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Energy-efficient multiperiod planning of optical core network to support 5G networks

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Abstract

With the rapid growth of traffic and power consumption in information and communication technology industry for decades, improving energy efficiency has become a challenging issue in recent years. Especially, the pervasive access to Internet via mobile devices will cause wireless traffic volume increment by 1000+ times in near future, which is expected to be carried by the fifth generation ultradense cellular network. Following this trend, the core network where optical fibers are deployed to deliver aggregated traffic needs upgrading to accommodate the increasing traffic volume. To match with the traffic growth rate, we should conduct efficient network planning over multiple time periods. Moreover, considering the heterogeneity in the bandwidth requirements among various network services, flexible mixed line rate scheme is adopted in network provisioning. In this paper, we study the long-term multiperiod planning of optical core network by considering the traffic growth with the objective of high energy-efficiency. Three planning strategies, say All-period, Incremental, and End-of-Life, respectively, are studied and formulated as mixed integer linear programming models with the objective to minimize power consumption of optical core network. Given the estimation on the reduction of power consumed by various network devices, we can deploy network devices flexibly in each period through the optimization models. Performance of the proposed models is also evaluated and compared via case studies.

1 | INTRODUCTION

The high-speed development in information and communication technology has stimulated the exponential growth of end users and the emergence of bandwidth-intensive services, resulting continuously increasing traffic volume for decades. Although the growth is slowing down, it is estimated that the compound annual growth rate of Internet Protocol (IP) traffic will be kept at 22% from 2015 to 2020.[1] As common concerns about global energy crisis grow, the power consumption problem of information and communication technology industry, which is for approximately 2% to 4% of carbon dioxide emissions worldwide yearly, is becoming an increasingly important issue.[2]

One of the major contributors of the ever-increasing traffic volume is the pervasive access to Internet via mobile devices.[3,4] More specifically, the wireless traffic volume will increase by 1000+ times in the next decade. To provision the increasing wireless traffic, the fifth generation (5G) cellular network is becoming a promising technology and has received tremendous attentions in both telecommunication companies and academia.[5–7] Pioneering studies have been conducted to address the spectral efficiency, energy efficiency, and densification problems in 5G ultradense cellular network.[8–11] In 5G cellular networks, hundreds of multiple-input multiple-output antennas will be integrated into base stations and generate gigabit-level wireless traffic.[2,12] Besides, energy-efficient multiple-input multiple-output transmission or cooperation technologies can also be combined with cognitive mobile terminals, such as vehicles, to enhance quality of service and spatial diversity in mobile communications.[13–16] All backhaul traffic from small cells is aggregated at the macro-cell base station and forwarded to core network by optical fibers. This sharply increasing wireless traffic volume certainly contributes to a large part of the overall volume in core network.[17,18] Currently, the core networks are implemented by optical wavelength division multiplexing (WDM) technology, which can provide huge network transmission bandwidth. To satisfy the ever-increasing traffic volume, we made elaborations on extending the transmission bandwidth of each wavelength.[19,20] For instance, the bandwidth of each wavelength has been continuously improved from 10 to 40 Gbps and nowadays, 100 Gbps. Nonetheless, the network infrastructures for supporting huge network capacity are estimated to account for 12% of the total power consumption at present, and this portion will increase to 20% by 2020.[21,22] Hence, energy efficiency in optical core network needs to be improved correspondingly for better supporting 5G ultradense cellular network.[23–26]

Besides the ever-increasing network traffic volume and power consumption, network traffic also shows obvious heterogeneity in bandwidth requirements among different applications.[27–29] For example, some traffic demands may require transmission bandwidth that is less than 10 Gbps,[30–32] but some may require huge transmission bandwidth larger reach up to 20, 40, or even 100 Gbps.[33–35] Hence, it is not efficient to deploy high speed single-line-rate (SLR) scheme in optical core network, in which all the wavelengths on a fiber run at the same data rate, such as 100 Gbps. Resource will be wasted when applications with low-bandwidth demand are allocated to a whole wavelength excessively. Specifically, supporting a 10 Gbps traffic demand on a 100 Gbps wavelength channel leads to a waste of 90 Gbps. Although 100 Gbps SLR networks can supply huge capacity in a cost-efficient way due to volume discount effect (that is, a 100Gbps transponder is cheaper than the cost of 10 10 Gbps transponders), the cost-efficient solution is not always energy efficient. As an alternative solution to guarantee both cost-efficiency and energy-efficiency, the mixed-line-rate (MLR) scheme can be used to provision various traffic demands flexibly.[36]

More specifically, current 100 Gbps technology is expensive and with low energy-efficiency. In contrast, 10/40 Gbps technologies are less expensive with relatively higher energy-efficiency. As a compromising way to achieve both of cost-efficient and energy-efficient network configuration, network operators can use a mixed-line-rate scheme, in which more 10/40 Gbps wavelength channels and only a few 100 Gbps wavelength channels can be deployed to provision enough capacity and wait for the power reduction and maturity of 100 Gbps technology. For instance, we can divide the future few years, such as 12 years, into three 4-year periods. With the increasing periods, we assume that the price of 100 Gbps wavelength channels decreases at some fixed/changeable rate per period. In the early periods, when 100 Gbps wavelength channels are still expensive, we can deploy more 10/40 Gbps wavelength channels; while in the later periods, when 100 Gbps wavelength channels become relative cheaper, we can deploy relatively more 100 Gbps but less 10/40 Gbps wavelength channels.

Thus, deploying and upgrading network devices at appropriate time can reduce the overall power consumption in the whole life of networks.[37,38] There are various planning strategies: All-period planning, Incremental planning, and End-of-Life (EoL) planning.[39] Figure 1 illustrates the difference among the 3 planning strategies. In the example, there are 3 time periods, which start at the time point P_1, P_2, and P_3. The solid circles indicate the calculation time of planning. The arrowed lines point out the prediction of future traffic as well as power consumption of network devices. In All-period planning, the complete knowledge of the future traffic growth and power consumption reduction for all considered periods are estimated. The calculation of All-period planning is solved by a 1-step way and obtains an overall optimized solution for all periods. For Incremental planning, routing and dimensioning are calculated sequentially for each period via iterative single-period planning. Incremental planning may achieve optimal decision for a single period but can be less optimal than All-period planning for the same input. For EoL planning, the traffic demand in the last period is estimated, and the planning decision is made only once before the first period without considering the improvement on energy efficiency in future periods.

Although several literatures[39–42] have advocated multi-period planning, none of them has explored the energy-efficient issue. Meusburger et al[39] studied the All-period planning and Incremental planning to optimize network capital expenditure. Rival et al[40] proposed a heuristic algorithm for multi-period planning, aiming to adopting the benefits of elastic optical network over MLR in required transponders. Schupke et al[41] introduced various planning approaches by proposing optimization model. As a summary, the above literatures focused on 3 time-dependent input parameters: equipment costs, equipment characteristics, and demand requests. The impact of decreasing equipment cost, network with higher transmission bitrates, and different demand forecasts was evaluated in cost. Nag et al[42] analyzed and compared the energy-efficient and cost-efficient capacity upgrade problem. But the improvement on energy efficiency of network devices was not considered. There are other related works[43–48] that also improve the energy efficiency of mobile device. In this paper, we study the energy efficient planning problem of optical core networks by considering the traffic growth and the power consumption reduction of network devices. We propose MILP models for the 3 strategies with the objective of minimizing the network power consumption.

The rest of this paper is organized as follows. Section 2 describes the problems statement. Section 3 presents and explains the mathematical models; in Section 4, the MILP models are evaluated and compared via case study and the numerical results will be analyzed. Finally, we conclude the paper in Section 5.

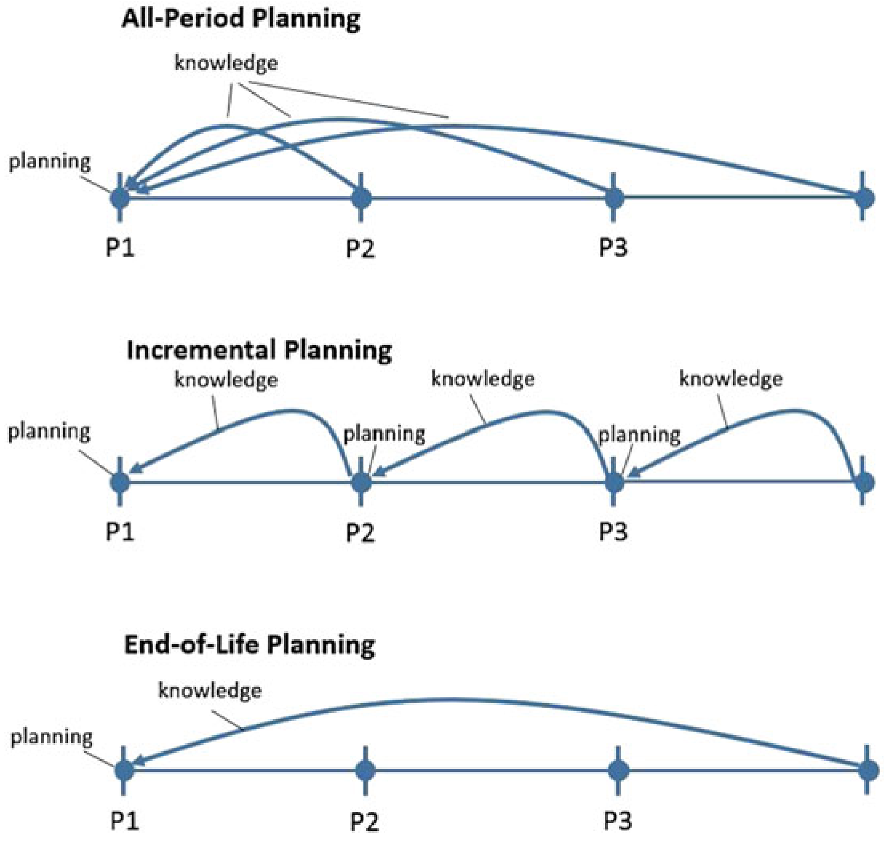


FIGURE 1 Network planning strategies

2 | PROBLEM STATEMENT

Transmitting IP packets directly over WDM channel (IP-over-WDM) is considered as a promising paradigm for optical core networks. IP-over-WDM network can be implemented in different ways, namely, IP with no Bypass, Transparent IP with Bypass and Grooming, Opaque IP with Bypass and Grooming, etc. Among these schemes, Transparent IP with Bypass and Grooming is the most energy efficient solution since the wavelengths can bypass at some intermediate nodes and low demand traffic flows can be groomed onto high-speed wavelength channels and transmitted integrally.[49] As a result, the electronic processing at some intermediate nodes is avoided and the utilization of wavelength channels is improved, inducing lower power consumption of whole network.

Figure 2 depicts the architecture of IP-over-WDM optical core networks and the accommodation of connection requests. IP-over-WDM network consists of 2 layers: electrical layer (IP layer) and optical layer (WDM layer). IP routers are deployed at network nodes and constitute the IP layer. The functions of IP router is to generate (as a source node), process (as a grooming node), and drop (as a destination node) IP services. They are connected with an optical cross-connect (OXC) via transponders, which are used to emit and terminate lightpaths. Two adjacent OXCs are connected by an optical fiber and responsible for switching lightpaths. Each optical fiber can support multiple wavelength channels. All the OXCs and optical fibers construct the WDM layer. IP packet flows are groomed at IP layer and then transmitted directly on optical WDM channels. Based on the transparent architecture with bypass and grooming functions, the major power contributors considered here are (1) IP routers, for electronically processing traffic when grooming is needed; (2) transponders, for establishing lightpaths; (3) router port, for interconnecting source and destination IP routers over lightpath; and (4) in-line optical amplifier, such as erbium doped fiber amplifier, for enabling optical signals to travel a long distance. Note that

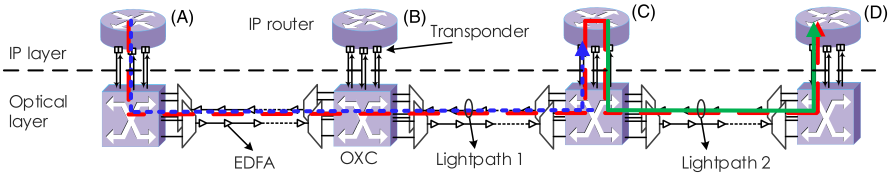


FIGURE 2 IP over wavelength division multiplexing network architecture. EDFA indicates erbium doped fiber amplifier; OXC, optical cross-connect

the electronic processing is dependent on the traffic amount. In contrast, the power consumption of transponders at a specific data rate is constant, and not relative to the actual traffic amount transmitting on lightpath.

The long-term network planning problem can be formulated as MILP model and stated as follows. The inputs include network topology, traffic matrix predicted for all periods in All-period planning, next period in Incremental planning, and the last period in EoL planning, respectively, and the power consumption of network devices estimated for each period. The goal is to find the optimal number of network devices to be deployed at the start of each period. Constraints which should be considered include (1) the optical transmission reach of a lightpath at certain line rate; (2) capacity of a lightpath at certain line rate; (3) the number of ports supported by a router; and (4) the number of lightpath supported by an optical fiber.

3 | MATHEMATICAL FORMULATION

3.1 | All-period planning

In All-period planning, the traffic growth and the power reduction of network devices for all considered periods are predicted, and input at the first (and only) planning point. The routing and grooming of all requests, the establishment of lightpaths, and deployment of network devices for each period are obtained in a 1-step computation. This strategy works as a global optimization for network operation time hence can achieve greater energy saving. However, the performance depends on the prediction accuracy. However, the prediction problem is out of the scope of this paper and will not be further discussed. The All-period planning MILP model is summarized as follows.

- Indexing rules:

(s, d)	The source and destination node pair of a traffic demand
(m, n)	A physical link
(i, j)	A virtual link which may consist of 1 or more lightpaths between node i and j

- Given:

$G(V, E)$	Network physical topology consisting of node set V and edge set E
λ_t^{sd}	Traffic demand from s to d at time period t, s, $d \in V$
$t \in T$	Set of time periods, t = 1, 2, …, |T|, where |T| is the number of time periods
$TM_t = \left[\lambda_t^{sd}\right]$	Traffic matrix at time period t
$R = [r_k]$	Available data rate set. k = 1, 2, 3, i.e., r_1= 10Gbps, r_2= 40Gbps, r_3= 100Gbps

- Notations and parameter:

$P_{tr}^{k,t}$	Power consumption of a transponder with data rate r_k at period t
P_{rp}^{t}	Power consumption of an IP router port at period t
P_{oa}^{t}	Power consumption of an optical amplifier at period t
P_{ep}	Power consumption for electronic processing per Gbps
C_k	Capacity of a wavelength channel with data rate r_k
L_{mn}	Distance of physical link (m, n)
L_k	Maximum optical reach of a lightpath at data rate r_k
A_{mn}	Number of Erbium-doped Optical Fiber Amplifiers (EDFAs) needed on physical link (m, n)
W	Maximum number of wavelength channels that 1 optical fiber can support

- Variables:

$f_{ij,t}^{sd}$	Traffic flow of λ_t^{sd} routed on virtual link (i, j) at time period t
$\mu_{mn}^{ij,k,t}$	Binary variable, equals to 1 if the virtual link (i, j) containing a lightpath with data rate r_k traverses physical link (m, n) at time period t
$VL_{ij,k,t}$	Number of lightpaths with data rate r_k on virtual link (i, j) at time period t
$PL_{mn}^{ij,k,t}$	Number of lightpaths at data rate r_k between node i and j, being routed through physical link (m, n) at time period t
$N_{i,t}^{k}$	Number of transponders with data rate r_k at node i during time period t
F_{mn}^{t}	Number of optical fibers deployed on physical link (m, n) during time period t

According to the notations defined, the objective is to minimize overall network power consumption during the whole time:

$$Minimize \;\; PC_{Net.whole}, \tag{A1}$$

where

$$\begin{aligned} PC_{Net.whole} = \sum_{t \in T} \Bigg\{ & P_{ep} \times \sum_{(i,j), i \neq s} \sum_{(s,d)} \left(f_{ij,t}^{sd} \times \lambda_t^{sd} \right) \\ & + (T + 1 - t) \times 2 \left(P_{tr}^{k,t} + P_{rp}^{t} \right) \cdot \sum_{k} \sum_{(i,j)} \left(VL_{ij,k,t} - VL_{ij,k,t-1} \right) \\ & + (T + 1 - t) \times P_{oa}^{t} \times A_{mn} \times \sum_{(m,n)} \left(F_{mn}^{t} - F_{mn}^{t-1} \right) \Bigg\}. \end{aligned}$$

The network power consumption and each component in period t are calculated as follows:

$$\begin{aligned} & PC_{Net}(t) = PC_{ep}(t) + PC_{tr}(t) + PC_{rp}(t) + PC_{oa}(t), \\ & PC_{ep}(t) = P_{ep} \times \sum_j \sum_{s, i \neq s} \sum_d \left(f_{ij,t}^{sd} \times \lambda_t^{sd} \right), \\ & PC_{tr}(t) = 2 \times P_{tr}^{k,t} \times \sum_k \sum_i \sum_j \left(VL_{ij,k,t} - VL_{ij,k,t-1} \right) + PC_{tr}(t-1), \\ & PC_{rp}(t) = 2 \times P_{rp}^{t} \times \sum_k \sum_i \sum_j \left(VL_{ij,k,t} - VL_{ij,k,t-1} \right) + PC_{rp}(t-1), \\ & PC_{oa}(t) = P_{oa}^{t} \times A_{mn} \times \sum_m \sum_n \left(F_{mn}^{t} - F_{mn}^{t-1} \right) + PC_{oa}(t-1). \end{aligned}$$

- Constraints:

$$\sum_{j \in N, j \neq i} f_{ij,t}^{sd} - \sum_{j \in N, j \neq i} f_{ji,t}^{sd} = \begin{cases} 1, & \text{if } i = s \\ -1, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix} \forall t \in T, \forall i \in V, \\ \forall (s, d) \end{matrix}, \tag{A2}$$

$$\sum_n PL_{mn}^{ij,k,t} - \sum_n PL_{nm}^{ij,k,t} = \begin{cases} VL_{ij,k,t}, & \text{if } m = i \\ -VL_{ij,k,t}, & \text{if } m = j \\ 0, & \text{otherwise} \end{cases} \quad \forall t \in T, \forall (i,j), \forall m \in V, \ \ \forall k \in K, \tag{A3}$$

$$\sum_{s \in V} \sum_{d \in V, d \neq s} f_{ij,t}^{sd} \times \lambda_t^{sd} \leq \sum_k C_k \times VL_{ij,k,t}, \quad \forall i,j \in V, \forall t \in T, \tag{A4}$$

$$PL_{mn}^{ij,k,t} \leq \mu_{mn}^{ij,k,t} \times M, \qquad \forall (i,j), \forall m,n \in V, \forall k \in K, \tag{A5}$$

$$\sum_{n \in V} \mu_{mn}^{ij,k,t} \leq 1, \qquad \forall (i,j), \forall m \in V, \forall k \in K, \forall t \in T, \tag{A6}$$

$$\sum_{m \in V} \sum_{n \in V} \mu_{mn}^{ij,k,t} \cdot L_{mn} \leq L_k, \quad \forall (i,j), \forall k \in K, \forall t \in T, \tag{A7}$$

$$\sum_k \sum_{(i,j)} PL_{mn}^{ij,k,t} \leq W \cdot NF_{mn,t}, \quad \forall (m,n) \in E, \forall t \in T, \tag{A8}$$

$$VL_{ij,k,t-1} \leq VL_{ij,k,t}, \qquad \forall i,j \in V, \forall k \in K, \forall t \in T, \tag{A9}$$

$$\sum_j VL_{ij,k,t} = N_{i,t}^k \qquad \forall i \in V, \forall k \in K, \forall t \in T, \tag{A10}$$

In the MILP model, equations A2 and A3 are the flow conservation constraints in grooming layer and optical layer, respectively. The connection request between source and destination nodes is serviced as an integral network flow and cannot be bifurcated. But multiple network flows can be groomed onto a common channel to use the capacity of wavelength efficiently. Constraint A4 guarantees that total traffic amount transmitting on all lightpaths between node i and j cannot beyond the capacity supplied by these lightpaths. Constraints A5 and A6 limit that only 1 physical path can be used for the routing of virtual link (i, j). Constraint A7 ensures that the length of a lightpath cannot beyond the maximum optical transmission reach for any data rate r_k. Equation A8 calculates the number of transponders at certain data rate r_k for each node. Constraint A9 guarantees that the maximum number of lightpaths supported by a physical link (m, n) cannot beyond the total number of wavelengths on fibers. Equation A10 calculates the number of transponders at node i. All constraints should be satisfied at any time period t.

3.2 | Incremental planning

Different from previous scheme, Incremental planning only needs the traffic and power consumption forecast for the next period. The calculation for each period is conducted just before the period starts (ie, there are |T| iterative calculations during the whole considered time horizon of network). Comparing to All-period planning, the prediction is more accurate based on updating information of traffic growth tendency and the devices on the market. If the same inputs are given, All-period can achieve lower bound of energy saving. But the computation of Incremental planning is simpler and faster to run. In the following section, we assume the same given conditions for all planning strategies. Note that the parameters and variables used in incremental planning model do not indicate period stamp. Hence, all notation and parameters shown in previous section need to remove the index, t, which indicates the period. (The definition and notations are not listed here because of the space limitation.) Moreover, the input of incremental planning should include the network dimensioning in previous period, eg, router port, optical fiber and amplifier, transponder deployment, and lightpaths, which are already set up. The information are obtained from the calculation in the previous iteration and stored, then input to the computation for the planning in the next period. These parameters are defined as follows.

- Parameter:

$PL'^{ij,k}_{mn}$	Number of lightpaths at data rate r_k between node i and j, being routed through physical link (m, n) in previous period
$VL'_{ij,k}$	Number of lightpaths with data rate r_k on virtual link (i, j) in previous period
F'_{mn}	Number of optical fibers deployed on physical link (m, n) in previous period
PC'_{rp}	Power consumed by IP router ports in previous period
PC'_{tr}	Power consumed by transponders in previous period
PC'_{oa}	Power consumed by EDFAs in previous period

The objective for incremental planning is to minimize the network power consumption in current period:

$$Minimize \qquad PC_{Net} \ , \tag{I1}$$

where

$$\begin{aligned} &PC = PC_{ep} + PC_{tr} + PC_{rp} + PC_{oa}, \\ &PC_{ep}(t) = P_{ep} \times \sum_j \sum_{s,i \neq s} \sum_d \left(f_{ij}^{sd} \times \lambda^{sd} \right), \\ &PC_{tr} = 2 \times P_{tr}^k \times \sum_k \sum_i \sum_j \left(VL_{ij,k} - VL'_{ij,k} \right) + PC'_{tr}, \\ &PC_{rp} = 2 \times P_{rp} \times \sum_k \sum_i \sum_j \left(VL_{ij,k} - VL'_{ij,k} \right) + PC'_{rp}, \\ &PC_{oa} = P_{oa} \times A_{mn} \times \sum_m \sum_n \left(F_{mn} - F'_{mn} \right) + PC'_{oa}. \end{aligned}$$

- Constraints:

$$\sum_{j \in N, j \neq i} f_{ij}^{sd} - \sum_{j \in N, j \neq i} f_{ji}^{sd} = \begin{cases} 1, & \text{if } i = s \\ -1, & \text{if } i = d \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix} \forall i \in V, \\ \forall (s,d) \end{matrix}, \tag{I2}$$

$$\sum_n PL_{mn}^{ij,k} - \sum_n PL_{nm}^{ij,k} = \begin{cases} VL_{ij,k}, & \text{if } m = i \\ -VL_{ij,k}, & \text{if } m = j \\ 0, & \text{otherwise} \end{cases} \quad \begin{matrix} \forall (i,j), \forall m \in V, \\ \forall k \in K \end{matrix}, \tag{I3}$$

$$\sum_{s\in V}\sum_{d\in V,d\neq s} f_{ij}^{sd}\times\lambda^{sd}\leq\sum_{k} B_k\times VL_{ij,k},\quad \forall i,j\in V, \tag{I4}$$

$$PL_{mn}^{ij,k}\leq\mu_{mn}^{ij,k}\times M,\qquad \forall(i,j),\forall m,n\in V,\forall k\in K, \tag{I5}$$

$$\sum_{n\in V}\mu_{mn}^{ij,k}\leq 1,\qquad \forall(i,j),\forall m\in V,\forall k\in K, \tag{I6}$$

$$\sum_{m\in V}\sum_{n\in V}\mu_{mn}^{ij,k}\cdot L_{mn}\leq L_k,\quad \forall(i,j),\forall k\in K, \tag{I7}$$

$$\sum_{k}\sum_{(i,j)} PL_{mn}^{ij,k}\leq W\cdot NF_{mn,t},\quad \forall(m,n)\in E, \tag{I8}$$

$$\sum_{j} VL_{ij,k}=N_i^k\qquad \forall i\in V,\forall k\in K, \tag{I8}$$

$$VL'_{ij,k}\leq VL_{ij,k},\quad \forall i,j\in V,\forall k\in K, \tag{I9}$$

$$\sum_{j} VL_{ij,k}=N_i^k\qquad \forall i\in V,\forall k\in K. \tag{I10}$$

In this MILP model, constraints are similar to those in the previous section without time stamp. Incremental planning model can only guarantee the optimality in each period.

3.3 | End-of-life planning

For the EoL planning, only the cumulative demand forecast for the last period is given as an input to the planning. The development of equipment in energy efficiency over the considered time horizon cannot be taken into account. The planning is a 1-time event and leads to an optimal overall solution for the last period. Since the EoL planning adopts the forecasted demand in the last period yet implements state-of-art network devices with low energy efficiency, over-provisioning problem exists in all periods except the last one. (That is, the necessary network devices for provisioning the traffic in the last period are computed so that traffic demand of all periods can be satisfied but the network devices are deployed at the beginning of the first period.) The objective is to minimize the overall network power consumption in the last period:

$$Minimize\quad PC_{Net,final}\ , \tag{E1}$$

where

$$\begin{aligned}
&PC_{Net,final}=PC_{ep,final}+PC_{tr,final}+PC_{rp,final}+PC_{oa,final},\\
&PC_{ep,final}=P_{ep}\times\textstyle\sum_j\sum_{s,i\neq s}\sum_d\left(f_{ij}^{sd}\times\lambda_{final}^{sd}\right),\\
&PC_{tr,final}=2\times P_{tr}^{k}\times\textstyle\sum_k\sum_i\sum_j VL_{ij,k},\\
&PC_{rp,final}=2\times P_{rp}\times\textstyle\sum_k\sum_i\sum_j VL_{ij,k},\\
&PC_{oa,final}=P_{oa}\times A_{mn}\times\textstyle\sum_m\sum_n F_{mn}.
\end{aligned}$$

Constraints:

$$\sum_{j\in N,j\neq i} f_{ij}^{sd}-\sum_{j\in N,j\neq i} f_{ji}^{sd}=\begin{cases}1, & \text{if } i=s\\ -1, & \text{if } i=d\\ 0, & \text{otherwise}\end{cases}\qquad \forall i\in V,\forall(s,d), \tag{E2}$$

$$\sum_{n} PL_{mn}^{ij,k}-\sum_{n} PL_{nm}^{ij,k}=\begin{cases}VL_{ij,k}, \text{if } m=i\\ -VL_{ij,k}, \text{if } m=j\\ 0, \text{otherwise}\end{cases}\quad \begin{matrix}\forall(i,j),\\ \forall m\in V,\forall k\in K\end{matrix}, \tag{E3}$$

$$\sum_{s\in V}\sum_{d\in V,d\neq s} f_{ij}^{sd}\times\lambda_t^{sd}\leq\sum_{k} B_k\times VL_{ij,k},\quad \forall i,j\in V,\forall t\in T, \tag{E4}$$

$$PL_{mn}^{ij,k}\leq\mu_{mn}^{ij,k}\times M,\qquad \forall(i,j),\forall m,n\in V,\forall k\in K, \tag{E5}$$

$$\sum_{n\in V}\mu_{mn}^{ij,k}\leq 1,\qquad \forall(i,j),\forall m\in V,\forall k\in K, \tag{E6}$$

$$\sum_{m\in V}\sum_{n\in V}\mu_{mn}^{ij,k}\cdot L_{mn}\leq L_k,\quad \forall(i,j),\forall k\in K, \tag{E7}$$

$$\sum_{k}\sum_{(i,j)} PL_{mn}^{ij,k}\leq W\cdot F_{mn},\quad \forall(m,n)\in E, \tag{E8}$$

The EoL planning model optimizes power consumption in the last period. The deployed network devices, the routing, grooming, and establishment of lightpaths can be obtained to satisfy the forecasted demand in the final stage of network operation. However, all of these network resources are underused before the last period starts. Once deployed and put into use, the devices consume energy. In addition, the decision is made in early stage when network devices are with low-energy efficiency, resulting in more energy wasted.

4 | NUMERICAL RESULTS

The numerical results will be shown and analyzed in this section. To evaluate the performance of the proposed models, we apply 3 schemes to case study. All the results are obtained via optimization software IBM ILOG CPLEX Optimization Studio Version 12.6 on the computer with Intel Core 2 (TM) i5–2500 CPU (3.30 GHz) and 8 GB RAM.

4.1 | Network topology and parameters

We apply the proposed MILP models to the 6N9L network shown as Figure 3, and the European COST239 network shown as Figure 4. In both figures, 1 link connects to 2 nodes by a pair of optical fibers. The number adjacent to link is the

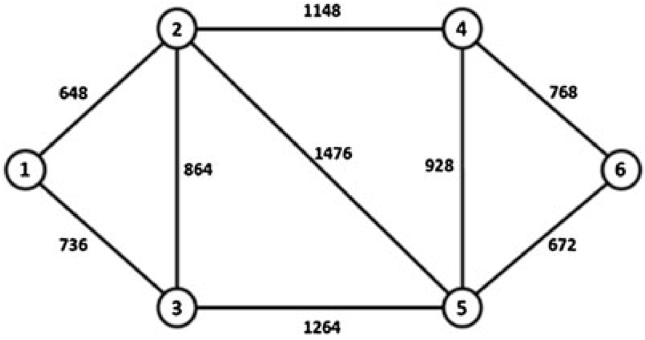


FIGURE 3 6N9L network topology

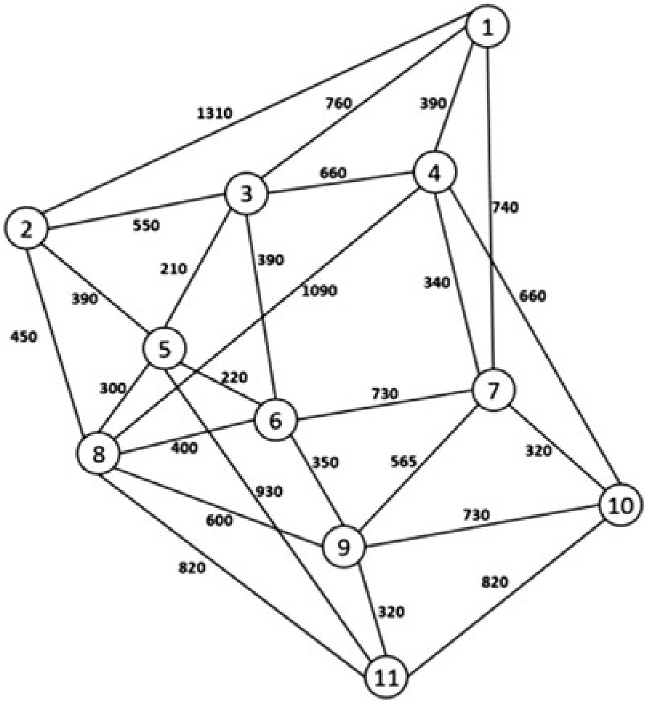


FIGURE 4 COST239 network topology

length of physical link in Km. Mixed-line-rate network can support 10/40/100 Gbps line rates. Single-line-rate network with line rate 100 Gbps is indicated as SLR100G. The optical transmission reach of 10, 40, and 100 Gbps lightpath is 3200, 2200, and 1880Km, respectively. Referring to some literatures and data sheet of commercial products,[50–52] the power consumption of network devices (in Watt) at different periods is given in Table 1.

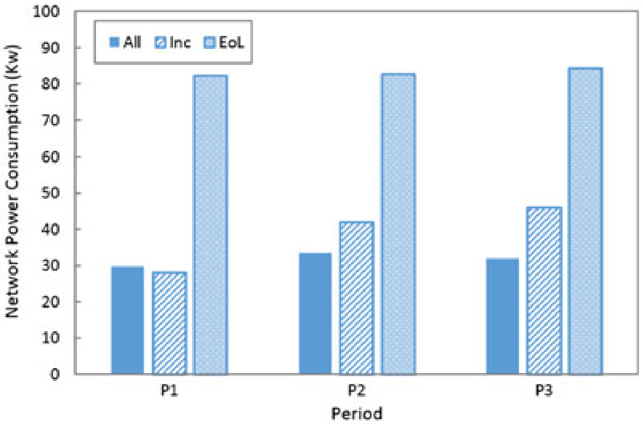
4.2 | Results and analysis

Figure 5 (a,b) compares the power consumption of MLR and SLR100G scenarios among different planning strategies for 6N9L network. The aggregate traffic load in the first time period is 600 Gbps. We consider 3 periods in our case studies. The following planning is made every 5 years with the annual traffic growth rate around 20%. Generally, MLR network achieves less power consumption than SLR100G network during all time periods. Among 3 planning strategies, All-period planning achieves the highest energy efficiency, while EoL planning performs the worst. The detailed results of different planning strategies based on 6N9L network are shown from Tables 2–7. In the following tables, the unit of power consumption items is Watt.

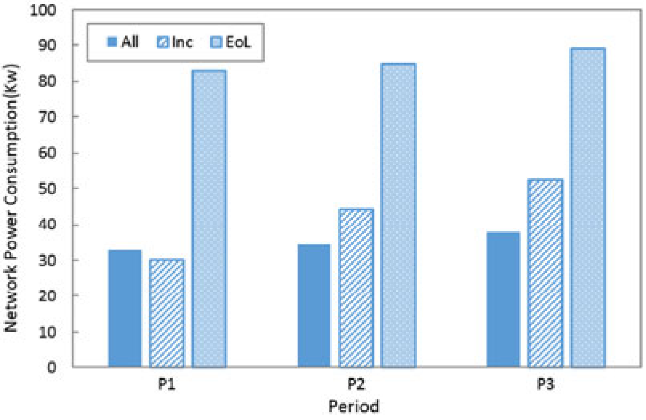
TABLE 1 Power consumption of devices

Device		P1	P2	P3
Transponder	10 Gbps	50	20	4
	40 Gbps	150	50	6
	100 Gbps	350	100	10
Router port		440	120	20
Optical amplifier		50	25	10
Electronic processing		25		

Based on All-period planning, SLR100G network consumes 11%, 3%, and 18% more power than MLR network during period P_1, P_2, and P_3 respectively. The extra power consumption by SLR100G network is 7%, 5%, and 14% at each period in the case of incremental planning. Under EoL scheme, SLR100G network consumes 1%, 2%, and 6% more power than MLR network. With full knowledge of traffic growth and reduction of device power consumption over all periods, All-period planning can make optimal decision in the full extent of time. As time goes by and traffic increases,



(A) MLR network



(B) SLR100 network

FIGURE 5 Power consumption of 6N9L network. A, MLR network. B, SLR100 network

TABLE 2 Results of MLR based on All-period (6N9L)

		P1	P2	P3
No. of transponders	10 Gbps	0	0	12
	40 Gbps	4	8	38
	100 Gbps	18	38	68
PC_Tr		6900	9100	9628
PC_rp		9680	12560	14000
PC_ep		5150	3625	0
PC_oa		8000	8325	8425
Network_PC		29730	33610	32053
Total network PC		95393		

TABLE 3 Results of SLR100 based on All-period (6N9L)

	P1	P2	P3
No. of transponders	20	44	92
PC_Tr	7000	9400	9880
PC_rp	8800	11680	12640
PC_ep	10000	5250	7200
PC_oa	7100	8125	8125
Network_PC	32900	34455	37845
Total network PC	105200		

TABLE 4 Results of MLR based on Incremental (6N9L)

		P1	P2	P3
No. of transponders	10 Gbps	0	4	22
	40 Gbps	18	30	44
	100 Gbps	10	28	64
PC_Tr		6200	10580	11572
PC_rp		12320	19760	22360
PC_ep		2950	1125	0
PC_oa		6650	10475	12105
Network_PC		28120	41940	46037
Total network PC		116097		

TABLE 5 Results of SLR100 based on Incremental (6N9L)

	P1	P2	P3
No. of transponders	22	50	92
PC_Tr	7700	12700	13620
PC_rp	9680	15680	17520
PC_ep	4650	3500	7200
PC_oa	8000	12325	14145
Network_PC	30030	44205	52485
Total network PC	126720		

TABLE 6 Results of MLR based on End-of-Life (6N9L)

		P1	P2	P3
No. of transponders	10 Gbps	0	0	0
	40 Gbps	32	32	32
	100 Gbps	68	68	68
PC_Tr		28600	28600	28600
PC_rp		44000	44000	44000
PC_ep		400	1000	2400
PC_oa		9150	9150	9150
Network_PC		82150	82750	84150
Total network PC		249050		

TABLE 7 Results of SLR100 based on End-of-Life (6N9L)

	P1	P2	P3
No. of transponders	92	92	92
PC_Tr	32200	32200	32200
PC_rp	40480	40480	40480
PC_ep	1200	3000	7200
PC_oa	9100	9100	9100
Network_PC	82980	84780	88980
Total network PC	256740		

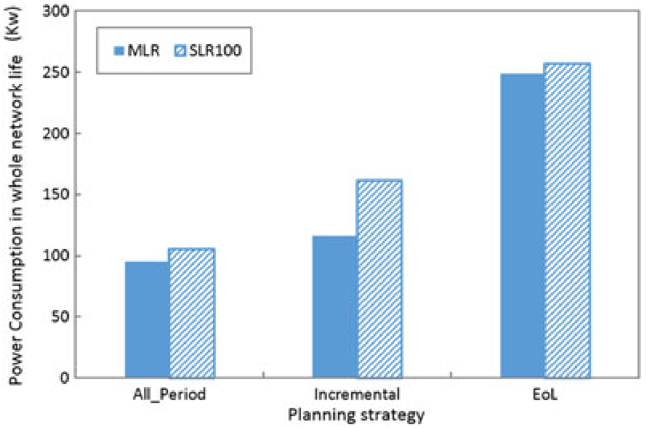


FIGURE 6 Comparison on the power consumption between mixed-line-rate (MLR) and single-line-rate (SLR)100 6N9L network

the difference between All-period and other 2 schemes becomes larger. On the other hand, EoL planning over-provisions at the first period. In the following periods, network power consumption increases slightly, resulting from the growth of demand actually carried in network.

Figure 6 compares the overall power consumption during the whole time horizon of network operation between MLR and SLR100G based on different planning strategies for 6N9L network. It is obvious that MLR always outperforms SLR100G in power consumption. Among 3 planning strategies, again, All-Period is the most energy efficient planning strategies. In addition, more benefit of MLR over SLR100G can be found under Incremental planning. With the capability to adopt transponders at various data rates, Incremental planning can exploit the flexibility of MLR at each calculation round.

Figure 7 compares the necessary number of ports for MLR and SLR100G under different strategies of 6N9L network. The number of deployed ports by EoL is fixed from P_1 to P_3. All-Period and Incremental require much less ports in first 2 periods, comparing to EoL scheme, while in the final period EoL requires less ports. This is due to the nature of EoL, which optimizes the network for the last period. Additionally, MLR deploys slightly more ports than SLR100G scheme. The difference under incremental planning is much larger than the other 2 strategies.

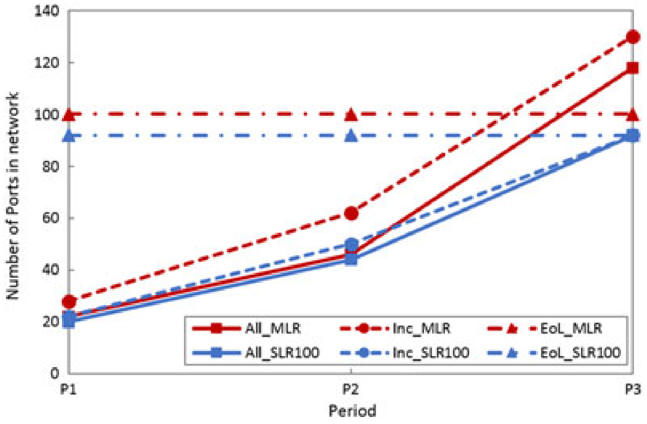
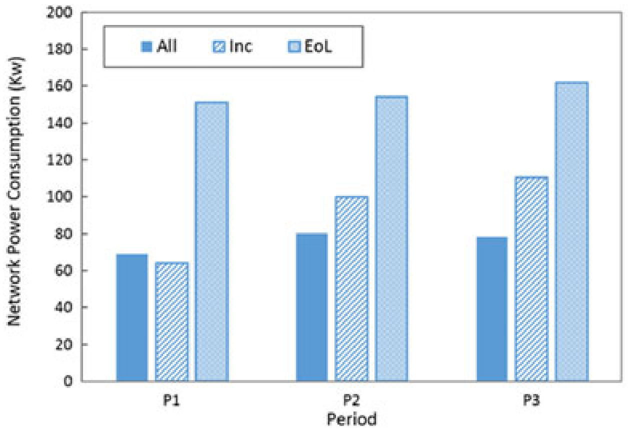
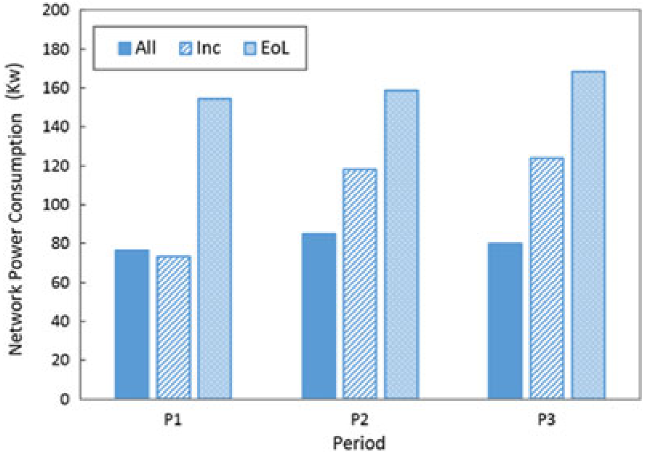


FIGURE 7 Comparison on the number of ports required for 6N9L network

Figure 8 (a,b) compares the power consumption of MLR and SLR100G scenarios among different planning strategies for COST239 network. The aggregate traffic load in the first time period is 1 Tbps. Other parameters are set the same as that for 6N9L network. Mixed-line-rate network achieves less power consumption than SLR100G network during all time periods. Among 3 planning strategies, All-period planning achieves the highest energy efficiency, while EoL planning performs the worst. The detailed results of different planning strategies based on 6N9L network are shown from Tables 8–13. Based on All-period planning, SLR100G consumes 11%, 6%, and 2% more power than MLR network during the periods P_1, P_2, and P_3 respectively. The extra power consumption by SLR100G network is 14%, 18%, and 12% at each period in the case of Incremental planning. Under EoL scheme, SLR100G network consumes 2%, 3%, and 4% more power than



(A) MLR network



(B) SLR100 network

FIGURE 8 Power consumption of COST239 network. A, MLR network. B, SLR100 network

TABLE 8 Results of MLR based on All-period (COST239)

		P1	P2	P3
No. of transponders	10 Gbps 40 Gbps 100 Gbps	12 36 28	24 52 56	112 112 104
PC_Tr		15800	19640	20832
PC_rp		33440	40160	44080
PC_ep		8650	8250	0
PC_oa		11000	12100	13340
Network_PC		68890	80150	78252
Total network PC		227292		

TABLE 9 Results of SLR100 based on All-period (COST239)

	P1	P2	P3
No. of transponders	64	108	304
PC_Tr	22400	26800	28760
PC_rp	28160	33440	37360
PC_ep	14000	12375	0
PC_oa	11700	12450	13790
Network_PC	76260	85065	79910
Total network PC	241235		

TABLE 10 Results of MLR based on Incremental (COST239)

		P1	P2	P3
No. of transponders	10 Gbps 40 Gbps 100 Gbps	8 48 16	24 92 40	28 172 156
PC_Tr		13200	22280	24984
PC_rp		31680	50400	57520
PC_ep		7900	4125	0
PC_oa		11400	23000	27940
Network_PC		64180	99805	110444
Total network PC		274429		

TABLE 11 Results of SLR100 based on Incremental (COST239)

	P1	P2	P3
No. of transponders	68	160	308
PC_Tr	23800	39800	42880
PC_rp	29920	49120	55280
PC_ep	8700	8125	0
PC_oa	10700	20850	25790
Network_PC	73120	117895	123950
Total network PC	314965		

TABLE 12 Results of MLR based on End-of-Life (COST239)

		P1	P2	P3
No. of Transponders	10 Gbps	4	4	4
	40 Gbps	44	44	44
	100 Gbps	136	136	136
PC_Tr		54400	54400	54400
PC_rp		80960	80960	80960
PC_ep		2200	5500	13200
PC_oa		13300	13300	13300
Network_PC		150860	154160	161860
Total network PC		466880		

TABLE 13 Results of SLR100 based on End-of-Life (COST239)

	P1	P2	P3
No. of transponders	176	176	176
PC_Tr	61600	61600	61600
PC_rp	77440	77440	77440
PC_ep	2800	7000	16800
PC_oa	12400	12400	12400
Network_PC	154240	158440	168240
Total network PC	480920		

MLR network. Since COST239 network is of larger size and with heavier load, the difference in power consumption among 3 strategies is increased, comparing to 6N9L network.

Figures 9 and 10 compared the overall power consumption and required ports between MLR and SLR100G based on different planning strategies for COST239 network.

Comparing the deployment of transponders between MLR and SLR100G according to time periods, we can find that in the last period, 10 Gbps transponders are still deployed even though the advantage of 10 Gbps in power consumption itself is not obvious (Table 1). Even though the demand in P_3 is 6 times of that in P_1, the variation of demand among different s-d pairs is large. Moreover, traffic grooming that has to be done in electrical layer consumes huge energy. Large capacity of 100 Gbps channel means high possibility of grooming because: First, more requests can be groomed onto 100 Gbps; second, 100 Gbps lightpath has shorter transmission reach, leading to more network ports and power consumption.

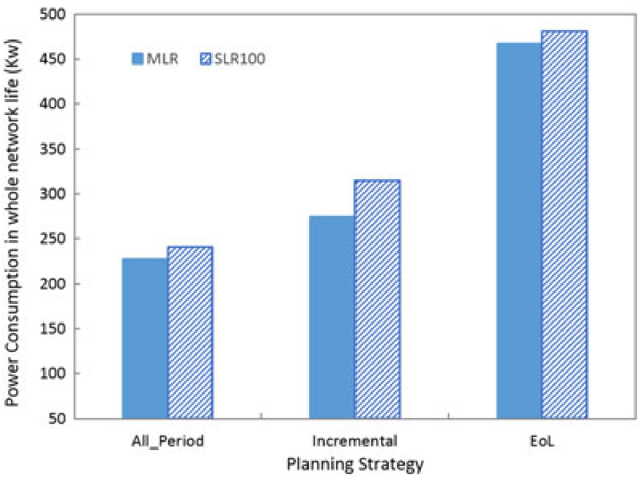


FIGURE 9 Comparison on the power consumption between mixed-line-rate (MLR) and single-line-rate (SLR)100 COST239 network

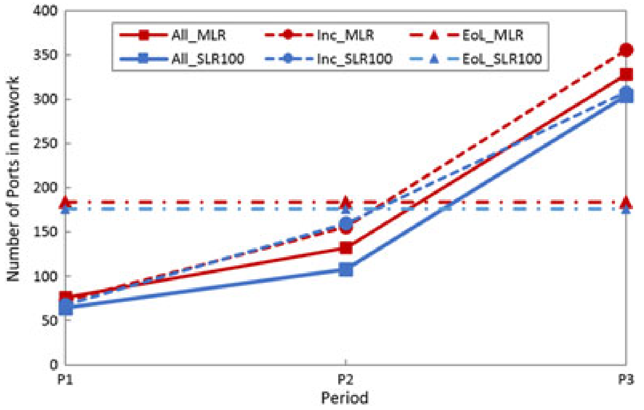


FIGURE 10 Comparison on the number of ports required for COST239 network. MLR indicates mixed-line-rate; SLR, single-line-rate

5 | CONCLUSIONS

In this paper, we studied the energy efficient multiperiod planning problem in optical core networks for supporting 5G traffic. By considering the traffic growth and the improvement in energy efficiency of network devices, we proposed MILP models for 3 planning strategies, All-period, Incremental, and EoL planning, with the objective to minimize the network power consumption. In addition, MLR scheme and the quality of transmission were considered in the formulation. The models were applied and compared via case studies. The numerical results showed that All-period planning could achieve highest energy efficiency among 3 strategies. Moreover, MLR network achieved lower power consumption than SLR100G based on all planning strategies.

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