IP over A–Thousand–Wavelength Division Multiplexing: Is It Useful and Feasible for Resolving the Network Bottlenecks?

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Abstract

A WDM (Wavelength Division Multiplexing) technology is emerging as a practical and future–proof solution to provide an infrastructure of the next generation Internet. It is still not clear, however, what kind of structures of IP over WDM networks is best suitable to satisfy the growing bandwidth requirements in the future Internet. The number of wavelengths is probably a key factor, and then, the question is; is it feasible to realize IP over a–thousand–wavelength division multiplexing? And is it useful to resolve the network bottleneck against an explosion of the traffic demand of the end users? The answers are yes. In this article, we first present the way to multiplex a thousand wavelengths on the fiber link, by which the link bottleneck would be solved. We then examine how the IP over WDM network utilizing wavelength routing can relieve the router bottleneck through the numerical examples using the actual traffic data and network topology.

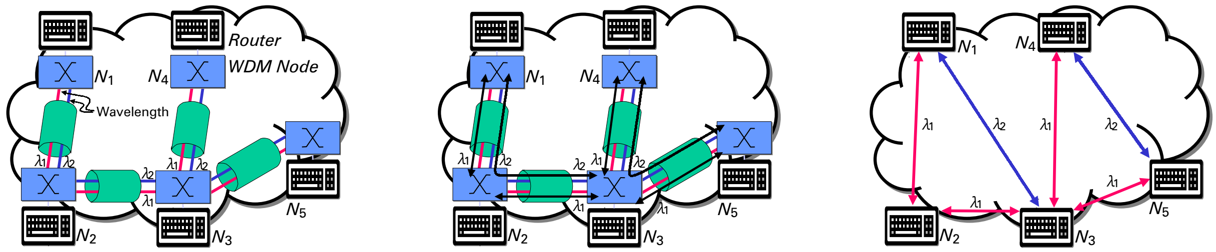
1 Introduction

A WDM (Wavelength Division Multiplexing) technology is emerging as a practical and future–proof solution to provide an infrastructure of the next generation Internet [1]. The WDM transmission experiment of 40Gbit/s, 168-wavelength with the aggregate capacity of 6.4Tbit/s has been achieved [2], and a currently available technology uses WDM on the fiber link (Figure 1(a)). That is, each wavelength on the fiber is treated as the link between adjacent IP routers, and multiple links are offered by the WDM technology. A conventional multiple–link handling technique can be utilized in this case. In the currently available products, only four to eight wavelengths are provided, but if we have more wavelengths on the fiber link, the bottleneck of the link bandwidth would be resolved.

Actually, as opposed to a common belief, multiplexing of a thousand wavelengths on the fiber must be feasible in the near future. By looking carefully at the loss spectrum of silica-based optical fiber, a super-wide transmission window of about 350nm (roughly 50 THz) extends over the spectral range of 1310-1660 nm, whose attenuation is below 0.3 dB/km. Had the bandwidth of 50 THz, wavelengths on the WDM link could be increased by a factor of more than ten, say, 1000 wavelengths with the channel spacing of 50 GHz. Alternatively, by resorting to denser WDM approach with the channel spacing of 25GHz, for example, the transmission window is narrowed to 1460-1660nm (25THz). In Section 2, we will explain the realization method in more detail.

A thousand wavelengths would resolve the link bottleneck against an explosion of the traffic demand for the current and future Internet. However, it is insufficient since a thousand wavelengths might only result in that the bottleneck is shifted to an electronic router. To relieve the bottleneck at the router, an introduction of optical switches has actively been discussed. One possible realization is that a logical topology is constituted by wavelengths on the physical network (see, e.g., [3, 4, 5] and references therein). The physical network consists of the optical nodes and the optical–fiber link connecting nodes. Each optical node has optical switches directly connecting an input wavelength to an output wavelength, by which no electronic packet processing is necessary (see the upper part of Figure 2 for the structure of the optical switch). Then, a direct wavelength path can be set up even if a distance of nodes is more than two hops on the physical network. An example is shown in Figure 1(b). From node N_1 to node N_3, a direct wavelength path is set up by using the wavelength λ_2, by which the processing for packet forwarding at node N_2 is not necessary. We note here that in the above example, wavelength changes at the optical switch are not considered. If it will be available, more flexible wavelength routing can be achieved [6].

By establishing the wavelength–routed network as in Figure 1(b), we have the logical topology consisting of wavelength paths as illustrated in Figure 1(c), showing a logical view of the underlying network to the IP routers. In



(a) Physical Tolopogy

(b) Wavelenth Routing on the Physical Tolopogy

(c) Logical Tolopogy

Figure 1: Physical and Logical Topologies

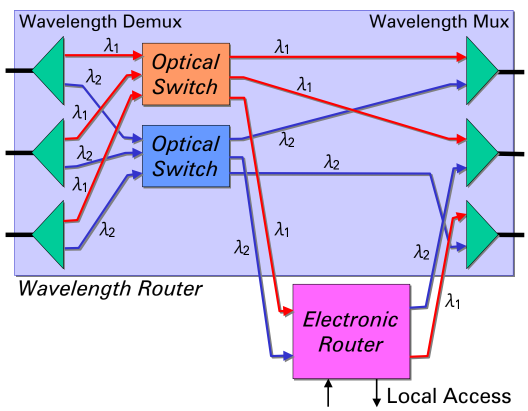


Figure 2: Structure of Wavelength Router [3]

Figure 1(c), there are no direct wavelength paths for packets from node N_1 to N_4. It is because the wavelength is not available to establish the wavelength path, and therefore, those packets should be passed to the electronic router at node N_3 for further forwarding the packets destined for node N_4 (see the lower part of Figure 2). By comparing Figures 1(a) and 1(b), however, it is apparent that required packet processing at the router can be reduced by introducing the optical switches. We should note here that the other structure of optical nodes can also be considered, but the above–mentioned node architecture is preferable since there is no need to modify the IP routing mechanism.

It is desirable to have many wavelengths since it increases an opportunity to establish a larger number of wavelength paths. However, one problem that we have to consider is a constraint on the amount of optical hardware that can be provided, which limits the number of wavelength paths terminated at a node. The number of ports the electronic switch at the router can handle is another factor restricting the number of wavelength paths. Those numbers limit the degree of the logical topology. The wavelength router shown in Figure 2 corresponds to node N_3 in Figure 1(b). The packets from node N_1 to N_4 are once forwarded to the electronic router and again put on the wavelength path from node N_3 to N_4 since the wavelength path is terminated at node N_3. In Figure 2, the degree of the logical topology is two; just same as the number of wavelengths. However, as the number of wavelengths becomes large, the constraint on the degree of the logical topology would be dominant to determine the performance of IP over WDM networks. By taking account of those constraints, we will derive the bound on the required processing capability of packet forwarding at the electronic router in Section 3.

While a lot of researches have been devoted to the design method of logical topologies for wavelength–routed optical networks (see, e.g., [6, 7] and the survey paper [3]), it is still not clear how much the increased number of wavelengths can reduce the requirement on the processing overhead of the electronic router. As a second part of this paper, we will investigate it by numerical examples in Section 3. More recently, the IP over WDM network based on the MPLS (Multi-Protocol Label Switching) technology is discussed in the IETF [8, 9]. A fundamental principle presented in [8] is very similar to the above–mentioned IP over WDM networks using the logical topology. Our discussion in this paper is also applicable to the MPLS–based IP over WDM networks.

This paper is organized as follows. In Section 2, we will describe how WDM with a thousand wavelengths can be realized. We next demonstrate how much the network bottleneck can be relieved by such a technology in Section 3. For this purpose, we first summarize several bounds including the traffic congestion, which shows the maximum traffic load on the logical link, and the processing capacity necessary to accommodate the growing traffic. Then, using the actual traffic data and network topology provides numerical examples. Some concluding remarks are described in Section 4.

2 Challenge for WDM with A Thousand Wavelengths

In Figure 3, a loss spectrum of typical low–loss optical fiber is shown. We will focus on the moderate channel spacing of

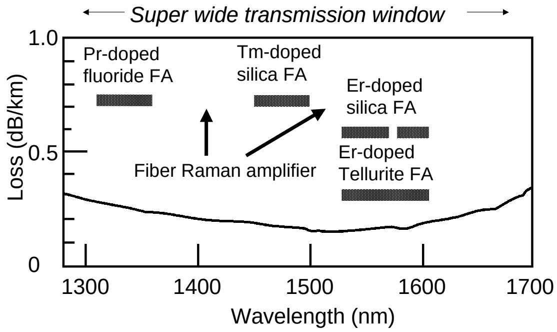


Figure 3: Loss Spectrum of Typical Low-Loss Optical Fiber

50GHz, rather than the denser WDM approach. This is because the low loss spectral region of optical fibers must be eventually pioneered and exploited in the long run, although its task is challenging. A super–wide transmission window below 0.3 dB/km extends over 400nm (roughly 50 THz) in the spectral range of 1290-1690nm [10]. Note that the absorption peak at the wavelength of 1390nm is eliminated in the figure. Had the bandwidth of 50 THz, the wavelength channels of WDM could be increased by a factor of more than ten from conventional WDM channel count up to 100. For example, the number of channels which can be accommodated in the window with a moderate tolerance of optical frequency of light source can be calculated to be 2500, 1000, and 556 with the grid intervals of 20 GHz, 50 GHz, and 90 GHz, respectively, for 2.5 Gbps, 10 Gbps, and 40 Gbps [11]. As currently available gain bandwidths of optical amplifiers are limited up to 80nm (10 THz) within a range of 1530-1610nm, it is not wide enough to accommodate 1000 wavelengths. even if dense WDM approach is adopted.

It is a challenge to exploit the wavelength resource by fully utilizing the super–wide window of optical fibers. The challenge includes both the dispersion compensation of optical fibers and both the gap filling and flattening of optical amplifiers over the super–wide window. To the authors' knowledge, the above issues have not been well addressed in depth.

The dispersion of optical fiber determines the product of bit rate and distance. There would be two approaches to realize low dispersion over a wide spectral range. Dispersion compensation is a conventional technique that uses dispersion compensation fibers (DCFs) having a reverse dispersion to cancel the dispersion. Recently, reverse dispersion fiber (RDF), a special class of DCFs, has shown to nearly cancel the dispersion below 1 [ps/nm/km] in the spectral range of 100nm. Dispersion flattened fiber (DFF) is another candidate having nearly zero dispersion in a desired spectral range. By tailoring the refractive–index profile of the fiber, the value of dispersion less than 6 [ps/nm/km] would be realizable over the super–wide window of 50 THz. Although, the dispersion compensation over the super–wide window has not been achieved in practice, either RDF or DFF would be promising to realize the dispersion less than a few ps/nm/km in the super–wide window. With this amount of dispersion, the product of bit rate and distance, (bit rate)^2 $\times$ (distance) is roughly estimated around 4×104 (Gbps)^2-km. This value allows the bit rate of 2.5 Gbps for 6400 km, 10 Gbps for 400 km or 40 Gbps for 25 km. The details will be shown in a forthcoming paper.

The gap filling and flattening of the gain over the super–wide window of 1290-1690nm would be feasible with fiber–based optical amplifiers by the composition of gain bandwidths of different types of amplifiers such as doped fiber amplifiers (FAs) together with fiber Raman amplifier. Gain bandwidths of currently available doped–fiber amplifiers are shown in Figure 3 [12]. It include a composite Er-doped silica–based FA in 1530-1560nm and 1575-1600nm, Er-doped fluoride FA having a broad gain bandwidth of 80nm in 1530-1610nm band, Tm-doped silica–based FA in 1450-1500nm band, and Pr-doped fluoride FA in the 1280-1320nm band. These gain bandwidths are not wide enough to cover the super–wide window, and the pump wavelengths specific to FAs are required. There still remain uncovered spectral regions, and so searches for appropriate dopants and the fiber materials are currently underway. On the other hand, unique to fiber Raman amplifier is that the operation wavelength is arbitrary with the Raman shift of 400cm^{-1} and the gain bandwidth of 6 THz. Therefore, the gain gaps of doped–fiber amplifiers can be filled with the fiber Raman amplifier by using appropriate pump wavelengths.

As for the optical hardware, it would not be practical to provide each node with a thousand optical transmitters and optical receivers. A 1000×1000 wavelength router of Figure 2 has to be also accommodated at each node. A multi–wavelength light source combined with wavelength demultiplexer can be used for the optical transmitter because it does not require the wavelength tunability, and it is compact. The promising for the multi–wavelength light source are a super–continuum laser [13], an optical frequency comb generator [14], and a mode–locked laser as well as monolithically integrated multi–wavelength laser diode array. The SC laser is particularly promising which generates picosecond pulses at several tens of Gbit per second over an extremely broad spectral range. The seeding short pulse at a specific repetition rate is broadened continuously in its spectrum due to the fiber nonlinearlities, and thus by filtering desired wavelength components out of the SC spectrum the single light source can serve a multi-wavelength pulse source. Advantages are; it uses only one pump laser, and its fixed channel spacing with accuracy equivalent to that of a microwave oscillator (-Hz), enabling to lock the entire chain to absolute standard by locking just one mode of the chain. Recently, 1,010-channel with the frequency interval of 12.5GHz at 2.5Gbit/s over 100nm in 1550nm spectral region has been achieved [15]. For the wavelength router, 2.56 Tb/s, 16×16 wavelength division/space division switch using 16 wavelengths has been realized [16]. There is a promising large-scale optical crossconnect switch which is a key device of the wavelength router. It uses micro-electro mechanical systems (MEMs). A micromechanical space optical switch fabric is constructed by using tiny movable mirrors controlled by actuator on silicon chip based upon MEMs. Two-axis beam steering tiny mirror routes light beam between in/output fiber bundles. The mirror rotates up to 90 degrees by fine step by step by applying bias pulses to actuator. Advantages include large port count, scalability, low loss and high uniformity of loss. The switching speed is relatively slow, but the reconfiguration time of a few millisecond will meet this switching speed. A fully provisioned 112 x 112 micro-mechanical optical cross-connect switch with 35.8Tbit/s has been demonstrated [17]. An arrayed waveguide grating (AWG) is promising for the wavelength multiplexer/demultiplexer. The number of ports up to a hundred and the wavelength spacing down to 10 GHz have been realized. The AWG will be no problem to scale up to 1000 ports. To realize a 1000×1000 optical switch, technologies for the assembly of optical components as well as either monolithic or hybrid integration of the above devices have to be developed to maintain a low consumption power and its compactness.

3 A Thousand Wavelengths are Useful against the Router Bottleneck?

In this section, we first summarize bounds on (1) the traffic congestion, (2) the required number of wavelengths and (3) the required packet processing capacity of the electronic IP router. Numerical examples are then presented using the actual traffic data and network topology to discuss how a thousand wavelengths can relieve the router bottleneck.

In what follows, we will call the IP over WDM network using the physical topology directly as the *WDM link network* and the IP over WDM network using the logical topology as the *WDM path network*.

3.1 Performance Bounds for the Logical Topology

For obtaining the logical topology from the physical topology of the WDM network, we need to introduce some design algorithm [3]. However, since our main purpose of this paper is to compare WDM link and path networks, we simply consider the bounds on performance metrics.

Let $G_p(N, E_p)$ represent the directed physical topology, where N and E_p are the numbers of nodes and links, respectively. The logical topology $G_l(N, E_l)$ built from G_p has several bounds. In what follows, we briefly summarize the results obtained in [6] with an extension. Let us introduce $T = \{e^{sd}\}$ as the traffic matrix where e^{sd} shows the packet arrival rate from source node s to destination node d. For a specific logical topology and routing scheme, we can determine the arrival rate e_{ij} on logical link (i, j) of the logical topology. In a directed logical network with E_l links, the *traffic congestion* defined by

$$e_l^{max} = \max_{ij} e_{ij} \tag{1}$$

is determined as

$$e_l^{max} \geq \bar{H}/E_l, \tag{2}$$

where $\bar{H}$ is a traffic–weighted average number of hops between a source–destination pair, and is determined in several ways.

To our best knowledge, a lowest bound on $\bar{H}$ for any logical topology and maximum degree Δ_l is shown in [6] as follows. Consider the idealized logical topology in which for each source the Δ_l destinations with the largest traffic are connected by one–hop paths, the next Δ_l^2 destinations in a descending order of traffic rate are connected by two hop paths and so on. For $1 \leq s \leq N$, let π_s be a permutation of $(1, 2, \ldots, N)$, such that

$$e^{s\pi_s(d)} \geq e^{s\pi_s(d')}, \quad \text{if } d \leq d'. \tag{3}$$

Let m be the largest integer satisfying the following inequality:

$$N > 1 + \Delta_l + \ldots + \Delta_l^{m-1} = \frac{\Delta_l^m - 1}{\Delta_l - 1}. \tag{4}$$

Further define

$$n_k = \begin{cases} 0, & \text{if } k = 0, \\ \sum_{s=1}^{k} \Delta_l^s, & \text{if } 1 \leq k \leq m-1, \\ N-1, & \text{if } k = m. \end{cases} \tag{5}$$

Then, for all logical topologies with maximum degree Δ_l and all routing schemes on the topologies, we have

$$\bar{H} \geq \bar{H}_{min} = \sum_{s=1}^{N} \sum_{k=1}^{m} \sum_{d=n_{k-1}+1}^{N-1} e^{s\pi_s(d)}. \tag{6}$$

The minimum bound for the congestion is finally given as

$$e_l^{max} \geq \bar{H}_{min}/E_l. \tag{7}$$

In the above, however, the wavelength capacity is not explicitly considered. It is likely that the traffic between some node pair cannot be accommodated by the single wavelength, and two or more wavelengths would be necessary. To account for it, we modify it as follows. First, let us introduce $\bar{e}^{sd}$ defined by

$$\bar{e}^{sd} = \lceil e^{sd} \rceil, \tag{8}$$

which shows the required number of wavelengths for source–destination pair (s, d) by assuming that the traffic matrix is given in the unit of the wavelength capacity. Then the sum of traffic originated from node s, $E_s = \sum_d \bar{e}^{sd}$, gives the total number of wavelength paths for source node s. Since the first Δ_l traffic can be sent by one–hop paths, the next Δ_l^2 traffic by two–hop paths and so on, as before. Eqs. (4) and (5) defined above now becomes

$$E_s \geq \Delta_l + \Delta_l^2 + \cdots + \Delta_l^{m_s}, \tag{9}$$

and

$$n_k = \begin{cases} \sum_{s=1}^{k} \Delta_l^s, & \text{if } 1 \le k \le m_s, \\ E_s - \sum_{s=1}^{m_s} \Delta_l^s & \text{if } k = m_s + 1. \end{cases} \tag{10}$$

We then have

$$\bar{H}^*_{min} = \sum_{s=1}^{N} \sum_{k=1}^{m_s+1} n_k. \tag{11}$$

Or, if we want to take account of the traffic rate less than the wavelength capacity, more minute derivation is possible, but we omit it due to lack of space.

An establishment of the degree Δ_l of the logical topology depends on the number of wavelengths on the fiber. For given directed physical topology $G_p(N, E_p)$, we have the bound on the required number of the wavelengths, Λ, as follows [6]. Let h_{ij} denote the number of hops in the shortest path from node i to node j. For each node i, let $l_i(\Delta_l)$ denote the sum of the Δ_l smallest values of h_{ij} for different j. Then, we have

$$\Lambda \ge (1/E_p) \sum_{s=1}^{N} l_s(\Delta_l). \tag{12}$$

We finally obtain the bound on the required processing capability of the electronic router as

$$c_l \ge e_l^{max} \Delta_l. \tag{13}$$

We next consider the WDM link network. For given physical topology, the congestion e_p^{max} on the link can be determined directly if the shortest path routing is assumed. For this, we assume that the propagation delays between routing nodes are a dominant factor to determine the end–to–end delays, i.e., we do not consider the queueing delays at the routing nodes. To process the incoming packets at the electronic router, its capacity for packet processing should be at least larger than the traffic load; i.e.,

$$c_p \ge e_p^{max} \Delta_p, \tag{14}$$

where Δ_p is a maximum degree of the physical topology. We note that for the WDM link network, the larger number of wavelengths can lead to less utilization of each wavelength, but it does not help decreasing the total packet processing requirement at the router.

3.2 Numerical Examples

In this subsection, we show how a thousand wavelengths can meet the growing demand of the Internet traffic. For this purpose, we use the NTT's 49-node backbone network in Japan (Figure 4. We change names of cities in the figure to English. In the NTT's network, the node is placed at each prefecture, and the nodes at developed cities tend to have a larger number of degrees. It has a maximum degree of nine while a minimum two. For the traffic pattern, we use the publicly available traffic data provided by NTT [18] [1]. It

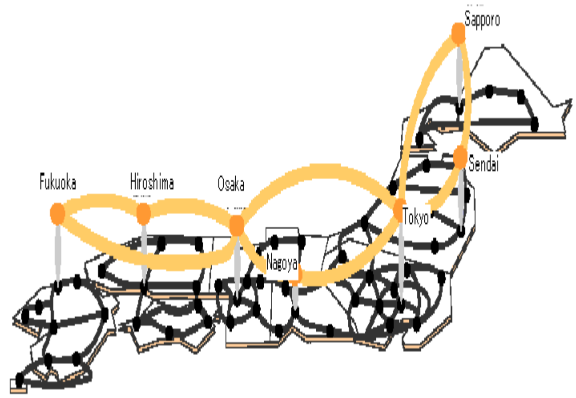


Figure 4: NTT's Backbone Network

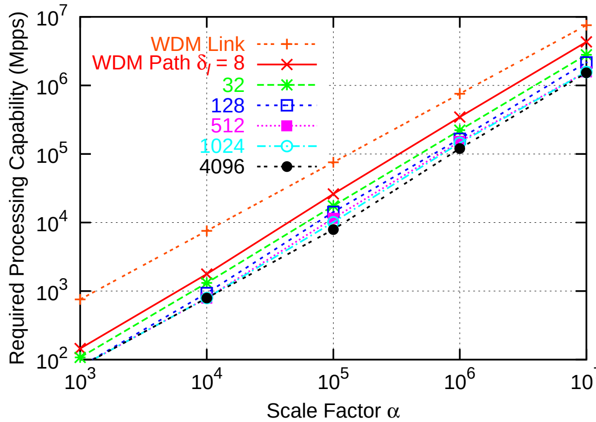
is a summary of the telephone traffic represented in Erlang between the nodes, and therefore, it is not really the IP traffic. However, after we examine the data carefully, we convinced that it reflects the population distribution in Japan and the development level of the industries. At the same Web site, subscription numbers of the Internet accesses (actually 2B+D ISDN lines) are available. We also found that the distribution of those numbers is very similar to the traffic data of the telephone network. Therefore, we believe that the results can also be applied to the IP network to some extent.

We assume that each wavelength has a capacity of 10 Gbps. Since the telephone traffic load is given in Erlang, we determine the traffic load by assuming that each telephone traffic is generated at 64 Kbps. However, the traffic data itself is for the telephone network, and the amount of traffic volume is not large. The total traffic load is about 3 Gbps, and the maximum traffic load between nodes be 70 Mbps[2]. We thus introduce the scale factor α, which is used for increasing the amount of total traffic load artificially. Furthermore, we assumed the distance of every link to be one in obtaining the results, which is necessary in determining the shortest paths between nodes. Last, we assume that the packet length is 1,000 bits, and the required packet processing capacity at the electronic router is simply derived by dividing the offered load by the packet length.

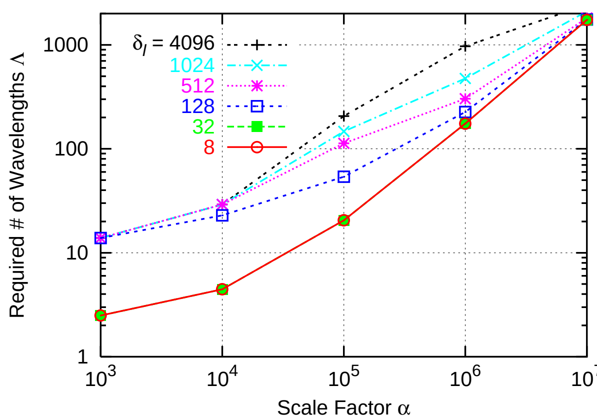
Figures 5(a) and 5(b) show the required maximum packet processing capacity at the router and the required number of wavelengths on the fiber, respectively. The horizontal axis shows the scale factor α, which starts at $\alpha = 10^3$ corresponding to 3 Tbps in total. As shown in the figure, the introduction of the WDM path network can reduce the required packet processing capacity in one magnitude, and the larger logical degree and many wavelengths leads to less processing capacity. However, it may be difficult to have the large logical degree since it means that a larger number of ports becomes necessary at the router. However, even

[1] The figure is available at `http://www.ntt.co.jp/databook/setubi/gif/setubi_sise_map.gif`

[2] Here, we only consider the average traffic load and the traffic load during busy hours may be, say, ten times larger than the average.

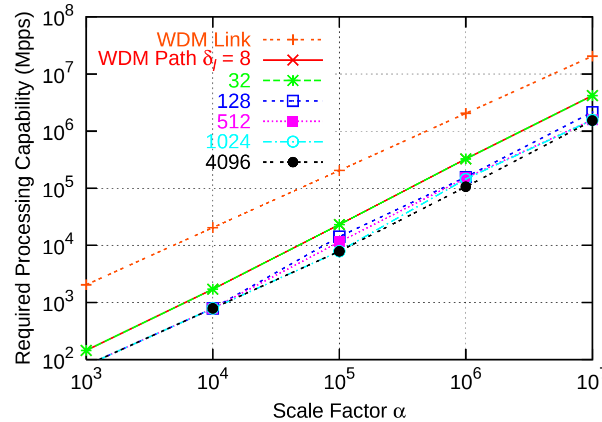


(a) The Required Packet Processing Capacity



(b) The Required Number of Wavelengths

Figure 5: Results for NTT's Traffic Case



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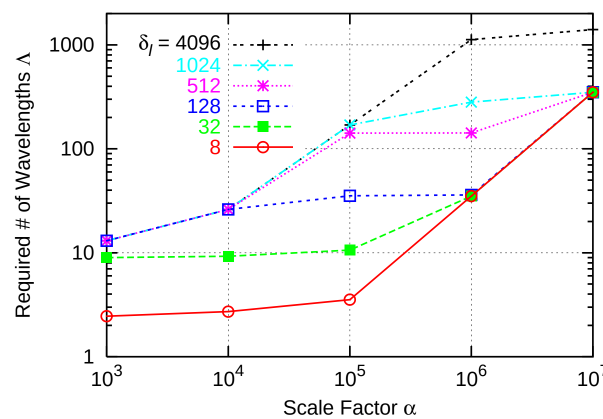


(b) The Required Number of Wavelengths

Figure 6: Results for Homogeneous Traffic Case

when the logical degree is restricted, the necessity of at least several hundreds of wavelengths is clear as the scale factor of the traffic load exceeds 10^6. We should note here that we assume the idealized logical topology to obtain the bounds shown in the figure while the actual physical topology is used for the WDM link network. It is likely to overestimate the ability of the WDM path network to some extent. Actually, heuristic algorithms presented in the literature do not offer the minimum bounds. See, e.g., [6].

Since the data we used is NTT's telephone traffic, one may think that the generality of results is questionable. For only comparison purpose, we next examine the other traffic distribution. We set the traffic between every node–pair to be same while the total traffic is kept identical to the previous case. The results are shown in Figure 6, where the same tendency can be observed, and the introduction of the WDM path network becomes more remarkable.

One problem observed from the figures is that the required processing capacity at the router becomes too large. While it depends on the advancement of the router technology, the requirement of about $10^4 \sim 10^5$ Mpps for $\alpha = 10^5$ does not seem to be acceptable at least in the near future. Perhaps, one solution is to distribute the traffic by introducing more optical nodes. For this purpose, we next consider a hierarchical structure of the network topology. More specifically, the ring network is attached to each node of Figure 4 as the metropolitan area network, and the number L_N of local nodes are connected to the ring (see Figure 7). To keep the traffic distribution of the national network same, the traffic load at the original node is equally distributed among the local nodes. Note that even in this configuration, the bounds derived in Subsection 3.1 still hold.

Figure 8 shows the results dependent on the number of local nodes. In obtaining the figure, we set the scale factor $\alpha = 10^5$, corresponding to 300 Tbps of the total traffic. Note that the local ring might not be necessary for the node sending and/or receiving the small amount of traffic, but we consider that all nodes have the local ring in this example. Thus, the total number of nodes becomes $49 \times L_N$ in the numerical example. The effect of having more local nodes is remarkable; the required processing capacity can be much reduced as shown in Figure 8(a). On the other

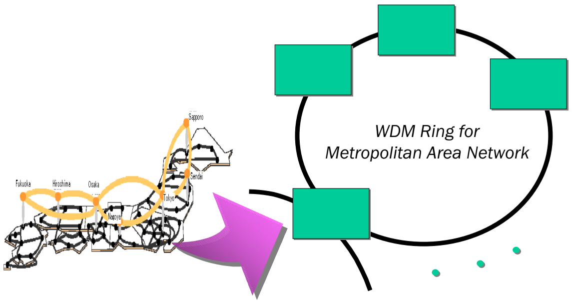
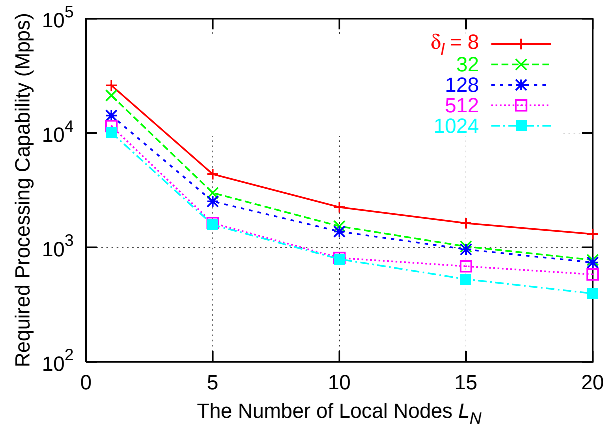
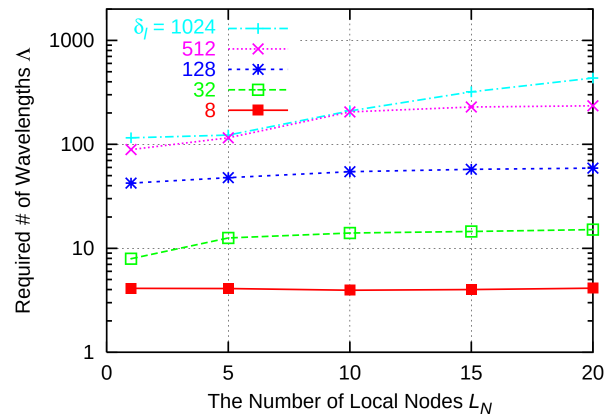


Figure 7: WDM Ring for MAN attached to the National Network



(a) The Required Packet Processing Capacity



(b) The Required Number of Wavelengths

Figure 8: Effects of the Number of Local Nodes

hand, Figure 8(b) indicates that the increase of the required wavelengths can be limited. In this case, the required processing capacity at the router is sustained below 10^3 Mpps even for the 300 Tbps total traffic. While we do not show in the figure, the required packet processing capacity for the WDM link network is still large (beyond 10^5 Mpps) since the introduction of the local ring does not help resolving the bottleneck at the node directly connected to the backbone network. In WDM path networks, on the other hand, a relief of the router bottleneck can be achieved by intrdocing the local ring with an increased number of wavelengths.

4 Concluding Remarks

In this article, we have first presented the way to multiplex a thousand wavelengths on the fiber link, by which the link bottleneck can be solved. We have then addressed how the IP over WDM network utilizing wavelength routing can relieve the router bottleneck through the numerical examples using the actual traffic data and network topology.

From the discussions, we are now able to point out several research topics that we should challenge for the next–generation high–performance Internet. The advancement of high–performance router technology is very important to enjoy a large capacity of WDM with a thousand wavelengths. The router with the larger number of ports is especially important.

In Section 3, we have assumed that the physical topology is given since in many cases, it is determined by the geographical conditions. The restriction by the physical topology can be relaxed by introducing the hierarchical network as shown in Section 3. However, the topology design of the physical network is helpful if it is possible, since the degree of the physical topology is an important factor to determine the network performance.

As described in Section 3, our results for the logical topology (i.e., WDM path network) were based on the several bounds while the actual data was used for the physical topology (WDM link network). The bounds assume the idealized logical topology, but we may not be able to have it since the existing algorithms in the literature are heuristic and may only provide the sub–optimal solutions except for the very small–sized network. How about the large size of the network? The existing algorithms may or may not provide the near–optimal solution within an acceptable computational time. The further research on the development of the design algorithm for the logical topology is still necessary.

References

[1] J. Anderson, J. S. Manchester, A. Rodriguez-Moral, and M. Veeraraghavan, "Protocols and architectures for IP optical networking," *Bell Labs Technical Journal*, pp. 105–123, January-March 1999.

[2] T. Ito, K. Fukuchi, K. Sekiya, D. Ogasahara, R. Ohhira, and T. Ono, "6.4tb/s (160x40gbit/s) wdm transmission experiment with 0.8bit/s/hz spectral efficiency," in *Proceedings of 26th European Conference on Optical Communications (ECOC 2000)*, pp. PD–1.1, September 2000.

[3] R. Dutta and G. N. Rouskas, "A survey of virtual topology design algorithms for wavelength routed optical networks," *Optical Networks Magazine*, vol. 1, January 2000.

[4] B. Mukherjee, *Optical Communication Networks*. McGraw Hill, 1997.

[5] R. Ramaswami and K. N. Sivarajan, *Optical Networks: A Practical Perspective*. The Morgan Kaufmann, 1998.

[6] R. Ramaswami and K. N. Sivarajan, "Design of logical topologies for wavelength–routed optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 840–851, June 1996.

[7] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, "Some principles for designing a wide-area WDM optical network," *IEEE/ACM Transactions on Networking*, vol. 4, pp. 684–695, October 1996.

[8] D. O. Awduche, Y. Rekhter, J. Drake, and R. Coltun, "Multi-protocol lambda switching: Combining MPLS traffic engineering control with optical crossconnects," *IETF Internet Draft*, 1999.

[9] N. Ghani, "Lambda-labeling: A framework for IP-over-WDM using MPLS," *Optical Networks Magazine*, vol. 1, pp. 45–58, April 2000.

[10] H. Yokota, H. Kanamori, and Y. Ishiguro, "Ultra-low-loss pure-silica-core single-mode fiber and transmission experiment," in *Proceedings of 1986 Optical Fiber Conference (OFC '86)*, p. PD3, 1986.

[11] A. Onae, K. Ikegami, K. Nakagawa, M. Koga, and M. Teshima, "Ultra-stable oscillation circuits and applications: Optical frequency measurement technology and application for a WDM optical network," *Transactions of IEE Japan*, vol. 119-C, pp. 765–770, 1999.

[12] "Catalog of NEL Photonic Devices, NTT Electronics," available at `http://www.nel.co.jp/photo/`.

[13] K. Mori, H. Takara, S. Kawanishi, M. Saruwatari, and T. Morioka, "Flatly broadened supercontinuum spectrum generation in a dispersion decreasing fiber with convex dispersion profile," *Electron. Lett.*, vol. 33, no. 21, pp. 1806–1807, 1997.

[14] G. Sefler and K. Kitayama, "Frequency comb generation by four-wave mixing and the role of fiber dispersion," *IEEE Journal of Lightwave Technology*, vol. 16, p. 1998, 1596–1605.

[15] H. Takara, T. Ohara, K. Mori, K. Sato, E. Yamada, T. Morioka, K.-I. Sato, K. Junguji, Y. Inoue, and T. Shibata, "Over 1000 channel optical frequency chain generation from a single supercontinuum source with 12.5ghz channel spacing for dwdm and frequency standards," in *Proceedings of 26th European Conference on Optical Communications (ECOC 2000)*, pp. PD–3.1, September 2000.

[16] Y. Maeno, Y. Suemura, S. Araki, S. Takahashi, A. Tajima, H. Takahashi, and N. Henmi, "A bandwidth-effective Terabit/s opto-electronic packet-switch with skew-insensitive synchronisation scheme," in *Proceedings of 25th European Conference on Optical Communications (ECOC '99)*, p. TuA1.2, 1999.

[17] D. T. Neilson, V. A. Aksyuk, S. Arney, N. R. Basavanhally, K. S. Bhalla, D. J. Bishop, B. A. Boie, C. A. Bolle, J. V. Gates, A. M. Gottlieb, J. P. Hickey, N. A. Jackman, P. R. Kolodner, S. K. Korotky, B. Mikkelsen, F. Pardo, G. Raybon, R. Ruel, R. E. Scott, T. W. V. Blarcum, L. Zhang, , and C. R. Giles, "Fully provisioned 112x112 micro-mechanical optical crossconnect with 35.8tb/s demonstrated capacity," in *Proceedings of 2000 Optical Fiber Conference (OFC 2000)*, pp. PD12–1, March 2000.

[18] "NTT Information Web Station," available at `http://www.ntt-east.co.jp/info-st/network/traffic/index.html`. (in Japanese).