Analyzing Power Consumption in Optical Cross-connect Equipment for Future Large-Capacity Optical Networks

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***Abstract*—We describe a comparative analysis of the power consumption of optical cross-connect (OXC) equipment based on electrical and/or photonic matrix switching, which will be used for future large-capacity optical networks. The switch configurations used for both types of OXCs are also comprehensively discussed. For optical networks that accommodate traffic with a capacity of several Tb/s, the power consumption of the OXC equipment based on electrical switching could reach more than 50 kW; this can be reduced to 8 – 30 kW if photonic switching is used instead. In photonic switching-based OXC equipment, the power consumption of transponders becomes the most significant, and its reduction is the key issue for power-efficient large-capacity OXC equipment.**

***Index Terms*— transparent optical network, power consumption, optical cross-connect, optical switch**

I. Introduction

In general, as the traffic in a network increases, the power/energy consumed to transmit a broadband signal becomes greater. This means that we will suffer from the effects of significant power/energy consumption because of the rapid broadband-traffic growth that is expected to occur worldwide. A large increase in power consumption in telecommunication networks may lead to stringent requirements for saving energy to reduce climate change, i.e., the current accelerated warming of the planet thought to be due to the release of man-made greenhouse gases, as is true in other industries.

Information communications technology (ICT) industries are far from innocent in the matter of climate change. However, the ICT sector actually does not contribute a large amount of greenhouse gas emissions compared to its share of the global gross domestic product (GDP) because the primary sources of greenhouse gases are energy production and consumption, transport, buildings, and so on. ICT may also have a positive impact on climate change through use of computing and telecommunications networks, e.g., reducing carbon emissions of other sectors and offering a climate-change monitoring system. Therefore, most standardization organizations including ITU-T have intensively discussed the power consumption/saving issues of optical transmission equipment [1].

In addition to the environmental problem, a significant increase in power consumption could have a large impact on the operational expense of network operators. Therefore, specifications and proper management of power consumption in network systems are critical for coping with this situation. In addition, some telecommunication carriers have started making their own standards to measure the power consumption of telecommunications equipment [2], and accordingly, metrics and test procedures to determine the power consumption of core routers have also been developed [3].

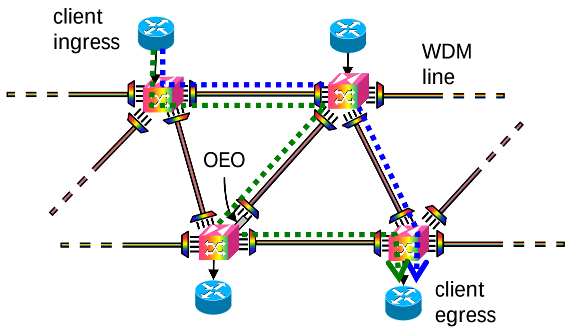

Fig. 1 Optical network consisting of optical cross-connects with 4 express and 1 add/drop branches in which OEO converters are used depending on route.

Next-generation optical networks are expected to offer a large traffic capacity to any destination at any time. Such networks will be achieved by using ring and/or mesh architecture and optical cross-connects (OXCs) linked to each other by wavelength-division multiplexing (WDM) transmission lines, as shown in Fig. 1. The OXC equipment should have a large number of input-output ports, e.g., more than 100, and handle wavelength signals of 10 Gb/s or larger to accommodate the expected significantly growing number of broadband users in the future. One type of OXC is based on electrical switching and is widely used as an established technology. The second type using photonic switching is expected to enable large-capacity networks without a large increase in power consumption.

We analyze and compare the power consumption of future large-capacity OXCs, one based on electrical

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switching and the other based on photonic switching. First, we will discuss configurations of electrical and photonic switches for large-capacity OXCs. Then, we calculate the power consumption of both types of OXCs and discuss the results with a view to further reduce power consumption for future large-capacity networks.

II. SWITCH CONFIGURATION

A. Electrical-switching-based OXC

The configurations of typical OXCs are illustrated in Fig. 2. The OXCs should have express ports, which flexibly connect a wavelength signal in an ingress WDM line to any egress WDM line. In addition, the OXCs have client ports, which drop/add any wavelength signal to/from an express port for transmission in a WDM line. Figure 2 shows an OXC based on electrical matrix switching technology, which consists of optical amplifiers, optical multiplexers (MUX)/demultiplexers (DEMUX), and optical-electrical (O/E) and electrical-optical (E/O) converters for express and client signal accommodation.

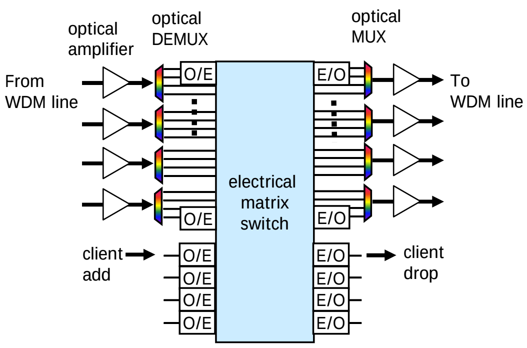


Fig. 2 Optical cross-connect configurations based on electrical switching.

A large-sized electrical matrix switch is usually achieved by integrating small switch elements. Typical configurations of integrated switch elements are shown in Table 1, and their arrangements are shown in Fig. 3 [4]. The number of switch elements required for configuring each type of switch is shown in Fig. 4.

TABLE I.
SWITCH CONFIGURATION

Configuration	Non-blocking type	Number of switch elements
Crossbar	Wide sense	N^2
Clos	Strict sense	$4\mathrm{Sqrt}(2)N^{1.5}$-4N
Benes	Re-arrangeable	$N(2\log_2 N-1)/2$
Spanke	Strict sense	2N(N-1)

The most basic configuration is the crossbar configuration, a simple integration of 2 × 2 switch elements as shown in Fig. 3 (a). This configuration has an advantage in that no blocking occurs in a wide sense but the increase of the number of switch elements required is expressed by the square of the number of switching ports, as shown in Fig. 4. The second one is the Clos configuration, which uses k switches having m ports in its input and output sides to configure an N × N large switch, where N = k × m. This configuration also has non-blocking of ports and fewer switching elements than the crossbar one; the increase of switching elements in this configuration is expressed by N to the power of 1.5. The Benes configuration can drastically decrease the number of switch elements because the increase is expressed by N × $(2\log_2 N-1)/2$ as shown in Fig. 4. However, this type of configuration requires some re-arrangement of the switching connection when blocking occurs. The Spanke

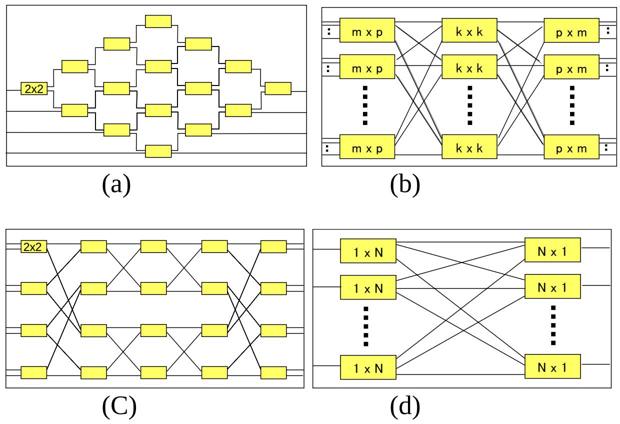


Fig. 3 Typical switch configurations:
(a) crossbar, (b) Clos, (c) Benes, (d) Spanke.

configuration is configured with 1 × N switches and has an advantage of non-blocking characteristics. However, if the 1 × N switches are created by 2 × 2 switches, the number of switch elements is as large as that of the crossbar configuration; its increase is estimated as the order of N square.

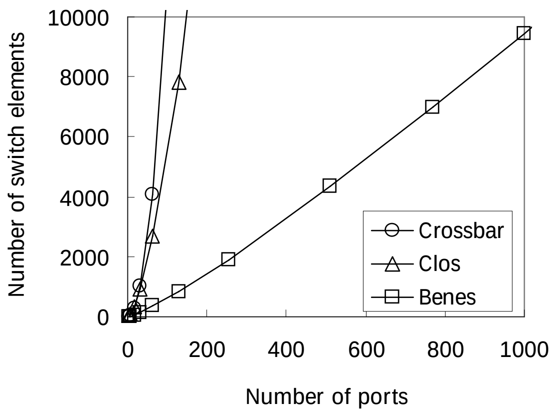


Fig. 4 Number of switch elements required to create each type of configuration.

Surveying actually available commercial OXC equipment, it seems the Benes configuration is the most useful and commonly adopted in many places. This means that the power consumption of a switching fabric itself used in the OXC equipment may increase by the order of N × $\log_2$N. However, an actual switch fabric may have other components that do not rapidly increase with the switching elements, and the increase of power consumption can be estimated as larger than linear but less than N × $\log_2$N.

B. Photonic-switching-based OXC

The use of photonic switching in OXCs is expected to contribute to reducing power consumption in future large-capacity networks because photonic switches do not depend on signal speed, while electrical switches require more power for higher speed signals. Moreover, it may lead to reduction in power consumption through the elimination of transponders if most wavelength signals are transparently cross-connected. However, it seems difficult to construct an optical network with only photonic switching, i.e., fully transparent. Figure 5 shows an OXC based on photonic matrix switching technology, which consists of optical amplifiers, optical MUX/DEMUX, and optical-electrical-optical (OEO) converters for client signal accommodation and wavelength conversion and/or extension of reach. The number of OEO converters for wavelength conversion will depend on the difficulty in transparently passing through the wavelength signals caused by wavelength resource conflicts in the WDM line at the egress ports.

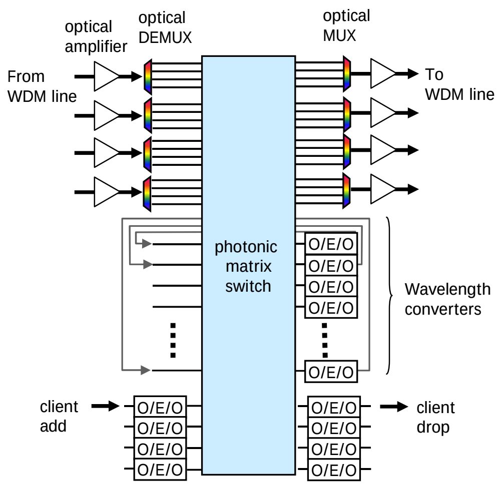


Fig. 5 Optical cross-connect configurations based on photonic switching.

The technologies to create a photonic switch are listed in Table 2. For 2-dimensional switches, the most promising way is to use planar lightwave circuit (PLC) technology. A typical PLC-based photonic switch can be composed of Mach-Zehnder interferometers acting as a 2 × 2 switch and uses the crossbar configuration. The power consumption of each switch element depends on the current changing the optical path delay of one of the arms of the interferometer to switch the optical output port. Typical power consumption was reported as 0.15 W per Mach-Zehnder interferometer [5]. In actual fabrication, the PLC switch elements are two Mach-Zehnder interferometers cascaded to attain sufficiently low crosstalk, and the power consumption of each switch element is double that of the Mach-Zehnder interferometer. It has been recently reported that a lower power consumption of 20 mW per interferometer was achieved in laboratory experiments [6].

TABLE II.
TECHNOLOGIES FOR PHOTONIC SWITCH

Technology / Dimensions	Wave guide	Free space
2	Mach-Zehnder interferometers on PLC	MEMS mirrors for on-off switching
3	Not available	MEMS mirrors with angle control in 3-D arrangement

Another type of 2-dimensional photonic switch uses free space optics with small mirrors fabricated by micro-electro-mechanical systems (MEMS) technology and has the benefit of free space optics, including lower crosstalk and typical power consumption as small as 5 mW.

When those 2-dimensional switch elements are integrated in the crossbar configuration, the total power consumption of an N × N crossbar switch reaches $N^2/2$ times that of each switch element, assuming that half of them are in the on-state. Moreover, it is still too difficult to create a larger size switch, e.g., over 100 × 100, with such a 2-dimensional configuration because of its physical size and difficulty in fabrication.

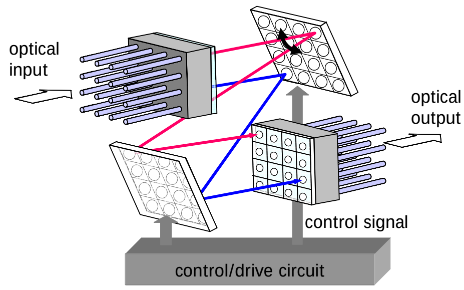


Fig. 6 Configuration of 3D MEMS switch.

Instead, we can find that the most significant advantage of photonic technology over electronics is the availability of 3-dimensional free space optics. Thus, the most promising approach to large size photonic switches is the 3-dimensional MEMS switch shown in Fig. 6, which directly connects any input port to an output port by controlling the tilt angles of two oppositely located MEMS mirrors [7-10]. The angles of the MEMS mirrors are determined by the balance between the torsion of the spring at the mirror hinge and the electro-static force driven by the high voltage control circuit. Basically no electrical current flows to maintain the mirror angle, and the only component consuming power is the circuit for creating the control signal with a high voltage of the order of 100 V. Moreover, unlike 2-dimensional switches, the number of switch elements in a 3-dimensional switch linearly increases and the driving circuits may be simply added according to the port increase. The features above mean that this type of switch inherently has an advantage in reducing power consumption in large capacity OXCs.

III. Analysis of Power Consumption

We need to create a generic OXC equipment model to calculate the power consumption. Figure 6 shows a typical schematic rack/shelf model of OXC equipment in which each shelf can be further divided into units or cards. The main rack may contain an electrical or photonic switch unit, an optical multiplexer and demultiplexer unit, and optical amplifiers. The additional sub-racks contain transponders (O/E/O in Fig. 5) as wavelength converters or receivers (O/E in Fig. 2), and transmitters (E/O) for express/client signal accommodation. We can then assign a typical power consumption value to each card or unit by referring to current manufacturers' actual products. For example, typical power consumption values in the O/E or O/E/O components of current OXC or WDM equipment may range from 50–100 W/card.

We calculated the power consumption of optical cross-connect equipment based on electrical switching (E-OXC) and photonic switching (P-OXC). Both types of equipment were assumed to have 10-Gb/s interface cards in the transmitters/receivers or transponders. Figure 7 shows the power consumption calculated against the number of ports, which is the sum of the express and client ports (one side).

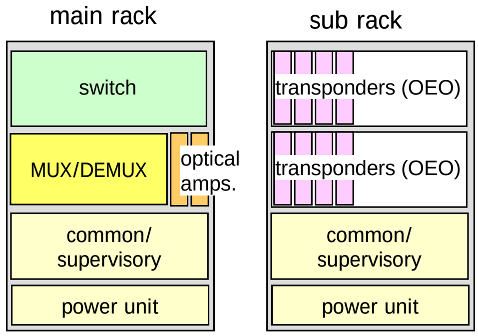


Fig. 6 Rack mount models of optical cross-connect equipment.

fabric because of many factors other than simple integration of the switch elements. However, this assumption of linear increase will not deviate by more than a factor of $\log_2 N$, which is about 6.6 and 9.9 for N = 100 and 1000, respectively, if the switch fabric uses the Benes configuration. Figure 7 shows that the power consumption increases with the number of ports and reaches over 10 kW if the number of ports is more than 160, i.e., the capacity handled in the equipment is 1.6 Tb/s and will increase to over 50 kW when the number of ports is 1000 or 10 Tb/s in capacity. Even this value, which may be conservatively estimated, could be difficult to accept for network operators because the power consumption of current large-capacity core routers, which is in the range of 10 kW, is already problematic for telecom carriers.

We then calculated the power consumption of a P-

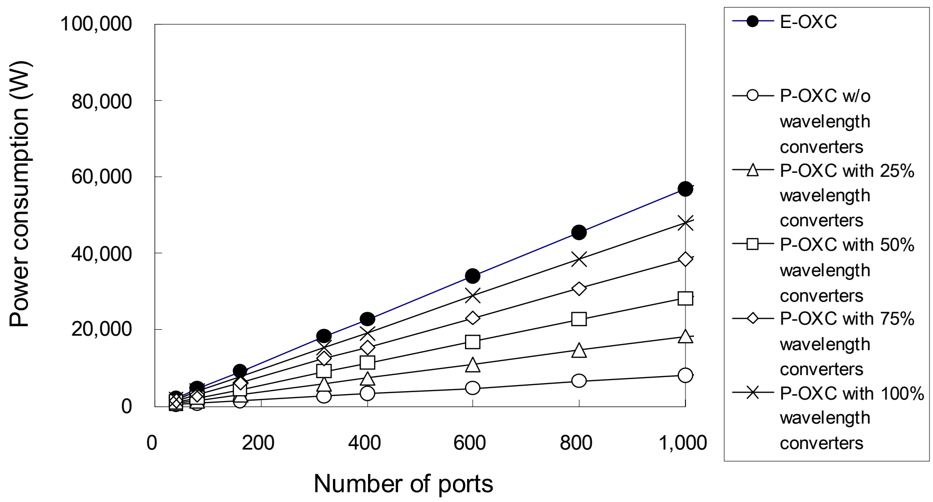


Fig. 7 Power consumption of various optical cross-connect configurations based on electrical and photonic switching technologies.

In the case of an E-OXC, we assume the power consumption of the electrical switch increases almost linearly with the number of ports or the capacity accommodated. It is quite difficult to predict exactly the increase of the power consumption of the actual switch

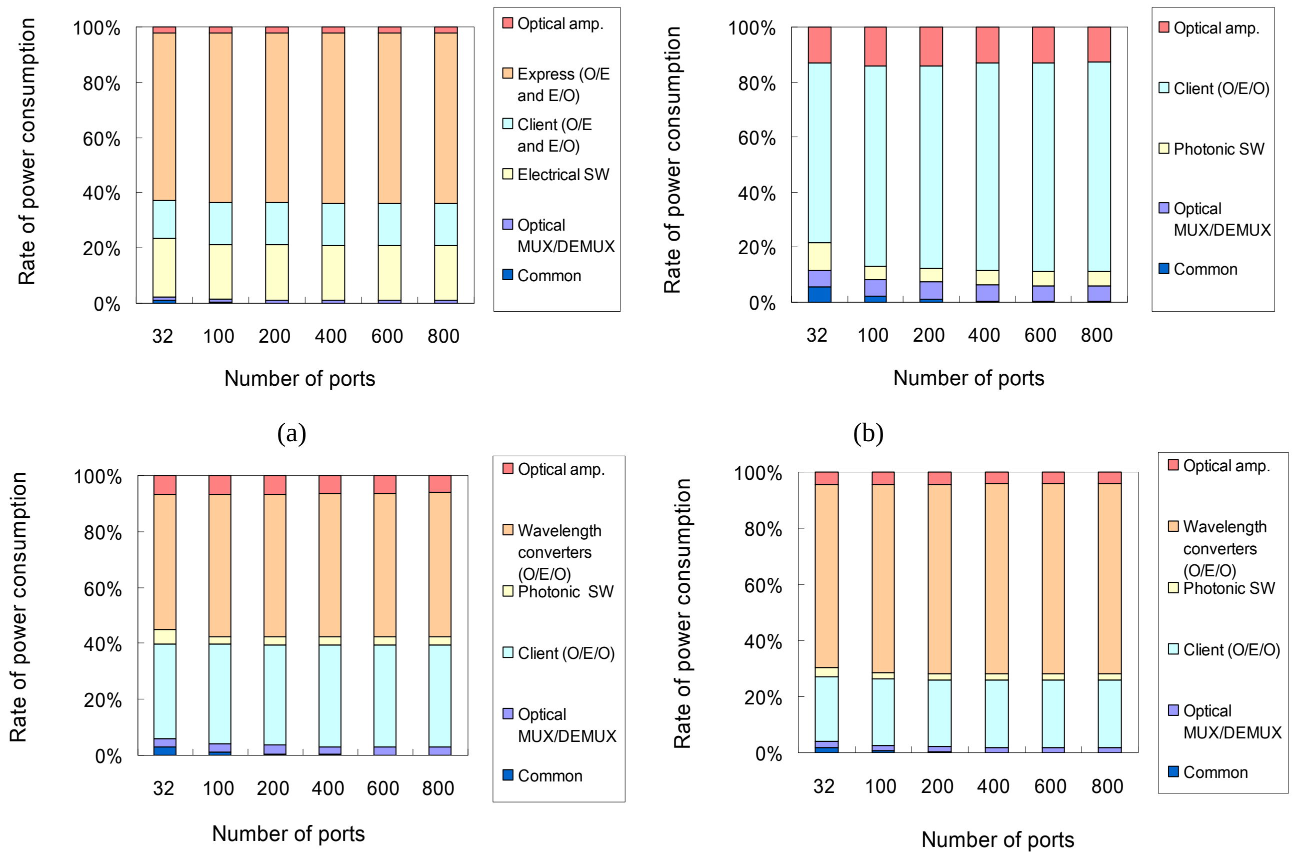
OXC for various configurations depending on the number of wavelength converters. The power consumption of the photonic switch fabric is assumed to linearly increase according to the formula 0.48×(port counts-80)+35 [W], which is created to fit currently available large-capacity

3D-MEMS-based photonic switches. When wavelength routing does not cause any conflict in a WDM line and no wavelength converter is equipped in the P-OXC, the power consumption could be drastically reduced compared to the E-OXC in all calculated ranges of the number of ports. The power consumption value of such a P-OXC is only 8 kW, which is almost 1/7 of that of an E-OXC, even if the number of ports is over 1000. This means that such a P-OXC could be a 10-Tb/s-class OXC with power consumption lower than that of current 1-Tb/s-class large core routers. However, the wavelength routing that avoids any wavelength resource conflict in a WDM line without wavelength conversion is not realistic if the network scale and number of nodes are not small.

Therefore, we calculated the power consumption of a P-OXC with varying numbers of wavelength converters equipped, as shown in Fig. 7. Some increase in the number of ports is inevitable for P-OXCs with less than 100% wavelength converters, while no additional ports are necessary for P-OXCs with 100% wavelength converters. The number of ports for wavelength converters is expressed as the percentage of the number of express ports in Fig. 7. It must be noted that the number of ports described in Fig. 7 does not include the increase in the actual port count in the matrix switch fabric for wavelength conversion, which may not be visible outside the equipment.

As clearly shown in Fig. 7, the power consumption of a P-OXC increases with the percentage of wavelength converters. However, even when 100% wavelength converters are equipped in a P-OXC, the power consumption values are still under those of an E-OXC. This is because the photonic switch consumes less power than the electrical switch. A P-OXC with a percentage of wavelength converters of around 25 – 50% could be realistic from the viewpoint of network operation. Then the power consumption of P-OXCs could be calculated in the range of 15 – 30 kW, even for a 10-Tb/s capacity.

Figure 8 shows the detailed contribution of each component to the power consumption of E-OXC and P-OXC equipment for 32 – 800 ports. For every case, the rate of contribution is almost constant if the number of ports increases to above 100. This means that the number of components is almost proportional to the number of ports. For a P-OXC, the contribution of the photonic switch is quite small compared with that of the other components, even for the one with no wavelength converters. In contrast, for an E-OXC, the electrical switch significantly contributes about 20% or more to power consumption. It is also noted that the most



(c) (d)

Fig. 8 Element contributions to equipment power consumption in percentages: (a) electrical switching, (b) photonic switching without wavelength converters, (c) photonic switching with wavelength converters occupying 25% of express ports, (d) photonic switching with wavelength converters occupying 50% of express ports.

significant contributions are made by the O/E, E/O, and OEO devices for express and client signal accommodation or for wavelength conversion. In particular, for a P-OXC without wavelength converters, the O/E/O devices for client signal accommodation significantly contribute more than 70%. The impact of the O/E/O devices is also significant for a P-OXC with wavelength converters, as shown in Figs. 8(c) and (d). Those results indicate that the key to reducing the power consumption of P-OXCs is to improve the power consumption efficiency of the O/E/O components.

The advantage of P-OXCs over E-OXCs, i.e., the optical transparency of the switch fabric, becomes salient when the optical signal speed increases to 40- or 100-Gb/s. The power consumption of the photonic switch fabric may not change even for such high-speed signals and the switching capacity can be simply increased with the optical signal speed, while that of the electrical switch fabric incurs significant increase in power consumption as the total switching capacity increases with the signal speed. In terms of the transponder or O/E/O converter, the power consumption has not necessarily increased in proportion to the signal speed so far, and thus it seems that the use of higher speed signals leads to reduction in power consumption per bit. However, modulation and demodulation schemes for higher speed signal transmission of 40 or 100 Gb/s use optical phase and/or polarization multiplexing instead of simple intensity modulation commonly used for 10-Gb/s systems [11]. Such a complicated scheme may cause inevitable increase in the number of discrete optical and electrical components in the O/E/O converters, and reduction in power consumption per bit may be difficult to achieve. The key technology to solve this problem will be the development of a power-efficient photonic integration circuit [12].

IV. Conclusion

Optical cross-connect (OXC) equipment is essential for future optical networks, which are expected to offer large-capacity traffic to any destination at any time. The use of photonic switching in OXC equipment instead of conventional electrical switching is effective in reducing power consumption, and this will be emphasized as the optical signal speed increases and larger switching capacity is accommodated. These advantages of photonic switching may result from free-space technology in 3-dimensional configurations. However, it seems that placing some O/E/O converters in the equipment is necessary in actual complicated optical mesh networks in order to settle wavelength resource conflict in a WDM transmission line and to meet the requirement for smaller switching granularity than the wavelength signal. The power consumption of such a realistic OXC configuration then significantly depends on the O/E/O conversion devices, more than 70% depending on the rate of inclusion. We expect further reduction in power consumption per bit to be obtained by increasing the optical signal speed to 40 or 100 Gb/s and developing higher-speed transmission technology. In such a high-speed signal region, complicated modulation/demodulation schemes will be inevitable and may not necessarily contribute to reducing power consumption effectively, i.e., reduction to less than 4 or 10 times the power of current 10-Gb/s transponders. Thus, lower-power-consuming transponders (O/E/O devices) obtained by developing un-cooled devices and photonic integration are expected to further reduce the power consumption in OXCs for future large-capacity optical networks.

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