Photonic Sub-Lambda Transport: An Energy-Efficient and Reliable Solution for Metro Networks

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***Abstract*—Telecom carriers need to reduce operational expenditures (OPEX) to reduce total network cost. Such OPEX include power consumption, maintenance, and repair related costs, all of which must be considered, especially when providing various network services nationwide. This paper thus presents the Photonic Sub-Lambda transport network (PSL network), an energy-efficient and reliable optical network architecture for metro networks. Numerical results reveal that the PSL network can simultaneously reduce power consumption by 30%+, failure-recovery operations by 40%+, and repair costs by 80%+ compared with reconfigurable optical add/drop multiplexer (ROADM)-based networks.**

Keywords—optical network architecture; metro network; operational expenditures; numerical analysis

I. Introduction

The transport networks of telecom carriers generally consist of a large amount of transport equipment deployed in thousands of office buildings [1, 2]. Such buildings are located everywhere from densely populated urban areas to sparsely populated rural ones for providing nationwide network service coverage. Moreover, such transport networks consist of many metro and core networks, and metro networks are more numerous and have much more equipment deployed in them than core ones (e.g., by two orders of magnitude each). Furthermore, telecom carriers need to deal with ever-diversifying user requirements while keeping both capital expenditures (CAPEX) and operational expenditures (OPEX) under control [3], especially in metro networks.

So far, telecom carriers have applied evolving optical transmission technologies and packet switching technologies, which reduce CAPEX per transported bit, to their networks. However, on-going OPEX are currently becoming more and more important than initial CAPEX for telecom carriers. For instance, it is indicated that yearly OPEX are now typically 2–5 times higher than CAPEX [4]. Note that OPEX in transport networks can be divided into several categories, such as continuous cost resulting from power consumption and space, maintenance and repair, service provisioning, and service management [5]. Business process optimization and automation of operations with SDN/NFV technologies have been widely investigated for OPEX savings [6, 7], and these methods can effectively save on service provisioning and management related OPEX. However, continuous power consumption, maintenance, and repair related OPEX (i.e., the major contributors to network OPEX in many cases) remain to be tackled [7]. Naturally, such OPEX in metro networks can be considerable when operating 1k-building scale network infrastructure. Therefore, in addition to SDN/NFV efforts, a promising metro network architecture is needed that not only further reduces CAPEX but also lowers power consumption and suppresses maintenance/repair frequency in order to reduce total network cost.

To meet this need, this paper presents the Photonic Sub-Lambda transport network (PSL network), an optical network architecture that not only requires low CAPEX but also offers energy-efficiency and reliability. The basic concept of the proposed architecture has already been presented [8], but our previous study [8] focused only on CAPEX reduction. In contrast, this paper describes how the PSL network can reduce power consumption, maintenance, and repair related OPEX and extensively analyzes such OPEX. Specifically, the PSL network consumes less power and has lower failure frequency than traditional metro networks since it minimizes O/E/O conversions and leverages optical passive devices. Moreover, numerical results quantitatively clarify the OPEX benefits of the PSL network.

This paper is organized as follows. In Sec. II, we describe the conventional metro networks and summarize some related work. Section III presents our PSL network in detail. Then we show and discuss the results of numerical analysis in terms of power consumption, maintenance, and repair related OPEX in Sec. IV. Finally, we provide conclusions in Sec. V.

II. Metro Network Architectures and Related Work

Metro networks are basically aggregation networks between several access and core networks. Whereas limited numbers of buildings (i.e., nodes) in urban cities are interconnected by optical links in core networks, metro networks aggregate/distribute various traffic demands between access and core networks. Naturally, metro networks are more numerous and have more equipment deployed in them than core networks. Note that traffic volume to be accommodated in metro networks strongly depends on the area: there are large differences in traffic volume between rural and urban areas.

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Today, two main architectures have been widely deployed in metro networks: the reconfigurable optical add/drop multiplexer (ROADM)-based wavelength-routed network and the electronic-switch based opaque network. The former can often waste lambda capacity since traffic volume can be smaller than rigid and coarse-grained path bandwidth, which can result in high CAPEX. On the other hand, the latter enables flexible resource utilization, but O/E/O conversion and electronic processing are required in every node, which can lead to high power consumption. Thus, neither can optimize both CAPEX and power consumption.

From an operational point of view, redundant configurations and failure-recovery operations must be executed to maintain service quality. Note that component failures are inevitable, and telecom carriers need to conduct numerous failure-recovery operations, especially in metro networks, when operating 1k-building scale networks. In general, such failure-recovery operations in transport networks require human intervention and transportation to/from buildings in which the failed equipment is deployed. This can be a significant cause of OPEX, hence a metro network architecture that has lower network-failure frequency would be useful. However, in the abovementioned conventional network architectures, end-to-end paths traverse multiple optical or electronic switches (active components) at every node. Thus, the failure rate of such switches affects end-to-end reliability and network-failure frequency. Their failure rates are not negligible, so both component failure rates and number of active components used must also be considered to minimize total network costs.

Several optical metro networks have recently been proposed [9–12]. Although these solutions can flexibly utilize optical fiber capacity while reducing electronic processing, the component cost of high-end devices such as high-speed optical switches needs to be considered, especially when traffic volume to be accommodated is small. This is mainly because expensive solutions cannot suppress CAPEX per transported bit in small-traffic areas. Moreover, the failure rate of high-end devices and the power consumption of corresponding drivers must be considered to suppress OPEX. Also, an "open" optical transport solution is now actively being discussed [13], which has the potential to prevent vendor lock-in scenarios and reduce CAPEX. However, a new OPEX factor of integrating various equipment of various vendors needs to be considered. Furthermore, the architectural change from the current networks is marginal and cannot lead to significant OPEX savings. Therefore, to drastically reduce not only CAPEX but also OPEX even in small-traffic areas, a new network architecture is needed, which is presented in the next section.

III. Photonic Sub-Lambda Transport Network (PSL Network)

The PSL network is intended to aggregate various services' traffic from geographically separated nodes in a low-CAPEX, energy-efficient, and reliable way. For achieving this, time division multiplexing in the optical domain with optical passive devices is utilized, which enables resources to be flexibly utilized without electronic switching or sophisticated components. An outline of the PSL network is shown in Fig. 1,

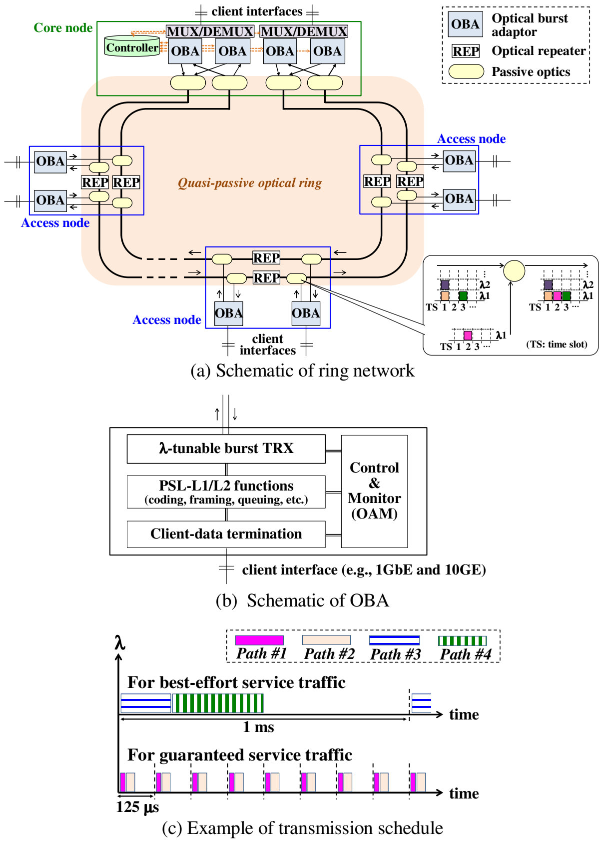


Fig. 1. Outline of PSL network.

where a particular node (core node) is connected to the core network, while the other nodes (access nodes) are connected to access networks. As shown in Fig. 1, this network mainly consists of a quasi-passive optical ring, optical transceiver (TRX) modules, and electronic functions. Note that quasi-passive means that some access nodes require optical repeaters (REPs) for supporting transmission distance in metro networks. Every node has optical passive devices (e.g., couplers and arrayed waveguide gratings (AWGs)) and optical burst adaptors (OBAs; see Fig. 1(b)) that encapsulate the traffic from client interfaces in an optical burst and execute an optical burst transmission. To avoid optical burst collisions, the controller at a core node manages a burst transmission schedule. An example of such a schedule is illustrated in Fig. 1(c), in which best-effort service traffic and guaranteed service traffic is simultaneously accommodated while multiple wavelength resources are utilized. This collision avoidance mechanism enables multiple bursts/paths to be multiplexed in the optical domain with optical passive devices that consume no power and have quite a long lifetime. As a result, resources can be shared across many paths while minimizing O/E/O conversions and electronic functions such as header processing, buffering, and electronic switching. Moreover, the number of OBAs required at each node can be flexibly determined to meet traffic conditions, which allows right-sized solutions and pay-as-you-grow designs. Thus, the PSL network can use fewer TRXs than

ROADM-based networks, which can lead to lower CAPEX, power consumption, and failure frequency.

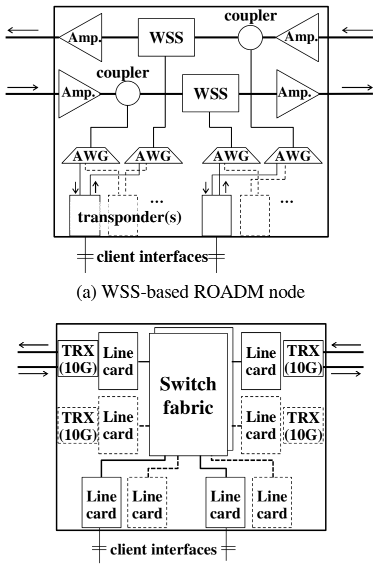
It is important to note that optical burst transmission is already a mature technology in passive optical network (PON) systems in access networks. In addition, the capacity of PON systems is continuously increasing, and emerging PON technologies such as next-generation PON stage 2 (NG-PON2) [14] are making WDM burst transmission feasible for practical use. NG-PON2 systems and related devices are now commercially available. Therefore, in the PSL network, commodity low-power PON devices such as TRXs and LSIs can be used instead of proprietary components. Also note that conventional optical burst amplification technologies (e.g., [15]) can be utilized for longer-reach optical burst transmission while using standard EDFAs. Hence, the PSL network can also be a highly practical solution for flexible metro networks.

IV. Power Consumption and Failure-Recovery Related Cost Evaluation

This section evaluates power consumption and failure-recovery related costs to quantify the OPEX benefits of the PSL network through numerical analysis. In the following, we first describe the assumed network model including detailed node architectures of the PSL network and comparative networks. Second, we compare network power consumption of the PSL network to those of comparative networks to evaluate the energy efficiency of the PSL network. We then estimate failure-recovery related costs in large-scale network infrastructure where a number of metro networks are in operation to verify how effectively the PSL network reduces OPEX.

A. *Network Model*

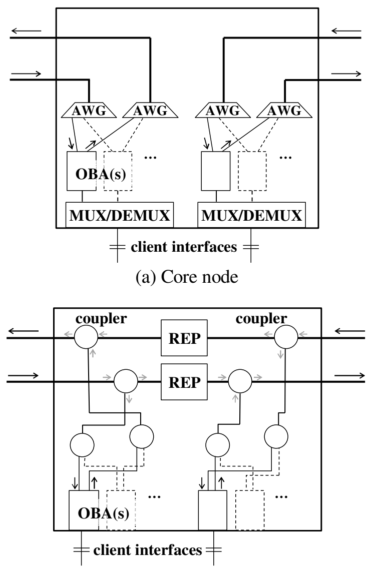
In this paper, we basically assume a 9-node bi-directional ring network with 1 core node and 8 access nodes. Traffic is assumed to flow between each core and access node pair, where the volume of each flow is static and uniformly distributed. Note that a protection switching function is assumed to be implemented in external routers/switches connected to transport equipment to simplify the transport layer, just as in previous work [16]. Specifically, data duplication and select are executed at such routers/switches, and transport networks simply provide two disjoint paths to each traffic demand. Moreover, we select a ROADM-based network and a packet transport network (PTN) using multiprotocol label switching - transport profile (MPLS-TP) as comparative architectures, both of which are already used in metro networks. Simplified ROADM and PTN nodes are illustrated in Fig. 2. As shown in Fig. 2(a), a ROADM is assumed to be a wavelength selective switch (WSS)-based architecture and does not have colorless, directionless, and contentionless (CDC) functionality. In PTN nodes, the number of line cards and required switching capacity strongly depend on traffic volume to be accommodated. Additionally, node architecture in the PSL network is depicted in Fig. 3, which shows how to use optical passive devices. As shown in Fig. 3, AWGs are utilized in core nodes since traffic is aggregated to core nodes from access nodes and more wavelengths than access nodes need to be handled. On the other hand, optical couplers are utilized for multiplexing and distribution in access nodes. Note that optical filters equipped at receivers of OBAs select and extract the desired data signals, just as in PON systems. Each access node in the PSL network is assumed to be equipped with REPs for simplicity. In addition, we used the component cost, power consumption, and mean time between failure (MTBF) values in Table I, on the basis of previous work [17–21]. Note that OBAs in the PSL network are assumed to be implemented with PON devices, and the effect of forward error correction (FEC) (e.g., RS (248, 216)) is considered.



(a) WSS-based ROADM node

(b) PTN node

Fig. 2. Comparative architectures.



(a) Core node

(b) Access node

Fig. 3. Node architecture in PSL network.

TABLE I. COST, POWER CONSUMPTION, AND MTBF VALUES OF EACH COMPONENT

Components				Relative cost	Power consumption	MTBF
Common	Optical coupler			0.6	0	12,000,000 h
	Amplifier			15	12 W	1,000,000 h
	AWG (1 : N)			0.3×N	0	4,000,000 h
ROADM	10G transponder			18.75	50 W	350,000 h
	WSS			37.5	30 W	250,000 h
PTN	Switch fabric[a]			1.45 /10G	10 W /10G	400,000 h
	10G line card			9.84	50 W	350,000 h
	1G×10 line card			1.87	40 W	350,000 h
PSL network	Core node	OBA	10G burst TRX	2.5	2.5 W	500,000 h
			L1/L2 LSI	5	6 W	450,000 h
		MUX/DEMUX[a]		1 /10G	10 W /10G	400,000 h
	Access node	OBA	10G burst TRX	2.5	2.5 W	500,000 h
			L1/L2 LSI	0.6	3 W	450,000 h
		REP		40	100 W	1,000,000 h

[a] Component cost and power consumption depend on switching or MUX/DEMUX capacity.

B. Power Consumption Evaluation

We evaluate network power consumption by multiplying power consumption of each component by the required number of components under the given condition. Note that the ratio of power consumption to total transmission capacity is a widely used metric suitable for core networks but not metro networks since traffic volume in metro networks covering rural areas may be much smaller than the overall transmission capacity of high-capacity systems. The calculated power consumptions in Fig. 4 show that the PSL network can achieve the lowest power consumption of the three architectures. The results show that the PSL network can reduce power consumption by more than 30% compared with ROADM-based networks when traffic volume per access node is smaller than 2 Gbps or larger than 10 Gbps, even when power-hungry REPs are used in all access nodes. This is due to leveraging optical passive devices, sharing TRXs, and avoiding the use of proprietary transponders. Also note that PTNs can be more energy-efficient than ROADM-based networks when traffic volume is quite small, though power consumption of PTNs sharply increases as the traffic volume increases. However, the PSL network can share resources as flexibly as a PTN while reducing the amount of electronic processing and consumes 80% less power than a PTN when traffic volume per access node is larger than 4 Gbps.

To clarify the power consumption structure and discuss the characteristics of the three architectures, Fig. 5 shows a breakdown of network power consumption when traffic volume per access node is set to 4, 8, and 12 Gbps. In a ROADM network, the main contributor to total network power consumption is the transponder, since the amplifier and WSS are optical devices that consume less power. In addition, in a PTN, the main contributor is the 10G line card, and power consumption of all components increases as traffic increases because of an opaque solution. On the other hand, in the PSL network, the main contributor is REP when traffic volume is small. Although the numbers of optical burst TRXs and L1/L2 LSIs increase as traffic increases, such components (PON devices) consume much less power than proprietary components, and resource sharing can suppress the required number of such components. As a result, total power consumption does not sharply increase when traffic increases. Note that reducing power consumption of REPs can naturally achieve more energy-efficient networks.

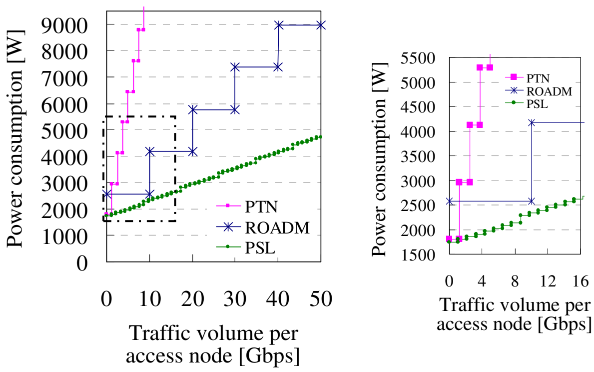


Fig. 4. Network power consumption of three architectures.
(Right graph is a closeup of the dash-dotted square in the main graph.)

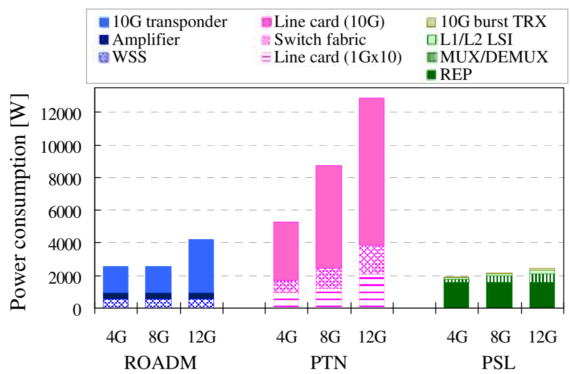


Fig. 5. Power consumption breakdown of three architectures for various traffic scenarios.

C. Failure-Recovery Related Cost Evaluation

We quantify the reduction of failure recovery operations and repair costs achieved with the PSL network and assess the impact of different network architectures on reliability. In this paper, individual component failures are assumed to occur randomly in accordance with MTBF values, and failed components need to be replaced. For simplicity, the repair costs are calculated by multiplying each component cost by the number of failures per component. A number of metro networks are assumed to be operated, where each network is a 9-node ring network as previously described and traffic volume per access node is set to 4 Gbps. Annual required numbers of failure recovery operations with various network numbers are shown in Fig. 6. The results verify that the PSL network using a quasi-passive optical ring can reduce operations by 40% compared with ROADM-based solutions. Thus, the PSL network can be very effective, especially when the number of operating networks is large, since the absolute number of the required recovery operations is naturally large. For instance, 350 operations can be eliminated per year when 500 networks are operated. This can directly save OPEX, though maintenance strategies and cost structures may vary among network operators. Moreover, such a reduction would be very beneficial for rural areas that generally occupy a large share of land [22, 23]. This is because smaller traffic volume tends to make cost per transported bit higher and long-distance transportation from network operation centers is required in many cases. Note that the PSL network requires 60% fewer failure recovery operations than a PTN, which has a larger number of active components. In addition, the calculated repair costs in Fig. 7 reveal that the PSL network can reduce repair costs by more than 80% compared with a ROADM network. This is due to not only reducing failure-frequency as shown in Fig. 6 but also leveraging mass-produced low-cost components instead of proprietary and/or high-end components. As a result, both failure recovery operations and repair costs can be reduced, which will lead to significant OPEX savings in transport networks of telecom carriers.

To demonstrate the impact of active/passive components on failure frequency (i.e., failure recovery operation), the contribution of each component is shown in Fig. 8 for traffic volumes per access node of 4, 8, and 12 Gbps when operating 500 networks. In a ROADM network, the contributions of the WSS and transponder are comparable when traffic volume is small, and the transponder becomes the main contributor as traffic increases. On the other hand, in a PTN, the main contributor is the 10G line card, the number of which to deploy strongly depends on traffic volume, just as in Fig. 5. Moreover, in the PSL network, the major contributors are naturally the 10G burst TRX and L1/L2 LSI, the sum of which is comparable to that of the transponder in a ROADM network. Thus, differences in the number of failure recovery operations between a ROADM network and the PSL network result from optical devices used (active WSS or passive coupler). In addition, the contribution of each component to repair costs in 500 networks is shown in Fig. 9. In a ROADM network, the main contributor is not the transponder but the WSS when traffic volume is small, which results from the difference in component cost. A PTN has smaller total repair costs than a ROADM network even though it has higher failure frequency since its well-matured components are low cost. Furthermore, in the PSL network, the main contributor to cost is REPs since other active components (i.e., TRXs and LSIs) are mass-produced, inexpensive PON devices. Therefore, we can conclude that leveraging a quasi-passive optical ring and PON devices effectively suppress both the failure frequency and repair costs.

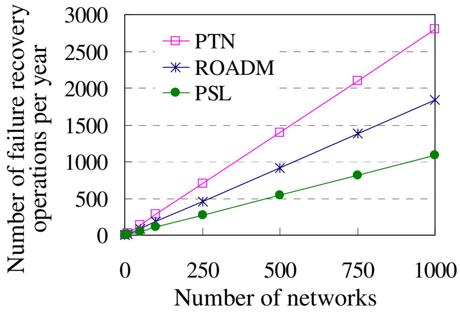


Fig. 6. Number of failure recovery operations in three architectures.

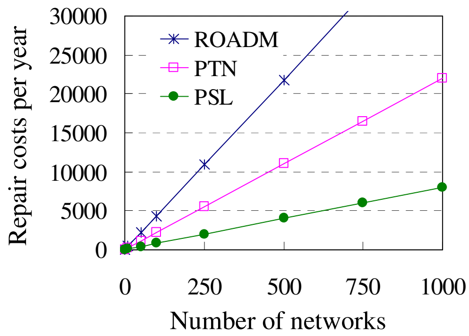


Fig. 7. Repair costs of three architectures.

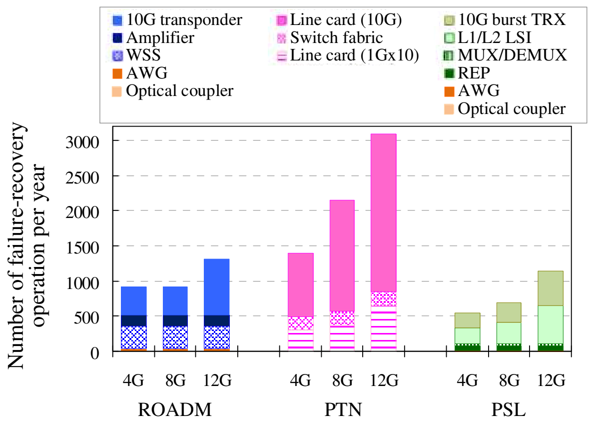


Fig. 8. Comparison of component failure frequency per year for various traffic scenarios.

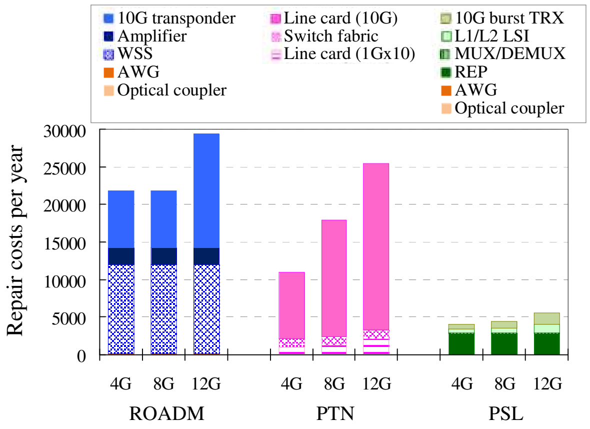


Fig. 9. Comparison of component repair costs per year for various traffic scenarios.

Remark: Most of conventional flexible metro networks leverage not only proprietary transponders (e.g., optical OFDM transponders in elastic optical networks (EONs) [12], optical OFDM burst transponders in a TISA network [11]) but also many active components (e.g., high-speed optical switches in a POADM based network [9] or a TSON [10], bandwidth-variable WSSs in EONs) at every node, leading to more failure-recovery operations. Such proprietary components generally have higher costs than mass-produced PON devices, leading to higher repair cost. Therefore, we can conclude that the PSL network offers lower OPEX than conventional flexible metro networks.

V. Conclusion

Telecom carriers need to optimize operational expenditures (OPEX), especially in metro networks, to cost-effectively provide various network services nationwide. In this paper, we presented a promising optical network architecture, the Photonic Sub-Lambda transport network (PSL network), as an energy-efficient and reliable solution for metro networks. The PSL network utilizes a quasi-passive optical ring, enabling lower power consumption and higher reliability than conventional optically or electronically switched architectures such as a reconfigurable optical add/drop multiplexer (ROADM)-based network and a packet transport network (PTN). We also provided numerical evaluations, which revealed that the PSL network can effectively reduce power consumption and failure recovery-related OPEX. Such results indicate that our PSL network can be effective even in 1k-building scale scenarios where accommodated traffic volume per node is smaller than wavelength capacity.

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