Design of Wavelength–Convertible Edge Nodes in Wavelength–Routed Networks

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Wavelength converters reduce connection blocking probability in wavelength–routed networks by eliminating the *wavelength continuity constraint*. We develop a method for deployment of wavelength converters in wavelength–routed networks with overlay model. In these networks, most wavelength converters are deployed on edge nodes to cover the difference in the numbers of wavelengths multiplexed on access and core links. Therefore reduction of wavelength converter cost on edge nodes leads to minimizing the wavelength converter cost in the whole network. We propose an ingress edge node architecture with fixed wavelength converters that have limited wavelength convertibility but are more economical than full wavelength converters. In our architecture, each input access link of ingress edge nodes is equipped with fixed wavelength converters and input wavelengths from the access links are evenly distributed on the output core link. As a result, competition for a free wavelength on an output core link is avoided. Simulation results show that our edge node architecture offers about 20% cost reduction compared with a node architecture that only uses full wavelength converters where networks are actually under operation and a full wavelength converter cost to fixed one ratio is three.

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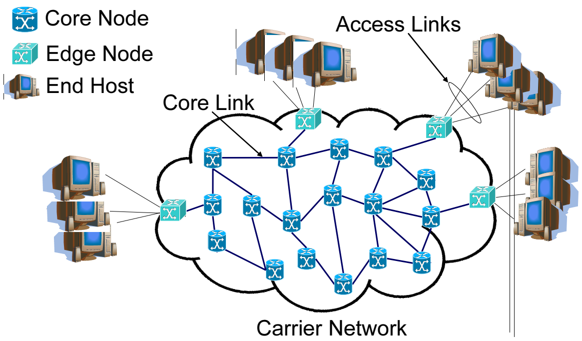


Fig. 1. Wavelength–Routed Network with Overlay Model

1. Introduction

Appearances of new services such as GRID computing lead to the need for end-to-end lightpath provisioning (e.g., OptIPuter [1], Lambda Grid [2] and λ–computing [3, 4]). One promising candidate for the networks that realize the end-to-end lightpath provisioning is a wavelength-routed network with overlay model (i.e., controls of users and a carrier are separated). In this network, end hosts of users are connected to a carrier network via access links (Fig. 1).

The important features of the network are the increase in the number of access links and the diversity in the numbers of wavelengths multiplexed on links. More users motivated by the new serivices connect the access links for the lightpath provisioning, which leads to increase in the number of access links. The diversity arises due to the following actions. Users prepare access links and communication interfaces with a few wavelengths multiplexed for cost reduction. In particular, the common wavelengths (e.g., some wavelengths in C band) may be used among most users. On the other hand, a carrier prepares a core link with tens or hundreds of wavelengths multiplexed for accommodating traffic from access links. The above-mentioned increase in the number of access links motivates such large number of wavelengths on core links. In this senario, it is important to cope with the difference in the numbers of wavelengths multiplexed on access and core links because the wavelength continuity constraint (i.e., the same wavelength must be assigned to a lightpath on links along a route) must be satisfied.

Wavelength conversion improves the blocking performance of wavelength–routed networks. Wavelength converters change an input wavelength to another output one, thus eliminate the fragmentation of wavelength resource. As a result, the utilization rate of wavelength resource is improved. As few wavelength converters as possible should be deployed for achieving an objective performance because wavelength converters remain expensive in the near future. In order to cost–effectively utilize wavelength converters, methods for deployment of wavelength converters have been developed. In [5, 6], deploying wavelength converters only on a few nodes leads to the cost reduction. In [7], deploying wavelength converters on about 1–5% of all ports in a network achieves the blocking performance close to performance of a case for full–complete wavelength conversion where all ports on all nodes are equipped with wavelength converters.

In conventional researches [5, 6, 7], they focus on networks where each link has an identical number of wavelengths multiplexed. In those networks, wavelength converters are used for eliminating fragmentation of wavelength resources between adjacent links that have the same number of wavelengths multiplexed. In a wavelength-routed network with overlay model, however, we also need to utilize wavelength converters to cover the difference between the numbers of wavelengths on links. If the number of wavelength converters used for covering the difference is much larger, covering the difference with as low wavelength converter cost as possible is inevitable for constructing the cost–effective network.

In this paper, we first show that edge nodes, to which both access and core links are attached, need much more wavelength converters than core nodes, to which core links are only attached. Then, we propose an ingress edge node architecture with *fixed wavelength converters* that convert a predetermined input wavelength to another predetermined output wavelength. In our node architecture, fixed wavelength converters evenly distribute wavelengths from input access links to wavelengths on an output core link. Adopting fixed wavelength converters for distribution of input wavelengths leads to lower costs than nodes with *full wavelength converters* that convert any input wavelengths to another output one.

The rest of this paper is organized as follows. Section 2 includes an explanation of wavelength–routed networks and a simulation result that shows edge nodes need most wavelength converters. In section 3, we discuss cost models of full and fixed wavelength converters and propose an ingress edge node architecture with fixed wavelength converters. We then compare our node architecture with a node architecture that only uses full wavelength converters and show our node architecture reduces wavelength converter cost. Finally, section 4 concludes this paper.

2. Effect of Deploying Wavelength Converters on Edge Nodes in Wavelength–Routed Networks with Overlay Model

2.A. Wavelength–Routed Network with Overlay Model

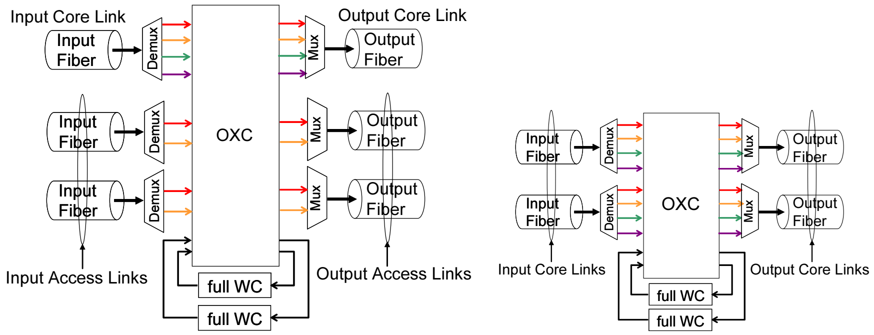
There are some inter–connection models between optical networks and other networks or end hosts [8]. In the peer model, optical networks and others are treated as a single network and they exchange topological and routing information with each other. In the overlay model, on the other hand, they are independent and do not exchange those information. From the security viewpoint, we adopt the overlay model because advertising internal information of the carrier network to end hosts is not safe.

In wavelength–routed networks with overlay model, end hosts are connected to a carrier network via access links. Each end host establishes lightpaths to another one for communication. We assume end hosts as computers providing the grid computing [9]. A carrier network consists of nodes and fibers. We refer to the node, to which access links are attached, as an edge node and another node as a core node. To investigate how many wavelength converters are needed only for covering the difference in wavelength number, we assume that an edge node is connected to a single core node and does not relay lightpaths among core links. We assume that a few wavelengths are multiplexed on an access link and tens or hundreds of wavelengths are multiplexed on a core link.

2.B. Node Architecture

Figs. 2(a) and 2(b) depict an edge and a core node architecture. A node consists of demultiplexers (DEMUX), multiplexers (MUX), Optical Cross–Connects (OXC) and full wavelength converters. When a node relays a wavelength for establishment of a lightpath, a DEMUX first demultiplexes an input signal into each wavelength. Then, an OXC switches each wavelength to an appropriate output port. Finally a MUX multiplexes wavelengths into an output signal. When the wavelength same as an input wavelength is not idle on an output fiber, the input wavelength is switched to a full wavelength converter and converted to another wavelength idle on an output fiber.

Full wavelength converters are deployed on nodes in a trunk–type basis [10]. In the trunk–type, full wavelength converters are shared among input ports. The input port that



(a) Edge Node

(b) Core Node

Fig. 2. Node Architecture

actually needs wavelength conversion is switched to an output port with a full wavelength converter. As a result, the number of full wavelength converters deployed is reduced.

2.C. Optimal Distribution of Full Wavelength Converters to Edge/Core Nodes

We verify that edge nodes need much more full wavelength converters than core nodes in wavelength–routed networks with overlay model. To achieve this, we obtain by simulation an optimal distribution of full wavelength converters to edge and core nodes, which leads to minimizing the call blocking probability with given full wavelength converters. We use NSFNET (Fig. 3) as a network model. An edge node is attached to each core node. End hosts are attached to each edge node with access links. Followings are parameters in simulation. Values of parameters are shown in Tab. 1.

L_a : Number of access links attached to an edge node.

W_a : Number of wavelengths multiplexed on an access link.

W_c : Number of wavelengths multiplexed on a core link.

a : Arrival rate to an end host. Poisson arrival.

$\frac{1}{\mu}$: Average holding time of a lightpath. A holding time follows exponential distribution.

ρ_c : Load on an output core link attached to an edge node. The load on output core link is defined as a ratio of arrival rate to an edge node to the number of wavelength on output core link. $\rho_c = \frac{aL_a}{\mu W_c}$.

In simulation, we obtain blocking probabilities caused by fragmentation of wavelength resource (i.e., there exist idle wavelengths on each link but no identical wavelength is idle on the consecutive links along the route) when ratio between the number of full wavelength converters on edge nodes and that on core nodes varies. After determining the ratio, we uniformly deployed full wavelength converters among edge or core nodes. We selected the total number of full wavelength converters so that blocking by fragmentation of wavelength resource does not occur in an optimal distribution. A lightpath request arrives at end hosts following a. A destination end host is uniformly selected from a set of end hosts that

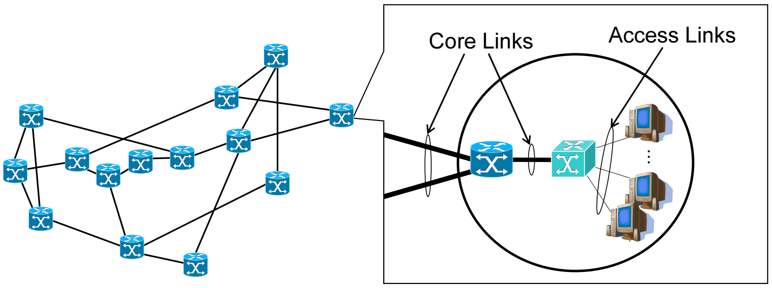


Fig. 3. NSFNET

Table 1. Parameters in Simulation

L_a	W_a	W_c	a	$\frac{1}{\mu}$	ρ_c
$\frac{\rho_c \mu W_c}{a}$	8	$\{16, 32, 64, 128\}$	4	1	0.5

are not connected to the same edge node as the source end host is. We use a minimum–hop routing algorithm for route selection. For wavelength assignment, we use a modified version of MFF (Modified First–Fit) [7], in which we randomly select an idle wavelength instead of First–Fit policy. Concretely, we divide route of a lightpath into segments, in which wavelength continuity constraint must be satisfied, in following order.

1. A set of links from a source end host to a destination end host corresponds to a segment.
2. Sets of links from a source end host to an ingress edge node, from an ingress edge node to an egress edge node, from an egress edge node to a destination edge node individually correspond to a segment.
3. Each link on a route corresponds to a segment.

Then, we randomly select an idle wavelength in each segment. When two consecutive segments use different wavelengths, a wavelength converter is used in the intermediate node. A lightpath request is blocked if there exists no idle wavelength on a link or required wavelength conversion cannot be performed because of the lack of full wavelength converters.

Figure 4 shows blocking probabilities caused by fragmentation of wavelength resource with different ratio between the number of full wavelength converters on edge nodes and that on core nodes. Blocking caused by the lack of idle wavelengths is not counted because wavelength conversion cannot avoid it.

When W_c is 16, deploying about 53% of given converters on edge nodes minimizes the blocking probability. Optimal ratios with W_c = 32, 64 and 128 are about 75%, 93% and 100%. These results mean that, for minimizing a blocking probability with given converters, more number of full wavelength converters should be deployed on edge nodes as the difference between the numbers of access and core links gets larger. This is because more fragmentation of wavelength resources occurs between access and core links in wavelength–routed networks with overlay model. Therefore, reducing the number of full wavelength converters on edge nodes leads to reducing wavelength converter cost in the whole network. In the next section, we propose an edge node architecture with reduced number of full wavelength converters.

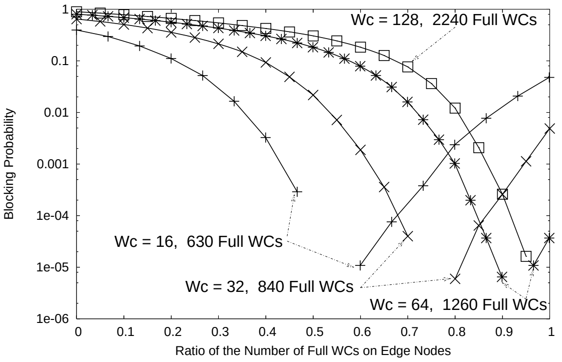


Fig. 4. Blocking Probabilities with Different Ratio of the Number of Full Wavelength Converters on Edge Nodes

3. Edge Node Architecture with Fixed Wavelength Converters

3.A. Wavelength Converter Model

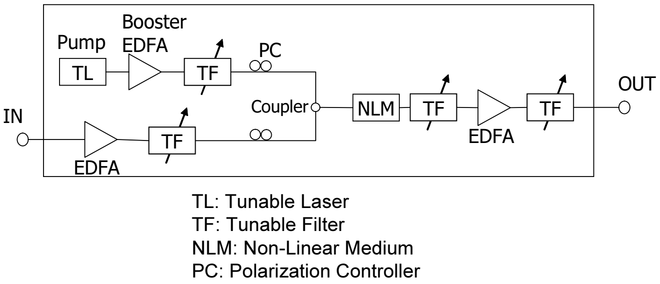
In this section, we introduce two kinds of wavelength converters; full wavelength converters and fixed wavelength converters. We further discuss the cost ratio of those converters. Full wavelength converters and fixed wavelength converters are realized with FWM (Four–Wave Mixing) [11, 12, 13].

Architectures for a full wavelength converter and a fixed wavelength converter are shown in Fig. 5. The wavelength conversion process is as follows. In both wavelength converters, the input beam is amplified by EDFA (Erbium–Doped Fiber Amplifier). Then, the input beam is combined with the pump beam that was amplified to the a power of more than 20 dBm by a booster EDFA. The combined beam is input into NLM (Non-Linear Medium) and a beam whose wavelength is different from both the input beam and the pump beam is generated. After filtered, amplified and reshaped, the generated beam is output as a converted wavelength. In a full wavelength converter, a tunable laser is used as a pump source because an output wavelength needs to be adjusted by changing a wavelength of the pump beam. In fixed wavelength converter, on the other hand, a laser diode is used as a pump source that produces a fixed wavelength.

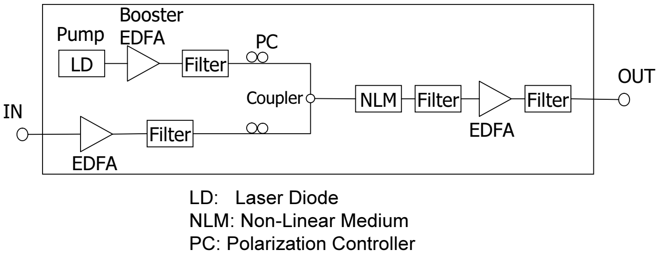
To evaluate how much cost–reduction fixed conversion offers, we need to determine the ratio of a full wavelength converter cost to a fixed wavelength converter cost. The ratio depends on costs of a tunable laser, a laser diode and other devices. In this paper, we decided the ratio based on the following internal study [14].

- The tunable laser cost to a laser diode (with a wavelength locker) cost ratio is about 10.
- A tunable laser costs more than 1 million yen (9,000 dollars) and will not go down in the near future.
- The design cost of non–linear medium is as high as a tunable laser cost. However, the cost of non–linear medium can be much lower than a tunable laser cost when it is mass–produced.
- The cost of EDFA can be 30 or 40% of a tunable laser cost when it is a module type and mass–produced.

Another forecast of the cost of EDFA is about 1,000 dollars [15]. The booster EDFA will more expensive than other EDFAs. Therefore, in this paper, we assume that the cost of



(a) Full Wavelength Converter



(b) Fixed Wavelength Converter

Fig. 5. Architectures for Wavelength Converters

booster EDFA follows the value in [14] and total costs for other EDFAs, NLM, polarization controllers is 1/10 of a tunable wavelength converter cost.

From the above discussion, the full wavelength converter cost to fixed wavelength converter cost ratio can be at least 3. We may expect a larger ratio: for example, when optoelectronic conversion instead of all–optical conversion is used, the ratio will be almost the same as 10, the ratio of a tunable laser cost to a laser diode cost. If we apply waveband conversion [16] for fixed wavelength conversions of a set of wavelengths (e.g., wavelengths multiplexed on an access link), much larger ratio may be obtained. In this paper, based on the above discussion, we investigate whether fixed conversion can reduce wavelength converter cost of a wavelength–routed network with overlay model when the ratio ranges from 3 to 10.

3.B. Node Architecture with Fixed Wavelength Converters

Figure 6 depicts out node architecture with fixed wavelength converters. Fixed wavelength converters are deployed on input ports from input access links. We utilize fixed wavelength converters to uniformly distribute lightpath requests from input access links to wavelengths on an output core link.

Correspondence between an input wavelength and an output wavelength of a fixed wavelength converter is determined as following. λ_w ($0 \leq w \leq W_a - 1$) on kth ($1 \leq k \leq L_a$) input access link is converted to $\lambda_{((k-1)W_a+w) \mod W_c}$. When an output wavelength is the same as an input wavelength, no fixed conversion is performed. In Fig. 6, Wavelengths on the upper access link do not need wavelength converters because the same wavelengths are assigned to them on an output core link. On the other hand, a fixed wave-

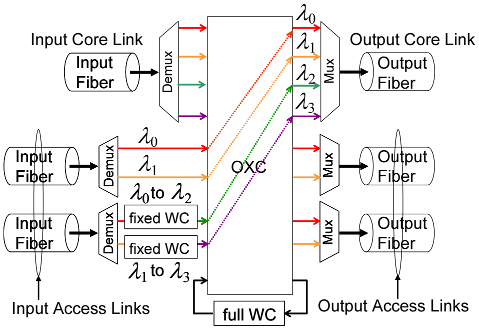


Fig. 6. Node Architecture with Fixed Wavelength Converters ($L_a = 2$, $W_a = 2$, $W_c = 4$).

length converter is deployed for each wavelength on the lower access link to convert λ_0 and λ_1 to λ_2 and λ_3, respectively. When we cannot avoid competition with only fixed wavelength converters because multiple wavelengths are converted to the same wavelength on an output core link, we use full wavelength converters.

Fixed conversion is not performed on egress edge nodes that relay wavelengths from an input core link to an output access link. This is because even if fixed wavelength converters are on egress edge nodes, the wavelength assigned to lightpaths on core links are seldom identical to expected input wavelengths of the fixed wavelength converters.

3.C. Numerical Examples

We compare wavelength converter cost in our edge node architecture with that in an edge node architecture that only uses full wavelength converters by simulation. To evaluate how much wavelength converter cost on an ingress edge node is reduced, we use a network model that consists of two edge nodes, two core nodes and three core links (Fig. 7). Performance metrics are (1) the number of full wavelength converters needed on an ingress edge node and (2) total wavelength converter costs needed on an ingress edge node. There are 8 and 128 wavelengths multiplexed on access and core links, respectively. Lightpath requests arrive at source end hosts according to a Poisson process with rate a. A destination end host is selected among all destination end hosts according to uniform distribution. The holding time for lightpaths ($1/\mu$) follows an exponential distribution with an average of 1. We used the wavelength assignment method in section 2.C. To investigate whether our architecture reduces cost of an ingress edge node, we focus on the ingress edge node in Fig. 7. Core nodes and an egress edge node are equipped with unlimited number of full wavelength converters.

We regard X full wavelength converters as the sufficient number of full wavelength converters on an ingress edge node when the node with X full wavelength converters provides almost the same blocking performance as the node that has unlimited number of wavelength converters. Therefore, we introduce *approximation factor* [17] as following;

$$\frac{P_B(X) - P_B(\infty)}{P_B(0) - P_B(\infty)} < \varepsilon. \tag{1}$$

$P_B(X)$ is a blocking probability when X full wavelength converters are deployed on an ingress edge node. $P_B(0)$ and $P_B(\infty)$ are blocking probabilities when no and unlimited number of full wavelength converters are deployed on an ingress edge node, respectively. We set ε to 0.001, which is low enough to achieve an objective end–to–end blocking performance in connection–oriented networks (e.g., a target probability of end–to–end blocking

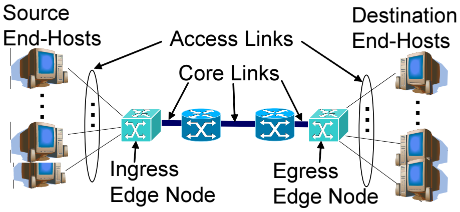


Fig. 7. Network Model

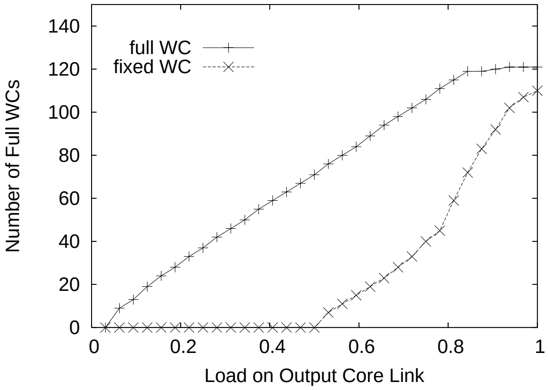


Fig. 8. Number of Full Wavelength Converters on an Ingress Edge Node ($a = 4$)

is between 0.02 and 0.05 in ISDN [18]). In this case, difference of blocking probabilities between $P_B(\infty)$ and $P_B(X)$ is under ε as following;

$$P_B(X) < \varepsilon(P_B(0) - P_B(\infty)) + P_B(\infty) < \varepsilon + P_B(\infty).$$

Figure 8 shows the minimum number of X in Eq. (1). The horizontal axis represents load on the output core link that is attached to the ingress edge node (ρ_c). The graph label “full WC” indicates a node architecture that only uses full wavelength converters and “fixed WC” does our architecture. The load is proportional to the number of input access links attached to the ingress edge node.

In the node architecture that only uses full wavelength converters, the number of full wavelength converters increases proportionally to load on the output core link. This is because more lightpath requests from access links compete for the same wavelength on an output core link as the load increases.

In our node architecture, no full wavelength converter is needed when the load is lower than 0.5. This is because input wavelengths on each input access link are converted to different wavelengths on an output core link with fixed converters. When the load is over 0.5, the number of full wavelength converters needed increases because we need to perform full wavelength conversion in addition to fixed wavelength conversion. However, the number of full wavelength converters is greatly reduced in our node architecture.

Figure 9 shows the number of full wavelength converters when the load on the output core link is fixed and an arrival rate of lightpath requests changes. The horizontal axis represents an arrival rate of lightpath requests at an source end host. In this case, the number of input access links decreases as the arrival rate increases. We set the load to around 0.6, which is an average wavelength utilization when networks are actually under operation [7].

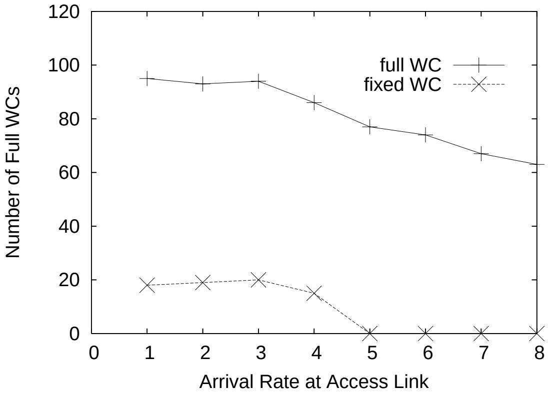


Fig. 9. Number of Full Wavelength Converters on an Ingress Edge Node When ρ_c is around 0.6

In both architectures, the number of full wavelength converters decreases as the arrival rate increases. This is because larger arrival rate leads to more blocking on input access links and less lightpath requests arrive to the output core link. In our node architecture, no full wavelength converter is needed when the arrival rate is larger than 4 because competition for the same wavelength on an output core link is avoided only with fixed wavelength converters. The above simulation results show that utilizing fixed wavelength converters leads to great reduction of the number of full wavelength converters needed on an ingress edge node.

Total wavelength converter costs on an ingress edge node are shown in Fig. 10. The horizontal axis is the load on the output core link that is attached to the ingress edge node. A full wavelength converter cost is normalized as 1. In our node architecture, the total wavelength converter cost is the sum of the cost of deployed full wavelength converters and the cost of deployed fixed wavelength converters. We determine ratios of a full wavelength converter cost to a fixed wavelength converter cost as (1) 3:1, (2) 5:1 and (3) 10:1.

In Fig. 10, we first focus on wavelength converter costs when the load is around 0.6. When the load is around 0.6, wavelength converter cost in ours are about 79 % (cost ratio 3:1), 56 % (cost ratio 5:1) and 38 % (cost ratio: 10:1) of the cost in the node architecture that only uses full wavelength converters. When the load is lower than 0.5, cost in ours is proportional to the load because the number of fixed wavelength converters only increases. With the load lower than 0.5, cost in ours are about 54 % (cost ratio 3:1), 32 % (cost ratio 5:1) and 16 % (cost ratio 10:1) of the cost in the node architecture with only full wavelength converters.

When load is over 0.8, our architecture shows higher WC cost. However, the load is far higher than that under operation. Therefore, it is important that our node architecture provides lower wavelength converter cost than the node architecture that only uses full WCs when the load is below 0.6.

Wavelength converter costs when the load is fixed to around 0.6 and an arrival rate of lightpath request changes are shown in Fig. 11. When a is below 2, our node architecture shows higher cost than the node architecture with only full wavelength converters with cost ratio 3:1 and 5:1. This is because the number of input access links increases as the arrival rate decreases and the increase in the number of input access links leads to more fixed wavelength converters needed. However, in multi–point communication such as grid computing, source end host generally sets up lightpaths to multiple end host, that is, it is important for our node architecture to provide lower wavelength converter cost when a is

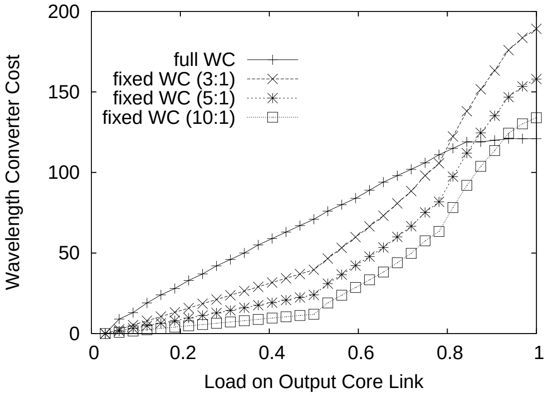


Fig. 10. Wavelength Converter Cost ($a = 4$)

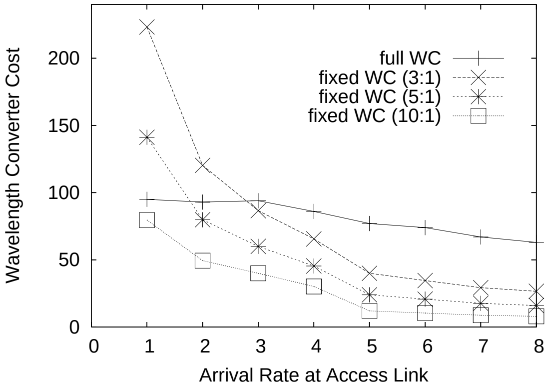


Fig. 11. Wavelength Converter Cost When ρ_c is around 0.6

large.

Figure 12 shows the total wavelength converter costs on an ingress edge node when the difference in the numbers of wavelengths on access and core links is relatively small ($W_c = 32$). Our node architecture achieves almost the same cost reduction as that in Fig. 10. Therefore utilizing fixed converters leads to the reduction of wavelength converter cost regardless of the difference in the numbers of wavelengths multiplexed on access and core links.

4. Conclusion

In this paper, we investigated the deployment of wavelength converters in wavelength–routed networks with overlay model. We showed that, in wavelength–routed networks with overlay model, most wavelength converters are deployed on edge nodes for covering the difference in the numbers of wavelengths multiplexed on access and core links by simulation. We then proposed an ingress edge node architecture with fixed wavelength converters to reduce the number of full wavelength converters and wavelength converter cost on an ingress edge node. In simulation, our node architecture achieved an objective blocking performance with lower wavelength converter cost than a node architecture that only uses full wavelength converters. When the load on the output core link is in the situation where networks are under operation and wavelength converter cost ratio is 3, our node architecture

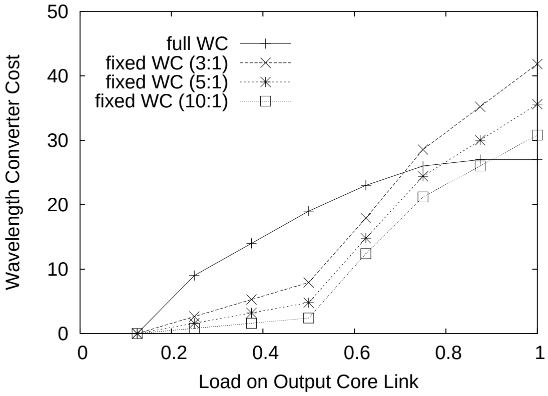


Fig. 12. Wavelength Converter Cost ($a = 4$, $W_c = 32$)

offered about 21 % cost reduction compared with a node architecture that only uses full wavelength converters. When load is lower, our node architecture offered more than 46 % cost reduction. In addition, fixed wavelength conversion offers more cost reduction as the wavelength converter cost ratio gets larger. Utilizing fixed converters leads to cost reduction regardless of the difference in the numbers of wavelengths multiplexed on access and core links.

Power consumption is also an important metric for node architecture. We will evaluate power consumption in our node architecture in our future work.

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