good revenue-generating service, and the price per bit is relatively high, as shown in Fig. 2. On the other hand, video service demands extremely high quality (low packet loss rates), and the bandwidth can be very high (more than 10 Mbits/s for high-definition TV transmission), and, as a result, the price per bit can be very cheap as shown in Fig. 2. IP networks must thus support services the attributes of which are widely diversified; price per bit differs by 7 orders of magnitude [21], and the upper bound of the packet loss ratio differs by 2 orders of magnitude (see Fig. 2). The inefficiency and difficulty of transporting all these services with their extremely wide range of service attributes and traffic characteristics by a single transport mechanism, IP, will become more and more apparent as video-related traffic increases.

In designing future networks we must consider the accommodation of new broadband services such as streaming video, lambda-leased line services, optical virtual private network (VPN) services, and broadband connections for e-science as mentioned above. It is very difficult to predict future services; however, it

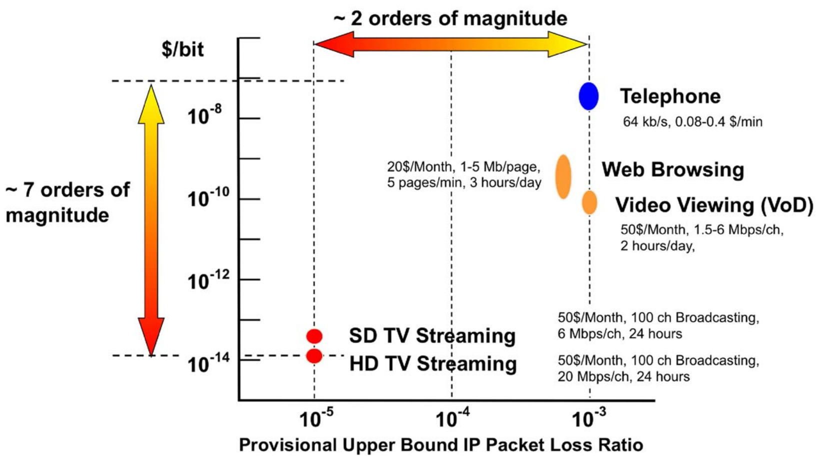


Fig. 2. (Color online) Price per bit and upper bound of packet loss for various services.

is reasonable to expect that video will be the dominant medium in future bandwidth-demanding services, although how the videos will be utilized will greatly differ, and when the new services will erupt is uncertain. Compared with other data services, video generates a more constant bit rate data, and its burstiness is smaller. In future networks, video traffic will predominate, and hence the networks must be suitable for transporting less-bursty but quality-demanding high-bit-rate real- or near-real-time services.

III. Requirements for the Future Optical Network

The advances in electrical processing such as TDM and in electrical router/cross-connect/server throughput, which basically followed Moore's law until the early 2000s, have been slower than the traffic growth rate. To fill this gap, we have been developing and introducing photonic network technologies; DWDM (dense WDM) transmission with almost terabit per second capacity has been widely deployed, and wavelength routing using ROADMs has been widely introduced. This represents the first boost in network performance to be provided by photonic network technologies. At this stage, traffic growth has been driven mainly by existing applications such as image, music, and video downloading, including peer-to-peer traffic and web browsing. After around 2005, the traffic increase rate fell to 40%–50% every year, while router throughput became almost saturated (see Fig. 3) due to the high IP-related processing burden and the energy issues. The traffic growth rate of 40% a year is still huge and results in traffic that is 30 (160) times the present traffic in 10 (15) years. Given the emergence of new video-centric bandwidth-hungry services, which will include the broadcasting or multicasting and streaming of IP TV, high-quality videos using high-definition (1k × 2k pixels), superhigh-definition (2k × 4k pixels), and ultrahigh-definition (4k × 8k pixels) videos, the traffic volume will explode. Superhigh-definition video, which requires about 6 Gbits/s for uncompressed real-time transmission, is now being utilized in digital cinema [22]. Ultrahigh-definition TV [23], which requires at most 72 Gbits/s (12 bit coding) for uncompressed real-time transmission, was first demonstrated at the Aichi Exposition in 2005 by NHK (Japan Broadcasting Corporation). The progress in technology development is steady, and experimental and commercial services via satellite are expected to start by 2015 and 2025, respectively, in Japan [4].

To cope with this expected burst in traffic volume, further advances in network performance and cost reductions must be attained; hierarchical optical path technologies [24–28,9] and superdense WDM technologies need to be deployed in the next step. The extent of the optical domain needs to be enhanced, but a new effective network architecture is needed that can exploit these technologies, as will be discussed in Section IV.

Another important attribute for the future networks is agile reconfigurability. Unlike POTS (plain old telephone service), the Internet demonstrates unpredictable changes in bandwidth and geographical traffic patterns. When a new data center begins opera-

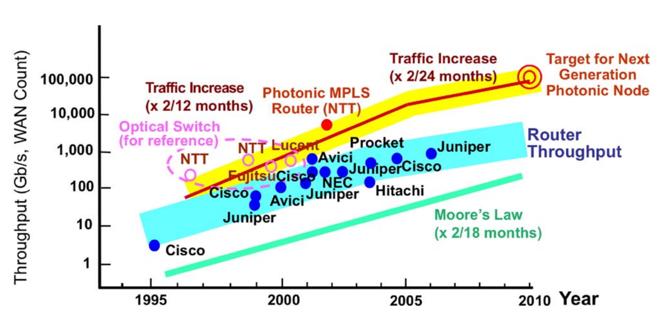


Fig. 3. (Color online) Trend in router throughput and traffic increase.

tion or a service provider starts a new service, abrupt traffic volume and pattern changes can occur. This was seen when Google acquired YouTube [29]. New broad-bandwidth on-demand provisioning services, such as Optical Mesh Service by AT&T [30] and JiT (Just in Time) service by Verizon [31], and optical VPN services require networks that offer agile reconfigurability. Abrupt traffic changes are also induced during network protection/restoration. Optical layer path protection/restoration requires optical level network reconfigurability. Fast rerouting of MPLS label switched paths (LSPs) generates abrupt and large electrical packet-level traffic changes. We have to be careful because these changes in traffic pattern and volume will be enhanced when TDM transmission speed differences between WAN/MAN and LAN become small. The burstiness observed in LANs will have a more direct impact on WAN/MAN traffic, since a relatively small statistical multiplexing effect with other traffic is expected for the LAN traffic. This trend is certainly occurring, as is shown in Fig. 4. The figure shows transmission capacity advances in Japan and advances in Ethernet interface speed; the key point is the very fast increase after the mid 1990s. The highest TDM transmission speeds for WAN/MAN and LAN will coincide at 40 Gbits/s or 100 Gbits/s within some years. The requirement for adaptability or reconfigurable capability of networks will become more and more critical, and therefore the architecture that realizes this must be developed, which is discussed in the next section.

IV. Waveband and Optical Circuit/Flow Switching

A. Electrical Router Cut-Through on Optical Path

Optical paths are utilized to cut through electrical routers, and this architecture greatly enhances network throughput and reduces energy consumption; a detailed discussion is given in [9]. One of the salient features of optical paths is that switch complexity does not depend on the bit rate or the protocols carried by the optical paths for the same scale switches. In other words, an optical switch is transparent to the bit rate carried, which is completely different from electrical cross-connect switches. With electrical technologies, switching becomes more and more difficult and consumes more electrical power as the bit rate increases. Thus, the wide deployment of optical path technologies will be driven by traffic increase and increasing demand to reduce the power consumption; it is impractical to resolve this issue through electrical switching.

B. Role of Optical Circuit/Flow Switching

Against the background of the bottlenecks of present IP network technologies, discussed in Section II, and the requirements for future optical networks, discussed in Section III, we propose the introduction of connection-oriented optical transport capability—fast optical circuit switching. Please note that the optical circuit switching networks will overlay the Internet, and the Internet will be utilized for a long time in the future, although it will evolve with the introduction of new technologies such as IPv6 and MPLS-TP [32]. Optical fast circuit switching will be suitable for transporting broadband data streams such as nationwide video content distribution, video on demand, and IP-TV. The video-oriented traffic is expected to be dominant in future networks as discussed before. Thus, different traffic will be delivered by using different transport mechanisms exploiting each characteristic, and the dominant future traffic will be delivered with optical circuit switching. Other broad-bandwidth on-demand services, and the optical VPN service mentioned in Section III, will also be accommodated within the optical circuit-switched network.

Regarding optical circuit switching, clarification of the terminology used in this paper is given below.

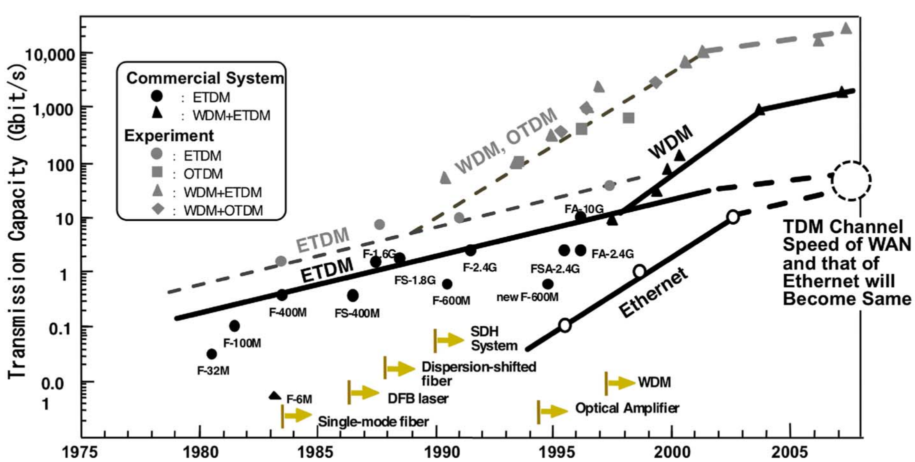


Fig. 4. (Color online) Evolution in transmission speed for core or metro networks and that for LAN.

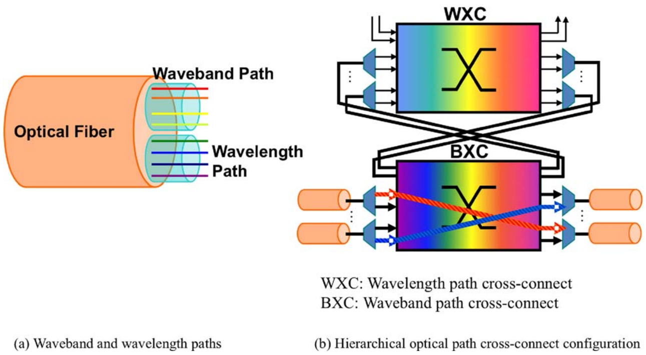


Fig. 5. (Color online) Wavelength path and WB path, and hierarchical optical cross-connect configuration.

Connection establishment/tear-down is done by either external control or traffic driven; we call the former optical circuit switching and the latter optical flow switching. In order to emphasize the speed in connection establishment/tear-down for optical circuit switching, we use the term "fast optical circuit switching." This is attained by a fast signaling mechanism that will differ from the signaling scheme used in POTS (signaling system No. 7, for example) [33]. In the following, connection establishment/release procedures are not discussed, and optical circuit and flow switching are discussed without distinguishing between them. Further, the optical circuit/flow in optical circuit switching utilizes optical paths, and so optical "circuit" and "path" will be used interchangeably.

C. Role of Wavebands

Many publications have discussed optical circuit switching performance, in particular blocking probability and the network resources necessary for establishing optical connections. Few papers have discussed the network architecture, an omission that is rectified here. We clarify the role of WBs in realizing efficient optical circuit switching networks. Figure 5(a) depicts wavelength path and WB path, and Fig. 5(b) depicts the hierarchical optical path cross-connect configuration [9]. Figure 6 depicts optical path establishment in a single-layer optical path network and that in a multilayer optical path network. In a single-layer optical path network, optical path establishment/tear-down requires node-by-node (optical cross-connect node) optical switch setting. On the other hand, in a multilayer optical path network, optical path establishment can be done utilizing one (direct) or multiple WBs. This means that, in the connection establishment/release phase, the number of nodes involved is greatly reduced, and the connection setup/release delay is minimized. WBs are usually established semipermanently. This scheme requires WB bandwidth reservation even when the optical paths/circuits that can be accommodated within the WB are not used, which results in reduced resource utilization. The relationship between the optical wavelength path cross-connect and the WB cross-connect corresponds to that of the electrical switching system and the cross-connect system in POTS networks. In regard to connection establishment and signaling, centralized and distributed control schemes can be applied as demanded by service requirements.

Compared with single-layer optical path networks, the introduction of WBs can greatly reduce network cost except when traffic volume is small. Evaluation results on the network cost reduction attained with introduction of WB technologies are shown in Fig. 7 for $M \times M$ regular mesh network topologies of different scales [34]. It is clear that when traffic is relatively large, the attained cost reduction is large. One important point to be emphasized is that the WB is effective when traffic volume is rather small. This will multiply the effectiveness of WB technologies in terms of network migration from single-layer optical path networks.

The fundamental benefit of WBs is that they permit node efficiencies. In other words, the switch scale necessary for realizing a specific throughput can be reduced with the introduction of WB technologies. This is critical in creating bandwidth-abundant future networks. Figure 8(a) shows a basic hierarchical optical

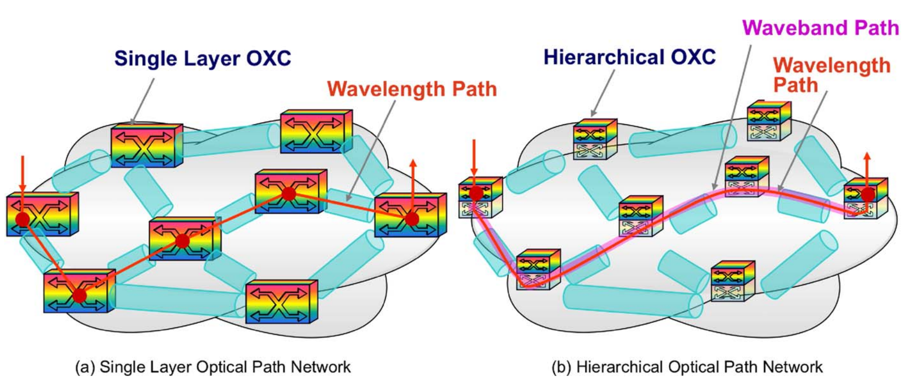


Fig. 6. (Color online) Comparison of single-layer optical path network and hierarchical optical path network.

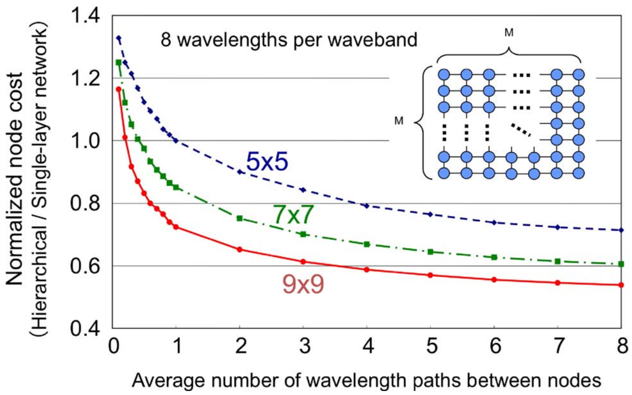


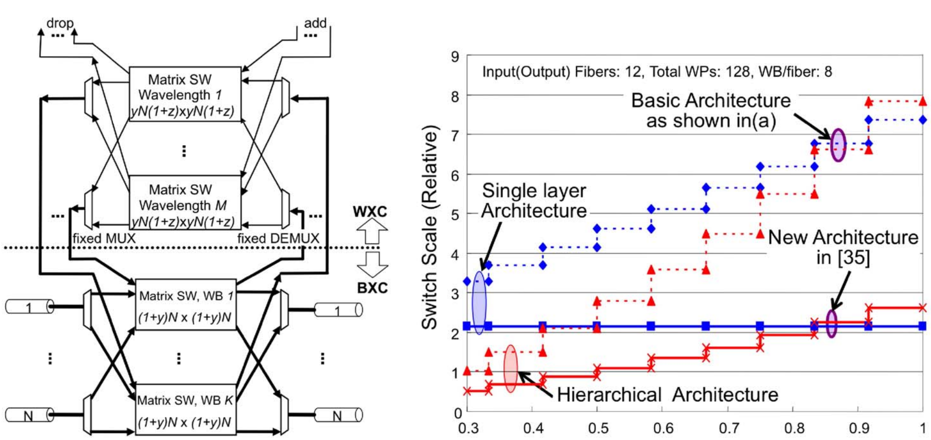
Fig. 7. (Color online) Effectiveness of WBs and network size dependency.

cross-connect switch architecture using matrix-type switches; Fig. 8(b) shows the switch scale reduction available compared with the corresponding single-layer optical cross-connect switch [35]. Here the switch scale is measured by the number of element 2 $\times$2 switches needed to construct the matrix switches. The conventional optical path add/drop ratio for each transit node ranges from 0.25 to 0.5, and the ratios yield switch scale reductions of more than 50% with the addition of WB technologies. The other important switch architecture is the one that utilizes the WSS (wavelength-selective switch) and the waveband-selective switch (WBSS). The WSS architecture was originally proposed in 1993 and presented in [36,37]; it was then called delivery and coupling switches (DC-SWs) [36–38]. These switches are used in the optical cross-connect systems employed to create nationwide testbed networks [39]. Figure 9(a) shows a basic hierarchical optical cross-connect switch architecture that uses WBSSs and WSSs to create WB cross-connects and wavelength path cross-connects, respectively. Figure 9(b) shows the switch scale reduction possible compared with the corresponding single-layer WSS-based optical cross-connect switch [40]. Here, for simplicity, the switch scale is measured by the number of elemental 3D MEMS mirrors needed to construct WSSs and WBSSs. This is because the number of mirrors is the key factor that determines the performance, cost, and reliability of the 3D MEMS WSS/WBSS system. For optical path add/drop ratios of 0.25–0.5, a switch scale reduction of 21%–48% is possible by introducing WB technologies. In the hierarchical optical path cross-connect architecture depicted in Fig. 9(a), the input side and the output side WSS and WBSS can be replaced by optical couplers. The switch scale reduction shown in Fig. 9(b) is not altered by this use of optical couplers.

V. Advances in Hierarchical Optical Path Network Realization Technologies

A. Network Design Algorithm

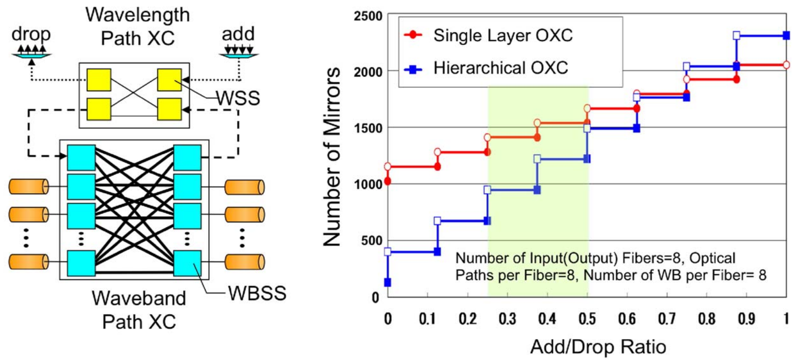
The effectiveness of hierarchical optical path networks strongly depends on the network design algorithm. Effective algorithms are much more difficult to develop than those used in single-layer optical path networks. The WB routing and WB assignment problem of hierarchical optical path networks is a generalization of the single-layer optical network design problem. The problem is to minimize cost functions subject to WB and wavelength continuity constraints. The problem is NP-complete and can equivalently be formulated as a combinatorial optimization problem that targets minimizing the total number of optical ports [41–43] of cross-connect systems or maximizing the utilization of fiber capacity [44]. The number of binary variables in the combinatorial optimization problem explodes with network size. This characteristic makes the problem computationally impossible to solve accurately for large networks. Previous publica-



(a) Hierarchical optical path cross-connect switch architecture based on matrix switches

(b) Comparison of switch scales for single layer and hierarchical optical path cross-connect switches

Fig. 8. (Color online) Comparison of single-layer and hierarchical optical path cross-connect switch scale.



(a) Hierarchical optical path cross-connect switch architecture based on WBSS and WSS

(b) Comparison of switch scales for single layer and hierarchical optical path cross-connect switches

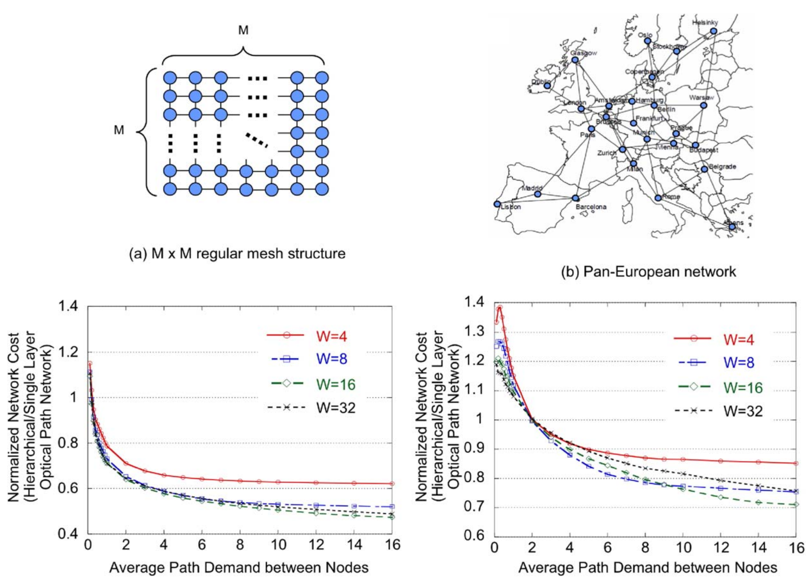
Fig. 9. (Color online) Comparison of single and hierarchical optical path cross-switch scale.

tions, therefore, provide alternative algorithms based on heuristics or relaxation [41–47].

A very efficient network design algorithm that uses the cluster-search method in a source–destination Cartesian product space was recently developed [34,48]. The Cartesian space can be used to effectively locate WB paths that can reduce total cost. For each set of wavelength paths, a WB path is first constructed so as to maximize the degree of cost reduction. The wavelength paths that are not accommodated in the first step are finally accommodated in WBs by identifying the shortest paths in a multilayered graph considering WB tunnels [34,48]. Figure 10 shows the cost reduction possible with the hierarchical optical path network design in a comparison against a single-layer one for, Fig. 10(c), a 9×9 polygrid network and for, Fig. 10(d), the pan-European network with 26 nodes, where wavelength path demands are randomly distributed. The vertical axis of the graph is cost normalized against the cost of a single-layer optical network designed by locating the shortest paths with rerouting of wavelength paths in sparsely used fibers to attain cost reduction. In the calculation, WB bandwidth, W, is changed, and it is shown that the optimal W depends on traffic volume. It has been demonstrated that a significant cost reduction can be attained with the proposed design algorithm even for rather small traffic demand regions.

B. Waveband Network Protection Algorithm

Failure survivability is a crucial requirement in developing reliable networks. A heuristic design algorithm for hierarchical optical path networks that considers protection at the wavelength path level, not the WB path level, has been proposed [49]. A novel heu-



(a) M x M regular mesh structure

(b) Pan-European network

(c) Normalized network cost for M x M regular mesh network

(d) Normalized network cost for pan-European network

Fig. 10. (Color online) Network cost reduction attained with introducing WB technologies.

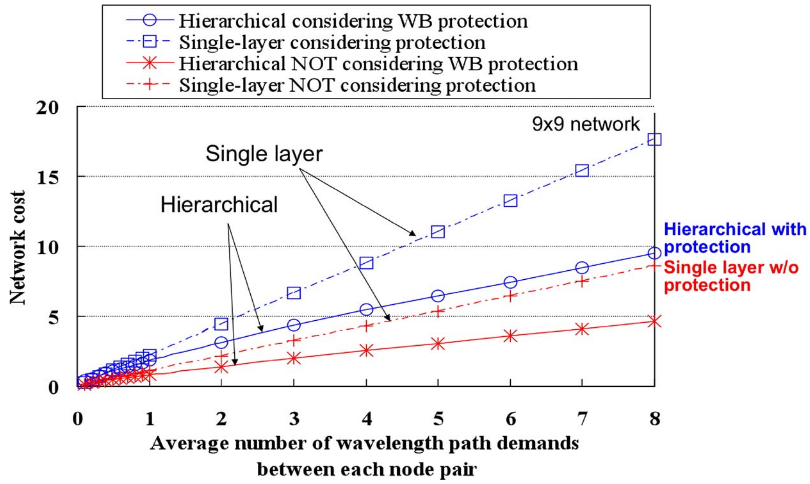


Fig. 11. (Color online) Cost comparisons between optical path protected networks and WB path protected networks.

ristic design algorithm that incorporates failure survivability with WB protection [50] has also been proposed. The algorithm was shown to be much more effective than that using simple end-to-end WB assignment. The effectiveness of WB networks with WB-level protection as compared with networks based on single-layer optical paths and optical path level protection has also been investigated and verified recently [51]. The developed algorithm is based on the observation that a pair of primary and backup WB segments (a portion of a WB) forms a loop to attain link and node disjoint protection for each segment. Figure 11 shows the network costs of hierarchical and single-layer optical path networks with or without WB protection. For WB network design without protection, we used the design algorithm proposed by Yagyu *et al.* [34,48], which has been shown to be very efficient. It is noted that the effectiveness of hierarchical optical path networks strongly relies on the utilized algorithm. It was proved that hierarchical optical path networks that adopt the WB protection scheme are more cost effective than single-layer networks with optical path protection for a wide range of traffic demand. It was also revealed that reliable hierarchical networks with WB protection can be realized with only marginal cost increases from single-layer networks without protection. This work has eliminated one of the key barriers preventing the full adoption of hierarchical optical path networks.

C. Network Control Protocol

GMPLS [52] has been proposed as a common control mechanism among different path layers (and a fiber layer) that utilizes IP-based signaling; intensive technical development and standardization activities have been undertaken so far for TDM paths, LSPs, and optical paths. Extension is necessary to control hierarchical optical path layers, but this appears to be fairly straightforward. An experimental demonstration of GMPLS control systems for hierarchical optical path networks has been presented [53].

D. Cross-Connect System Technologies

The key to the hierarchical optical path networks is the hierarchical optical cross-connect system or switching system. As discussed in Section IV.B, to realize the multilayer optical path cross-connect, WBSS, an extension of WSS, is essential. Some of the recent advances in WBSS system development are presented below.

Different arrangements are possible for defining WBs as shown in Fig. 12 [54]. One integrates wavelength paths in a sequential manner, whereas the other integrates them in a periodic manner. The WB arrangement used has virtually no impact in terms of network provisioning and operation, administration, and maintenance. However, the WBSS architecture does depend on the WB arrangement adopted.

WSS allows switching of any of the wavelength paths on an input fiber to any of the output fibers at the wavelength level. Figure 13(a) depicts the generic architecture of the $1 \times N$ WSS, where M wavelength

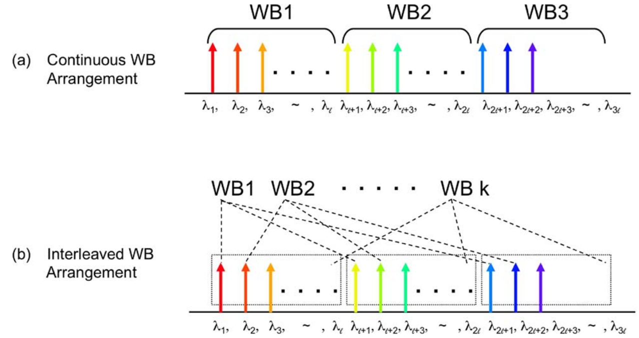
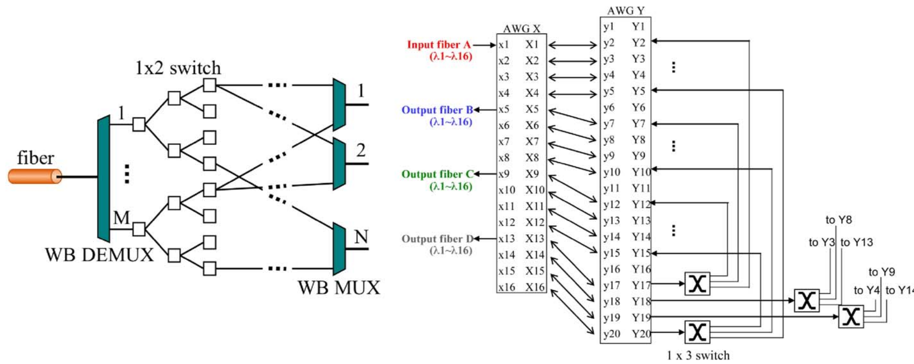


Fig. 12. (Color online) Different WB arrangements.

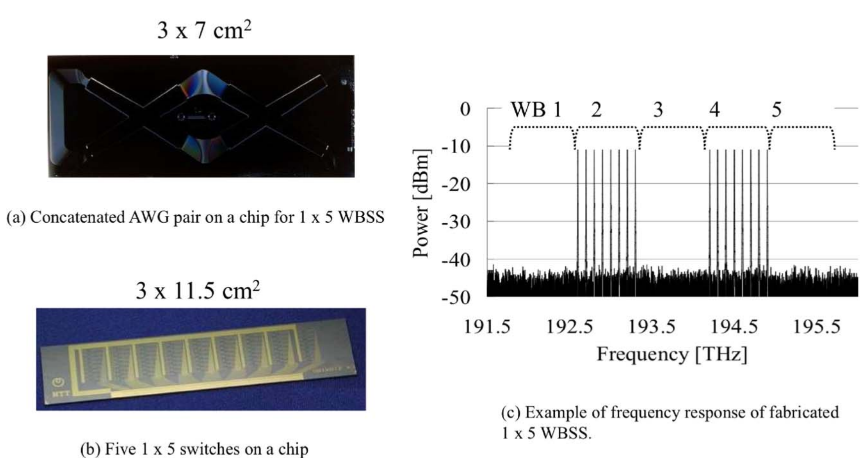


(a) Generic architecture of one by N WBSS

(b) Arrangement of 1x3 WBSS fabricated with two AWGs and four 1x3 switches

Fig. 13. (Color online) Generic architecture of WBSS and an example of 1×3 WBSS that can be realized with two AWGs and four 1×3 optical switches.

paths are accommodated in the input fiber. Using multiple WSS modules creates a cross-connect or ROADM (see Fig. 9). WBSS allows switching of any of the WBs on an input fiber to any of the output fibers. The WB cross-connect and ROADM use WB mux/demux instead of wavelength mux/demux. Figure 13(b) depicts one example of our proposed 1×3 WBSS that uses the WB mux/demux as presented in [55], and four 1×3 switches. The WB mux/demux part is created by concatenating two cyclic AWGs, 16×16 and 20×20, where four fibers (one for input and three for output) are accommodated simultaneously. Each fiber carries 16 wavelength channels that are divided into four continuous WBs; each WB consists of four channels. The WBSS can switch any of the WBs on input fiber A to any of the three output fibers, B–D. The WBSS is for continuous channel allocation and prevents waveguide gratings crossing between the two component arrayed waveguide gratings (AWGs) as shown in Fig. 13(b). This is advantageous for monolithic realization, and it can be realized by using planar lightwave curcuit (PLC) technologies. To confirm the feasibility of the proposed WBSS, a 1×5 WBSS prototype using PLC technology has been developed [56]; two chips were connected by fibers: one for WB mux/demux (Fig. 14(a)), the other for eight 1×5 switches (Fig. 14(b)). The WB mux/demux part was designed to accommodate forty 100 GHz spaced channels ($191.8+0.1\times n$ [THz]; $n=0-39$) on the ITU-T grid; it can support six input fibers as a WB mux/demux. Each fiber carries 40 channels (8 channels $\times 5$ continuous WBs). The chip size was 3 cm$\times$7 cm. The average fiber-to-fiber insertion loss and the coherent crosstalk were 3.7 and −39.5 dB, respectively. The size of eight 1×5 switches on a chip was 3 cm $\times$11.5 cm. The average fiber-to-fiber insertion loss and polarization-dependent loss (PDL) were 2.4 and 0.1 dB, respectively. A WBSS that consists of the two chips can accommodate one input fiber and five output fibers (1×5 WBSS). Figure 14(c) shows an example of the output channel spectra at one output port when two WBs (WB 2 and 4) are selected from five WBs (WB 1–5). Different WB output arrangements and outputs from other output ports were also measured. The routing capability of the prototype device was confirmed to be accurate. The measured average fiber-to-fiber in-



(a) Concatenated AWG pair on a chip for 1 x 5 WBSS

(b) Five 1 x 5 switches on a chip

(c) Example of frequency response of fabricated 1 x 5 WBSS.

Fig. 14. (Color online) Prototype 1×5 WBSS fabricated with PLC technology; two chips were connected by fibers.

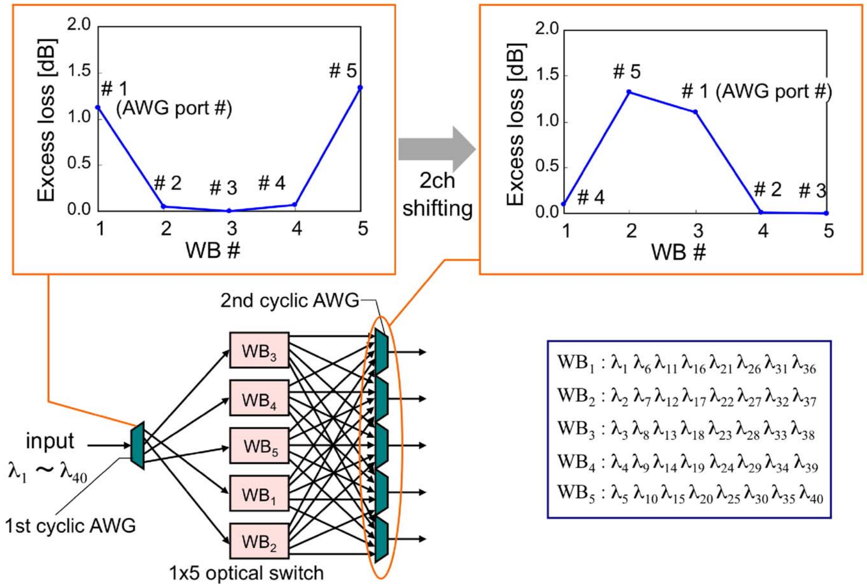


Fig. 15. (Color online) WBSS for interleaved channel allocation constructed with cyclic AWGs.

sertion loss of the 1×5 WBSS was 6.1 dB.

Next, a WBSS for interleaved channel allocation is shown in Fig. 15 [57]. This potentially allows us to use cyclic AWGs for WB mux/demux in the band cross-connect part in Fig. 15 and to use wide channel bandwidth AWGs as mux/demux in the wavelength cross-connect part, which allows us to utilize cost-effective athermal AWGs. Here, cyclic means that the free spectral range of the $1\times M$ AWG corresponds to a width that covers M consecutive channels.

Forty C-band channels on an ITU-T grid with a channel spacing of 100 GHz are utilized; they are divided into five WBs; each WB consists of eight individual channels as shown in Fig. 15. The proposed 1×5 WBSS consists of six 1×5 cyclic AWGs and five 1×5 optical switches (Fig. 16). The cyclic AWG has a periodic transmission response whose period equals the free spectral range [58], 500 GHz. This enables the first AWG to demultiplex the input signal into the interleaved WBs. Each WB output from the first AWG can be routed to any of the five output AWGs (second AWGs) through the 1×5 switches. Finally, the second AWGs multiplex the WBs and output them. While the logical implementation explained above achieves the desirable optical operation, there is an issue to be cleared up. The outer ports of a cyclic AWG have larger channel loss than the inner ports. The measured excess loss values of a test sample of the first cyclic AWG for WB1–WB5 are shown in Fig. 15; the excess loss deviation was 1.3 dB. In the proposed WBSS, each channel passes through the first and second AWGs, and hence the total AWG loss and the loss deviations are doubled. To overcome this problem, we shifted the center wavelength of the second AWG so that the offset relative to the first AWG equals two channel frequencies (200 GHz), as shown in Fig. 15. With this scheme, the resulting excess loss deviation after passing through the two AWGs is reduced to 1.3 dB, while it is 2.6 dB without this channel shift approach (also, the total maximum excess loss of the two AWGs is almost halved). We note that with this arrangement, waveguide connections between WB switches and the second AWG must be changed, as shown in Fig. 15. A WBSS module (100 mm $\times$100 mm) was fabricated so as to include a WBSS monolithic PLC chip; the chip size is 34 mm$\times$64 mm as shown in Fig. 16. It includes six AWGs and five 1×5 switches. The device is designed to accommodate forty 100 GHz spaced channels ($195.6+0.1\times n$ [THz]; $n=0-39$) on the ITU-T grid. The major performance measures of the device are summarized in Fig. 16. It is confirmed that the loss deviation is reduced as in-

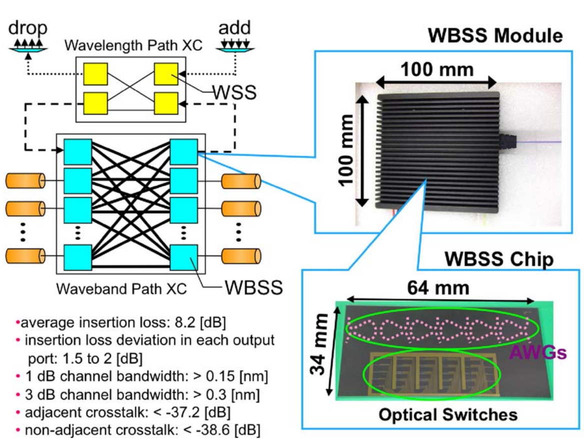


Fig. 16. (Color online) WBSS and WSS-based hierarchical optical path cross-connect system and developed WBSS module using integrated PLC circuits

tended. Its small size, no adjustment requirement, and good performance further strengthen the advantages of the multilayer optical path cross-connect.

VI. Conclusions

Until ten years ago, we looked at N-ISDN and SONET/SDH as the next step technologies on which to base the development of access and core networks, respectively; the agreement was universal. The advent and penetration of IP, new technical developments including WDM and photonic network technologies, rapid advances in access technologies, and the emergence of IP-based control protocols such as MPLS and GMPLS, provide powerful tools for creating the next-generation networks that support IP convergence. The technology alternatives are extremely varied, and this allows us to develop optimized networks that match each country's or region's or carrier's situation. In this environment, IP convergence is now ongoing; however, we should be prepared for future evolution by identifying the best approach, since the IP bottleneck is becoming more and more tangible. It will limit the network expansion envisaged; the energy bottleneck and throughput bottleneck must be overcome. It is very difficult to predict future services; however, video is expected to be the dominant medium among the bit-rate-demanding services. High-quality video technologies are steadily advancing. The future networks must be extremely efficient at transporting the video data streams.

To create future networks, the hierarchical optical path network and node technologies and network architectures that fully harness the power of optical transmission are of great importance. Fast optical circuit/path switching will play a key role in creating cost-effective and bandwidth-abundant future networks. Those technologies need to be fully developed soon, and some of the recent advances have been demonstrated.

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