An Evaluation of Cost-efficiency by Extending ROADM-based Metro-Access Converged Optical Networks to cover Point-to-Multipoint Connections

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***Abstract*— We propose to extend ROADM-based metro-access converged optical networks to cover Point-to-Multipoint connections. Numerical equipment cost evaluation results verify that a 35.4% cost reduction is possible assuming users can be aggregated into groups of four.**

Keywords—Point-to-MultiPoint, cost calculation, metro-access converged network, ROADM

I. INTRODUCTION

Cyber Physical Systems (CPS) should become a reality in order to revitalize industry and solve social problems such as advanced mobility management and smart factories [1]. A feature of CPS is that it collects various data from the physical space and analyzes it using large-scale data processing technology in cyberspace; analysis results are fed back to the physical space via bidirectional dynamic communication. Focusing on the viewpoint of the traffic flow, data flows generated by new services on the metro and access network, which accommodates data centers (DCs) and sensors as an information collection platform, tend to be concentrated in one place [2]. Therefore, it is expected that handling large volumes of traffic and making effective use of network resources will be critical. In order to realize the new services based on CPS, a large capacity (e.g. over 48 Gbps for area management), low latency (e.g. less than 10 ms for mobility management) and a flexible network that can handle dynamic traffic is required [1].

Currently, reconfigurable optical add drop multiplexers (ROADMs) are being utilized to provide large capacity and flexible wavelength division multiplexing (WDM) based networks in the metro and core areas. The ROADMs provide direct optical connections between the transceivers in each ROADM node using functions of branching and insertion of optical signals called the Add/Drop function. So far, ROADM based metro-access convergence has been studied to simultaneously provide super-broadband capacity (significantly over 100 Gbps) and super-low end-to-end latency (e.g. < 1 ms) [3] for end users.

However, since the current ROADM system is based on Point-to-Point (PtP) connections, it is expected that the depletion of wavelength resources and increased networks costs may hinder the emergence of cost-effective services. Especially in applications like CPS, traffics are concentrated into one or some DCs. When Ethernet switches and IP routers are located at the boundaries of the segments (between metro–access, core-metro) to multiplex traffics, significant power-consumption increase is inevitable to keep guaranteeing the large capacity for each user. In addition, excess latency caused by the switches and routers may make it difficult to meet performance required by CPS.

In this paper, we propose an architecture combines ROADM-based converged optical networks with Point-to-Multipoint (PtMP) topology to optimize wavelength resource utilization and reduce network cost by sharing parts of the optical distribution networks and equipment. Quantitative evaluations of networks cost using proposed cost calculation model of the network configuration confirm the significant cost reduction offered of the proposed network architecture model.

II. NETWORK ARCHITECTURE FOR CALCULATION

A. ROADM based metro-access converged networks

The ROADM allows extraction and insertion of optical signals of any wavelength from wavelength-multiplexed optical signals, enabling flexible network construction. With the increasing demand for high-speed and dynamic networks, future networks must offer non-blocking switching and adding/dropping of wavelengths [4]. In particular, the colorless, directionless and contention less (CDC)-ROADM is an important technology; the colorless function for freely assigning

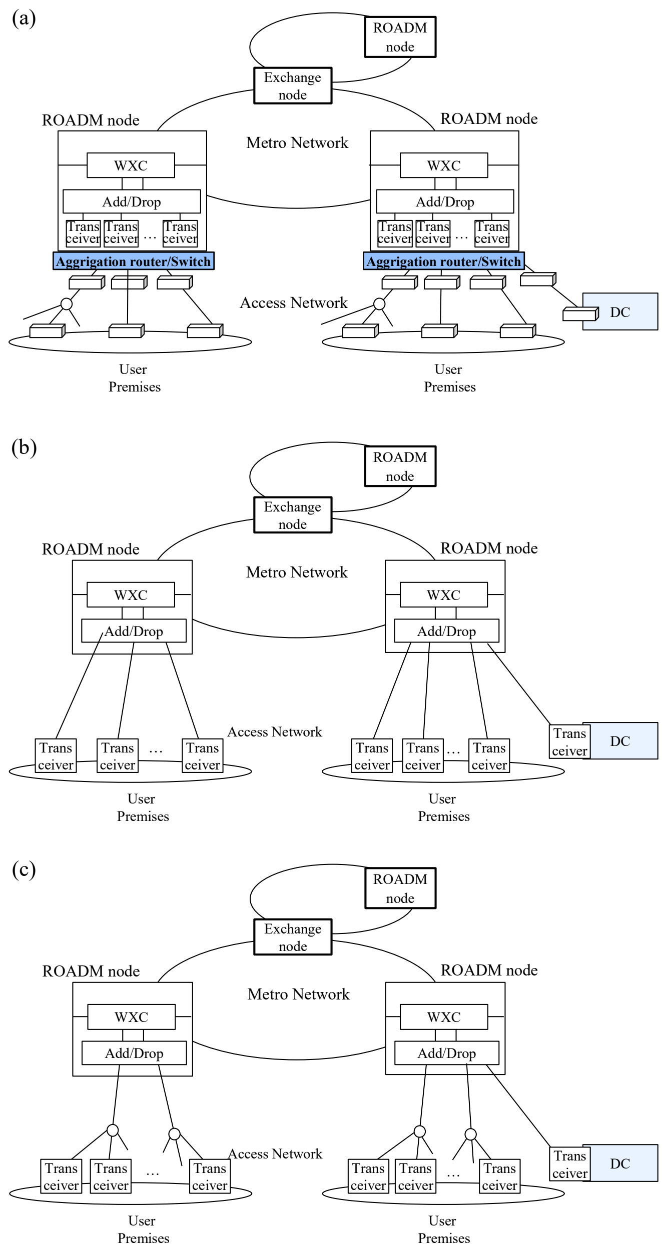

Fig.1 Network Models (a) ROADM architecture based network, (b) extended ROADM architecture based network, (c) proposed extended ROADM architecture with PtMP connections in metro-access converged network

input/output wavelengths to any ports, the directionless function for freely configuring the input/output path of transponders, and the contentionless functionality to enable output of the same wavelength to multiple transmission lines within the same device without constraints. Fig. 1(a) shows the typical configuration of the ROADM-based metro and access networks. The ROADM consists of wavelength cross-connect (WXC) function, add/drop function and optical transceivers [4]. Transceivers in each ROADM node are directly connected by optical paths with arbitrary wavelengths. Aggregation switches and routers in the ROADM nodes accommodate user terminals placed in user premises. While this hierarchical configuration is based on electrical domain aggregation and provides cost-effective broadband services to users, Ethernet and IP based electrical domain aggregation causes huge delays, such as signal conversion delays and packet queuing delays. Therefore, linking resources in different segments demands low latency and high speed communication [5]. It is assumed to be unsuitable for applications that demand low latency but use the computing resources of edge DCs connected to ROADMs.

To minimize the delay caused by signal transmission between segments, metro-access convergence by extended ROADM configuration has been studied. Fig. 1(b) shows a configuration of the extended ROADM based metro-access converged networks. The extended ROADM features optical transceivers set at user premises. This configuration offers direct end-to-end optical connection between users by different ROADM nodes without any electrical domain aggregation or conversion. In addition, the following benefits are expected; direct optical connections between users accommodated by the same ROADM node using extended add-drop functions and direct optical connections to computing resources on edge DCs located on other ROADM nodes [5]. While extending the ROADM function can support short-term evolution assuming limited end points, there will be future difficulties, described below, in accommodating full access network users such as mass-user and antenna sites of 6G mobile cells; increased fiber costs in access networks, limited number of users accommodated due to the limited number of add/drop ports on ROADMs, and depletion of wavelength resources due to the traffic concentration on edge DCs. Therefore, further expansion of this configuration is essential to provide more flexible networks and to converge metro-access networks.

B. *Proposed Network Architecture*

As mentioned before, the architecture shown in Fig. 1(b) is based on PtP technology. The number of end points is expected to grow in the future which will deplete wavelength resources due to increased traffic, and increase network costs due to an increase in the number of fibers and transceivers. In order to solve these issues, we propose an extended ROADM network that supports PtMP optical connections.

Fig. 1(c) shows the proposed architecture, which combines an extended ROADM network with PtMP connections. PtMP connection is defined here as increasing the number of users per wavelength by the application of multiplexing technology and fiber aggregation in the access network section. In the proposed network, the fibers in the access section are aggregated; this reduces the number of fibers connected to the ROADM nodes, which reduces the number of ports required for the devices constituting the ROADM node and the number of transceivers. All of which lead to a reduction in network costs. In addition, the configuration not only reduces network device number but also improves network flexibility by the aid of multiplexing technology. As candidates multiplexing methods, time division multiplexing may be used to share wavelengths as in conventional PON systems [6], or it may be used in conjunction

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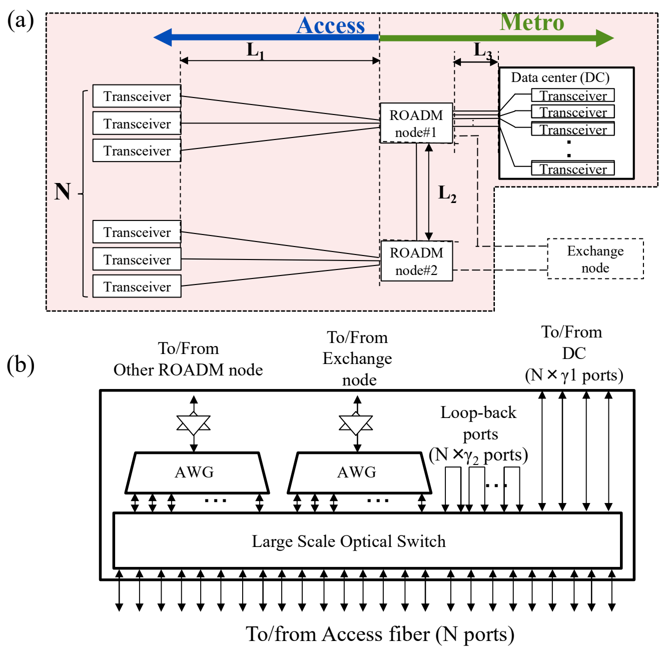

Fig.2 (a) Calculation model for the conventional PtP based extended ROADM network (b) assumed ROADM node architecture

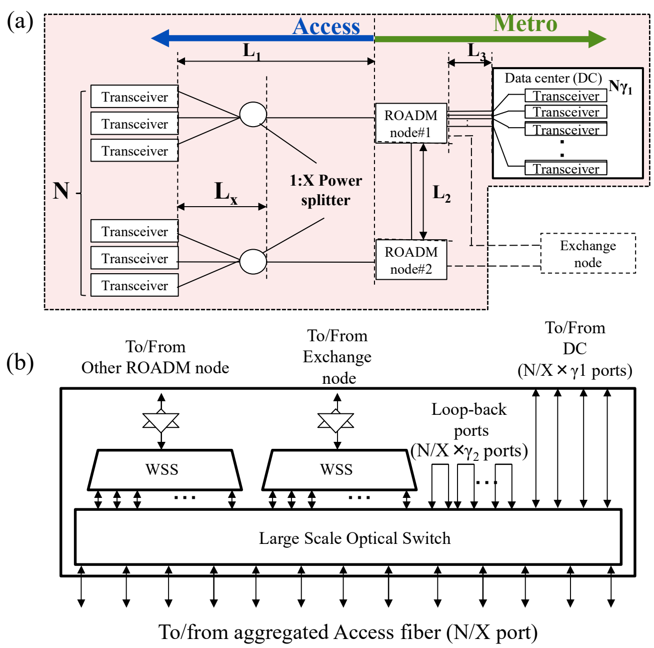

Fig.3 (a) Calculation model for the proposed PtMP based extended ROADM network (b) assumed ROADM node architecture

with wavelength multiplexing [7]. The application of frequency multiplexing is expected in the future [8]. Note that this configuration requires some configuration changes. In the conventional PtP-based Extended ROADM configuration, only a single wavelength is carried by each fiber in the access section, however, multiple wavelengths are likely to be superimposed on the access section of the proposed network, which makes the ROADM configuration relatively complex. In addition, the increased cost of transceivers associated with PtMP adoption may negate the cost-saving effect of the reduction for the number of fibers and transceivers.

Therefore, we conduct a quantitative evaluation of network cost using a cost calculation model of PtP-based and PtMP based extended ROADM networks and evaluate the effect of transceiver cost increases by adding functions for PtMP connections.

C. *Cost Calculation Models*

Fig. 2(a) shows a cost calculation model for the conventional PtP based Extended ROADM network. The calculation model consists of one Exchange node, two ROADM nodes, N units of transceiver as user terminals and one Edge DC connected to ROADM node #1 as a minimum configuration of the network. The Exchange node and ROADM nodes are connected to each other to provide direct optical connections. For simplicity, the Exchange node, which interconnects the network to core or other metro networks, and the fibers between the Exchange node and each ROADM node are not included in the calculations (these parts are shown as the dashed lines in Fig. 2(a)). The fiber lengths from user terminals to the ROADM node, between each ROADM node and from ROADM node ♯1 to DC are defined as L_1, L_2, and L_3, respectively. Here, we assume 100/200G-class digital coherent transceiver as the transceiver placed in user premise and edge DC. Therefore, it is expected that the architecture uses duplex fiber-optic cables and ports for each section.

Fig. 2(b) shows a configuration of the ROADM node assumed here. While several CDC-ROADM configurations are likely, this paper adopts the ROADM node architecture consisting of large-scale optical switches and arrayed wavelength guides (AWGs) from the viewpoint of its scalability, as discussed in ref. [9]. To assume long-haul transmission, Erbium doped fiber amplifiers (EDFAs) are placed at the top of AWGs for each direction. The transmitted signals from other nodes are demultiplexed by AWG. Then, the optical switch drops the signals to any access fiber port since each access fiber transmits just a single wavelength in this configuration. Additionally, the optical switch contains loopback ports to provide direct optical connection between each users accommodated in the same ROADM node.

Fig. 3(a) shows the cost calculation model for proposed PtMP based Extended ROADM network. The differences from the configuration shown in Fig. 2(a) is optical aggregation by the 1:X power splitter in the access sections. Thus the number of fibers connected to the ROADM node is reduced by 1/X. That saves not only the fiber costs but also the required number of ports on optical switches for access fiber accommodation, ROADM node and Exchange node interconnects, loopback function and DC connection. Here, we define the fiber length between user terminals and 1:X power splitters as L_x. Fig. 3(b) shows the configuration of the ROADM node that offers PtMP topology. The main difference is the use of WSS instead of AWG to drop/add multiple wavelengths for any port so as to realize flexible WDM connection in the access fiber.

Based on the calculation models above, we evaluate the cost per user, C_{USER}, which is the sum of fiber and equipment costs divided by the number of users. The formula for calculating C_{USER} is developed as follows.

$$C_{USER} = \frac{1}{N}\left(C_{ACCESS} + C_{METRO}\right) \ , \tag{1}$$

$$C_{ACCESS} = C_{TRANSCEIVER} * N + 2 * C_{FIBER} * \left(L_x * N + (L_1 - L_x) * \frac{N}{X}\right) + 2 * C_{SPLITTER} * \frac{N}{X}, \ , \tag{2}$$

$$C_{METRO} = C_{ROADM-NODE} * 2 + 2 * C_{FIBER} * \left(L_2 + L_3 * \frac{N}{X} * \gamma_1\right) + C_{TRANSCEIVER} * \frac{N}{X} * \gamma_1 \ , \tag{3}$$

where C_{ACCESS} is total costs of the user transceivers and the fibers from the users premise to each ROADM node as shown in equation (2), and $C_{SPLITTER}$ is 0 for the case of PtP calculation. C_{METRO} is total equipment cost from the ROADM node to the DC as shown in equation (3). As shown in equation (2), C_{ACCESS} is the sum of N transceivers, N fibers in the section before the aggregation point, and N/X fibers after the aggregation point. Here, the number of power splitter branches, X, is 1 for the PtP based network. The C_{METRO} in equation (3) is the sum of the costs of two ROADM nodes, the fibers connected to the L2 and L3 sections, and the transceivers placed at the DC. The cost of each ROADM node, $C_{ROADM-NODE}$, is given by

$$C_{ROADM-NODE} = C_{SW} * \left(2 + 2 * \frac{N}{X} * (1 + \gamma_1 + \gamma_2)\right) + C_{Agg} * 2 * \frac{N}{X} + C_{EDFA} * 2 \ . \tag{4}$$

$C_{ROADM-NODE}$ is calculated from the costs of optical switch and AWGs/WSSs and EDFAs. The costs of the optical switch can be calculated the multiplexing the price per port of C_{sw} and required number of ports for each configuration (see Fig. 2(b) and Fig. 3(b)). Here, the connection to the DC and the loopback connection are provided in the ratio of γ1 and γ2 for the fiber connected from the access side. Since the equipment of the concentrator differs between PtP and PtMP, different port unit costs were used for the calculation (equation (5)).

$$C_{Agg} = \begin{cases} C_{MUX}, & (PtP) \\ C_{WSS}, & (PtMP) \end{cases} \ . \tag{5}$$

From the above equation, it can be confirmed that the cost reduction efficiency of applying the proposed architecture depends on the number of power splitter branches X.

The costs of each component are summarized in Table 1. Some of the costs of components shown in Table 1 are relative costs normalized by the cost of an EDFA as shown in ref. [10]. Costs for fiber and transceivers not mentioned in ref. [10] refer to the actual market value [11]. Here, $C_{SPLITTER}$ is same as C_{MUX} for the simplification. The parameters for the calculations are shown in Table 2. These were determined based on the CPS use case.

Table.1 Component Costs

Variable	Component	Rel.cost
C_{FIBER}	FIBER (per km)	0.05x
C_{EDFA}	EDFA	x
$C_{TRANSCEIVER}$	Transceiver	22x
C_{SW}	Optical Switch (per port)	0.3x
C_{WSS}	1 × 20 WSS (per port)	0.4x
C_{MUX}	AWG	0.004x

Table.2 Calculation Parameters

Variable	Value
N	100
L_1	40
L_2	20
L_3	10
L_x	1
X	4,8,16
γ_1, γ_2	0.5

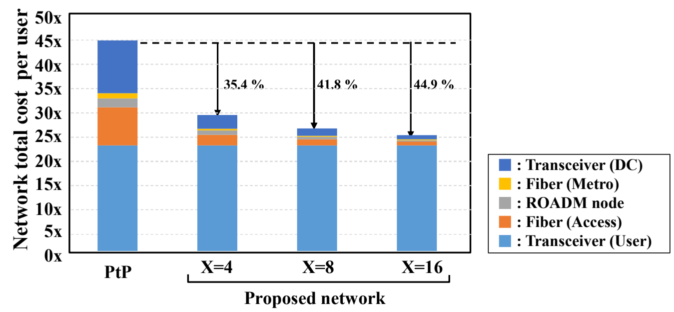

Fig.4 Cost-effectiveness by applying PtMP

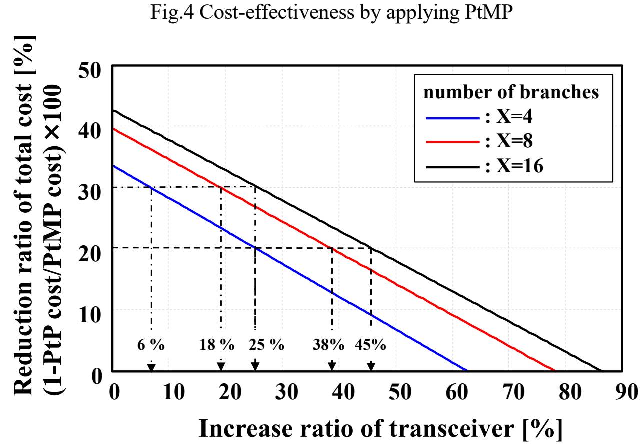

Fig.5 Transceiver Cost's impact on Cost Reduction

III. Numerical Results

A. Analysis of Total Network Cost

Fig. 4 shows the network cost calculation results for the PtP and the proposed PtMP architecture as functions of the number of power splitter branches X. Here, X was 4, 8 or 16. It was confirmed that the proposed network can reduce the network total cost per user (C_{USER}) by 35.4 % compared to the PtP architecture when X was set to 4. Increasing the value of X, increases the cost reduction effect, with a cost reduction of about 41.8% when X is 8 and 44.9% when X is 16.

The analysis focused on each element of network cost, and the element with the highest cost reduction ratio due to PtMP was the cost of fiber in the access section, which was reduced by about 72.1% for X= 4. The distance L_x to the aggregation point has a strong influence on the cost reduction, and in this calculation, L_x was small compared to L_1, so most of the fiber in the access section could be aggregated, resulting in a high reduction ratio. Moreover, the reduction in the number of transceivers installed in the DC by applying PtMP architecture can significantly contribute the reduction in total cost. The reason for this is thought to be that the transceivers used in the cost calculation are much more expensive than the other devices.

B. *Analysis of Transceiver Cost*

Focusing on the total cost of the proposed network, our results confirm that the user side transceiver accounts for about 70 % of the entire cost. The cost calculation results in Fig. 4 assume that PtP and PtMP have the same transceiver cost. However, the transceiver's cost is actually expected to increase with the extension to cover PtMP connections. Therefore, we analyzed the impact of total cost reductions in proposed architecture assuming increases in transceiver cost. Fig. 5 shows the reduction ratio of total cost with respect to the relative increase in transceiver cost. The blue, red, and black lines plot the reduction ratio of total cost for the number of power splitter branches X =4, 8, 16, respectively. Cost reduction can be achieved by keeping the increase in transceiver cost below 62 % when the number of power splitter branches X is set to 4. In addition, it found that for X values of 8 and 16, the total cost reduction of the proposed architecture compared to the PtP architecture can be achieved if the increase ratio of transceiver cost is less than 77 %, and 86 %.

Finally, we evaluated the permissible increase ratio of transceiver cost of the proposed architecture with regard to the targeted total cost reduction compared to the PtP architecture. If the targeted total cost reduction of 20 % is assumed, the increase ratio of transceiver cost must be kept below 25 %, 38 %, and 45 % for X values of 4, 8, and 16, respectively. For the targeted total cost reduction of 30 %, the increase ratio of transceiver cost must be kept below 6 %, 18 %, and 25 % for X values of 4, 8, and 16, respectively. The design procedure is to set the targeted reduction ratio of the total cost according to the deployed services and applications, and then determine the number of power splitter branches after considering the increase ratio of transceiver cost due to the extension to cover PtMP connections.

IV. CONCLUSION

An optical network configuration extending ROADM-based metro-access converged optical networks to cover PtMP topology was proposed; network costs were calculated and compared. The cost calculation results showed that PtMP reduced costs by about 35.4 % assuming the aggregation of 4 users. The cost reduction effect increased with the number of users aggregated, and the cost reduction effect increased to 44.9 % with the aggregation of 16 users. An analysis was also conducted to determine the impact of the increase in transceiver costs due to the addition of functions for PtMP connections. The results of the analysis showed that a 30 % cost reduction was possible even with a 25 % increase in transceiver costs by converting up to 16 branches to PtMP. These cost calculation results reveal the cost benefits of implementing the proposed architecture of PtMP for ROADM-based networks.

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