Architecture design and performance evaluation of multigranularity optical networks based on optical code division multiplexing

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In traditional lambda-based multigranularity optical networks, a lambda is always treated as the basic routing unit, resulting in low wavelength utilization. On the basis of optical code division multiplexing (OCDM) technology, a novel OCDM-based multigranularity optical cross-connect (MG-OXC) is proposed. Compared with the traditional lambda-based MG-OXC, its switching capability has been extended to support fiber switching, waveband switching, lambda switching, and OCDM switching. In a network composed of OCDM-based MG-OXCs, a single wavelength can be shared by distinct label switched paths (LSPs) called OCDM-LSPs, and OCDM-LSP switching can be implemented in the optical domain. To improve the network flexibility for an OCDM-LSP provisioning, two kinds of switches enabling hybrid optical code (OC)–wavelength conversion are designed. Simulation results indicate that a blocking probability reduction of 2 orders can be obtained by deploying only five OCs to a single wavelength. Furthermore, compared with time-division-multiplexing LSP (TDM-LSP), owing to the asynchronous accessibility and the OC conversion, OCDM-LSPs have been shown to permit a simpler switch architecture and achieve better blocking performance than TDM-LSPs.

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1. Introduction

In generalized multiprotocol label switching networks [1], according to bandwidth granularities, label-switched paths (LSPs) are classified into packet-switched LSPs (P-LSPs), time-division multiplex LSPs (TDM-LSPs), lambda-switched LSPs (L-LSPs), waveband-switched LSPs (WB-LSPs), and fiber-switched LSPs (F-LSPs). Interfaces capable of switching the relevant LSPs are referred to as packet-switched capable (PSC), time-division multiplex capable (TDM), lambda-switched capable (LSC), waveband-switched capable (WBSC), and fiber-switched capable (FSC), respectively. All LSPs listed above can be nested and allowed to be forwarded by building a hierarchical switching system. In particular, networks enabled to switch L-LSPs, WB-LSPs, and F-LSPs simultaneously are called multigranularity optical networks, where an adopted switch is named a multigranularity optical cross connect

(MG-OXC) [2]. Furthermore, L-LSPs, WB-LSPs, and F-LSPs are called optical multigranularities, as those LSPs can be switched in the optical domain. We call a multigranularity optical network that supports L-LSPs, WB-LSPs, and F-LSPs a three-tier network in this paper. Although there have been a few studies about multigranularity optical networks [2–9], an L-LSP is still taken for the basic unit, and any optical path with a granularity smaller than a wavelength is incapable of being switched in the optical domain with the present MG-OXC architectures. P-LSPs and TDM-LSPs defined in generalized multiprotocol label switching networks are alternative approaches that allow multiple users to share a wavelength. However, the complexity of the buffering mechanism and the immature wavelength conversion for conflict resolution still remain critical to P-LSPs [10]. In the case of TDM-LSPs, time-slot interchangers (TSIs) or a time-slot synchronization mechanism is required along the route from a source to a destination [11–13].

Optical code division multiplexing (OCDM) technology is able to multiplex channels coded by distinct code sequences on a single wavelength [14]. Although the OCDM technology has been studied a lot as the access technology in OCDMA networks, little attention has been paid to using it for transmission in the transport layer. In Refs. [14,15], a novel routing concept based on this OCDM technology was presented, where a hybrid wavelength–optical-code (OC)-routed network was considered. Owing to the asynchronous access property inherent to the OCDM technology, problems in P-LSPs and TDM-LSPs described above can be easily resolved by using distinct code sequences.

MG-OXC architectures able to handle different optical multigranularities can be classified into the following two categories. One is described in Refs. [3–5,8,16], where no switching label type is specified at the input ports, and the path bundling is implemented in the control plane. In the other, the input ports are assumed to be labeled by specific switching types, which simplifies the control and design for LSP switching [6,7,9]. However, both types can only provide switching capability ranging from L-LSPs to F-LSPs. In this paper we propose a novel OCDM-based MG-OXC architecture capable of fiber switching (FS), waveband switching (WBS), lambda switching (LS), and OCDM switching (OCDMS), and it takes LSPs based upon OCDM switching for the minimum granular optical paths. Henceforth, we term optical paths based upon the OCDM technology "OCDM-LSPs" and the OCDM-based multigranularity optical network a "four-tier" network.

This paper focuses on providing an insight into the effect of introducing OCDM technology into up-to-date multigranularity optical networks, including physical implementation and performance evaluation. The remainder of this paper is organized as follows. In Section 2, related issues of the OCDM-based MG-OXC architecture and the OCDM-LSP switching scenario are described. Advantages of using OCDM-LSPs are emphasized by comparison with TDM-LSPs from an architectural view. In Section 3, the concept of network topology conversion with preset F-LSPs, WBS-LSPs, and L-LSPs is described, and an algorithm for OCDM-LSP establishment is given. In Section 4, simulations comparing the four-tier network with the three-tier network and those comparing OCDM-LSPs with TDM-LSPs are conducted. Finally, we summarize our study briefly.

2. OCDM-Based MG-OXC

2.A. Architectural Considerations

Figure 1 illustrates the OCDM-based MG-OXC architecture. It consists of four switching types: FS, WBS, LS, and OCDMS. With this design, LSPs from the input ports can be switched to specific layers by the switching boxes on the left-hand side according to their labels and can be bundled again by the space switching box on the right-hand side. Employing the OCDM switching box at the top is the most distinguishing difference from traditional wavelength-based MG-OXC. This OCDM switching box is also referred to as a WDM version of OCDM OXC (WDM-OCDM-OXC), where OCDM-LSPs encoded by different code sequences carried by the same or different wavelengths from the incoming ports are first demultiplexed in the wavelength level and then switched in the WDM-OCDM-OXC, consisting of n switching planes (n is the number of wavelengths per input port). At the output ports of the WDM-OCDM-OXC, the switched OCDM-LSPs are bundled into an L-LSP again before LS. It should be

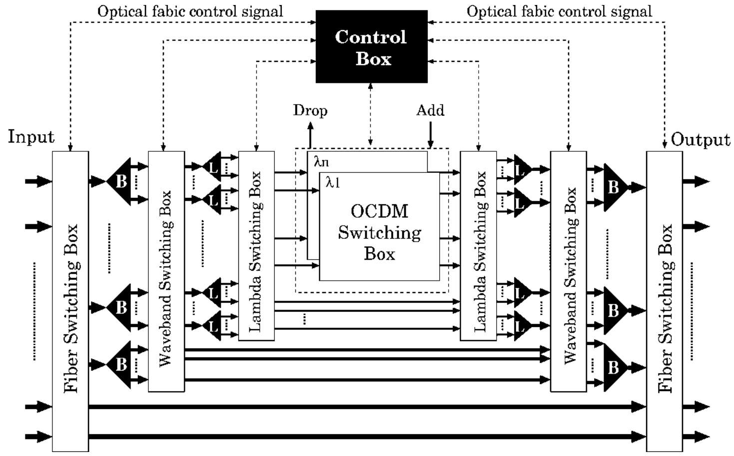


Fig. 1. Architecture of OCDM-based MG-OXC.

noted that no two OCDM-LSPs with the same OC can be grouped in the same wavelength. With the concept of OC conversion presented in Refs. [14,15] and wavelength conversion, the following two schemes are considered for conflict resolutions at the output ports.

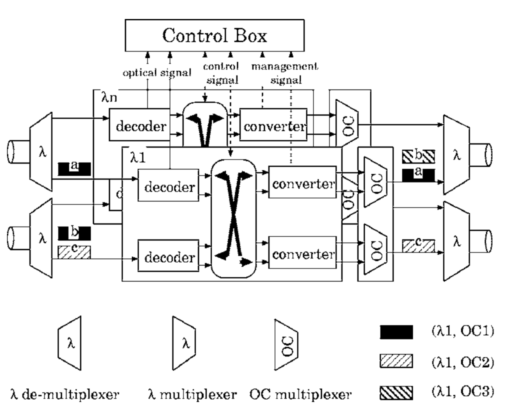
1) In the scheme $(\lambda_i, OC_j) \rightarrow (\lambda_i, OC_k)$, there is no wavelength conversion, but OC conversion can be performed to resolve conflicts at an intermediate node [15].

2) In the scheme $(\lambda_i, OC_j) \rightarrow (\lambda_k, OC_l)$, a hybrid conversion including OC and wavelength conversion are available along the path and can be performed at an intermediated node.

2.B. Hybrid WDM-OCDM-OXC Enabling Optical Code–Wavelength Conversion, and OCDM Switching Implementation Issues

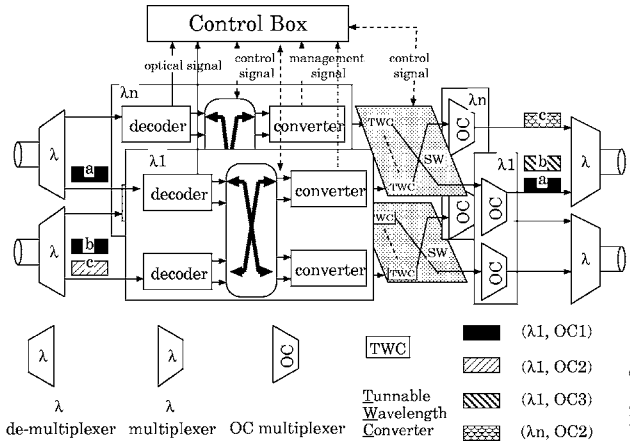
2.B.1. Architectures of Hybrid WDM-OCDM-OXC

In Ref. [15], a WDM-OCDM-OXC was proposed to provide OCDM-LSP switching in WDM networks (shown in Fig. 2). It has a switch for OCDM-LSP switching (called the data plane in generalized multiprotocol label switching networks) and a control box (called a control plane) taking responsibility for the switch configuration as well as local port information management. As described above, the switching box is composed of n switching planes sorted by wavelengths. Each switching plane contains an OC decoder, optical switch, and OC converter. The OCDM-LSPs enter the OC decoder, where the optical correlation is performed to discriminate paths OC by OC. Full explanations of the optical correlation will be given in the next part of this paper. If the optical switch is preset by the control box, signals from the OC decoder can be forwarded directly to specific input ports of the OC converter, where they are encoded again with different optical codes before being grouped into an L-LSP by an OC multiplexer. Conflict resolution by using OC conversion is illustrated on the right-hand side of Fig. 2.



		a	b	c
IN	port	1	2	2
	λ	λ1	λ1	λ1
	OC	OC1	OC1	OC2
OUT	port	1	1	2
	λ	λ1	λ1	λ1
	OC	OC1	OC3	OC2

Fig. 2. WDM-OCDM-OXC architecture with 1-dimension conversion (OC conversion).



		a	b	c
IN	port	1	2	2
	λ	λ1	λ1	λ1
	OC	OC1	OC1	OC2
OUT	port	1	1	1
	λ	λ1	λ1	λn
	OC	OC1	OC3	OC2

Fig. 3. WDM-OCDM-OXC architecture with 2-dimension conversion (OC and wavelength conversion).

The symbols a, b, and c represent different OCDM-LSPs, and they are carried by the same wavelength λ_1. Assume that packets in a and b with (λ_1, OC_1) should be forwarded from the respective input ports IN-1 and IN-2. Before taking OUT-1, OC_1 in OCDM-LSP b must be converted to OC_3 to avoid conflict at OUT-1. Moreover, if no OC is available in λ_1 at OUT-1, packets in c can be forwarded only to OUT-2 instead of to OUT-1. That is because here no wavelength conversion is allowed to change λ_1 to another wavelength.

In contrast, we also propose an WDM-OCDM-OXC capable of OC–wavelength conversion simultaneously along the path from a source to a destination, whose structure is illustrated in Fig. 3. The difference from that in Fig. 2 is that switching planes with tunable wavelength converters (TWCs) are inserted between the OC converter and OC multiplexer. The number of TWCs contained in each switching plane is equal to the number of wavelengths per port.

By employing these switching planes, the wavelength of an OCDM-LSP can be converted to another one before being grouped into an L-LSP. In the case described above, OCDM-LSP c with (λ_1, OC_1) due to be forwarded to OUT-1 can have its wavelength converted to another one with available OCs, even though no OC is available in λ_1. This contributes to a lower blocking probability, which can be observed in the performance evaluation section. As shown in Fig. 3, OCDM-LSP c can take OUT-1 instead of OUT-2 after wavelength conversion.

2.B.2. OCDM Switching Based on Optical Correlation

Figure 4 illustrates the key structure of the switching plane explained above. The OC

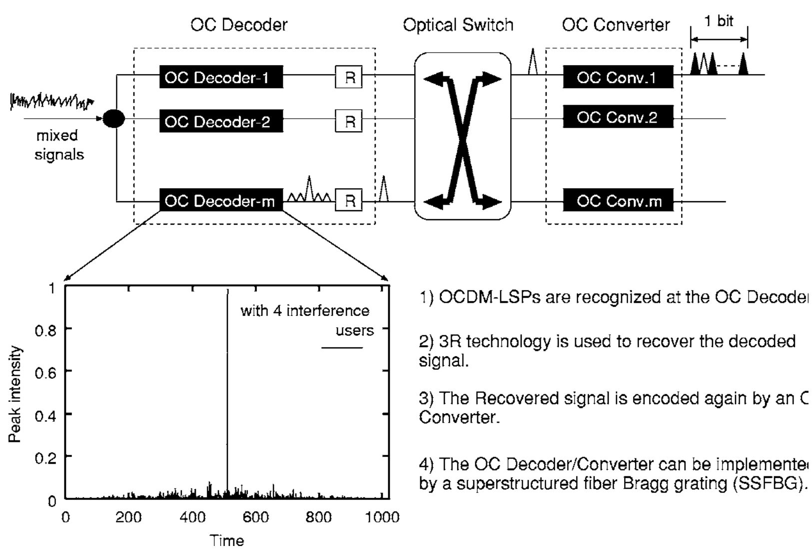


Fig. 4. OCDM-switching by the optical correlation and OC conversion.

decoder is a decoder array that consists of m (m is the number of OCs per wavelength) decoders. The mixed (multiplexed) signals on the same wavelength will be first split into m copies by a coupler. Each copy can be considered the same for the multiplexed signals. As each copy passes a decoder, a peak will be generated by the optical correlation if the multiplexed signals include the signal encoded by an OC that matches the decoder (called it an autocorrelation) [17]. The figure below the structure shows the simulated optical correlation waveform of a 511-chip Gold code with a binary-phase-shift-keying (BPSK) time-spreading scheme. For the signals encoded by other OCs that do not match the decoder, the correlation waveforms will remain low values, an outcome referred to as multiple access interference (MAI). We call these cases cross correlations.

The above working principle is the same as that in the OCDMA networks. The node architecture differs from that in the OCDMA networks in that the decoded signals will be forwarded to different outgoing ports by an optical switch and encoded again by other OC converters before entering the next node. The signal performance of an OCDM-LSP is always degraded at the decoder because of the MAI noise. We assume that 3R (reshaping, retiming, reamplification) technology is used to recover the original signal after the optical correlation. Specifically, Wang [18] proposed that an optical thresholder using supercontinuum (SC) generation in normal dispersion-flattened-fiber (DFF) be used to reshape the decoded signal with MAI noise to achieve better BER performance. In this paper, no physical impairment will be taken into account, as many studies deal only with the ideal case in the WDM networks, to make our purpose more straightforward.

The key components for decoding and encoding can be implemented by the same passive devices, e.g., superstructure fiber Bragg gratings (SSFBGs) [19,20]. With an SSFBG, path recognition can be implemented at ultrafast speed, which depends only on the propagation delay in the decoder [21].

Therefore, our proposed OCDM-based MG-OXC has the following advantages.

a) The scalability of a switch is extended to support FS, WBS, LS, and OCDMS, and finer granular optical path provisioning is enabled.

b) OCDM-LSP switching can be performed in the optical domain, which enables high traffic throughput. As no optical to electronic (O–E) or electronic to optical (E–O) operation is involved in each switching stage, the OCDM-based MG-OXC can be regarded as an all-optical switch.

c) Because they are encoded by distinct optical codes, OCDM-LSPs can access each node asynchronously, and no network synchronization mechanism is needed, which is of great benefit to a simple network control.

d) Hybrid OC–wavelength conversion is available for conflict resolution.

2.B.3. Comparisons: OCDM-LSP versus TDM-LSPs versus P-LSP

Table 1 compares the OCDM-LSP with alternatives, the TDM-LSP and P-LSP. "Constraint on OCC, TSI, or Header" indicates whether the OC, time slot, or header can be changed along the path from a source to a destination. From the routing and provisioning viewpoint, the OCDM-LSP, TDM-LSP with O-TSI or E-TSI, and P-LSP can be regarded as the same, because an OC, a time-slot, or a header can be changed to another free one along the path. But O-TSI or E-TSI and packet-LSP will involve buffer processing [11,15,22], which increases the switch and management complexity. In Ref. [15] we studied the P-LSP (called the OC-labeled path) and OCDM-LSP (called

Table 1. OCDM-LSP versus TDM-LSP versus P-LSP[a]

TSI Type	LSP	Constraint on OCC, TSI, or Header	LSP Switching	Buffer Control	Refs.
	OCDM	no	optical	no	[15]
Without TSI	TDM	yes	optical	no	[12,13]
O-TSI	TDM	no	optical	yes (FDL)	[22]
E-TSI	TDM	no	electrical	yes (RAM)	[11]
	packet	no	optical	yes (FDL)	[15]

[a]LSP, label-switched path; TSI, time-slot interchanger; OCC, optical code conversion; O-TSI: optical TSI; E-TSI, electrical TSI; FDL, fiber delay line; RAM, random-access memory.

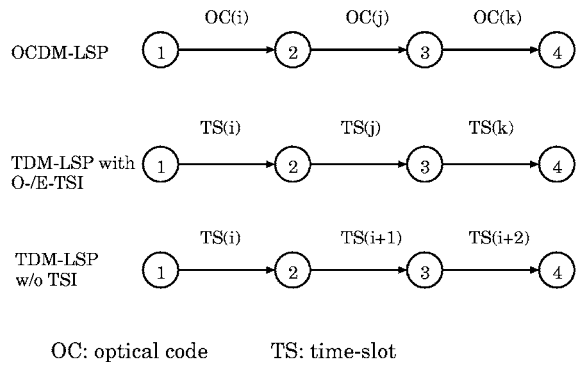


Fig. 5. OC per time-slot allocation in OCDM-based and TDM-based networks. i, j, k are the sequence number of OC or TS.

the OCDM path), and the OCDM-LSP is shown to be more suitable for bursty traffic. Considering a bufferless optical network, the TDM-LSP without O–TSI or E-TSI is more attractive than the TDM-LSP with O-TSI or E-TSI and P-LSP. However, because of propagation and switching delay, a shifted time-slot mechanism [12,13] is needed to maintain the time slots allocated to a connection along the path shown in Fig. 5, which imposes constraints on time-slot allocation and increases the switch complexity. From the above analysis, what distinguishes OCDM-LSPs from other approaches is that this is no buffer processing and no constraint on OC allocation. A simulation is also conducted to show how the OCDM-LSP outperforms the TDM-LSP.

2.C. Switching Process

The proposal of a "tunnel," referring to a group of consecutive wavelength channels bundled and switched together [6], turns out to be a simple approach to resolve the RWA problem in multigranularity optical networks. The tunnels in Ref. [6] are classified into fiber tunnels and waveband tunnels. In our study, as an OCDM-LSP is regarded as the basic unit for connection provisioning, the tunnel concept has been extended to include fiber tunnels (FTs), waveband tunnels (WBTs), and lambda tunnels (LTs), and they are equivalent to F-LSP, WB-LSP, and L-LSP as defined in Ref. [1]. Before describing the switching scenario in our proposed four-tier network, we first clarify the assumptions in our study as follows.

1) The network is nested by FTs, WBTs, and LTs.

2) An extended capacity-balanced static tunnel allocation (CB-STA) for tunnel establishment in an off-line manner is employed to achieve relatively high network throughput [6]. All the tunnels nested in a network are marked as long life and will never be reconfigured or torn down.

3) All the OCDM-LSPs belonging to a tunnel have to be switched together at each input port. Moreover, the OCDM-LSPs in a tunnel will never be OCDM switched while traversing the tunnel.

4) An OCDM-LSP can possibly take more than one tunnel along the path established between a source and a destination, and the OCDM switching is required to pick out the OCDM-LSP from one incoming tunnel and migrate it into another outgoing tunnel. Additionally, OCDM-LSPs have to be OCDM-switched at the source and the destination to complete adding and dropping traffics.

5) OC conversion along with nonwavelength–wavelength conversion can be performed at each node.

Figure 6 illustrates the OCDM-LSP switching scenario with our proposed MG-OXC. Suppose there are three kinds of available tunnel, FT, WBT, and LT, between nodes 0 and 7; as described above, these tunnels bypass OCDM switching at the nodes they traverse. However, at nodes 3 and 5 OCDM switching is prepared for tunnel transition. As shown in Fig. 6, the OCDM-LSP is first added at node 0 with (λ_1, OC_1); then OC_1 is converted to OC_2 by OC conversion at node 3; next, only wavelength conversion is performed to change λ_1 to λ_2 at node 5; finally, the path is dropped at node 8. The switching process can be equivalent to that shown in Fig. 6. From a network topology viewpoint, the tunnels can be regarded as edges, and the black nodes can be regarded as vectors. We will introduce the concept of network topology conversion from a physical network to a tunnel-nested network in Section 3.

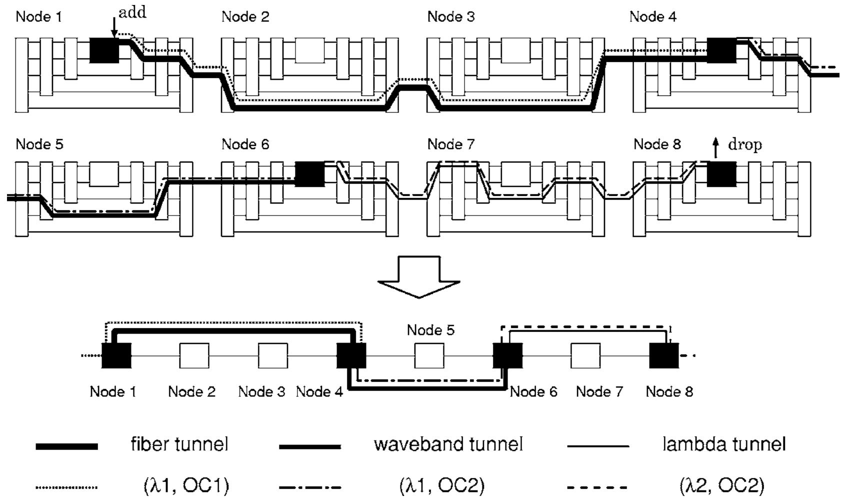


Fig. 6. LSP establishment paradigm in the four-tier network. The black boxes stand for the nodes performing OCDM switching.

3. OCDM-LSP Provisioning in the Four-Tier Network

Based on the above descriptions, OCDM-LSP provisioning can be divided into the following two subproblems:

1) Nesting the tunnels (FT, WBT, and LT) in the network,
2) Establishing OCDM-LSPs dynamically in a tunnel-nested network.

3.A. Network Topology Conversion with Tunnels

In this paper an extended CB-STA algorithm is studied for nesting FTs, WBTs, and LTs in the four-tier network. Details of tunnel establishment can be found in Ref. [6]. Here we focus on the difference between the routing and OC assignment in a physical network topology and those in a tunnel-nested network topology. Suppose a call from A to F arrives; in the case without tunnels in a physical network, a path may be established through the network along A→B→C→D→E→F, shown in Fig. 7(a), where the OCDM switching has to be performed at each node along the path. This means that fewer paths can have the chance to access the OCDM switching box and may suffer a higher probability of being blocked. However, in a tunnel-nested network, because of the tunnels, OCDM switching is performed only at some of the nodes along the path.

As shown in Fig. 7(b), OCDM switching is bypassed at nodes B, C, and E by use of a fiber tunnel and a waveband tunnel, respectively. Hence, in a tunnel-nested network, the path is established with A→D→F instead of A→B→C→D→E→F.

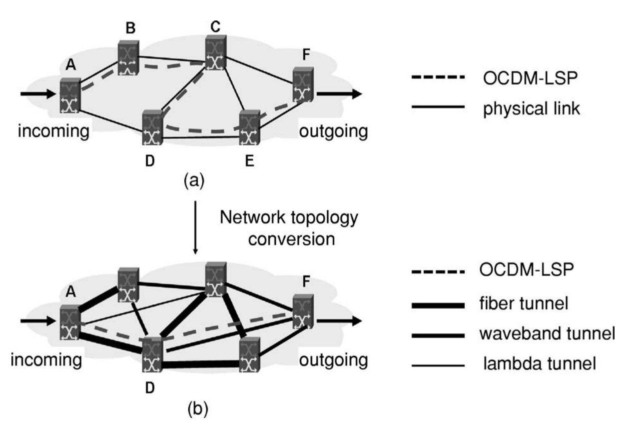
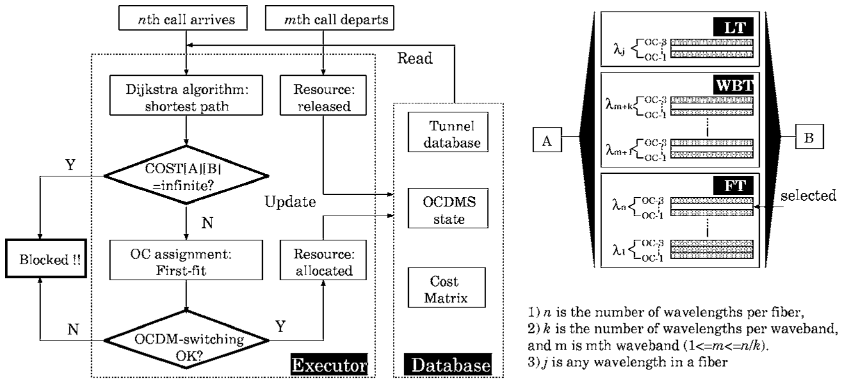


Fig. 7. Network topology conversion paradigm. (a) OCDM-LSP establishment with a physical network topology: A→B→C→D→E→F; (b) OCDM-LSP establishment with a tunnel-nested network topology: A→D→F.



(a) (b)

Fig. 8. (a) OCDM-LSP establishment algorithm; (b) first-fit OC allocation scheme for OCDM-LSP, e.g., (λ_n, OC_2) in the FT is selected.

3.B. Establishing OCDM-LSPs in the Four-Tier Network

Let CS(T) denote the cost for tunnel switching, where $T \in \{\mathrm{FT}, \mathrm{WBT}, \mathrm{LT}\}$, and CS(OCDM) denote the cost for OCDM switching. Let length(A,B) denote the tunnel length defined as the minimum integer average length of all paths [6], and $\mathrm{OCDMLSP}_i(T,[\mathrm{A}][\mathrm{B}])$ the status of an i th OCDM-LSP accommodated in a tunnel, "0" if occupied, and "1" if free. Here (A,B) denotes the (ingress, egress) pair of a tunnel described above. Hence, we define the cost function of a tunnel with A for ingress and B for egress, taking OCDM-LSPs into account as follows:

$$\mathrm{Cost}(T,[\mathrm{A}][\mathrm{B}]) = \frac{\mathrm{CS}(T) \times [\mathrm{length}(\mathrm{A},\mathrm{B}) - 1] + \mathrm{CS}(\mathrm{OCDM})}{\sum_{T} \sum_{i} \mathrm{OCDMLSP}_i(T,[\mathrm{A}][\mathrm{B}])}. \tag{1}$$

The denominator in the above formula equals the total free OCDM-LSPs in all the tunnels taking A and B for their ingress and egress, respectively. Cost(T,[A][B]) becomes infinite without any free OCDM-LSP between A and B. Based on the above formula, the overall cost of a path passing nodes A and B can be defined as the cost summation of all the tunnels between A and B,

$$\mathrm{COST}[\mathrm{A}][\mathrm{B}] = \sum_{T} \mathrm{Cost}(T,[\mathrm{A}][\mathrm{B}]). \tag{2}$$

Figure 8 shows the OCDM-LSP establishment algorithm for in a tunnel-nested network. When the nth call arrives, the Dijsktra algorithm will be performed to calculate a shortest path from a source to a destination based upon the cost functions described above. As no physical impairment is considered in this paper, an OC can be treated as a wavelength in the WDM networks, so it makes sense to employ the first-fit algorithm to assign a free OC channel in a wavelength. Note that, as lower cost can be achieved in the lower switching layer, the OCDM-LSPs in a FT should be considered first, then a WBT and a LT. For example, OC_2 in λ_n of a FT is selected, as illustrated in Fig. 8(b). A connection request will be blocked in the following cases: (1) no free OCDM channels between A and B or (2) insufficient OCDM switching capability at the entrance of a tunnel, as OCDM switching is required for the tunnel transition described so far. When an OCDM-LSP is torn down, all the resources assigned have to be released. The database managing the tunnel state and the OCDM-switching box state has to be updated after establishing or tearing down an OCDM-LSP.

4. Simulation Results

To compare our proposal with that in Ref. [6], we apply the same network shown in Fig. 9 in the simulation with the following assumptions.

(1) Symmetric source-destination (S, D) pairs are generated in the tunnel establishment stage.

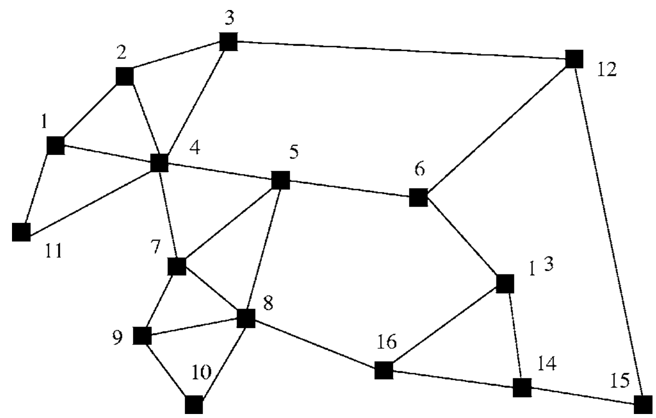


Fig. 9. 16-node network topology.

(2) To each (S, D) pair, a connection request arrives dynamically with a rate of λ in Possion distribution and will hold an exponentially distributed period with a mean of $1/\mu$. For simplicity, offered load $\rho = \lambda/\mu$ is set to be uniform for all the (S, D) pairs.

(3) In the three-tier network, a wavelength is taken for the basic unit for connection provisioning, whereas in the four-tier network, an OC is regarded as the basic unit.

4.A. Notation and Network Configurations

Notation and OXC configurations used in the simulation are shown in Tables 2 and 3. Note that, the capacity C per wavelength in the three-tier network is referred to as the physical transmission bit rate B, so $C = B$; but in the four-tier network, it is defined as $C = \text{numOCs} \times B'$, where B' is referred to as the physical transmission bit rate of an OCDM-LSP. In this simulation, the capacity C per wavelength is set to OC 192. Therefore, B in the three-tier network is 10 Gbits/s; in the four-tier network, B' is 2 Gbits/s with configuration 2, where numOCs is 5.

Table 2. Notation in the Simulation

Notation	Definition
F	fiber switching ports
B	waveband switching ports
L	lambda switching ports
OC	OCDM switching ports
numWBs	wavebands per fiber
numLambdas	wavelengths per waveband
numOCs	OCs per wavelength
+WC	with wavelength conversion
−WC	without wavelength conversion

Table 3. MG-OXC Configurations

Network	Configuration
Three-Tier Network	
Configuration 1	1F1B3L, 8WBs/8Lambdas
Configuration 2	1F2B2L, 8WBs/8Lambdas
Four-Tier Network	
Configuration 1	1F1B1L2OC, 8WBs/8Lambdas/10OCs
Configuration 2	1F1B1L2OC, 8WBs/8Lambdas/5OCs
Configuration 3	1F1B1L2OC, 8WBs/8Lambdas/2OCs
Configuration 4	1F1B1L2OC, 8WBs/8Lambdas/1OC

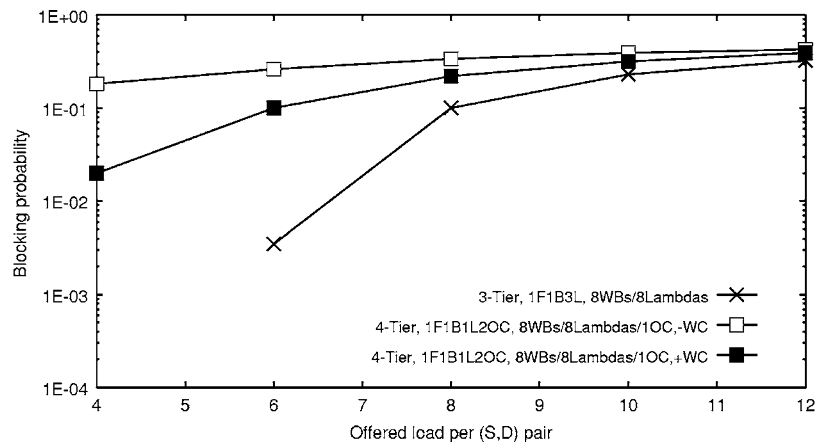


Fig. 10. 10 Gbits/s per call: three-tier (configuration 1) versus four-tier (configuration 4).

4.B. Three-Tier Network versus Four-Tier Network

4.B.1. Single-Optical-Code Allocation Scheme

Figures 10–12 show the comparison between the three-tier network and the four-tier network in terms of call blocking probability. In the three-tier network, wavelength conversion is allowed along an optical path. But in the four-tier network, as described in Section 2, (1) hybrid OC–wavelength conversion (two-dimensional conversion), and (2) OC conversion only (one-dimensional conversion) are considered. This means that OC and wavelength conversion can be implemented along the path in the former, but only OC conversion in the latter. Simulations dealing with dynamic connection requesting different bandwidths have been performed, including 10 Gbits/s per call, 5 Gbits/s per call and 2 Gbits/s per call plotted in Figs. 10–12.

As a wavelength is taken for the basic unit, the performance of the three-tier network remains constant regardless of the bandwidth demanded by a connection request in Figs. 10–12. In contrast, the four-tier network behaves quite differently, because a different number of OCs are deployed in a single wavelength with different bandwidth requests.

Recalling the description in Section 3, a call will be blocked if (1) there is insufficient capacity in a tunnel, which is referred to as the "tunnel capacity constraint," or (2) there is insufficient switching capability at the ingress node of a tunnel, which is referred to as the "transiting capability constraint." In the following analysis, we will investigate how these two constraints influence the blocking performance in the three-tier and four-tier networks.

With calls requesting 10 Gbits/s bandwidth, Fig. 10 illustrates that the four-tier (configuration 4) is outperformed by the three-tier (configuration 1). That is because, first, as the number of ports used for transiting LSPs between different tunnels in the three-tier (configuration 1) is 3, but only 2 in the four-tier (configuration 4), so a higher flexibility for LSP establishment can be achieved in the three-tier (configura-

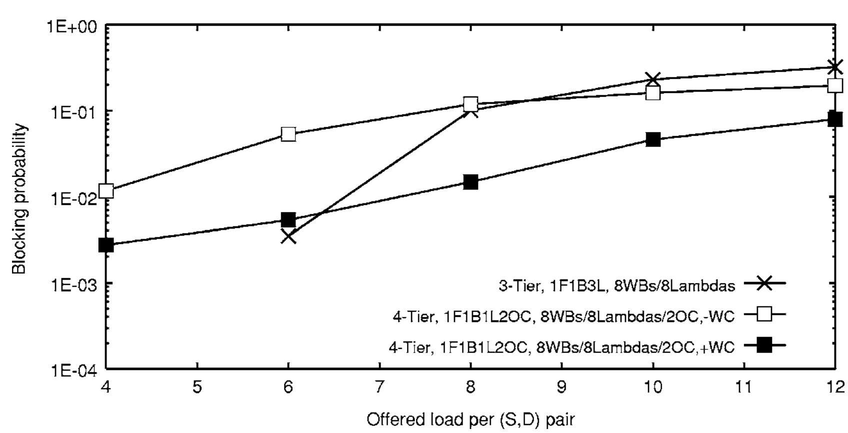


Fig. 11. 5 Gbits/s per call: three-tier (configuration 1) versus four-tier (configuration 3).

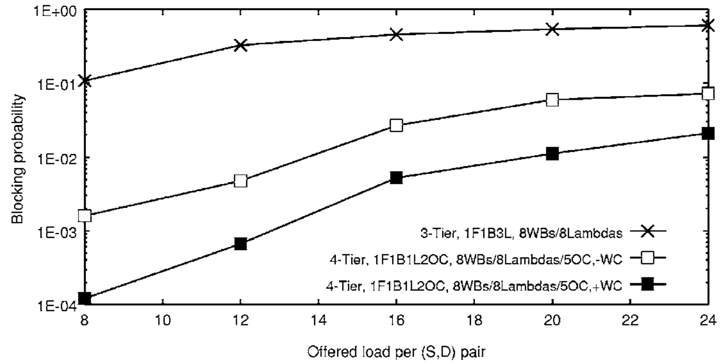


Fig. 12. 2 Gbits/s per call: three-tier (configuration 1) versus four-tier (configuration 2).

tion 1) than in the four-tier (configuration 4) network; second, the wavelength continuity constraint is imposed on the lambda tunnel establishment stage in the four-tier network, which further reduces the flexibility. However, with calls requesting 5 Gbits/s bandwidth, as shown in Fig. 11, with a light load, e.g., 8 and 6, the four-tier (configuration 3) is still outperformed by the three-tier (configuration 1). This means that the transiting capability constraint and the wavelength continuity constraint in lambda tunnel establishment in the four-tier network are still the main factors. But with a heavy load larger, than 6 or 8, the four-tier (configuration 3) yields better results than the three-tier (configuration 1) because of the enlarged tunnel capacity achieved by employing OCs, and the tunnel capacity constraint affects the three-tier network more than the four-tier network. Compared with Figs. 10 and 11, Fig. 12 relieves the above constraints of the tunnel capacity, tunnel transiting capability, and wavelength continuity in the LS layer of the four-tier network, as five OCs are deployed in a wavelength. Therefore, the four-tier network greatly outperforms the three-tier network. From these results, it can be concluded that an increase of OCs can be of great benefit to reduce call blocking.

4.B.2. Multiple-Optical-Code Allocation Scheme

A multi-OC allocation scheme is introduced when 10 OCs are deployed in four-tier (configuration 1) network. In this scheme, multiple OCs could be assigned to a single call according to its bandwidth, which means that multiple OCDM-LSPs would be established between a source and a destination. The multi-OC scheme has the following properties.

(1) A call will be declared blocked if any of the required multiple OCDM-LSPs fail to be established.

(2) Multiple OCDM-LSPs belonging to one call would possibly traverse different routes through different switching layers or distances (hop counts).

(3) Any two OCDM-LSPs from different directions may conflict with each other while being dropped to assemble the original large chunk at the destination node if they are carried on the same wavelength, and the packet transmission delay may be

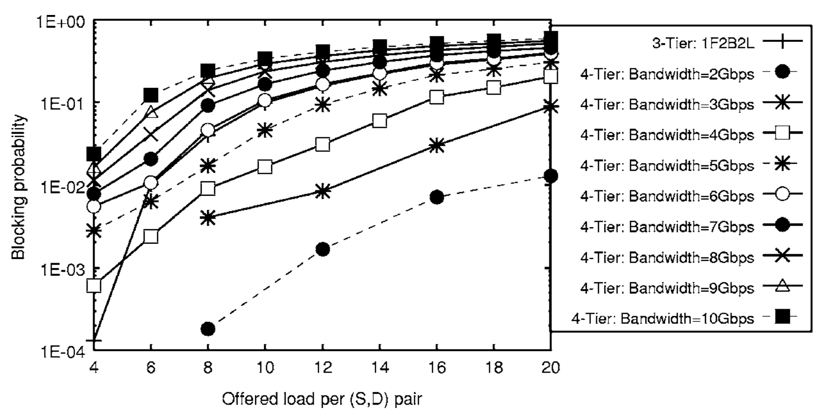


Fig. 13. Three-tier (configuration 2) versus four-tier (configuration 1) with the multi-OC scheme; wavelength conversion is available.

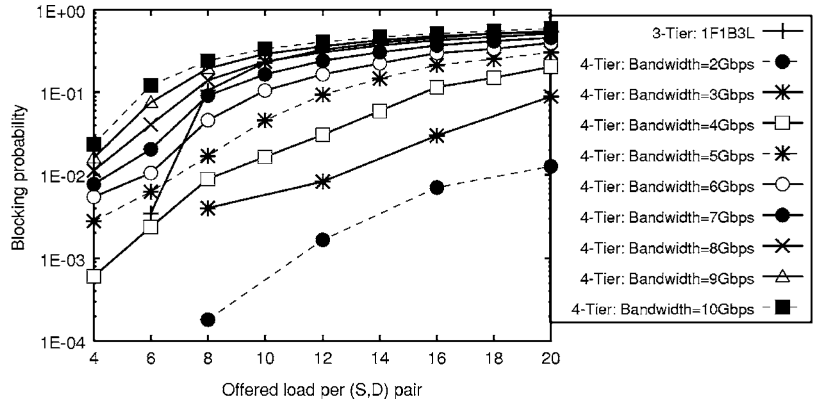


Fig. 14. Three-tier (configuration 1) versus four-tier (configuration 1) with the multi-OC scheme; wavelength conversion is available.

different because of different transmission distances. Buffer, wavelength conversion, or OC encoding technology can be used to avoid this conflict before reassembling the packets into the original large chunk; and Internet Protocol [23] can be employed to resolve the packet reassembling order problem.

For simplicity, we that assume the bandwidth (number of OCs) demanded by calls is uniformly distributed. Multiple OCDM-LSPs belonging to a connection request are handled individually with the fixed-path routing scheme according to the algorithms presented in Section 3. Thus the network state should be updated whenever one of the multiple OCDM-LSPs is established successfully. As shown in Figs. 13 and 14, in the four-tier (configuration 1) case, the blocking probability increases with the increase in bandwidth granularity demanded by a call. This is because a call with a larger bandwidth leads to an increase of OCDM-LSPs and will consume more network resources. In Fig. 13, only under a bandwidth granularity demand smaller than 6 Gbits/s and an traffic load ρ larger than 6 will the four-tier (configuration 1) network outperform the three-tier (configuration 2), whereas in Fig. 14, under a demanded bandwidth smaller 8 Gbits/s and an offered load larger than 8, the four-tier (configuration 1) network can outperform the three-tier (configuration 1).

In our simulation, the outcome shown in Fig. 15 has been also observed. In the four-tier network, results in the multi-OC scheme using configuration 1 and those in a single-OC scheme using configurations 2, 3, and 4 are compared. If a call demands a bandwidth granularity of 2, 5, and 10 Gbits/s, respectively, these two schemes will achieve similar performance. However, the four-tier (configurations 2, 3, and 4) have fewer OCs than the four-tier (configuration 1), which implies that with a bandwidth demand of 2, 5, or 10 Gbits/s, a small size of OCDM OXC can be employed instead of a large one (10 OCs), and cost savings will be much greater.

4.B.3. Effect of Blocking Probability with Different Bandwdith Granularities

To highlight the effect of our proposal to improve flexibility and to allow different bandwidth granularity demands, performances in the three-tier network and four-tier

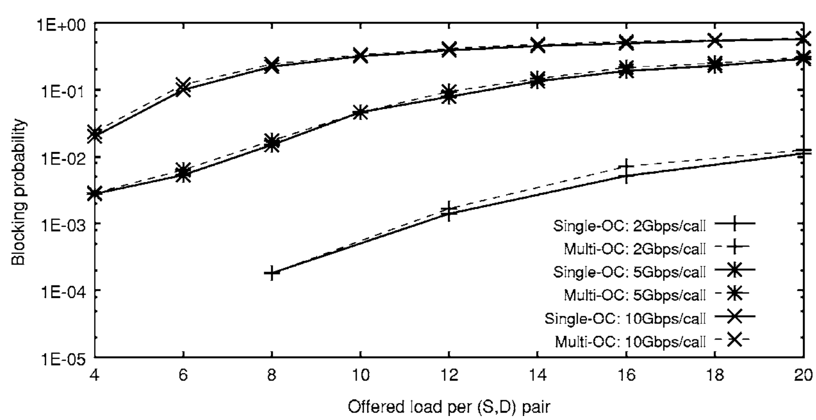


Fig. 15. Single-OC versus multi-OC schemes in four-tier network.

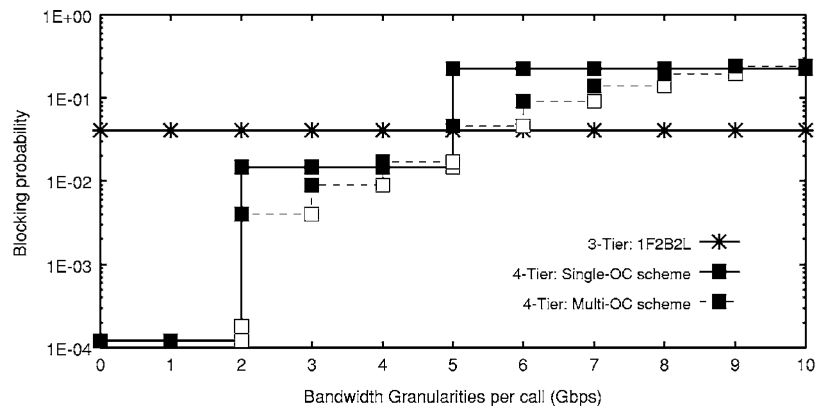


Fig. 16. Three-tier network versus four-tier network with different bandwidth granularities; offered load $\rho=8$; wavelength conversion is available.

network are compared. Figure 16 illustrates that the blocking performance in the three-tier network remains constant, which is consistent with what is shown in Figs. 10–12. The four-tier networks using the single-OC scheme can provide different blocking performances with different OXC configurations. But the four-tier network with the multi-OC scheme obviously performs the best among these three cases, as it can provide the exact bandwidth that a call demands and support more different service grades. However, more OCs in the multi-OC scheme will lead to higher costs. Hence it is regarded as a trade-off between network performance and costs.

4.C. OCDM-LSP versus TDM-LSP without TSI

Even though the TDM-LSP with TSI can perform as well as the OCDM-LSP, the complex switch architecture and network control will be involved in the form described above. In this part we concentrate only on all-optical networks based on the OCDM-LSP and the TDM-LSP without TSI. The difference between these two cases is that, in the OCDM-LSP, an OC can be changed to any free one by OC conversion, but in the TDM-LSP without TSI, time-slot allocation has to be performed by a shifted time-slot mechanism [12,13]. A comparative study of these two four-tier networks has been carried out.

With a fixed multiplexing degree per wavelength: First we examine the difference between these two networks with different numbers of wavelengths per fiber and set the multiplexing degree in each case to be 5, which means 5 OCs per time slot are deployed in a single wavelength. As shown in Fig. 17, the blocking probability in both cases decreases with the increase of wavelengths per fiber. However, owing to the OC conversion along the path, the OCDM-LSP performs better than the TDM-LSP without TSI. Letting Gain(λ) denote the blocking reduction of the OCDM-LSP with OC conversion and the TDM-LSP without TSI, we find that Gain(λ) varies with the number of wavelengths, and a larger Gain(λ) can be achieved with more wavelengths.

With a fixed number of wavelengths per fiber: Second, we compare these two cases

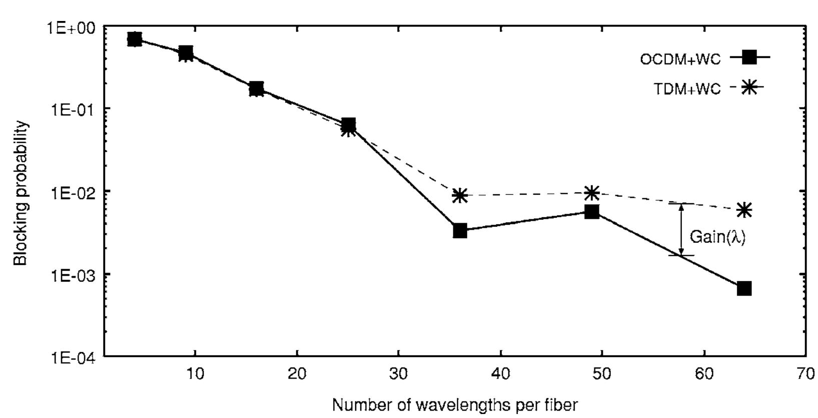


Fig. 17. Effect of OC conversion with different number of wavelengths per fiber; the degree of multiplexing per wavelength is 5, $\rho=12$.

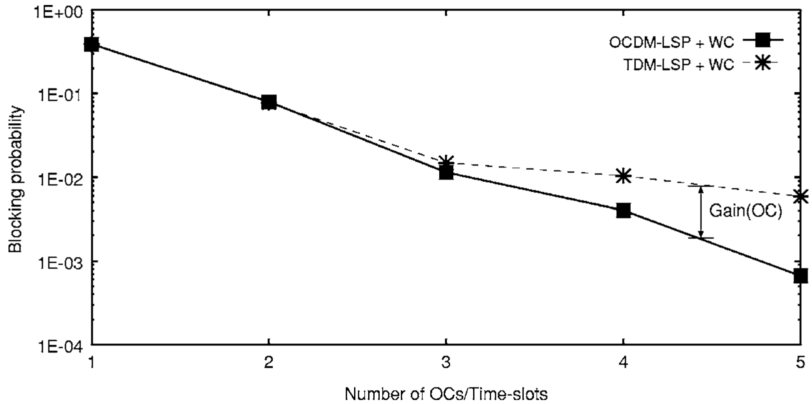


Fig. 18. Effect of OC conversion: with different multiplexing degree per wavelength, the number of wavelengths per is 16, $\rho=12$.

with different multiplexing degrees by fixing the number of wavelengths per fiber to be 64. In Fig. 18, obviously, the blocking probability is reduced with a higher multiplexing degree, which means more OCs or time slots are deployed in a single wavelength. Letting Gain(OC) denote the blocking reduction of the OCDM-LSP with OC conversion and the TDM-LSP without TSI, we can observe that Gain(OC) is fairly small with a low degree of multiplexing but becomes larger with an increase of multiplexing degree.

Based on the above observations, it can be concluded that with more wavelengths per fiber and a higher multiplexing degree the OCDM-LSP turns out to be more powerful than TDM-LSP without TSI.

5. Summary

We have proposed a novel OCDM-based MG-OXC whose switching capability is extended to include fiber switching, waveband switching, lambda switching, and OCDM switching. By using OCDM technology, granularity smaller than a wavelength can be switched and forwarded in the optical domain. Based on what has been studied here, the following should be highlighted for the application of OCDM-LSP. First, compared with the three-tier network, although introduction of OCDM-LSP results in an increase in of cost and complexity, high flexibility in the optical path provisioning can be possible, and a considerable performance improvement is observed, for example, 2 orders of blocking probability reduction has been realized with only 5 OCs per wavelength. Secondly, the four-tier network using TDM-LSP with TSI or OCDM-LSP should achieve the same performance in terms of blocking probability, basically, but bufferless operation in OCDM-LSPs enables lower switch complexity and simpler network control, which shows the OCDM-LSP to be the more powerful. Though the OCDM-LSP has the advantages of providing finer bandwidth granularity and realizing a simpler switch architecture than other alternatives theoretically, there are still many issues that should be studied to make the OCDM-LSP more reasonable for application. For example, the switch should be optimized to reduce the nodal cost, not full but sparse OCDM switching should be used in the network to reduce the network cost, and the routing and OC assignment algorithm taking into account the physical impairment due to the MAI noise should be also studied.

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