Towards large-capacity, energy-efficient, and sustainable communication networks

— Network topology research for dynamic optical paths —

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Internet traffic continues to increase due to the growth of video-related communication services. Such video-related services are expected to support future advanced communication services such as tele-presence based on real-time high resolution bidirectional video communication, tele-diagnosis, and remote education. However, the risk of an energy crunch in communication networks is increasing with the increase in traffic since energy consumption of current IP router based networks depends on traffic volume. In this paper, we present a network architecture, called "dynamic optical path network (DOPN)," whose energy scaling is much less dependent on traffic volume than that of the current networks. This paper demonstrates the validity of DOPN to realize greater bandwidth, national-scale, and energy-efficient network, by defining detailed network topologies and node architectures of DOPN.

Keywords : Large-capacity and low-energy-consumption communication network, optical path network, optical switch, super high vision video communication

1 Introduction

Communication infrastructure such as the telephone network or the Internet has become important lifeline equivalent to electricity, water, and gas. With the development of broadband communication infrastructure and advancements in video applications, the traffic volume accommodated in the network is increasing globally.[1] Taking a look at the case of Japan, the total traffic volume increases every year. As the subscribers to the broadband service increase, the subscribers to the digital subscriber line (DSL) have decreased while those for "fiber to the home" (FTTH) service are increasing. The traffic per subscriber also increases yearly due to the progress of the shift to higher broadband services. With such a trend, the Japanese network experiences a yearly growth of about 20~40 % in communication traffic.[2][3] The traffic increase is expected to continue in future due to the expansion of high capacity contents such as high definition videos. If the traffic increase of 20~40 % per year continues for the next 20~30 years, the future network must accommodate 1000 times larger traffic volume than the current demand.

As the traffic increases, the importance of the communication network increases, and once a disconnection occurs, it will have a major impact. Currently, in cases of failure such as disconnection, the continuity of the network service is maintained by having multiple routes between the communication points (such as west-bound and or east-bound routes), and switching to one route if the other is disrupted. However, in a major disaster such as the 2011 Off the Pacific Coast of Tohoku Earthquake (Great East Japan Earthquake), failure recovery doesn't work well since failures may occur in a wide region at many locations, and both routes can be disrupted. In that disaster, agile and wide-scale reconfiguration of the network was necessary. Moreover, to continue the network service without being affected by the instability of power supply due to the disaster, the importance of low power-consuming network operation in ordinary times has been recognized.

Communication networks consist of links that transmit the signals and communication nodes that process the signals. Signal transmission is mainly done in optical domain using optical fiber links. It is possible to transmit multiple optical signals through single optical fiber, as in wavelength division multiplexing (WDM), and the transmission experiment of capacity more than 100 Tbps in a fiber has been reported.[4] On the other hand, the signal processing in a communication node is mainly done in the electrical domain using optical-to-electrical converters and electric switches or IP routers. The power consumption of the converter, the electric switch, and the IP router increases in proportion to the signal transmission rate or the signal throughput. To realize a large-capacity future network, the increasing power consumption may become a bottleneck.[5] Reducing the power consumption in communication networks is an important issue not only to achieve disaster resistant networks but also to realize future

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large capacity networks.

Currently, to achieve a large-capacity communication network with low power consumption, there are studies on conducting traffic processing at nodes at lower layers that have low power consumption (IP traffic offloading).[6][7] One of the traffic offloading technologies includes the optical cut-through technology in which the destination of the optical signals are switched by the optical switches without using optical to electrical conversion at the node. This is being implemented along with the reconfigurable optical add drop multiplexer (ROADM) technology. However, these traffic offloading technologies are based on the current IP router network, and the signal processing at the network edge cannot be avoided. Therefore, the effect of reducing the power consumption is limited to about 20~30 %.[8][9] In the long-term prospect of triple digit increase in traffic volume, fundamental considerations are required.

To achieve a sustainable large-capacity communication network for the future, we are working on a network architecture called "dynamic optical path network (DOPN)."[10][11] The main cause of the future traffic increase will be video-related applications with high or ultra-high definition quality images. To support such large capacity applications, DOPN provides end-to-end path connectivity with Gbps or more capacity according to their requests. By focusing on such large-granular communication requests, DOPN can be constructed only from low power consuming optical switches and low-layer electric switches, to achieve power consumption property with low dependency on traffic volume. On the other hand, current communication services such as web and mail generate small-capacity and frequent communication requests. For such services, the current IP router network is suitable since it can handle packet switching and the capacity of the packets is several tens to several hundred kbit. Consequently, DOPN does not replace the current IP router network, but coexists in a complementary relationship. For the operation and management of DOPN, a new integrated resource management technology is necessary where not only the network resources (bandwidth) but also the storage resources (content) are comprehensively controlled.[12] The resource management system automatically selects the network to use according to the application. For example, the conventional IP router network can be used for the conventional service such as web or mail, while the DOPN can be used for a large-capacity service such as high definition video on demand (VOD) or teleconferencing(Fig. 1). The resource management system allows the user to use the IP network and DOPN seamlessly, without thinking about their differences. We are investigating the network resource management system in collaboration with the Information Technology Research Institute in AIST. In addition, the technologies for developing DOPN can also contribute to agile and large-scale network reconfiguration in an emergency such as disasters, as DOPN involves the dynamic switching of the physical layer defined in OSI 7 layer.[Term 1]

If large-capacity paths can be provided smoothly among users through the DOPN, it will become a platform for achieving numerous large-capacity communication services. One of the target applications of DOPN is video related service with ultra-high definition (UHD) images that is currently under development. UHD has 16 times higher definition than high-definition television (HDTV) requiring bandwidth of 72 Gbps or more for uncompressed data transmission. Compared to 40.5 Mbps, which is the peak connection speed of the current Japanese Internet,[13] there is a gap of over three digits. The necessary bandwidth for uncompressed transmission for UHD can be stably provided using the DOPN. Of course, the video compression technology is also being developed, but to achieve the highly realistic sensation that is almost equivalent to experiencing the real event, there is a limit in using the video compression technology. If a high-presence

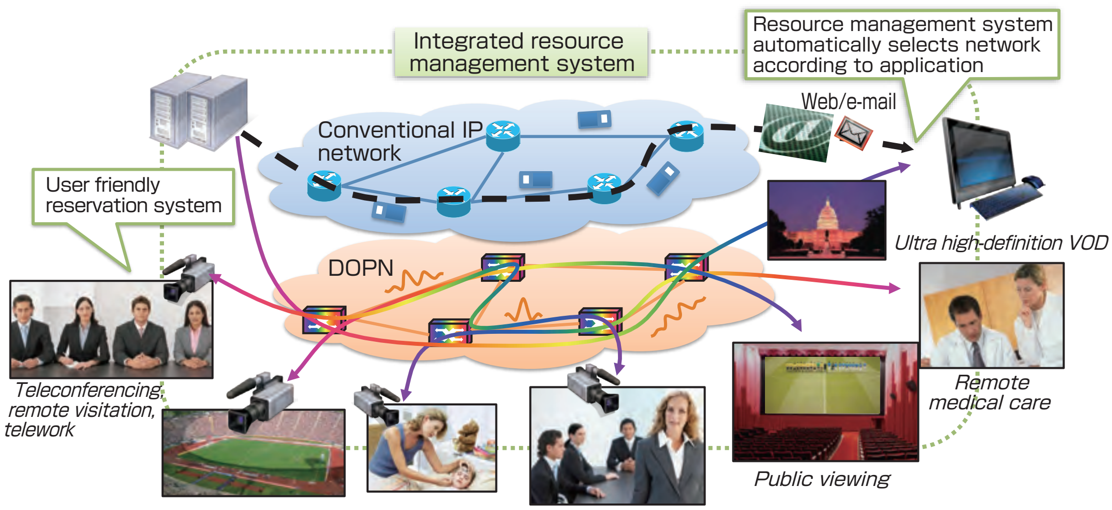


Fig. 1 Image of the future information communication network and service composed of the IP network and DOPN

communication can be achieved by using UHD technologies, the remote teleconferencing for important scenes such as meetings that involve decision-making or interviews for job qualification can be done. If the applications using UHD images such as teleconferencing, remote medical care, or remote education diffuse throughout society, collaborations that are not limited to geographical distance will become possible. It is expected to lead to major social values such as eliminating the regional gaps in education or medical care.

The goal of this paper is to present the validity of DOPN to realize a future communication network infrastructure. There are three requirements for the communication infrastructure that supports the future video services: 1) resolution of bottleneck of power consumption for increased communication demands, 2) scalability to accommodate tens of millions of users, and 3) ability to handle various large-capacity services from remote presence (~100 Gbps) to high definition VOD (several Gbps). This paper investigates the network topology and node structure of DOPN in detail, and shows that the DOPN is capable of accommodating over 50 million consumer users using the 1~2.5 Gbps path and over 600 thousand enterprise (business) users using the 40~100 Gbps path, as well as possessing the potential to improve the power consumption efficiency by two to three digits compared to the current network.

2 Dynamic optical path network (DOPN): its goals, issues, and elemental technologies

The dynamic optical path network (DOPN) tries to achieve a sustainable large-capacity and low power-consuming network for the future, by using the low-power-consumption optical and electric switches as its main components. Figure 2 shows the goals that are expected to be achieved by DOPN explained in this paper, and the correlations of the elemental technologies used to achieve the goals. The details are explained below.

Elemental Technology 1: Optical switch

One of the most important features of the optical switch is that the power consumption scales with the number of switch ports regardless of the total throughput. By using such optical switches as main components, the power consumption of DOPN will be less dependent on the traffic volume than the current router based networks. However, there is a technological problem that the optical switch is incapable of having large number of input/output ports. The current optical switch products have about only 8~200 ports while the switching equipment used in telephone networks have tens of thousands of ports. The number of subscribers would be limited by the number of switch ports in path switching-based networks. Moreover, there are two types of optical switches: optical matrix switch that switches optical signals in a fiber granularity; and wavelength selective switch (WSS)[Term 2] that switches optical signals in a wavelength granularity. One optical fiber can accommodate several Tbps and one wavelength channel can accommodate several tens to several hundreds of Gbps. There is an issue that the optical switch alone is inefficient for small-granular (of about several Gbps) communication demands.

Elemental Technology 2: Sub-wavelength switch

The sub-wavelength path is introduced to solve the issues in using the optical switches as the main components discussed above. The sub-wavelength path is assumed to address

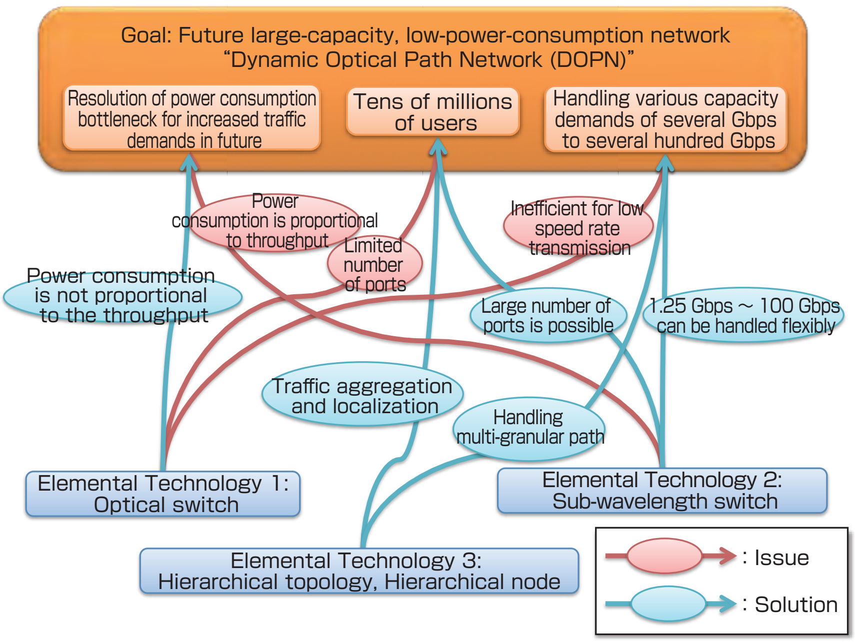


Fig. 2 Correlation among the goals, elemental technologies, and issues

electrical time-division multiple access and provides finer granularity than wavelength or optical fiber paths. In this paper, the use of the optical data unit (ODU) is expected as the sub-wavelength path.[14] Although the power consumption of the ODU switches scales with the throughput, the power consumption is one-sixth compared to the packet router since the granularity of data handled is large at 1.25 Gbps or more.[15] The ODU path can handle 1.25 Gbps ~ 100 Gbps with 1.25 Gbps tributary slot granularity (ODUflex), and the ODU switch with Tbps class throughput and several thousand ports is being developed. Figure 3 shows the path granularity handled by the DOPN in this paper.

Elemental Technology 3: Hierarchical topology, hierarchical node
The hierarchical topology/node is introduced to effectively use the elemental technologies 1 and 2. The hierarchical node architecture is to efficiently handle the multi-granular paths. The hierarchical node consists of multiple switches for different granularities such as the optical switches and sub-wavelength switches and they are hierarchically connected. By processing the demands in a large-granular path as much as possible, the size of the hardware needed in the whole network is reduced.[16][17] The hierarchical topology is a network topology where the access network on the user side, the aggregation network that bundles the traffic, and the core network for long-hole transmission are hierarchically connected. Since a number of demands is aggregated into the core network, a huge capacity is required for the core network. To mitigate the necessary capacity in the core network and support the network scalability to tens of millions of subscribers, the aggregation network loops back the local connection requests without connecting to the core network (localization of traffic). Such hierarchical network topology is highly compatible with the current network topology, and is effective from the perspective of facility sharing in the migration to DOPN.

3 Network topology and node architecture

The topology and the node architecture for the DOPN are investigated in this chapter. First, based on the number of broadband subscribers in Japan and the expected applications, the target numbers of DOPN subscribers and their bandwidth are considered. Based on the current optical switch technologies, the requirements for the optical devices and the topology are also considered. Specific topology and detailed node architectures are presented, and we shall demonstrate that the requirements can be satisfied.

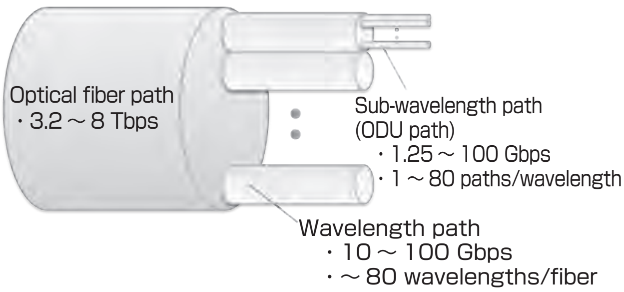


Fig. 3 Schematic diagram of the multi-granular hierarchical path addressed in this paper
For the optical fiber path capacity, maximum 100 Gbps per wavelength and maximum 80 wavelengths multiplexed in a fiber were assumed, based on the currently commercialized technology. In the future, this can be enhanced to 100 Tbps per fiber as described.

3.1 Goals and requirements

One of the main users of the future video application in the DOPN is consumer users that mainly use few Gbps for high definition VOD and TV phones. The other will be enterprise (business) users that mainly use several tens to 100 Gbps for ultra high-definition public viewing and large-capacity file exchange. Considering the current Japanese situation, there are about 50 million households and about 600 thousand businesses with dozens or more employees.[18][19] Hence accommodating 50 million or more consumer users with1 Gbps or more and 600 thousand or more enterprise users with 40~100 Gbps are set as target values for the DOPN.

The following four requirements were assumed for the optical devices and topology of the DOPN.

1) The number of optical matrix switch ports is equal to or less than 500: Although the technology for increasing the number of optical switch ports is being developed, the number of ports of the optical matrix switches that are currently released as products are: about 200 ports using the micro-electro mechanical system (MEMS) technology; and about 16 using the planar lightwave circuit (PLC) technology. A 32-port Si photonics switch is under development. The Si photonics technology has high expectations from the perspectives of switch speed and manufacturability. The 500-port switch can be constructed by combining multiple 32-port switches with 3-stage Clos-network structure.[20] From the above technological trends, the maximum number of ports for the optical matrix switch used in this paper was assumed to be 500.

2) Number of WSS ports is equal to or less than 1×35: Currently, the WSS with 1×9 or 1×4 ports using the liquid crystal on silicon (LCOS) or the MEMS technology are released by several manufacturers. Higher port count WSSs are being developed, and a product with 1×20 ports was announced in 2011.[21] Considering the technological advancement in the future, the maximum number of ports for the WSS used in this paper was assumed to be 1×35.

3) The basic fiber topology shall be tree, ring, and mesh topologies: Since the fiber ducts and the base station facilities that are used in the current network will be used, the geographic fiber location for DOPN will be common to the current network. That is, the tree topology that is highly

compatible with the passive optical network (PON) will be used as the geographic fiber location in the access region of the DOPN, ring in the metro region, and mesh in the core region.

4) Flexible grid accessibility shall be employed: In the current network, fixed bandwidth (ITU-T grid with 100 GHz or 50 GHz intervals[22]) is used regardless of the transmission data rate of the wavelength channel. To increase the spectral efficiency, the flexible grid technology that enables the flexible use of the channel bandwidths according to the signal data rate has been proposed and investigated, and about 25~50 % increase in efficiency is estimated.[23] To achieve an efficient large-capacity communication network, it shall be connectable to flexible grid from end to end, including the access network.

3.2 Topology

The DOPN topology that satisfies the requirements presented in subchapter 3.1 is investigated. The major issue is the limited optical switch port counts to provide path connectivity among tens of millions of users. As mentioned in Elemental Technology 2 of chapter 2, from the points of limited number of ports of the optical switch and traffic aggregation, a flat network structure cannot be used, and therefore, hierarchical topology where the user terminals are grouped and connected in a hierarchical manner is essential. In a hierarchical network topology, a simple structure with a small number of layers is preferable. There must be two layers: a lowermost layer for traffic aggregation, uppermost layer for long haul path establishment. The point is how many other layers are required for what purposes. In the DOPN, the sub-wavelength path is aggregated consecutively to the wavelength path and wavelength path to the fiber, according to the user's path granularity. The reasons for having two layers for traffic aggregation are to improve the efficiency of use of transmission line by aggregating from sub-wavelength path to wavelength path at a location close to the user, and to reduce the number of ports of the sub-wavelength path switch that will become necessary when aggregated to the fiber capacity. Considering the target number of users and the bandwidth per user, the traffic volume aggregated in the uppermost network will become enormous. To accommodate such enormous traffic volume, utilizing optical fiber switches in the uppermost network is essential; the number of optical fiber switch ports is currently much larger than that of wavelength switches and thus the optical fiber switch can handle larger capacity than the wavelength switches. At the same time, it is necessary to connect to the uppermost network under the condition where the wavelength and sub-wavelength paths are organized so that they can be switched with the fiber granularity (grooming[Term 3]). As a result of quantitative investigation of the node architecture used in the aggregation network, it was found that it is difficult to aggregate enough traffic due to the loss and number of the optical coupler branches for multiplexing the wavelength paths to the fiber paths. Before connecting to the uppermost network, there must be an additional network layer for the grooming operation. Through such investigation processes, we figured out a four-layered network as shown in Fig. 4. With a detailed numerical investigation, it was found that this network structure would satisfy the requirements discussed in subchapter 3.1. The details of the topology and the specific numerical investigation will be explained in the next section.

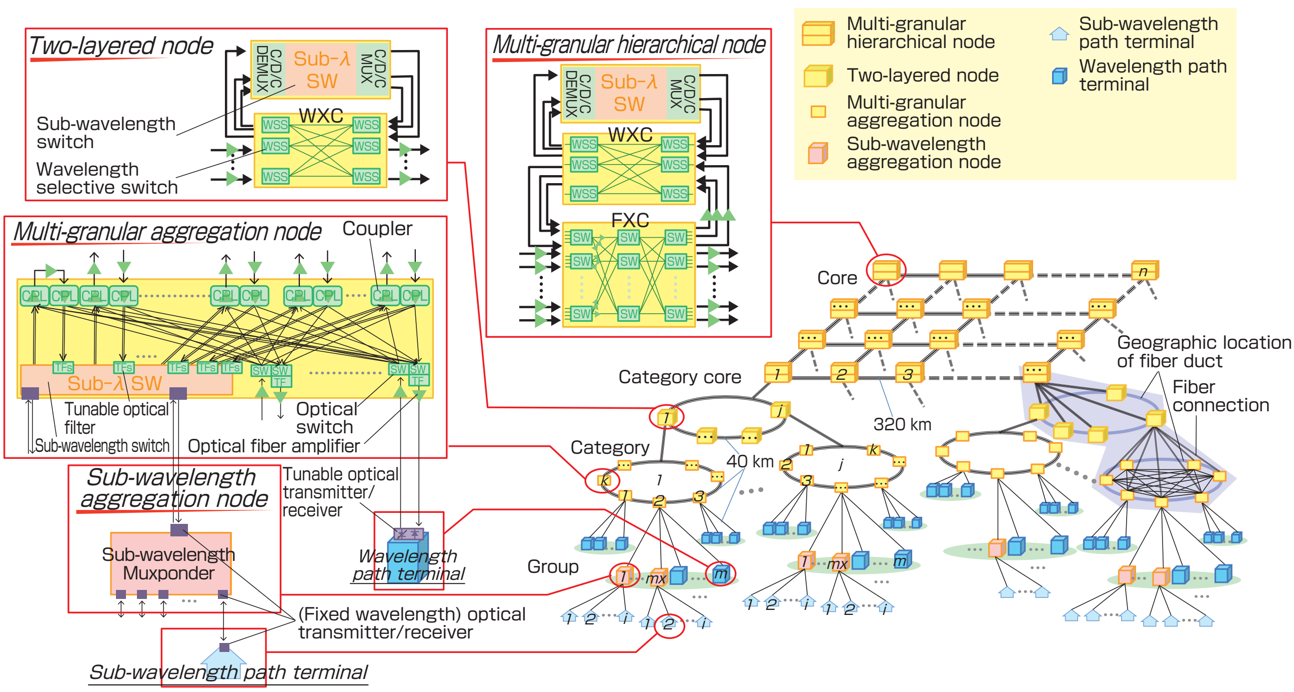


Fig. 4 Topology and node architecture of the DOPN

3.2.1 Role of each network

The network topology investigated here consists of four layers. They are the following: group networks (NWs) that consist of multiple user terminals, category NWs that aggregate multiple group NWs, the category core NWs that aggregate the multiple category NWs, and the core NWs that connect the multiple category core NWs. The group NW aggregates the traffic for the first phase, the category NW aggregates the traffic for the second phase, the category NW grooms the aggregated traffic, and then the core NW establishes the long-hole paths.

The group NWs consist of the sub-wavelength path terminals for consumer users, the wavelength path terminals for enterprise users, and the sub-wavelength path aggregation nodes that multiplexes the sub-wavelength paths to the wavelength paths. These terminals, nodes, and upper layer category NW nodes are connected with tree topology. This topology is compatible with the current PON. To achieve a flexible wavelength assignment with minimum blocking for the whole network, the tunable optical transmitter/receiver is assumed to be installed on the uplink side of the wavelength path terminal.

At the category NW, the multiple wavelength paths from the multiple group NW are multiplexed to the fiber paths, and are connected to the upper layer (category core NW) or another group NW within the same category NW according to the path destination. While the geographic fiber topology of the category NW is the ring, the logical fiber connectivity is assumed to be full mesh within a category NW. Consequently, the nodes that are not adjacent to each other on the ring topology will be connected directly by fibers at the nodes along the way as shown in the schematic diagram of Fig. 5. The logical fiber connectivity between the category and category-core NW is assumed to be star network. By using the full mesh and star connections, the category NW node can handle only the traffic transmitted/received from the group NW to which it connects. Since it does not have to handle the transit traffic that is generated/terminated from/at other group NWs, the node architecture can be simplified and the number of necessary optical switch ports can be reduced.

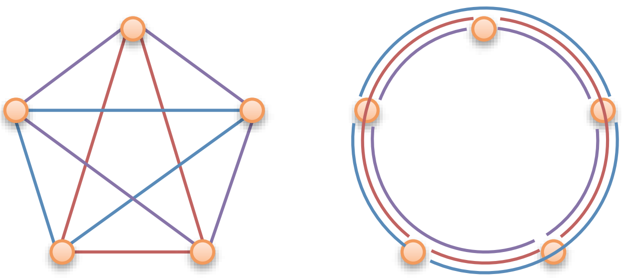


Fig. 5 Example of the intra-node fiber connection (left) and the geographic fiber location (right) at the category NW section

At the category core NW, the paths connected from the category NW is connected to the core NW. Here the paths are sorted to enable switching for each fiber as much as possible at the core NW. That is, the wavelength paths with the same destination node at the core NW are aggregated to the same fiber (wavelength path grooming), and the sub-wavelength paths with the same destination are aggregated to the same wavelength path (sub-wavelength grooming). While the geographic fiber topology of the category core NW is the ring, the fiber connectivity between the category-core and core NW is assumed to be star topology. Also, to simplify the node architecture and to reduce the number of necessary optical switch ports, the loopback at category NW is not considered.

At the core NW, long-distance paths will be established for the aggregated traffic.

3.2.2 Bottleneck of the network

In the network capacity design, it is not realistic to assume that all users continue to request connection at all times. To increase the network utilization, the network capacity of the core NW and the category core NW which share many users are limited compared to the category NW and the group NW. This is called oversubscription. An example of the capacity design is shown in Fig. 6. Here, the oversubscription is set as 10, and 10 % of the traffic from each group NW is allowed to connect to the category core NW through the category NW. For the remaining 90 %, the loopback connection is allowed within each category NW. This loopback connection enables connection with low blocking rate for the connection request within the same category NW. On the other hand, since the long-haul connection request must go through the core NW, this will be affected by oversubscription.

The optimal value of oversubscription is strongly dependent on the traffic pattern and application service model, and therefore detailed investigation is impossible at this point.

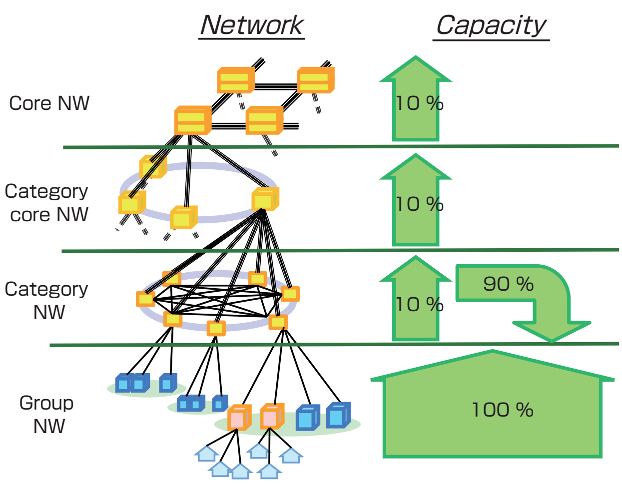


Fig. 6 Example of the network capacity design

As a typical example, considering the high definition teleconferencing application, a reservation service is expected. It can be expected that even with relatively high blocking rate of a few tens of percent or large oversubscription, meaningful service operation can be provided through efficient reservation algorithms and clear fee schedule according to the time zone of use.

For download services, the blocking rate can be reduced by allocating content servers appropriately. For example, allocating content servers for each category NW may substantially reduce the blocking probability since the blocking probability within the same category NW is very low. In addition, the DOPN can efficiently accommodate the connections between the servers since the requests from multiple users are aggregated at the servers and large-capacity demand occurs between the servers; the DOPN is capable of handling such large-capacity paths. On the other hand, there is a tradeoff relationship between the reduced blocking probability by contents server array and increased power consumption and cost. The optimal allocations of content servers with low blocking probability and low power consumption for download services depends on the server performance and the service format, and detailed study is necessary in the future. For the investigation of the efficiency of the download service, the file transfer time (path/service holding time) and path switching time are also important factors. That is, the path switching time must be much shorter than the path holding time. The switching time of the optical switch depends on the technologies: MEMS switches take several tens of millisecond order; Si photonics switches take microseconds to sub-milliseconds; WSSs of LCOS takes several tens of millisecond order. Assuming that the path switching time is several hundred milliseconds, the service with holding time of several minutes or more (file size about 40 GByte or more) is suitable as the target service of DOPN. If the path switching time is reduced to the order of sub-milliseconds, the file transfer of about 100 MByte (path holding time is several seconds) can be a target application of DOPN.

3.2.3 Network size

The number of users that can be accommodated by the whole network depends on how many nodes or terminals compose each network. Table 1 shows the list of parameters necessary for setting the network topology and the example of numerical values to achieve the requirements. In the given example, about 20 thousand user terminals can be accommodated per one group NW, and about 200 thousand user terminals per one category NW.

3.2.4 Details of each network node

As mentioned before, since each network has different roles and different aggregated traffic volumes, it is necessary to employ appropriate path granularities and node structures for each network. The details of the nodes used in each network are explained below.

Table 1. List of the network topology parameter and the numerical value example for 5,1840,000 accommodated users

	Expression	Numerical example
Number of nodes in core NW	n	25
Number of nodes in category core NW	j	10
Number of nodes in category NW	k	10
Number of fibers that connect from each category NW to upper layer category core NW	k_c	1
Number of wavelength path terminals within the group	$m(1-x)$	256(m=768, x=2/3)
Number of sub-wavelength path aggregation nodes within the group	mx	512(m=768, x=2/3)
Number of sub-wavelength path terminals per sub-wavelength path aggregation node	i	40
Number of wavelengths per fiber	w	80
Transmission rate of wavelength path user	B_w	40 Gbps
Transmission rate of sub-wavelength path user	B_s	1 Gbps
Total number of sub-wavelength path terminals	$ijkmnx$	
Total number of wavelength path terminals	$jkmn(1-x)$	

The sub-wavelength path aggregation node in group NW provides the function of aggregating/multiplexing i sub-wavelength paths to one wavelength path. Here, the use of ODU signal multiplexing function (muxponder) is expected. The oversubscription at group NW is avoided by setting $B_w \geqq iB_s$.

The category NW node is a multi-granular aggregation node shown in Fig. 4. The downlink side of this node has m ports for wavelength paths, and accommodates one group NW. The uplink side has $k+k_c$ fiber ports. Of these, k port is the loopback port within its own category NW, and the number of connecting fiber to the upper network is k_c. That is, the oversubscription is expressed as m/wk_c, and in the example shown in Table 1, it will be 9.6. This node is composed of m×1 optical couplers, $(k+k_c)$×1 optical switches, sub-wavelength path switch with throughput $imxB_s$, and tunable optical filters (TF).[Term 4] The flexible grid connectivity is achieved by using optical couplers with port/wavelength/bandwidth independent multiplexing capability for multiplexing wavelength paths to fiber paths.

The node used in the category core NW is a two-layered node consisting of the wavelength cross connect and sub-wavelength cross connect (Fig. 4). Each node has average $(1-x)wkk_c$ of wavelength paths and $iwxkk_c$ sub-wavelength paths connected from the category NW. To conduct wavelength path and sub-wavelength path grooming for all of these, the number of ports required for the wavelength path switch will be $kk_c+\lceil xkk_c \rceil$ and throughput $iwxkk_cB_s$ at the sub-wavelength path switch.

The node at the core NW is the multi-granular hierarchical node composed of the fiber switch, wavelength switch, and sub-wavelength switch (Fig. 4). At the core NW, the traffic is considered to be sufficiently aggregated and sorted by the grooming process in the category core NWs. Thus the switching operation in the core NW can be mainly done with the fiber path granularity. In cases where the grooming is insufficient, the grooming using the wavelength and sub-wavelength path switches are done in the core NW. The number of switch ports necessary for each multi-granular, hierarchical node is investigated in subchapter 3.3.

3.2.5 Variations of network topology

For the core NW structure, according to the geographic conditions, using the *N*×*M* ladder type or other asymmetrical topology instead of the *N*×*N* grid types can be considered as variations of network topology shown in Fig. 4. There is also a variation in correspondence with the content server allocation as mentioned in section 3.2.2. According to the allocation of content servers, partial changes in category NW or category core NW or slight modifications of the node architectures may be required. However, major changes involving the increase or decrease in the number of network layers is difficult. That is, decreasing the number of layers is difficult from the perspective of switch port numbers. Increasing the number of layers is not advisable since it leads to an increase of the necessary number of nodes and hence of cost and of network power consumption. To achieve the DOPN using a completely different structure from the network topology shown in Fig. 4, changes in goals for target numbers of subscribers and traffic volume, or changes in the device requirements involving the dramatic improvement in device technology such as increased number of optical switch ports are necessary. For example, if a WSS with several hundred ports can be realized, it may become possible to simplify the category core NW structure or to even eliminate the category core NW layer by introducing a large scale wavelength grooming operation in to the core NW instead of the grooming operation in the category core NW.

3.3 Number of optical switch ports and subscribers at core NW

For category NWs and category core NWs, the path route is uniquely determined because the fiber connection is a simple tree and star structure. Therefore, the number of switch ports needed at each node can be defined according to the number of subscribers and oversubscription rate accommodated or aggregated at each node independently of the traffic distribution. On the other hand, core NW has a mesh topology, and there are several path route candidates. Moreover, since each node has to handle the traffic from the terminals that do not belong to its own node (transit traffic), the number of switch ports depends on the traffic pattern and cannot be determined definitely.

The number of switch ports needed at the core NW is calculated as follows. A uniform distributed traffic pattern is assumed. As an ideal condition, all demands are assumed to be switched with fiber granularity. In this condition, the result of the optimal route assignment that minimizes the necessary number of switch ports is shown in Fig. 7. The horizontal axis at the top of the graph is the number of accommodated users in the case where the numerical example from Table 1 is used as the parameter except *n*. For parameter *n*, the values for 9 (3×3 topology) to 64 (8×8 topology) are considered.

The number of necessary accommodating fiber paths at core NW of DOPN topology investigated in this paper is $jnkk_c$, and $jnkk_c$=2,500 according to the numerical example of Table 3. The graph shows that to accommodate 2,500 fiber paths, optical matrix switch with 450 ports is necessary for 5×5 topology. If 500-port switches are used, the remaining 50 ports can be used for the grooming operation, connecting with the wavelength switches. In a case where more grooming operations are necessary, it is necessary to increase the number of optical matrix switch ports. For example, it is necessary to expand the number of stages of the optical switch structure if the multi-stage Clos network structure is used. The number of ports necessary for the grooming operation depends on the traffic patterns and the path accommodation algorithms, and these are future topics of investigation. However, from the perspective of power consumption, the percentage of power consumed by the core NW is small, as will be explained later, and the total power consumption is not greatly affected even if the number of optical fiber switches used in the core NW is increased.

4 Investigation of the optical signal transmission distance

The optical signal power is attenuated as it passes through optical devices such as the optical fiber or the optical switch. To compensate the loss, it is necessary to place the optical amplifier at a certain transmission distance or at a

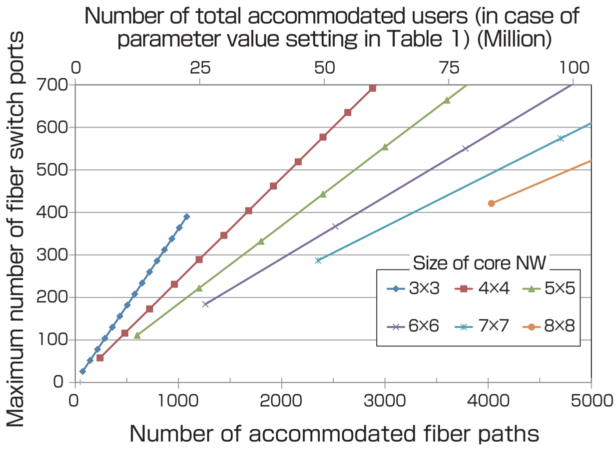


Fig. 7 Result of the calculation for number of optical switch ports needed at core NW in the optimal route assignment

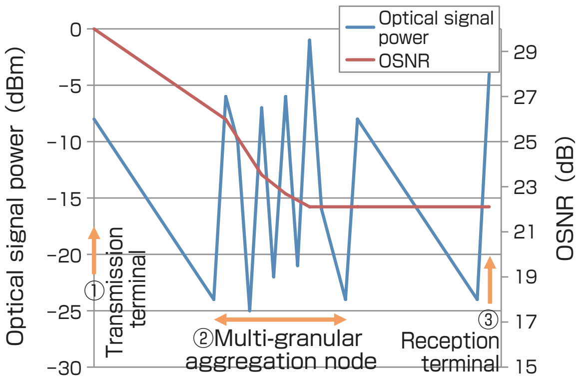
certain loss of optical signal power. For the amplification of optical signals at 1.55 μm-band used for long-distance communication, the erbium doped fiber amplifier (EDFA) is generally used. The optical signal that passes the EDFA has its power amplified, and also gains the spontaneously emitted light generated by EDFA, and this becomes the noise for the signal. If several EDFAs are cascaded, the noise is accumulated, and the signal-to-noise ratio is decreased. For receiving the signal properly, the signal must be regenerated and repeated while the signal-to-noise ratio is within a certain range. The necessary frequency of signal regeneration or the level of accumulated noise by EDFAs depends on the noise/gain profiles of the EDFA and the input signal power. Generally, when the EDFA with large gain is used at low frequency, the accumulated noise becomes great, and when the EDFA with small gain is used at high frequency, the accumulated noise can be kept low.

The number and the location of necessary signal regenerative repeaters and optical fiber amplifiers for the DOPN were investigated by calculating the optical signal-to-noise ratio (OSNR). The typical loss value of the optical device used in the calculation is shown in Table 2. The noise figure of the EDFA is assumed to 6 dB and the noise bandwidth is set to 12.5 GHz. The assumed fiber length at each network section is shown in Fig. 4.

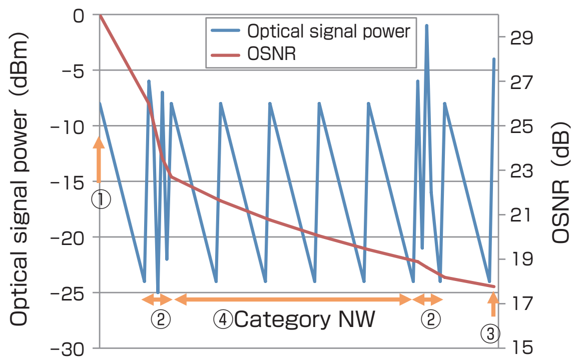
Table 2. Insertion loss value of each optical device used in estimation

Item		Loss
Optical fiber		0.4 dB/km
Multi-granular aggregation node	1×10 switch	4 dB
	1×768 optical coupler	30 dB (amplify at every 15 dB loss)
	Tunable optical filter	4 dB
Two-layered node	1×17 WSS	6.5 dB
Multi-granular hierarchical node	3-stage 500×500 matrix switch	24 dB (amplify between stage)
	1×35 WSS	6.5 dB

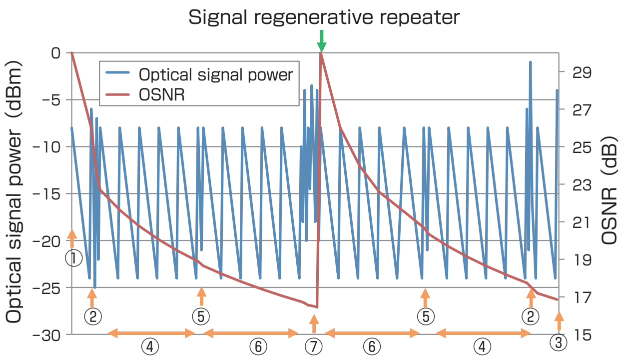
The result of the calculation is shown in Fig. 8. The level diagram shows the input optical signal power and gain of the EDFAs. In the multi-granular aggregation node, large loss occurs because couplers (CPL) with large numbers of branches are used. To reduce the OSNR degradation there, the EDFAs are placed at an intermediate stage of the branch.



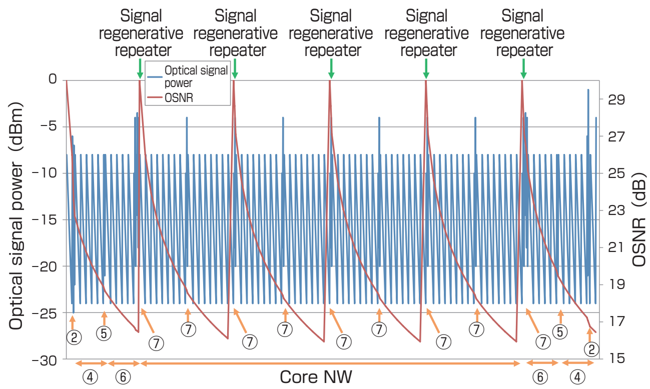
(a) Path within the same group



(b) Path between other groups within the same category



(c) Path within the same core node between other categories



(d) Path between other core nodes

Fig. 8 Level diagram of the typical path route and result of the OSNR calculation
The numbers inside the graph correspond as follows: ① transmission terminal, ② multi-granular aggregation node, ③ reception terminal, ④ category NW, ⑤ two-layered node, ⑥ category core NW, and ⑦ multi-granular hierarchical node.

Also, the EDFAs are placed at an intermediate stage of the 3-stage Clos network switch structure to prevent the OSNR degradation in the fiber path switch of the multi-granular, hierarchical node. The calculation results show the signal regenerative repeater had to be placed in the core NW node, and the signal regeneration must be done when the signal enters the core NW, when it leaves the core NW, and once every two nodes during the core NW transmission. The OSNR threshold was set at 15 dB assuming the use of 100 Gbps dual polarization quadrature phase shift keying (DP-QPSK),[Term 5] which employs the digital coherent transmission/reception technology that is recently being put to practical use.[24][25]

Table 3. Power consumption values for each device used in the estimation of the DOPN power consumption

Network equipment	Power consumption	Remarks
Single wavelength optical fiber amplifier	2 [W/span/fiber]	40 km/span
WDM optical fiber amplifier	20 [W/span/fiber]	40 km/span
Sub-wavelength cross connect	1 [W/Gbps]	
Wavelength path terminal	1 [W/Gbps]	40 Gbps or more
Sub-wavelength path terminal	5 [W/device]	Less than 5 Gbps
Optical matrix switch	0.05 [W/port]	The use of Si photonics switch is expected
Wavelength selective switch	20 [W/device]	
Tunable optical filter	5 [W/device]	

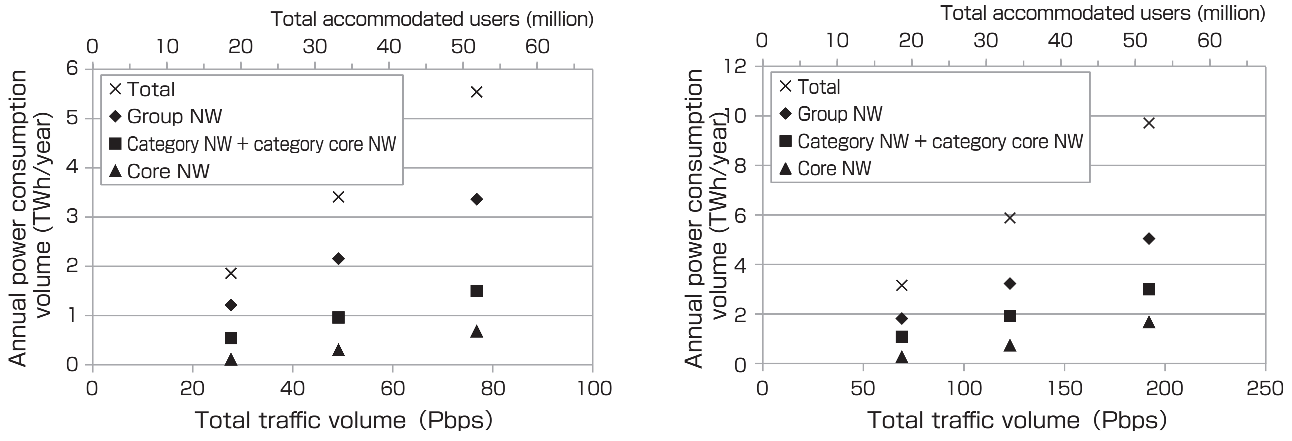
5 Estimate of power consumption

Through the investigations in chapters 3 and 4, the location and the necessary numbers of the main component devices for the DOPN topology including from the path switching devices to the signal regenerative repeater were clarified. By summing up the power consumptions of each device, the total power consumption of the DOPN can be estimated. Table 3 shows the power consumption of each device; the values are determined based on product catalogs and specification sheets. Figure 9 shows the result of the calculation of the power consumption of the whole network.

The estimation result shows the group NW or the communication terminals dominate the power consumption of DOPN. In the case where the terminal speed is constant, the total power consumption increases in proportion to the number of subscribers. If the terminal speed increases while maintaining the number of subscribers, the total power consumption increases in correlation to the increase in overall traffic volume. This is because the DOPN uses not only the optical switch of which power consumption is not dependent on the throughput, but also the sub-wavelength path switch, wavelength path terminal device, and signal regenerative repeater that are devices whose power consumption scales with the throughput.

In the current Japanese network, the total traffic volume is said to be 1.9 Tbps and total power consumption is ~10 TWh/year.[3][26] The DOPN can accommodate four to five digits more of traffic with about the same power consumption. Although the power consumption needed for control systems and the network utilization ratio are not considered in the estimation. However, even if the power consumption is multiplied ten-fold due to the overhead, the DOPN can offer an energy efficiency benefit of three orders of magnitude.

For further reduction of power consumption in the DOPN, the introduction of sleep function to the transceivers of the user terminal can be considered. Assuming that the average usage time of DOPN for each user is 5 h/day, and expecting that the terminal power can be turned off completely when not in use, the power consumption reduction of 22~37 % can be expected in the estimation of Fig. 9. Compared to the transceivers that are shared by multiple users within the network, it is expected that the sleep function can be readily introduced to the transceivers of the user terminal. Further, the improvement of the insertion loss of the optical switch and WSS is important. If the insertion loss of the



(a) In case of wavelength endpoint 40 Gbps and sub-wavelength endpoint 1 Gbps

(b) In the case of wavelength endpoint 100 Gbps and sub-wavelength endpoint 2.5 Gbps

Fig. 9 Result of the estimation of the power consumption in DOPN

optical device is reduced, the number of EDFA and signal regenerative repeater needed in the network can be reduced, and the reduction of power consumption particularly in the core NW can be expected.

6 Conclusion

The detailed topology and node architecture for the DOPN were investigated; the scalability of the DOPN was evaluated from the perspective of the number of subscribers, bandwidth per user, and the power consumption; and the validity of the DOPN as a future communication infrastructure technology was clarified in this paper. For the realization of DOPN, further R&D such as the development of a low-loss, compact optical switch, as well as efficient integrated resource management technology is necessary. The target of DOPN is not the application that is available on the current communication network, but is future applications requiring a high realistic sensation that involves remote medical care, remote education, and so on. For the DOPN to truly contribute to society, the development of the peripheral technologies that can utilize the DOPN is necessary, not only from the elemental technologies constructing the network mentioned above, but also to the display and video/sound technologies that can achieve realism almost equivalent to actual experiences, as well as business models to realize new services. Considering the above point, and looking at the device and application to the future, we plan to continue R&D to establish the communication infrastructure technology for the future.

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Terminologies

Term 1. OSI7 layer: The layer model for communication function for data communication that was established by the International Standards Organization (ISO). It is also called the open system interconnection (OSI) reference model. It is composed of the physical layer (layer-1), data link layer (layer-2), network layer (layer-3), transport layer (layer-4), session layer (layer-5), presentation layer, (layer-6), and application layer (layer-7). The IP router used commonly in the wide area network is a communication device that conducts connection and routing in layer-3, while the Ethernet switch used commonly in the local area network (LAN) conducts connection and switching in layer-2. The optical switch that is the main component of DOPN corresponds to layer-1 or the lower layer (sometimes called layer-0).

Term 2. Wavelength selective switch (WSS): This is a device with the basic structure of optical port with one input and multiple outputs. It has the function of switching the input WDM wavelengths to any of the output ports per-wavelength basis. Some switches are fixed to the 50 GHz grid or 100 GHz grid for the wavelength channel bandwidth, and others are flexible grids that can handle consecutive bandwidth every 12.5 GHz.

Term 3. Grooming: A process that enables the handling of small-granular communication requests as a large-granular request by grouping them. Here, the process includes the operation that enables switching the multiple sub-wavelength paths with the same destination as one wavelength path by accommodating them into one wavelength path, or the operation that enables switching the multiple wavelength paths with the same destination as one optical fiber path by accommodating them into one optical fiber.

Term 4. Tunable optical filter (TF): The optical device that transmits a certain wavelength bandwidth and can tune the central wavelength of the pass bandwidth. There is also the central wavelength bandwidth tunable optical filter that can change the central wavelength and the pass bandwidth.

Term 5. Dual polarization quadrature phase shift keying (DP-QPSK): One of the modulation formats for the digital signal, where the polarization multiplexing is applied to the quadrature phase shift keying. Since 2005, it has been developed along with the advancement in digital coherent optical communication technology to improve the spectral efficiency. In 2010, the standard for 100 Gbps DP-QPSK optical transceiver module was announced at the Optical Internetworking Forum (OIF). Currently, the products in compliance with this standard have been launched, and the transmission system with 100 Gbps per channel is developing rapidly. Also, the high-speed digital signal processing enables the linear compensation of various issues in transmission of over several thousand km without regenerative repeating has been reported.

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Discussions with Reviewers

1 Overall

Comment (Naoto Kobayashi, Center for Research Strategy, Waseda University)

This paper investigates the topology structure of the dynamic optical path network (DOPN), which is a method devised to handle the significant increase in power consumption due to increased communication capacity that is essential for the information and communication network in the near future, and demonstrates its efficacy. It is a paper with logical clarity and substantial content. The structure of the paper is also appropriate for publication in *Synthesiology*.

2 Network structure

Comment (Katsuhiko Sakaue, Research Environment and Safety Headquarters, AIST)

I understand that this research is a fine investigation of the network architecture to apply the DOPN, the subject of your research team, to the practical scale of Japan's network. However, you present the requirements of the network in subchapter 3.1, and suddenly you jump to the four-layered topology as the subject of investigation in subchapter 3.2. Although this topology is very practical and I have no objection to it, for *Synthesiology*, you should write out the arguments, or what thought processes and investigations results you went through before you arrived at this topology. Please explain them in the appropriate chapters.

Answer (Kiyo Ishii)

The number one issue when investigating the topology is to provide the path connectivity among tens of millions of users using the switches with several hundred ports as the main components. Also, since the traffic volume transmitted by the user is small or 1/80~1/6400 or less compared to the transmission line (optical fiber) capacity, it is necessary to aggregate the traffic at a point as close as possible to the user terminal to increase the utilization of the transmission line. Not only from the point of compatiblity with the existing network, but also from the port limitations and traffic aggregation, the achievement of DOPN using a flat network topology was difficult, and the hierarchical topology where the user terminals are grouped and hierarchically connected was necessary. In the hierarchical network topology, a simple structure with as less layers as possible is preferred, and the point was how many layers with which roles were necessary for the network, other than the two layers for traffic aggregation (lowermost) and long-hole path establishment (uppermost). For traffic aggregation, we decided to consecutively aggregate the sub-wavelength path to the wavelength path, and wavelength path to the fiber path, according to the users' path granularity. The reason for separating the aggregation to two steps were, to increase the utilization of the transmission line by aggregating the sub-wavelength path to the wavelength path at a position close to the user, and to reduce the number of sub-wavelength path switch port that will be necessary when the paths are aggregated to the fiber capacity. Considering the number of target users and the bandwidth per user, the traffic volume aggregated to the uppermost network will become enormous. In the uppermost network, the number of ports much greater than the wavelength switch can be expected, and the optical fiber switch that can accommodate larger capacity is essential. That is, as it becomes possible to switch by individual fiber, it is necessary to connect to the uppermost network in a state where the wavelength path and the sub-wavelength path are well sorted. As a result of investigating quantitatively the communication node architecture of the aggregation network, from the perspective of the number of optical switch ports and loss of optical couplers, it was difficult to aggregate the traffic demand with the same or nearby addresses to fill the fiber capacity using the aggregation network. It was therefore found that a network for grooming was necessary between the aggregating network and the uppermost network. This meant there would be a four-layered network with two layers of aggregating networks, one layer of a grooming network, and one layer of a long-hole path establishment network. Detailed numerical investigation was done, and it was found that the node architectures and topology set as shown in Fig. 4 would satisfy the requirements for the number of optical switch ports and user capacity. The above discussion was added to subchapter 3.2.

Question (Naoto Kobayashi)

The network structure of Elemental Technology 3 considers the similarity with the existing network structure and control characteristic of the upper and lower layers, and I think it is adequate. However, is there room for options such as other possible selections? If there is any, what kind of topologies or nodes can be considered?

Answer (Kiyo Ishii)

The network structure shown in this paper is the result of accumulation based on the adequacy of the goals and requirements shown in subchapter 3.1. Before arriving at this network structure, various topologies were investigated including the flat network structure, but they could not fulfill the requirements of subchapter 3.1. For example, reducing the number of the network layers is difficult from the perspective of the number of switch ports. Increasing the number of the network layers is not wise because it leads to increased nodes and therefore, increased device cost and power consumption. I think future investigations are necessary for fine modifications and partial changes in category NW and category core NW according to the expected traffic patterns and variations of the contents server allocation. Also, there are variations, such as using the N×M ladder type instead of N×N grid type or other asymmetrical topology, for the core NW according to the geographic condition. However, it is difficult to fulfill the requirements of subchapter 3.1 using a fundamentally different topology, and in such cases, changes in requirements such as the dramatic improvement of the device technology including the increase of the number of optical switch ports, or changes in the goals of the number of users or capacity must occur. Section 3.2.5 was newly added for the above discussion.

3 Elemental technology

Question (Naoto Kobayashi)

In this research, you predict the property of DOPN based on the current specifications of the individual elemental technologies including the optical switch of Elemental Technology 1. Can you give us prospects on which part of the elemental technology should be dramatically changed to greatly improve the network property?

Answer (Kiyo Ishii)

From the perspective of further reducing the power consumption, I can mention the sleep function for the user terminals (transceiver) that dominate the majority of the power consumption. Since the transceiver of the group network is mostly used by a single user, I suppose it is easier to introduce the sleep function compared to the transceiver of the upper network that is shared by multiple users. Assuming that the average use time of the DOPN for each user is 5 h/day, and expecting that the transceiver power can be turned off completely when not in use, the reduction in power consumption of 22~37 % can be expected for the estimation in Fig. 8. Also, if the insertion losses of the optical switch and WSS are improved, the number of necessary EDFA and signal regenerative repeaters can be reduced, which will further reduce the power consumption of the core NW. From the perspective of topology, if the WSS with several hundred ports is realized, the wavelength path grooming becomes easy, the category core NW layer for the grooming process can be simplified, and unifying the category core NW into the core NW may become possible. From the perspective of target service, if the switching speed of the WSS and optical fiber switch increases in the order of sub-milliseconds, the service with holding time of several seconds (HV or 4K VOD download) can be efficiently handled in DOPN, and this may expand the target services. These discussions were added to chapter 5, section 3.2.5, and section 3.2.2.

4 Issues concerning future application

Question (Katsuhiko Sakaue)

You mention in several places that the DOPN can be used in highly realistic video applications including in remote medical care and remote education that are expected to be developed in the future. However, these are being realized in the current IP router network, and in practice, the flexibility of the IP technology seems to surpass the low power consumption and high speed achieved by replacing the L1 switch with the optical switch. What is your expected scale of application that cannot be handled by the current IP router network?

Answer (Kiyo Ishii)

The quality of the video service targeted by DOPN is the ultra high definition (UHD) that is currently being developed. The UHD has 16 times higher definition compared to high vision (HV). It requires the bandwidth of 72 Gbps or more for uncompressed transmission, and compared with the peak connection speed 40.5 Mbps for the current Japanese Internet network, there is a gap of three digits or more. If the DOPN is used, the bandwidth needed for the uncompressed transmission of UHD can be provided stably. Of course, the video compression technology is also being developed, but there is a limit to compression in realizing the high realism equivalent to actual experiences, and the transmission bandwidth of about several Gbps to 100 Gbps that is the target of DOPN will be necessary. This discussion was added to chapter 1.

Question (Naoto Kobayashi)

You expect multiple users for video application in the future. However, in practice, there are extremely large amount of download services on the traffic, and there is a projection that there isn't much real-time video streaming. In section 3.2.2, you write, "It is possible to reduce the blocking rate in the download service by allocating the contents server for each category." In this case, won't the number and capacity of the content server become so large that it becomes inefficient?

Answer (Kiyo Ishii)

As you indicated, there is a tradeoff between the increased power consumption and cost by the allocating content server and the efficiency of the network through traffic localization. Yet, I think achieving high efficiency not only for the network resource but also for content resource is possible by appropriate server placement and topology design. The optimization of this tradeoff is also related to business models and resource management methods, and these are future topics of study. For content server placement, while connection between the servers is important, this can be accommodated efficiently with the DOPN that can handle the large-capacity paths, since large-capacity demand will occur as the requests from multiple users are aggregated. The above discussion was added to section 3.2.2.

5 Future usability

Question (Naoto Kobayashi)

In the future, the users will hope to use the existing IP network and the proposed DOPN seamlessly, without ever thinking about the differences. Is this actually possible? Or, since there is a reservation task to obtain the optical path when using the DOPN, will that make it less usable?

Answer (Kiyo Ishii)

For the operation management of DOPN, the introduction of a new resource management system to conduct the comprehensive reservation management from network to storage resources will be necessary. From the perspective of the concurrent use of the IP network and DOPN, the resource management system will automatically select the network to be used according to the application, such as web or mail using the IP network, while large-capacity file transfer such as high definition VOD using the DOPN, and the optical path is reserved as necessary. Also, as in the remote teleconferencing service where the user normally makes reservations beforehand, the resource management system will make prior reservation of the optical path based on the user's reservation. In this case, the user reserves the teleconferencing service, while the reservation of the optical path will be done by the resource management system, so the user does not have to be conscious of using the DOPN. The resource management system is being studied in collaboration with the Information Technology Research Institute, AIST. The above discussion was added to chapter 1.