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INVITED SURVEY PAPER

Recent Developments in and Challenges of Photonic Networking Technologies

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SUMMARY The transport network paradigm is changing as evidenced by IP convergence and the divergence of architectures and technologies. Harnessing the full power of light will spur the creation of new broadband and ubiquitous services networks. To attain this, however, not only must photonic technologies be optimized, but they must also be coordinated with complementary electrical technologies. With regard to photonic network design technologies, further developments are necessary including very large scale network design, quasi-dynamic network design, and multi-layer optical path network design.

key words: *photonic networks, photonic network design, multi-layer optical paths*

1. Introduction

Broadband access is penetrating throughout the world, and FTTH (Fiber to the Home) is being rapidly adopted in Japan and North America as the most powerful means of broadband access; there were more than six million users as of the middle of 2006 in Japan. Although this number is relatively small compared to ADSL (Asymmetric Digital Subscriber Line) subscribers (14.5 million), it continues to increase at a much higher rate than ADSL and is expected to exceed that of ADSL within a couple of years. Because of the rapid penetration of broadband access and the introduction of new services for businesses, the traffic of broadband users is increasing rapidly, i.e., more than 100 percent every year [1]. Considering further burst in the volume of traffic envisaged, which will be spurred by the penetration of bandwidth intensive new services based on video, another advances in network performance and cost reductions must be attained.

In designing future networks and systems, we must consider the current paradigm changes; IP (Internet Protocol) convergence and the divergence of architectures and technologies. To start with, we discuss past and present status of network development in Sect. 2. Harnessing the full power of light will spur the creation of new broadband and ubiquitous services networks. The key requirements of enhancing the performance and reducing the cost of future IP-based multimedia communication networks can be effectively achieved by exploiting wavelength routing. This requires, however, not only the optimization of photonic technologies but also coordination with complementary electrical technologies. MPLS (Multiprotocol Label Switching) will play the key role. Its status, the present perception of its insufficiency, and the on going enhancement, T-MPLS (Transport-MPLS [2]), are discussed. The evolution of ASON/GMPLS (Automatic Switched Optical Network [3]/Generalized Multiprotocol Label Switching [4]) will also be needed. In Sect. 3, we discuss key issues that we need to consider in the development of the photonic network, and directions towards network throughput expansion. Finally, we discuss some of the cutting-edge photonic networking technologies including segmented network design, quasi-dynamic network design, multi-layer optical path network design, and optical fast circuit switching.

2. IP Convergence and Technology Divergence

2.1 Transport Network Evolution

Figure 1 depicts the trends in transport network evolution over the last two decades. At the middle of the 1980's, core and metro networks are based on the plesiochronous digital hierarchy (PDH) [5]. The digital hierarchy of Europe, North America, and Japan were different as there was no world wide standard. Moreover, interworking between the equipment of different vendors has been very problematic. Regarding access networks, they are based on analog transmission and a huge number of variations in the transmission specifications exist, particularly in North America, the home of many independent telephone service providers. Up to the mid 1990's, tremendous efforts were made toward the development and standardization of universal transport technologies; SDH (Synchronous Digital Hierarchy) [6]–[8] for core and metro, and N-ISDN (Narrowband ISDN) for access networks. For data transport, Frame Relay (FR) service has been widely adopted and for the creation of integrated transport for the coming multimedia services, a new transfer mode, ATM (Asynchronous Transfer Mode) was proposed [9], [10]. Intensive development efforts worldwide resulted in the first standards from CCITT (Comité Consultatif International Téléphonique et Télégraphique: presently ITU-T; International Telecommunication Union Telecommunication Standardization Sector) in 1990 [11]. During this period, there was little divergence between the target transport networks and nation-specific strategies.

In the period 1995–2005, diverse transport network technologies were introduced. As for access, DSL/ADSL, FTTH, satellite, wireless and cable have been introduced. Even for the introduction of fibers in the ac-

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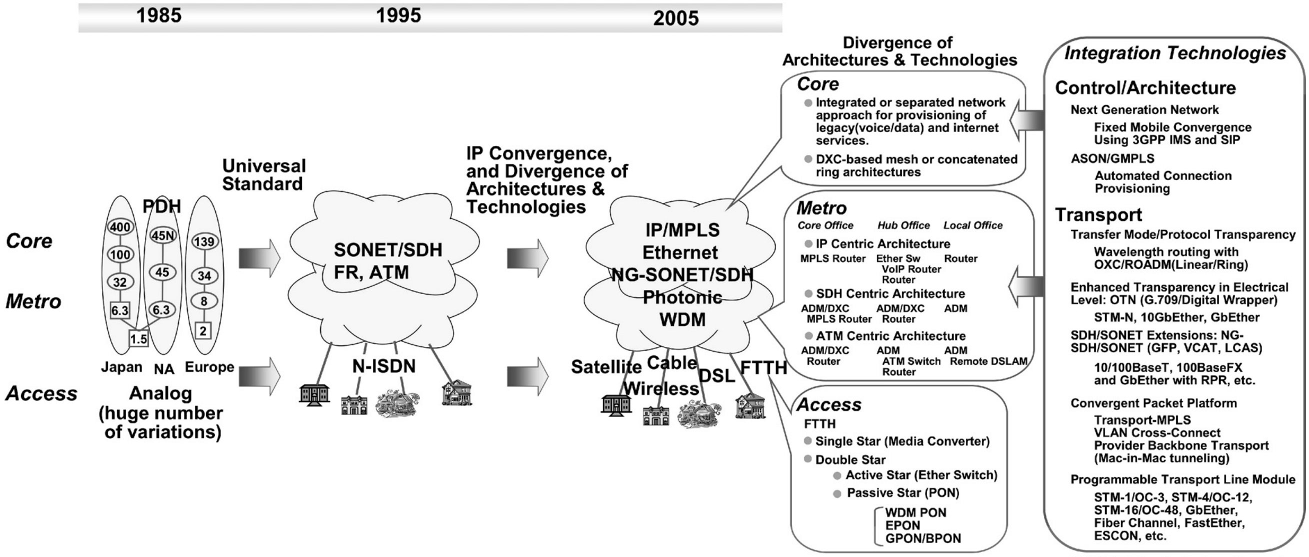
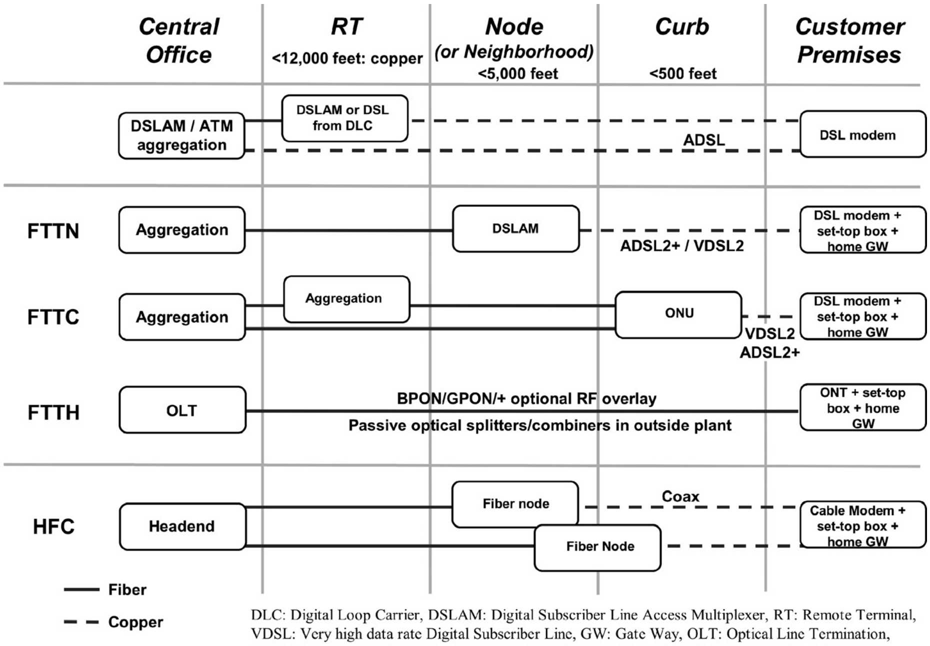


ESCON: Enterprise Systems Connection

Fig. 1 Transport network evolution.



DLC: Digital Loop Carrier, DSLAM: Digital Subscriber Line Access Multiplexer, RT: Remote Terminal, VDSL: Very high data rate Digital Subscriber Line, GW: Gate Way, OLT: Optical Line Termination, ONT: Optical Network Terminal, ONU: Optical Network Unit, HFC: Hybrid Fiber-Coaxial

Fig. 2 Access architecture example in North America.

cess networks, variation exists such as FTTN (fiber to the node/neighborhood), FTTC (fiber to the curb), and FTTH; an example of the FTTX configurations in North America is depicted in Fig. 2. Not only the architecture, but also the transmission technology for FTTH varies; BPON (Broadband PON) [12], GPON (Gigabit PON) [13], [14], and EPON (Ethernet PON) [15] are utilized, and 10G Ethernet PON and WDM (Wavelength Division Multiplexing) PON are now being considered. The advent and penetration of IP, new technical developments including WDM and photonic network technologies, the enhancement of Ethernet technologies (Carrier-Grade Ethernet [16]), the emergence of IP-based control protocols such as MPLS and GMPLS [4], [17], provide powerful tools for creating the next generation networks, including the metro and core, that support IP convergence.

This present situation stems from many factors. The death of the monopolies has enhanced the competition that is strongly driving the optimization of architectures and technologies according to the different physical/geographical and regulatory situations. The trend of diversity is reinforced by the extensive choices made available through rapid technical advancements. While IP convergence is well recognized among carriers and vendors, the key issues that carriers and vendors must consider also include the divergence of architectures and technologies. This also holds true of metro and core networking as depicted below.

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. For example, in developing the core network, some carriers adopted integrated Internet and legacy service networks. Others developed separate networks dedicated to Internet and legacy services. With regard to the physical architecture, some use digital cross-connect (DCS) systems based on the mesh network architecture while others use concatenated ring networks. Even metro networks have different architectures: IP centric, SDH/SONET centric, and ATM centric (see Fig. 1).

Developments in technology never stop. As mentioned above, recent technical advances allow us to utilize different sets of network elements. However, in order to assure the scalability, manageability, and cost-effectiveness, new integration technologies are required and some development work on this has been performed. They include NGN (Next Generation Network) [18], [19] at the network level to promote fixed mobile convergence using 3GPP IMS (3rd Generation Partnership Project, IP Multimedia Subsystem) and SIP (Session Initiation Protocol), ASON/GMPLS for integrated control, enhancement of transparency with wavelength routing that allows transport of different format data, and enhancement of transparency in electrical level with the introduction of OTN (Optical Transport Network) [20], [21]. Next-generation SDH/SONET technologies [22], [23] using GFP (Generic Framing Procedure), VCAT (Virtual Concatenation) and LCAS (Link Capacity Adjustment Scheme) provide flexible service transport to accommodate various services. To create a packet-switch-based transport platform, connection-oriented forwarding technologies such as VLAN-XC (Virtual LAN Cross-connect) [24], PBT (Provider Backbone Transport) [25], and T-MPLS [2] have been developed. To attain system level flexibility, programmable transport line modules that can adapt themselves to various data formats have been implemented. These recently developed integration technologies are summarized in Fig. 1.

2.2 Advances in IP Backbone Technologies

Figure 3 explains the developments in IP backbone network node systems and the QoS implications [26]. In the mid-1990's, IP routers based on software routing were replaced by those based on hardware routing. This was made possible by the development of ASICs (Application Specific Integrated Circuits), which greatly enhanced router throughput. In the early stage of IP networks, routers were connected to each other using leased line services (at 1.5 Mb/s (VC-11) and 45 Mb/s (VC-3) etc.) to produce the peer-to-peer configuration, called IP over SDH. To cope with the continual expansion in traffic, node throughput expansion is necessary. One possibility is to simply develop tera-bit electrical IP routers and to connect them with large capacity WDM links, the IP over (SDH over) WDM technique. As another approach to large-scale IP networks, ATM technologies were introduced in the mid-1990's as the underlying transfer mechanism to provide direct mesh-like connections of routers using VPs (Virtual Paths) and VCs (Virtual Channels) (IP over ATM). This enables cut-through of layer 3, which enhances network throughput. It also provides the basis for network traffic engineering. Many of the large-scale IP backbone networks in the world are based on this technology. In this approach, the ATM and IP layers are managed separately. Recently, an extension of the IP technology, MPLS [27], has been discussed and is now being widely introduced. MPLS provides connection-oriented switching capability based on IP signaling protocols. MPLS uses LSPs (Label Switched Paths) and can utilize various link-layer technologies including ATM, FR, PPP/HDLC (Point-to-Point Protocol/High-Level Data Link Control) and so on. MPLS was originally expected to be used for traffic engineering, and it is now mainly used for VPNs (Virtual Private Networks). MPLS will, however, need some enhancement to be able to replace existing TDM (Time-Division Multiplexing) cross-connect switches as will be discussed later. In Japan, Ethernet-over-MPLS has been widely introduced for the creation of VPNs. In Europe, Telecom Italia began introducing MPLS for the creation of a VoIP (Voice over IP) network [28] while BT announced the establishment of a single platform based on MPLS that is multi-service and future proof [29]. They aim at a consolidated packet-based architecture that can lower operational expenditure.

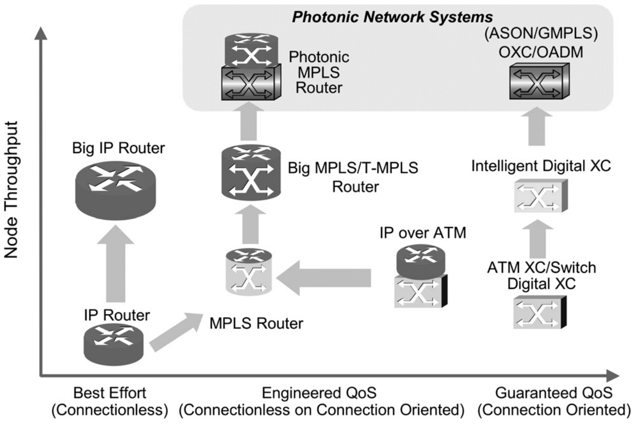


Fig. 3 IP backbone node systems and QoS.

The next round of enhancement involves IP over Optical Paths [30] (using OXC/OADM; Optical Cross-Connect/Optical Add-drop Multiplexer) and Photonic MPLS [31]. These enhance the performance of existing IP over ATM, and MPLS networks, and will be very effective, especially for creating large bandwidth backbone core networks. Figure 4 explains how the network attributes needed to create a large-scale IP core network can be realized with different configurations. The important requirements are

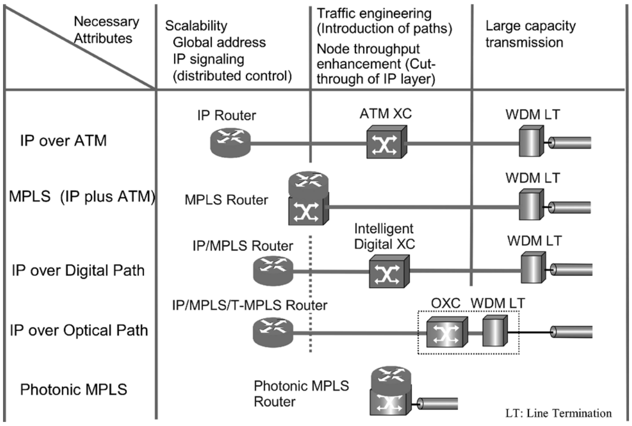


Fig. 4 Necessary IP core network functions and different system configurations.

scalability, traffic engineering capability, node throughput enhancement, and large capacity transmission. The different approaches, IP over ATM, MPLS or IP plus ATM, IP over digital path, IP over optical path, and photonic MPLS, utilize different technologies as shown in Fig. 4. The photonic MPLS router [31]–[33] (combination of IP router and optical cross-connect function and the seamless coordination, see 2.3) intends to realize all the attributes needed in an integrated fashion.

MPLS is becoming utilized more and more as mentioned before, however, I must note that DCS's (Digital Cross-connect Systems) are now used simultaneously and widely [34]. This indicates one weakness of the existing MPLS; it cannot replace all of the functions being provided by DCS's. Most MPLS routers implement neither per-LSP policing functions at the output port of the MPLS routers (although they do implement per-flow policing functions at the input port), nor efficient traffic management and control functions that can make the best use of path capabilities. When these deficiencies will be resolved will affect the introduction date of photonic MPLS routers along with the rate of traffic increase since carriers do not want to use DCS's concurrently. In other words, running photonic MPLS routers and DCS's concurrently will offset the benefit of cost saving that can be attained by introducing photonic MPLS routers. Photonic MPLS has dual path functions — optical paths for trans-access and LSPs for service access [30]. The additional path, the digital path, will be made redundant and can be replaced when fully mature MPLS functions are available.

T-MPLS (Transport-MPLS) was proposed recently to solve the deficiencies mentioned above, and was consented by ITU-T in February 2006. The final approval will be completed soon. T-MPLS is a connection-oriented packet switched transport layer network technology based on MPLS; the label merge possible in MPLS is not allowed in T-MPLS since it lessens the possible functionalities of connections. It can operate independently of its client layer and its associated control networks, unlike MPLS. T-MPLS can create a converged packet platform similar to PWE3 (Pseudo Wire Emulation End-to-End) defined by IETF. T-MPLS uses MPLS frame format and encapsulation method, and is empowered by common OAM (Operation, Administration, and Maintenance) functions based on the ITU-T transport functional model defined in Rec. Y. 1711 [35], protection switching in Y. 1720 [36], and control plane using TMN (Telecommunications Management Network) based [37] one and ASON/GMPLS. Because of its connection oriented nature, strong OAM and QoS (Quality of Service) capabilities, and enhanced reliability with protection/restoration, T-MPLS can be the basis of the future convergent packet platform that will effectively utilized with optical layer technologies.

2.3 Development of Photonic MPLS Router

The first great step forward in photonic MPLS router development occurred in early 2000's [32], [33]. The system consists of an electrical MPLS router part and a lambda routing unit (LRU) that sets-up and tears down OLSPs (Optical LSPs) using GMPLS. The LRU integrates WDM transmission functions and the layer one network protection (1+1 and 1:1) and restoration functions that are to be triggered by fault detection and optical signal quality monitoring functions [38]. The electrical MPLS part and LRU are controlled in an integrated fashion; in other words, the coordinated operation of the electrical and optical layers is realized so that plug-&-play operation is attained. The signaling protocol allows the establishment/release of bidirectional (upward and downward) OLSPs.

With regard to network control and management, given the rather diversified architectures shown in Fig. 4, the most pressing requirements are associated with a reduction in network operation cost, enhancement of service quality, and network simplification. The requirements are;

- Plug-&-play based on self-recognition of topology, resources, and neighbors
- One click prompt service provisioning that enhances service quality
- Simple transmission layer; core network with optical nodes employing wavelength routing, and separation of transport and service operation
- Mesh-based networks controlled and managed with distributed signaling that enhances network flexibility and network resource utilization.

GMPLS, which will enable these features, is being discussed and standardization activities are in progress. Upon completion of the standards, new services exploiting the above attributes will be launched. They will include Optical VPN (OVPN), λ-leased line service, and photonic IX (Internet exchange).

3. Expansion in the Application of Photonic Network Technology

3.1 Key Issues in Future Photonic Network Development

Previous sections have discussed past and present network technologies that have been and are to be deployed. In this section, we will discuss the next steps [39]. Let us now examine three fundamental parameters regarding network design: traffic volume, transmission capacity, and node throughput. The schematic relationship between them is illustrated in Fig. 5. We currently stand at the beginning of the broadband and ubiquitous network era. The advances in electrical processing such as TDM multiplexing and electrical router/cross-connect/server throughput, which almost follow Moore's law, 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 a tera bit per second capacity has been widely deployed and wavelength routing using reconfigurable optical add/drop multiplexers (ROADMs) has been widely introduced [40] and has attained cost reductions in metropolitan areas. Optical cross-connect systems have been used to create nation-wide high-speed testbed networks [41]. This has been the first boost to improve network performance with photonic network technologies. At this stage, traffic growth has mainly been driven by existing applications such as image, music, and video downloading, including peer-to-peer traffic. The next stage, in which traffic will increase even more, will be triggered by the penetration of new bandwidth-hungry services that will include the broadcasting/multicasting and streaming of IP-TV, high-quality videos using high definition (1k × 2k pixels) and super-high definition (2k × 4k pixels) images, grid computing, and e-science [42]. To cope with this burst in traffic volume, further advances in network performance and cost reductions must be attained, i.e., photonic MPLS router technologies, hierarchical optical path technologies [43], and super-dense WDM technologies need to be deployed in the next step. The extent of the optical domain will continue to increase, necessitating a new effective network architecture that can effectively employ these technologies.

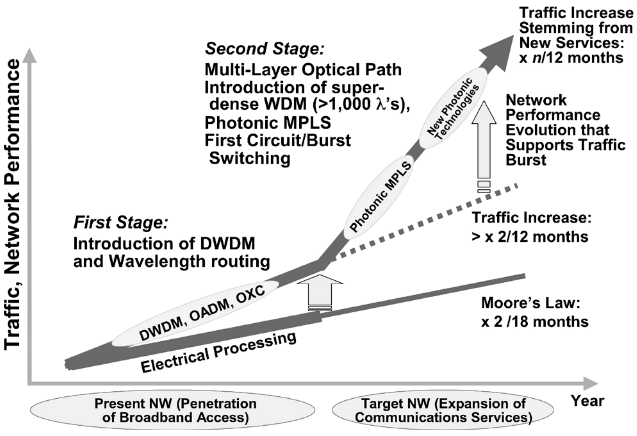


Fig. 5 Evolution of photonic network services and performance.

Further efforts to maximally exploit the inherent nature of light should be enhanced in the next stage [44]. Photonic nodes that process multi-format optical signals will be useful. GMPLS or new protocol suites must be extended before multiple domain, multiple-order optical paths, or multi-format photonic networks can be fully utilized. Lambdas will finally become a public utility through these developments. Some of the important issues to be considered for future photonic network development and directions toward the network throughput expansion are addressed below. The recently developed networking technologies necessary to solve them are discussed in the next section.

3.1.1 Service Uncertainty

In designing future networks that can meet the ever-increasing traffic demands, we must consider the accommodation of new broadband services such as streaming video, lambda-leased line services, optical VPN services, and broadband connections for e-science as mentioned before. The service contract terms or holding times will range from years/months to hours/minutes, unlike existing networks. As traffic or service demands increase, network expansion is necessary, which has been and will be done periodically (every quarter or half year). Therefore, network design criteria must be developed that allow both cost-effective network expansion (incremental growth) and accommodation of new services with different service holding times. This will be discussed in 4.1.3.

3.1.2 Power Consumption

One of the salient features of optical paths is that switch complexity does not depend on the bit rate carried by the optical paths. 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 the traffic increase and increased demand for minimizing power consumption; electrical switching will be difficult to solve this issue. Figure 6 shows the increase in electrical power consumption by one of the major carriers in Japan. The power consumption in 2003 fiscal year was 7.4 Tera Wh [45] which corresponds to one percent of total electric power purchased in Japan. The power consumption continues to increase due to recent broadband service penetration. Power consumption of electrical routers is also significant. The present largest throughput IP/MPLS router consumes about 16 kW per shelf [46] and the largest multi-shelve architecture (an 80 shelve structure) consumes more than one megawatt, which is not really practical.

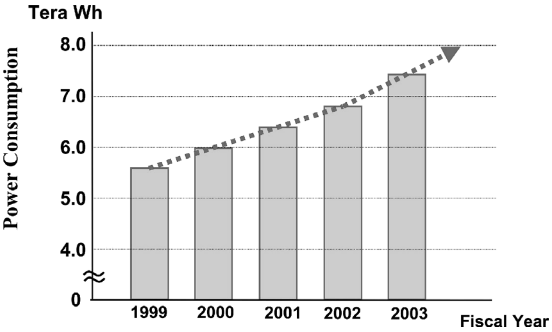


Fig. 6 Consumption of electricity by telecommunication carrier in Japan.

3.2 Toward Network Throughput Expansion

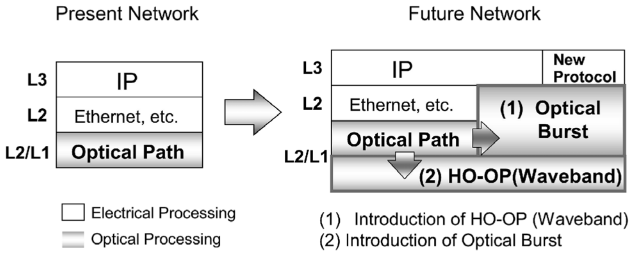
In order to enhance network throughput, the application of photonic network technology must be extended. The extension should be done in two ways; expansion of geographical application area and that of transport node throughput. They are discussed below;

3.2.1 Geographical Photonic Network Expansion

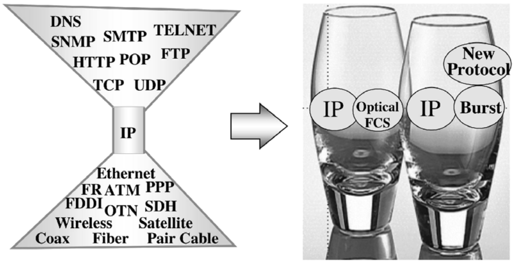
Recent advances in the distributed Raman amplifier [47] including the development of safety design criteria [48] have spurred practical implementation of this technology. This technology was introduced for commercial use in 2003 by NTT [48]. The system transmission capacity per fiber is 800 Gbit/s, which consists of 80 lambdas each offering 10 Gbit/s. The distributed Raman amplifier offers a significant improvement in SNR (Signal-to-Noise Ratio) and thus this technology will be used to increase the electrical repeater spacing. It was reported that the technology can enhance the optical SNR by 5.4 dB, which corresponds to a near four fold improvement in the average transmission distance compared to the lumped EDFA (Erbium-Doped Fiber Amplifier) [49]. The usage of this technology is currently limited to large-capacity applications, however, as the technology becomes more cost-effective, it will be introduced into metro networks as well. In metro networks, transparent networks with ROADMs are now being deployed and in the near future, small-scale transparent OXCs combined with the use of distributed Raman amplifiers will be an excellent choice for flexible broadband service offerings including optical VPNs. The transparent geographical area will thus expand more and more and effective networking technologies are necessary to make the best of it. The network design issues are discussed in 4.1.2.

3.2.2 Multi-Layer Optical Path Network [43]

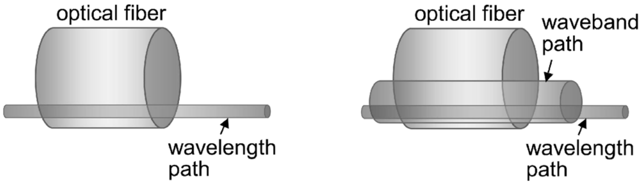
With regard to network throughput enhancement, different directions have been explored as shown in Fig. 7; introduction of higher-order optical paths (HO-OP; wavebands), Fig. 7(c), and the introduction of optical fast circuit switching (FCS) and optical burst switching, Fig. 7(b). Hierarchical optical path arrangement is a natural approach when traffic increases, and when optical layer services such as OVPN (Optical Virtual Private Network) services, lambda leased line services, and lambda switched services for e-science emerge. The optical paths are then used as a service-access path, and the introduction of higher-order optical paths as trans-access paths [30] is envisaged. Another important point is that some optical switches support optical signals with a wide range of wavelengths; this means that the same switches can be used for switching multiple optical paths. Switching multiple optical paths or switching wavebands can reduce total switch size (number of cross-connect switch ports needed) substantially. This mitigates one of the major present barriers to large scale space switch development in the creation of optical cross-connects.



(a) Different paths to network throughput expansion



(b) Introduction of OBS - Solving IP Bottleneck? -



(c) Introduction of higher order optical path

Fig. 7 Approaches to network throughput expansion.

Figure 8 explains the degree of total optical cross-connect switch port reduction that is attained by introducing multi-layer optical cross-connects. The ratio of total cross-connect switch ports, multi-layer/single layer, is expressed as;

$$\frac{(M+(L+1)+M)/\alpha}{M\times(L+1)}$$

where M is the number of optical paths per waveband, L is the number of average hops of each wavelength/waveband path. The hierarchical path structure can degrade link utilization, and this effect can be strengthened by the addi-

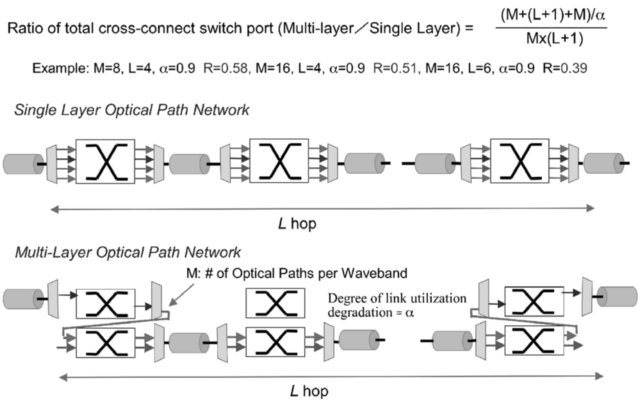


Fig. 8 Comparison of cross-connect switch port count.

tional complexity created by the waveband/wavelength assignment problem. The degree of link utilization degradation is represented by parameter α. This problem can be mitigated by the development of effective network design algorithms as explained in 4.1.4. When M, L, and α are 16, 6, and 0.9, respectively, the ratio is 0.39; that is, the reduction in total cross-connect switch port number attained by introducing multi-layer optical path cross-connects is about 60 percent.

3.2.3 Optical Burst Transmission

Although no settled definition of optical burst switching exists, many people have discussed optical burst switching [50]–[53]. The duration of optical paths or optical label switched paths is rather long for most present applications; it ranges from months/days to minutes. For the transmission of stream data, conventional optical switching will be used, but as new applications such as the download or transfer of DVD (Digital Video Disc) data or large files dominate, the period will fall to the order of millisecond or micro-second, and optical bursts and optical packets can be the unit of routing. In an optical burst switching network, the D-plane, in which the data is transferred, is separated from the C-Plane which carries the control signals. In burst switching, the control signal is generally sent across the C-plane prior to data transmission. Each node calculates the burst transfer route and wavelength of each burst when necessary, and sets it's optical switch. After all optical switches along the route are set up, the burst data is sent. At intermediate nodes, optical burst data is routed without being buffered or only small limited buffers are used. This feature is the major difference from optical packet switching, which is connectionless and utilizes substantial buffers at intermediate nodes to minimize packet loss.

Without reserving the network resources prior to burst transmission, the applicable geographical area will be limited since increasing the number of node hops will increase burst blocking probability. Furthermore, the combination of TCP (Transmission Control Protocol) and burst transmission is not always effective [54]. The throughput will be greatly reduced when burst loss and burst arrival delay/jitter exceeds certain limits. For example, to minimize TCP throughput deterioration when OBS-JET [55] is used, the burst loss should be less than 10^{-4}; when it reaches 10^{-3} the throughput will be 0.1 or less [56]. Thus the application area of burst switching will be geographically limited to MANs (Metropolitan Area Networks) and LANs (Local Area Networks). To make the best use of burst switching requires the development of a new layer three protocol that will suit OBS operation. Optical burst switching thus will take a much longer time to be seen as a practical service.

Dynamic operation may yet be useful for future services such as grid applications that demand large bandwidth. In this context, fast circuit switching, which is connection-oriented will be useful, although the required traffic granularity and the connection set-up time determine the effectiveness. This approach is briefly described in 4.2.

4. Recent Advances in Photonic Networking Technologies

4.1 Network Design

4.1.1 Electrical and Optical Path Layer Network

In designing large-scale networks based on electrical node technologies, a hierarchical network architecture (multiple tier structure) has generally been adopted [30]. In regard to transport network design based on transparent OXCs (ROADMs), however, a new physical constraint is introduced. The allowable maximum optical path length (number of OXCs and transmission links traversed) is limited. This constraint stems from the accumulation of various transmission performance impairments as the signal passes through multiple nodes and links without electrical regeneration. The major impairment, accumulated noise, can be significantly mitigated by using a recently developed technology, the distributed Raman amplifier [47], [49] as mentioned before. This can enhance the SNR so that the areas to which transparent transport can be applied can be expanded. This technology was initially introduced for commercial use in long-haul and large-capacity transmission systems [48]. This means that the development of new network design algorithms applicable to large-scale transparent OXC-based networks is increasingly important.

Network design algorithms that consider the hierarchical multi-layer path structure (electrical and optical path layers) were proposed in [57], [58]. The recently developed algorithms [59] extend those developed in [57] so that a protection path that shares no nodes or links with the working path (link and node disjoint) can be established and wavelength conversion is considered. The issues discussed in the paper are related to hierarchical LSP networks where the n:1 relationship between LSP and OLSP (Optical Label Switched Path) is considered ($n \geq 1$); other types of hierarchical networks have been extensively studied as in [60]–[62]. The objective and network conditions stated in

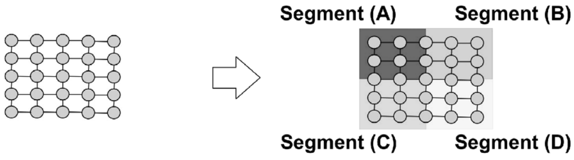
[60] are different from those considered here. The authors in [60] try to improve the network throughput under given optical network resources, while enforcing constraints on one pair of fibers between nodes. Other papers [61], [62] assumed multi-layer networks comprising waveband and wavelength paths. Each waveband can accommodate a fixed set of wavelengths, which imposes very severe restrictions on wavelength assignment (see 4.1.4). The objective of [59] is to minimize the network cost for a given LSP traffic demand; the photonic IP network consists of LSP and OLSP layers. The objective functions and network conditions are different. In [58] another segmentation method is discussed. This segmentation method focuses on dynamic routing in translucent optical networks under the assumption of sparse regeneration; the method evaluates blocking probability and resource utilization. The algorithm in [59] discusses the tradeoff between the size of segments and the network cost under more general conditions for multi-layer photonic IP networks.

4.1.2 Segmented Network Design

Here, hierarchical path networks consisting of higher-order paths (OLSPs) and lower-order paths (LSPs, electrical label switched paths) are considered. In order to take maximum advantage of transparent transport while simplifying OA&M (Operation, Administration, and Maintenance), it is effective to utilize a segmented network architecture consisting of transparent segments (Fig. 9). In other words, a large scale network is divided into several small scale networks (segments), and most of the necessary OA&M are completed within each segment.

Segment scale is determined by both the maximum non-regenerative hop count determined by the physical transmission constraint and the largest hop count, which will be determined by the minimum hop count for the longest connection within the segment plus the allowed hop slugs. The maximum non-regenerative hop count is determined by the performance of the transport systems (OXC+WDM transmission, with/without distributed Raman amplifiers etc.) and the node loss and link loss between nodes. The benefits for adopting this architecture are:

-Network design can be accomplished segment-by-segment. Electrical path accommodation within optical paths and the optical path accommodation within fibers can be confined within the segment. In other words, network optimization and the calculations can be done in parallel among different segments, which dramatically reduces the required calculation load.



(a) Without segmentation (b) With segmentation

Fig. 9 Segmented network architecture.

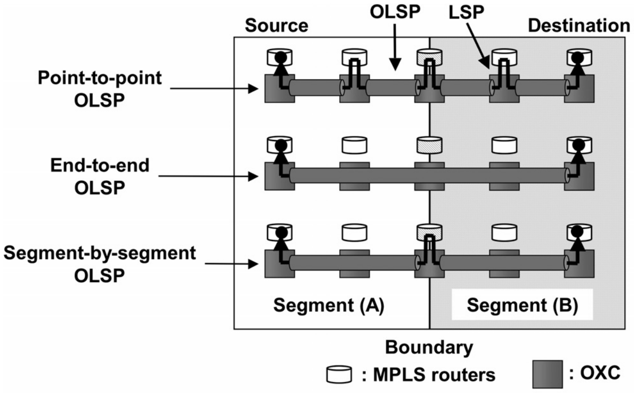
-Fast restoration from failures is possible since each segment is responsible only for failures that occur within that segment and restoration is completed within that segment.

-Network OA&M that covers the issues related to network topology changes can be simplified.

These benefits stem from the reduced network size of each segment and they will be apparent when a distributed control mechanism for network management including on-demand electrical/optical path set-up and network restoration is utilized. The number of instances where state information is exchanged with distributed control will be significantly reduced. Information exchange and the required OA&M processing among nodes regarding changes in topology can be confined to within each segment. These benefits, however, are offset by increased network costs that arise from ignoring global optimization, as will be evaluated and discussed in the following.

LSPs can span multiple numbers of segments, in other words the source and the destination nodes can be in different segments. To accommodate such LSPs within OLSPs, the following different types of OLSPs, which are depicted in Fig. 10, are assurred.

i) Point-to-point OLSP
An LSP is accommodated by a series of concatenated OLSPs, each of which is terminated node by node. Therefore, O/E and E/O conversion are necessary at every node.
ii) End-to-end OLSP
An LSP is accommodated within an OLSP whose source and destination nodes coincide with those of the LSP.
iii) Segment-by-segment OLSP
An LSP that spans multiple segments is accommodated by a series of concatenated OLSPs, where each OLSP is confined within a segment and the endpoints are on the segment



	Scenario (1)	Scenario (2)	Scenario (3)
$d \geqq C$	End-to-end OLSP	Segment-by-segment OLSP	End-to-end OLSP
$X \cdot C \leqq d < C$	Segment-by-segment OLSP	Segment-by-segment OLSP	End-to-end OLSP
$0 \leqq d < X \cdot C$	Point-to-point OLSP		

Fig. 10 Different types of OLSPs and adopted scenarios.

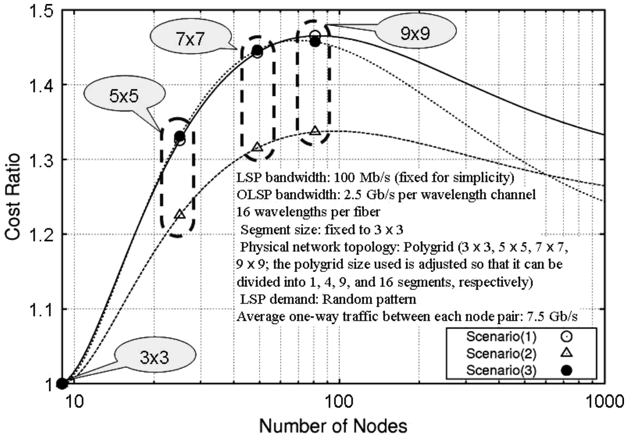


Fig. 11 Cost ratios of segmented networks.

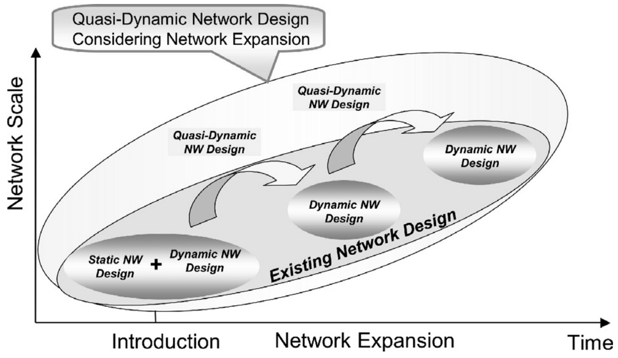


Fig. 12 Quasi-dynamic network design.

boundaries except for OLSPs that are connected to source and destination nodes.

In the OLSPs in i) and ii), LSPs can be routed/switched at (electrical MPLS) routers at each OLSP terminating node (see Fig. 10). In order to select OLSP types to accommodate the LSP demand, we have introduced parameter X ($0 < X < 1$) called the OLSP provisioning policy and set different scenarios according to the value of X. The details of these scenarios are given in Fig. 10 where symbols d and C represent the LSP traffic demand not yet accommodated and the bandwidth of the OLSP, respectively. For example, when X=0.5, d=64, and C=25, the configured OLSPs in Scenario (1) are two end-to-end OLSPs and one segment-by-segment OLSP ($d = 2 \times C + 14$, $0.5 \times C \leq 14 < C$).

Figure 11 shows an example of the evaluated cost ratios (network cost with segmentation to that without segmentation) and fitted curves [59]. Details of the network design algorithm are given in Ref. [59]. The simulation conditions are shown in the insert in the figure. It shows that, at the initial stage, the ratio increases monotonously, becomes almost constant, and then decreases slowly to approach one when the number or nodes becomes very large. The maximum value of the cost ratio is bounded to 1.5 where the average traffic value is 7.5 Gb/s. The maximum values decrease as the traffic increases. In Fig. 11, the relatively small segment size of 3×3 is utilized to more clearly demonstrate the effect of segmentation. As segment size increases, the cost ratio falls. Thus, it is shown that the segmented network can be achieved with a slight cost increase compared to conventional, globally optimized, network designs, and that the segmentation enables the effective design of large-scale networks of several hundred nodes by using parallel processing.

4.1.3 Quasi-Dynamic Network Design

As discussed in 3.1.1, future service contract terms or holding times will range from hours/days to months/years, which is quite different from existing network services. Therefore, novel network designs must be developed to handle these new services effectively. Conventional studies on designing photonic networks for existing and envisaged applications fall into two categories; static network design [57], and dynamic network design [63] that supposes future switched (optical) services. The target of static design, for a given fixed traffic pattern, is typically to minimize the network (hardware) cost needed to accommodate the given traffic. In dynamic design, the amount of traffic is assumed to change on the order of seconds or minutes and its objective is to minimize the blocking probability against service demand. Few works have been done, however, on network designs that consider traffic expansion [64] and future service uncertainty, for example, handling the traffic of new services with different holding times or contract terms.

Here we discuss the points of a quasi-dynamic network design [65] that considers incremental network expansion and service uncertainty. The relationship among existing static network design, dynamic network design and quasi-dynamic network design is schematically illustrated in Fig. 12. Static network design is necessary at the initial stage of network implementation. If switched services are provided, dynamic network design will be conducted after that. On incremental network expansion after the network introduction, the quasi-dynamic network design will be conducted. For incremental network expansion in terms of traffic, routes for existing network traffic (or routes of electrical/optical paths) will be left unchanged in order to minimize service disruption and any impairment or processing complexity due to path rerouting or from human-sourced errors. This is particularly important for mission-critical services. In designing future networks that exploit optical paths [30], it is necessary to consider multiple path layers that consist of electrical paths and optical paths (see 4.1.1). Investigations have been done on the multi-layered network design issues that include optimization of network resource utilization and minimization of network cost. With regard to the traffic, they assumed static traffic [60] or dynamic traffic with relatively short holding times [63], [66], [67]. A preliminary study has been done that considers IP traffic growth [68]. This paper briefly introduces recently developed multi-layered photonic IP network design algorithms that can cost-

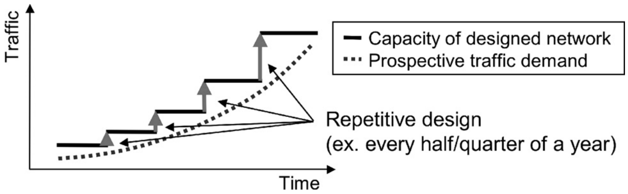


Fig. 13 Quasi-dynamic network design for incremental traffic growth.

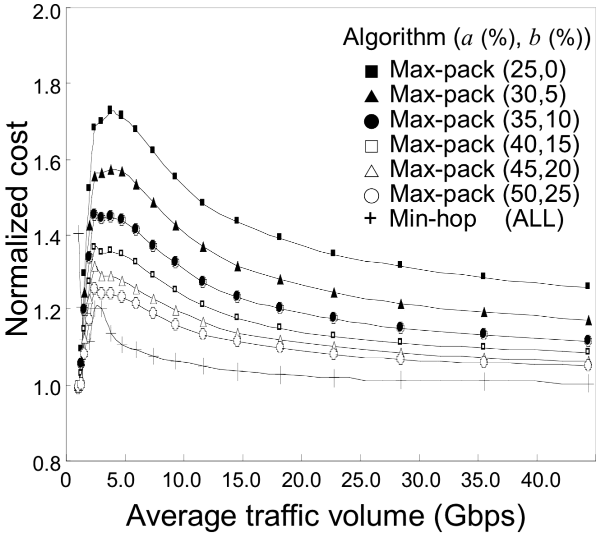


Fig. 14 Network cost with different contract/cancellation rates.

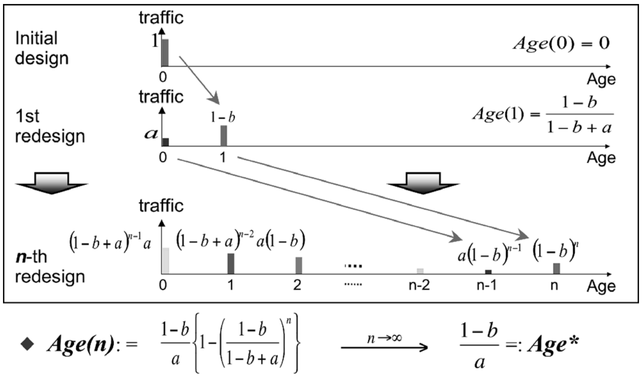


Fig. 15 Introduction of new parameter "*Age*."

effectively accommodate the expected traffic increase [65].

Electrical paths (EPs) such as LSPs and digital paths are accommodated within OPs and fall into two classes: (1) those that are accommodated within an OP that directly connects the end nodes of the EPs, and (2) those that are accommodated within concatenated multiple OPs. If there is a sufficient number of EPs (traffic) to fill a direct OP, the cost is minimized by using the direct OP since O-E-O conversion at intermediate nodes can be eliminated. On the other hand, if the ratio of the total capacity of the EPs between the end nodes to the capacity of the OPs is smaller than a specific value, the minimum cost will be attained by using multiple concatenated OPs. Therefore, the accommodation of an EP layer network within an OP layer network requires optimization. The OP layer network is accommodated within a fiber network. The quasi-dynamic network design considers incremental traffic growth as shown in Fig. 13. As traffic or service demands increase, network expansion is necessary, which has been and will be done periodically (every quarter or half year). Therefore, network design criteria must be developed that allow both cost-effective network expansion (incremental growth) and accommodation of the future new services with different service holding times.

The traffic increase is given by that of the EPs for simplicity. The increase in the number of OPs is easily included with a subtle modification of the algorithms. To accommodate the expected increase in the number of EPs at each step, two algorithms have been developed. The first one is an extension of the Min-hop algorithm [68] which accommodates every EP within direct OPs with minimum numbers of hops that connect the end nodes of the EPs. The other algorithm, the Max-pack algorithm, tries to minimize the total network cost at each design step by taking advantage of the spare capacity of the existing OP network (Note: a dynamic design algorithm that tries to use spare capacity of existing OPs subject to OP hop-limit is given in [63]). The total network cost, node and link costs, is evaluated.

Figure 14 shows the dependency of cost on the average traffic volume where the initial traffic is 1 Gbps, and the net traffic growth, $a - b$, is set at 25% while a and b are changed; a is the new service contract rate and b is the cancellation rate. As for the Min-hop algorithm, the results are all the same for different a and b values, and finally they asymptotically converge one (not shown in Fig. 14). The results of the Max-pack algorithm also approach one in the end (not shown in Fig. 14). As shown in Fig. 14, the behavior of the cost strongly depends on parameters a and b, and it has been found that the new parameter "*Age*" provides a more organized perspective [65], [69].

Age represents the average life of the existing traffic just after the n-th network re-design. *Age* is normalized by the redesign interval. *Age* is a function of n, new service contract rate a, and cancellation rate b, where a and b are values normalized by the existing traffic at the n-th redesign point (Fig. 15). The net traffic growth rate is $a - b$. Values a and b are set to be constant against n. As shown in Fig. 15, for example, just after the 1st network re-design, traffic at Age=1 is $1 - b$ and at Age=0 is a. Therefore $Age(1)$ is $(1 - b)/(1 - b + a)$. After a simple manipulation, *Age* can be expressed as [65]

$$Age(n) := \frac{1-b}{a}\left\{1-\left(\frac{1-b}{1-b+a}\right)^{n}\right\} \overset{n\to\infty}{\to} \frac{1-b}{a} =: Age^{*}$$

Figure 16 is the re-plot of Fig. 14 for the Max-pack algorithm with *Age* plotted on the horizontal axis. The *Age* values are upper bounded by *Age** for each set of a and b. In Fig. 16, the cost ratio approaches one as it did in Fig. 14. The figure can be split into three distinctive domains: 1) Domain 1: 0–65% to *Age**, 2) Domain 2: 65–75% to *Age**, 3) Domain 3: 75–100% to *Age**. In Domain 1, the normal-

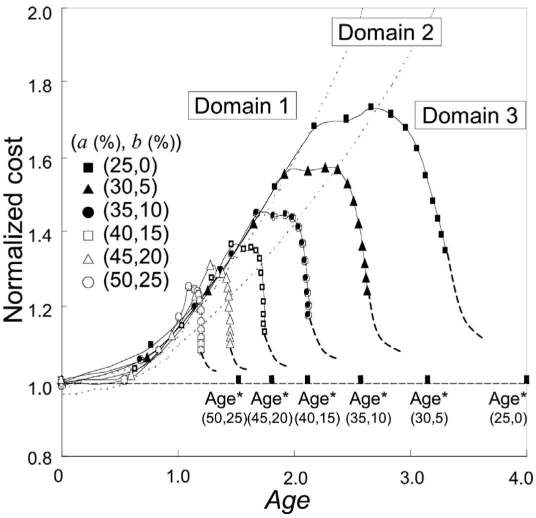


Fig. 16 Network cost variation in terms of *Age*.

ized cost increases in the second order of *Age*. The normalized cost remains almost constant in Domain 2, and in Domain 3 it suddenly approaches one. The boarders of the domains are determined by the granularity of the OP. The important point to note is that this tendency can be commonly observed in tests performed based on different values of the initial traffic demand and net traffic incremental growth over a wide range. The above investigations provide some useful insights in that (1) normalized network costs attained using the proposed design approach one (network cost obtained with zero-based ideal design) after certain network expansion iterations, and (2) the Max-pack algorithm should be selected if the estimated number of design steps is small (i.e., network-increment frequency is low during the network system life). Otherwise, the Min-hop algorithm provides good results. (3) The Age parameter can well characterize the variation in the network cost for the Max-pack algorithm, which enables us to estimate effectively the network cost after repeated network redesign by identifying the domain and using an empirically obtained estimation formula (Fig. 16). The results provide an organized perspective of the network design with the goal of accommodating future broadband services.

4.1.4 Multi-Layer Optical Network Design [43]

In order to realize the multi-layer optical path networks discussed in 3.2.2, hierarchical optical path network design algorithms need to be developed. The waveband routing and waveband assignment problem of multi-granular optical networks is a generalization of the single-granular optical path network design problem. Analogous to the single-granular case [70], the problem is inherently NP-complete and can equivalently be formulated as a combinatorial optimization problem that targets minimizing the total number of optical ports [71]–[73] of cross-connect systems or maximizing the utilization of fiber capacity [74]. The number of binary variables in the combinatorial optimization problem explosively increases with network size. This characteristic makes the problem computationally impossible to accurately solve for large networks. Indeed, previous publications that tackled the combinatorial optimization formulation gave up on exact solutions and provided alternative algorithms based on heuristics or relaxation instead. Several such methods have been proposed [71]–[77]; they are categorized as follows: Grooming of wavelength paths having common source/destination or partially shared routes [76], [77], waveband tunnel construction first [75], on demand waveband assignment [72], [73], and relaxation-based methods [71], [74].

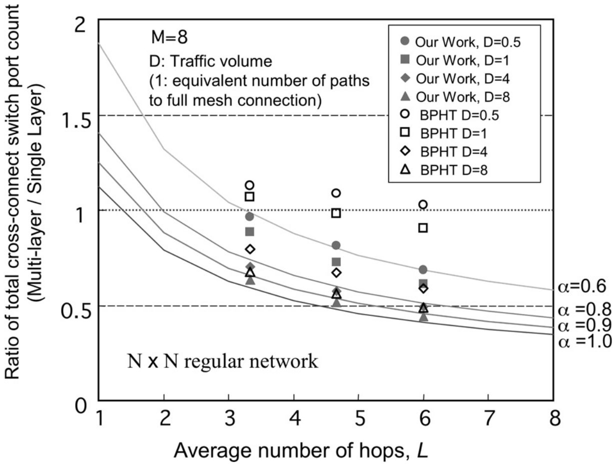


Fig. 17 Comparison of cross-connect switch port number.

Recently, a heuristic algorithm based on a different strategy was proposed [78], details and a performance analysis are given in [79]. To minimize the total cost, which consists of node cost and link cost, wavelength path cross-connection at intermediate nodes must be minimized and, at the same time, waveband utilization must be maximized. We must therefore search for a set of wavelength paths that are efficiently carried by a waveband path and can sufficiently occupy the waveband path. A space, named "s-d (source-destination) Cartesian product space," is newly defined to evaluate closeness among wavelength paths [78]. The space can be used to effectively locate waveband paths that can reduce total cost. For each set of wavelength paths, a waveband path is 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 wavebands by identifying the shortest paths in a multi-layered graph considering waveband tunnels.

The multi-layer optical network can reduce the number of cross-connect optical ports, but will lower fiber utilization. It is therefore important to clarify the conditions under which the waveband approach is attractive. Figure 17 shows evaluated ratios of the total cross-connect switch port count for multi-layer to single layer cross-connects, where the average number of shortest path hops of the wavelength paths (without wavebands) is changed by changing the network scale. The tested network is a polygrid network with randomly distributed wavelength path demands; other parameters are shown in the figure.

BPHT represents the results obtained by Balanced Path routing via the Heavy-Traffic first waveband assignment algorithm [77]. It is shown that the above algorithm [78] achieves a much larger port count reduction than BPHT. Indeed, even when traffic volume, D (see Fig. 17), is rather light, namely D is 0.5, the multi-layer optical path networks can reduce port count when the average hop number exceeds three. Further, with the proposed algorithm, the parameter α, which represents the degree of link utilization degradation caused by introducing multi-layer optical paths (discussed in 3.2.2), reaches 1 (no degradation) much faster than BPHT when traffic increases. The investigation provides not only performance comparisons of different methods, but also demonstrates the effectiveness of the multi-layer optical path network.

4.2 Optical Fast Circuit Switching

Recently, the photonic MPLS routers explained in Sect. 2.3 have been extended to offer fast switching capabilities [80]. Two way signaling is used to guarantee burst transmission, and GSMP (General Switch Management Protocol) is utilized. After receiving a GSMP request command, optical switch control is completed within 4 ms, and the GSMP acknowledge command is returned within 6 ms. A 10 Gbps burst transmission experiment (burst lengths ranged from 100–300 ms) with a switching time of less than 30 ms has been successfully demonstrated using a 6-node network [80]. The application area of fast circuit switching with distributed signaling is limited to a certain geographical area such as LANs and MANs due to the circuit establishment time (processing time at each node plus transmission delay) which determines the maximum usage of links. To minimize the circuit set-up time for large scale networks, a hierarchical network architecture is necessary as is adopted in telephone networks.

5. 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 next step, IP convergence, is supported by the advent and penetration of IP, new technical developments including WDM and photonic network technologies, rapid advances in access technologies including ADSL and FTTH, and the emergence of IP-based control protocols such as MPLS and GMPLS; all provide powerful tools for creating the next generation networks. The technology alternatives are extremely varied and this allows us to develop optimized networks that match each country's or region's and/or carrier's situation. The death of the monopoly and new regulatory conditions have spurred the divergence seen in technology and architecture. It is becoming more and more critical that telecommunication network engineers be able to grasp the right direction to proceed and promote the development of the necessary technologies. We demonstrated that in order to enhance the performance and reducing the cost of future IP-based multimedia communication networks, we need to not only optimize photonic technologies but also realize coordination with complementary electrical technologies; MPLS/T-MPLS will play the key role. Finally some issues key to the development of the future bandwidth abundant photonic network were discussed. New network design problems that are important for photonic network development were identified and some of the recent results were introduced.

Acknowledgments

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