EDFA Active-sleep Transition Frequency and EDFA Occupancy Aware Dynamic Traffic Provisioning for Energy-efficient IP-over-EON

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***Abstract*—In dynamic IP-over-elastic optical network (IP-over-EON), maintaining devices into sleep mode during off-peak hours and activating them during peak hours offers reasonably high energy efficiency compared to maintaining all devices always active. However, the approach may increase active-sleep mode transition frequency and occupancy of erbium-doped fiber amplifier (EDFA), which result in frequent temperature variation and temperature increase, respectively, thereby negatively impacting EDFA lifetime. In this paper, we propose an auxiliary graph-based EDFA active-sleep mode transition frequency and EDFA occupancy aware dynamic traffic provisioning heuristic to improve energy-efficiency in IP-over-EON. The proposed method does not violate the predefined upper thresholds of active-sleep mode transition frequency and occupancy in EDFA. We judiciously employ flexibility of sliceable bandwidth variable transponder and virtualized elastic regenerator, and use suitable transmission option(s) depending on the arriving traffic demand and existing network condition. The simulation result shows that the proposed heuristic method improves energy-efficiency and average EDFA lifetime compared to the shortest path based method, wherein traffic demands are accommodated in the existing/new lightpaths set up between respective source-destination node pairs following the shortest geographical distances.**

***Index Terms*—Elastic optical network; Energy efficiency; Dynamic traffic provision; Active-sleep transition frequency; EDFA occupancy.**

I. Introduction

Adaptation of new technologies, such as micro-services, distributed data-center networks, machine-to-machine (M2M) communication, cloud based gaming and 5G networking is contributing to high traffic growth in backbone network. To cope up with the rapid growth in traffic, conventional backbone network infrastructure needs to be upgraded with respect to improving adaptiveness, flexibility and ability to accommodate high data rate lightpaths, improving energy-efficiency and reducing cost per bit. Thus, widely used fixed-grid wavelength division multiplexing (WDM) network architecture is expected to be replaced by elastic optical network (EON) architecture as the next-generation backbone network architecture [1].

To improve device utilization, EON supports different lightpaths which are simultaneously set up from the same sliceable bandwidth variable transponder (SBVT) using optical layer grooming. The lightpaths may have different modulation formats, data rates, spectral efficiencies, transmission reaches and optimal launch powers. Optical signal pertaining to a lightpath degrades with distance traveled due to attenuation and accumulation of linear/non-linear impairments in fiber. Thus, lightpaths propagating over long distance may require regeneration(s) at intermediate node(s) to maintain the required quality of transmission at the receiving ends. Regeneration of lightpaths are executed at IP core routers or regenerators through 4R regeneration, i.e., re-shaping, re-timing, re-amplification and re-modulation. The authors in [2, 3] propose and demonstrate the architecture and working principle of virtualized elastic regenerator (VER) which enables simultaneous regeneration of multiple lightpaths in EON with distance-adaptive modulation format conversion and routing of lightpaths by merging frequency-slots when routes of the lightpaths after regeneration are the same.

IP layer interconnected with EON layer constitutes the IP-over-EON architecture that enables enhanced network flexibility in traffic provisioning. To improve energy efficiency, agile traffic demands from access network with different bandwidth requirements are provisioned through lightpaths judiciously exploiting the flexibility of SBVTs and VERs in IP-over-EON [4–6]. EON architecture is more energy-efficient compared to the fixed-grid WDM architecture ([7] for detailed survey). Zhang *et al.* show that the use of SBVT can reduce power consumption (PC) compared to using non-sliceable BVT, wherein only one lightpath can be generated/terminated in a non-sliceable BVT [4]. In [8], an adaptive modulation and regeneration aware routing algorithm is presented for dynamic traffic scenario, wherein a traffic demand may arrive or leave the network at any time instant. In [6], we explore an auxiliary graph (AG)-based algorithm for dynamic traffic provisioning in IP-over-EON and show that the use of regenerators reduces PC. In [5], AG-based energy-efficient network planning and traffic provisioning algorithms are explored where transmission option selection [i.e., selection of capacity, number of data slots, maximum transparent reach (MTR) and PC] of lightpaths, routing and spectrum allocation (RSA) of lightpaths, electrical and optical layer traffic grooming and traffic routing subproblems are taken into consideration.

The strategy of maintaining as many devices into sleep mode during off-peak hours and activating them with increased traffic load in peak hours offers reasonably low average PC compared to the scenario when all devices are always active [9]. The above-mentioned sleep mode based strategy is the commonly used strategy with reference to reducing PC. Even though, sleep mode based operational strategies provide improved energy-efficiency compared to always-active approach [10], several researchers show that the sleep mode based strategies may not be beneficial in terms of network device lifetime [11]. Chiaraviglio *et al.* investigate the impact of periodic transitions between active and sleep modes on network devices [12]. In sleep mode based techniques, cyclic temperature variation may occur in the devices due to frequent switching between active and sleep states, which eventually increases the chance of failure, thereby impacting reliable network performance [13]. Thus, operational expenditure (OpEx) using sleep mode based techniques may even be higher than always-active approaches, due to increase in maintenance cost of devices to such extent that it suppresses the savings achieved due to reduced PC [14].

Wiatr *et al.* present device reliability models as a function of temperature variation and average device occupancy, and measure mean device lifetime decrease due to variation in device occupancy and active-sleep switching frequency [13]. Natalino *et al.* study optical line amplifier (OLA) lifetime-aware network management for fixed-grid WDM network architecture, and with reference to improving energy-efficiency develop a mixed linear integer programming (MILP) model with an upper threshold limit on the mean lifetime decrease of OLA [15]. Natalino *et al.* also explore an optimization model to obtain operator's profit considering revenue from service, electricity cost and failure management cost due to lifetime degradation of line cards and erbium-doped fiber amplifiers (EDFAs) [14]. Natalino *et al.* propose temperature cycle aware traffic provisioning strategy that results into low blocking probability of traffic demands at the expense of increased PC in fixed grid WDM networks [16].

The above discussion shows that device occupancy, active-sleep mode transition frequency, device lifetime and overall PC are closely related issues with reference to dynamic traffic provisioning in IP-over-EON. To the best of our knowledge, these issues for IP-over-EON have not been adequately addressed till date. In this paper, we propose an AG based EDFA active-sleep frequency- and EDFA occupancy-aware dynamic traffic provisioning heuristic for energy-efficient IP-over-EON. The proposed approach focuses on energy-efficiency during accommodation and termination of traffic demands. The heuristic also keeps track of active-sleep mode transition frequency and lightpath occupancy in EDFA and maintain them within respective predefined upper threshold limits to improve EDFA lifetime. The network architecture is flexible and includes SBVT and regenerator to support simultaneous multiple lightpath transmission/reception and regeneration, respectively, from single device only. Electrical layer traffic grooming, optical layer traffic grooming and use of regenerator are judiciously exploited to improve energy-efficiency. We show numerical results for national knowledge network of India for different traffic loads.

The rest of the paper is organized as follows. In Section II, we describe network architecture, PC and device reliability model. The proposed heuristic scheme is presented in Section III. In Section IV, we discuss numerical results, and finally in Section V, we present conclusion and future works.

II. Network architecture, power consumption and device reliability model

An IP-over-EON may be represented by a graph with multiple nodes interconnected through optical fibers where each unidirectional fiber is used to carry traffic in one direction. As shown in Fig. 1, each node consists of one IP core router, multiple SBVTs, one bandwidth variable optical cross connect (BV-OXC) and multiple WDM terminals [5]. Some of the nodes may also be equipped with one or more regenerators. If needed, a lightpath enters regenerator from BV-OXC (through WDM terminal), gets regenerated, and again enters the BV-OXC (through WDM terminal) for onward transmission. Multiple access-side traffic streams may enter a node through

TABLE I: Multiple transmission options for a sub-transponder of an SBVT

Capacity (Gbps)	MTR (km)	Data Slot	PC (W)	Capacity (Gbps)	MTR (km)	Data Slot	PC (W)
40	600	1	154.8	100	600	1	198
	1900	1	183.6		1900	1	270
	2500	2	183.6		2500	2	270
	3000	3	183.6		3000	3	270
	4000	4	183.6		3500	4	270
200	500	1	333	400	500	4	432
	600	2	333		600	6	432
	750	3	333		750	8	432
	1900	4	432		1900	10	630
	2200	5	432		2200	12	630
	2500	6	432		2500	14	630

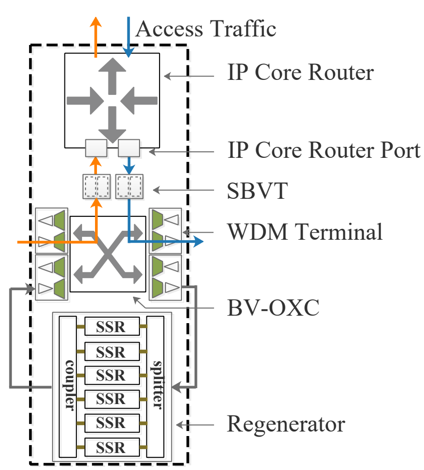

Fig. 1: An IP-over-EON node architecture with one regenerator attached to the BV-OXC.

ingress ports of the IP core router. We consider that each router port has the capacity of 400 Gbps and typically consumes 560 W power, inclusive of PC related to chassis overhead and other associated control and switching fabric cards [5]. Each router port is integrated with an SBVT which supports multiple sub-transponders. As shown in Table I, a sub-transponder has multiple transmission options with different capacity, number of data slots, MTR limits and necessary PC, where one frequency slot is 12.5 GHz [5, 17]. Each sub-transponder can be used to transmit/receive a lightpath using any of the multiple transmission options available with the SBVT. PC due to a lightpath transmission/reception is considered to be half of the PC of an active sub-transponder [4, 5]. The router ports (with each port accommodating an SBVT) are connected to a BV-OXC. The node in Fig. 1 has one regenerator (VER) attached to the BV-OXC, wherein the regenerator is constructed using a splitter, an array of spectrum selective regenerators (SSRs) and a coupler. Since regeneration of a lightpath is implemented through termination and generation of the lightpath, the PC for regeneration is considered to be same as the overall PC for generation and termination of the lightpath through sub-transponders, as shown in Table I. PC in a regenerator is the summation of PC for all lightpaths being regenerated therein, PC for the SSRs used and the overhead PC. We consider that PC for each SSR is 10 W and overhead PC is 25 W. A BV-OXC is connected to a fiber using a WDM terminal which has an elastic multiplexer (demultiplexer) followed (preceded) by a post-amplifier (pre-amplifier). An optical line amplifier (OLA) has two unidirectional optical amplifiers for amplification in both directions. OLAs are placed on a fiber with an interval of 80 km. We consider that each optical amplifier, i.e., pre-, post- and line-amplifier consumes 30 W power for each direction with 140 W power as overhead at each location [5, 18].

One of the major factors negatively impacting device lifetime is the operating temperature of the device [12, 19]. As per Arrhenius law, when a device is put into sleep mode, the device temperature reduces, thereby increasing its lifetime [12, 20]. However, in practice, a device cannot always be put into sleep mode; at the least, it needs to be made active when required. When a device is in active mode, following Joule's law, heat generated is proportional to PC, leading to increase in temperature [21]. PC can be modeled with respect to the device occupancy, i.e., utilization level of the device [13, 19]. Thus, it is important to reduce device occupancy to enhance device lifetime. In this paper, we consider improving EDFA lifetime due to its high recovery cost. EDFA lifetime depends on the utilization of EDFA, which in turn, depends on the number of lightpaths being amplified by it [19]. On the other hand, active-sleep cycle of a device creates cyclic temperature variation which leads to material fatigue that negatively impacts the device lifetime. Coffin-Manson model explains the impact on material degradation due to cyclic change in temperature, and it estimates the maximum number of temperature cycles a device can be subjected before failure [12, 22, 23]. Therefore, to reduce device failure due to material fatigue, we limit the variation in temperature by using an upper bound for the active-sleep switching frequency, which is considered to be the ratio of the number of mode transitions (i.e., transition from active mode to sleep mode and vice-versa) and the total observation time interval[1].

III. Heuristic Scheme

In this section, we present **E**DFA active-sleep mode transition **f**requency and EDFA **o**ccupancy **a**ware **d**ynamic traffic provisioning for **e**nergy-efficient **IP**-**o**ver-**EON** (EFOADE-IoE) heuristic. EFOADE-IoE focuses on energy-efficiency during accommodation and termination of traffic demands even though maintaining the maximum EDFA active-sleep transition frequency and EDFA occupancy within respective predefined threshold limits. A traffic demand is characterized by four attributes, viz., source, destination, bandwidth and service time, where source and destination represent the source and destination nodes of the traffic demand, bandwidth represents the requested bandwidth and service time represents the holding time of the traffic demand. The proposed heuristic has primarily two components: traffic demand accommodation and traffic demand termination. The pseudo code of the heuristic is shown in Algorithm 1.

With reference to accommodating a new/arriving traffic demand, first, based on the requested bandwidth, the capacity of the lightpath that may required to be set up from a free/unoccupied sub-transponder of an SBVT at the source node is set to the closest higher transmission capacity supported by a sub-transponder. We construct an AG, shown in Fig. 2, where a physical node is considered to be composed of an electrical layer auxiliary node (AN) A_E and multiple optical layer ANs, viz., A_1, A_2, etc., representing different available transmission options and connecting them using unidirectional edges [5]. The unidirectional edges may be [5]:

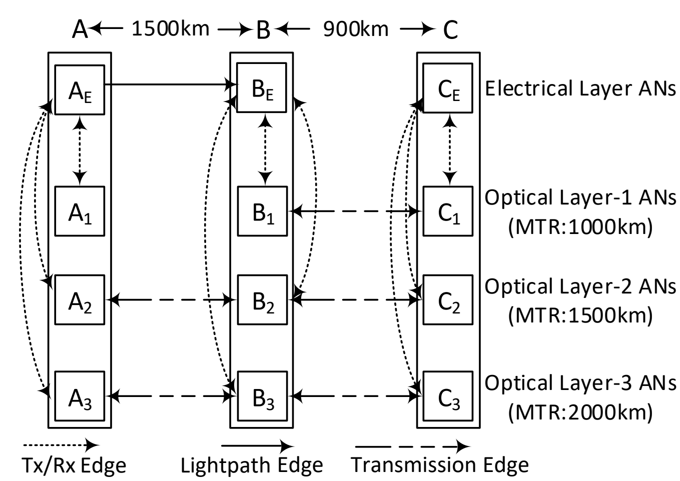

Fig. 2: Auxiliary Graph [5].

[1]In dynamic traffic scenario, a traffic demand may arrive or leave the network at any time instant. However, the proposed method addresses the arrival and departure events at the end of each equally spaced time interval (henceforth referred to as interval) only. The total observation time interval refers to the total number of intervals in the observation period.

(i) *Tx/Rx edge*: set up from (to) electrical layer AN to (from) an optical layer AN within the same physical node when the corresponding sub-transponder is available. The Tx/Rx edge weight represents the PC of IP core router and SBVT to transmit (receive) the lightpath,

(ii) *Lightpath edge*: set up between two electrical layer ANs of two different physical nodes in case a lightpath exists between them. Lightpath edge weight represents the PC to accommodate new traffic to an existing lightpath,

Algorithm 1: EDFA active-sleep mode transition frequency and EDFA occupancy aware dynamic traffic provisioning for energy-efficient IP-over-EON (EFOADE-IoE)

Traffic demand arrival:

Set the capacity of lightpath that may need to be set up between SD node pair.
AG is constructed.
k energy-efficient paths are identified and arranged in ascending order of PC.
for *each path* **do**
    Find the maximum EDFA occupancy.
    Find the maximum EDFA active-sleep mode transition frequency.
    if *maximum EDFA occupancy* and *maximum EDFA active-sleep mode transition frequency are within thresholds* **then**
        Select the path.
        Break.
    end
end
if *path is available* **then**
    if *Lightpath edge(s) appear in path* **then**
        Groom traffic demand in the existing lightpath(s).
    end
    if *Tx/Rx edge(s) appear in path* **then**
        Set up new lightpath(s).
    end
    Accommodate traffic demand.
    Update NRD.
else
    Block traffic demand.
end

Traffic demand departure:

Identify the lightpath(s) being used by the traffic demand.
if *the lightpath(s) do not carry any other traffic* and *maximum EDFA active-sleep mode transition frequency of associated fiber(s) is within threshold* α **then**
    Tear down the lightpath(s).
    Free up network resources.
else
    Remove the traffic demand from the lightpath(s).
end
Update NRD.

(iii) *Transmission edge*: set up between two similar type optical layer ANs of two different physical nodes if frequency slots are available in all fibers of the path and length of the path is within MTR of the related transmission option. Transmission edge weight represents the PC of optical amplifiers used on the fibers and the WDM terminals used at two ends.

In Fig. 2, the distances between physical nodes A and B, and B and C are considered to be 1500 km and 900 km, respectively. Different auxiliary graph edges: Tx/Rx edges A_E-A_1 (i.e., between A_E and A_1), A_E-A_2 etc., lightpath edge A_E-B_E and transmission edges A_2-B_2, A_3-B_3 etc. are shown. No transmission edge exists between A_1 and B_1 since MTR for optical layer-1 is less than the distance between A and B.

After the AG is constructed, k shortest paths, i.e., the most energy-efficient paths are identified over the AG (if available). The paths are arranged in ascending order of the related PC. For each possible path, the maximum EDFA occupancy and the maximum EDFA active-sleep transition frequency are computed. The maximum EDFA occupancy of a path is computed by the ratio of the maximum number of lightpaths (including the lightpath under consideration) accommodated in a constituent fiber of the path and the maximum allowable number of lightpaths that may be accommodated in a fiber. The maximum EDFA active-sleep transition frequency of a path is computed by the ratio of the maximum number of state transitions in a constituent fiber of the path and the number of elapsed intervals. The most energy-efficient path that satisfies both the predefined upper threshold limits, i.e., the EDFA active-sleep transition frequency threshold (α) and the EDFA occupancy threshold (β) is selected. If path is available and it contains Tx/Rx edge(s), new lightpath(s) is set up. If the path contains lightpath edge(s), the traffic is groomed with the traffic carried through the existing lightpath(s). Thereafter, network resource database (NRD) that maintains all details, such as the traffic demands accommodated, lightpaths set up and used (and available) resources in the network is updated. However, If no path is available, the traffic demand is blocked.

At the end of service time of a traffic demand, lightpath(s) used to accommodate the traffic demand are identified. If the lightpath(s) do not carry any other traffic demand and the maximum EDFA active-sleep transition frequency of the fiber(s) used by the lightpath(s) is within threshold α, the lightpath(s) are torn down and network resources are made free for future provisioning. If either of the previous conditions fails, only the traffic demand is removed from the lightpath(s). Finally, NRD is updated.

IV. Numerical analysis

We study performance of EFOADE-IoE heuristic for dynamic traffic scenario with national knowledge network (NKN) of India having 31 nodes and 81 fibers [24]. The fibers are considered to be laid along highways with distances obtained from Google map. Each fiber operates in C-band and each frequency slot has a width of 12.5 GHz. We consider that each node has five SBVTs wherein each SBVT has the capability to simultaneously support three lightpaths. Each of the 30%

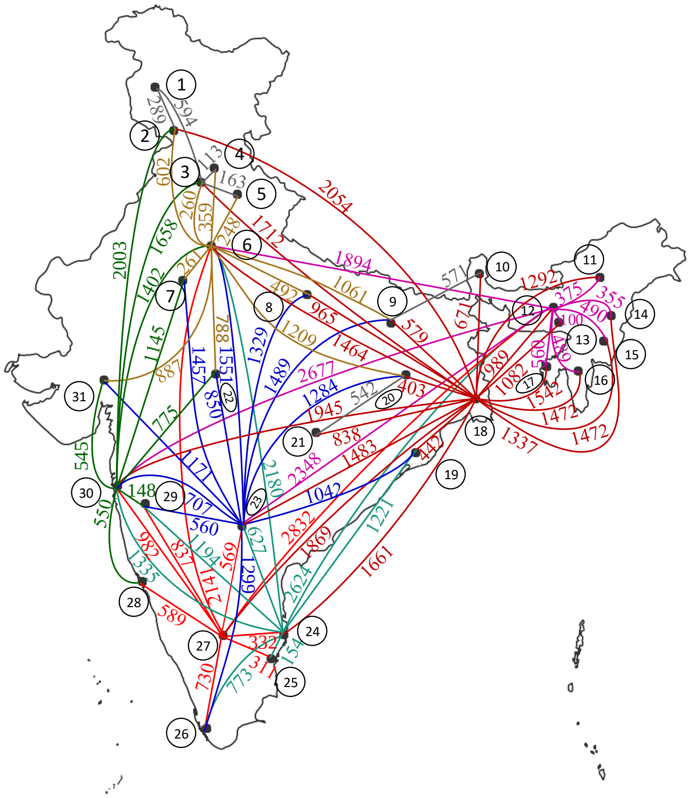

Fig. 3: 31-node NKN, India topology. Different colored links do not have any significance except improving readability [5].

highest degree nodes is equipped with three regenerators. For a given traffic demand, the source and destination nodes are selected with uniform random distribution, and the bandwidth is also selected using uniform random distribution within [5, $2X$-5] Gbps, where X(=160 Gbps) is the average bandwidth. Traffic demand arrival process follows poison distribution with arrival rate parameter λ and holding time follows exponential distribution with service rate parameter μ. To obtain result with a given traffic load, computed as λ/μ Erlang, we execute simulation with 10^5 number of traffic demands.

Results are evaluated for different scenarios using EFOADE-IoE method, viz., EFOADE-IoE with α=100% and β=100% [EFOADE (100,100)], EFOADE-IoE with α=50% and β=100% [EFOADE (50,100)], EFOADE-IoE with α=25% and β=100% [EFOADE (25,100)] and EFOADE-IoE with α=25% and β=5% [EFOADE (25,5)]. We compare performance in the above scenarios with that of the shortest path (SP) method, wherein an incoming traffic demand is accommodated in the existing lightpaths (if possible); otherwise, the traffic demand is accommodated in one/more lightpaths set up between respective source-destination (SD) node pairs following the shortest geographical distance.

Fig. 4 and Fig. 5 show performance, in terms of the blocking probability and the overall PC, respectively, for different traffic demand accommodation and termination methods. SP offers the lowest blocking probability and the highest PC compared to all EFOADE based cases. Among all EFOADE-IoE based cases, EFOADE (25,5) and EFOADE (100,100) show the highest and lowest blocking probability, respectively, due to imposing the most strict and relaxed restriction in threshold values, respectively. EFOADE (50,100) and EFOADE (25,100) show blocking in between EFOADE (25,5) and EFOADE (100,100). EFOADE (100,100) shows 10% to 28% lower PC while EFOADE (50,100) and EFOADE (25,100) show 5% to 24% lower PC compared to SP. EFOADE (5,25) shows small improvement in PC (within 2%) compared to SP. EFOADE-IoE selects suitable existing lightpaths and (or) sets up new lightpaths with suitable transmission options so as to accommodate incoming traffic demands in the most energy-efficient way. In general, to achieve improved energy efficiency, transmission option with larger MTR limit is selected to avoid signal regeneration at regenerators or intermediate IP core routers.

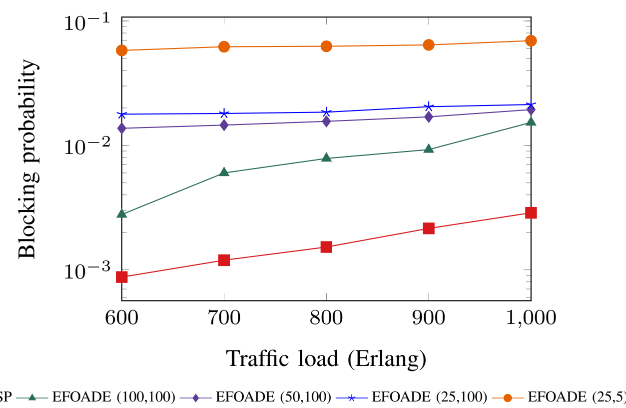

Fig. 4: Blocking probability for different traffic loads.

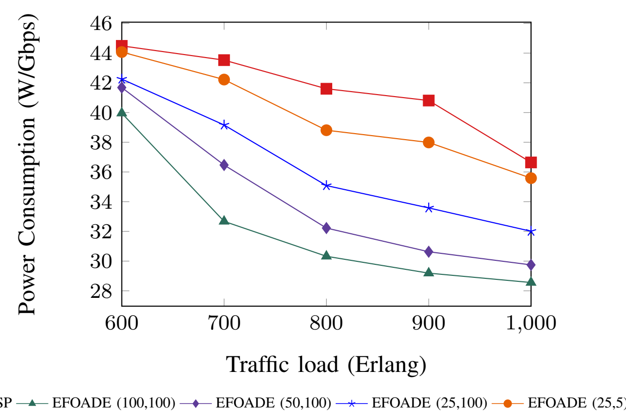

Fig. 5: Power consumption for different traffic loads.

We show the average EDFA occupancy (%) of the network for different traffic loads in Fig. 6. Average EDFA occupancy of network is computed by identifying the maximum values of EDFA occupancy for each fiber over the elapsed intervals, and finding the average over all fibers. We also show in Fig. 7, the average EDFA lifetime increase for

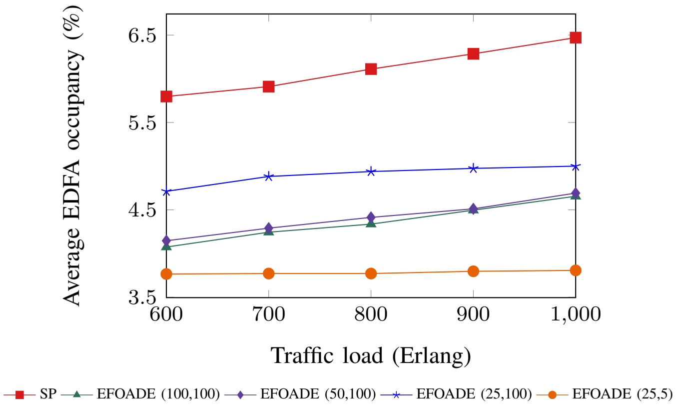

Fig. 6: Average EDFA occupancy for different traffic loads.

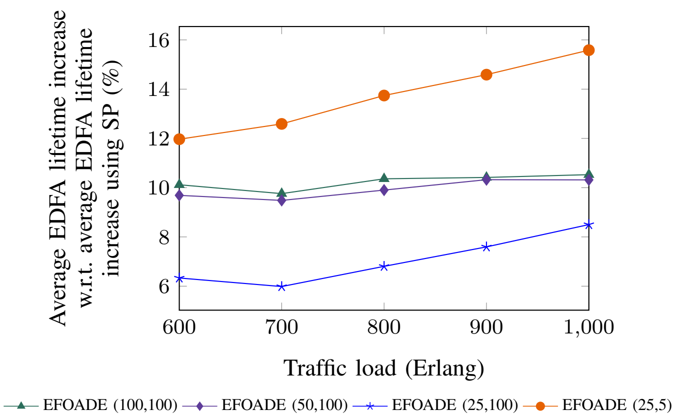

Fig. 7: Average EDFA lifetime increase with respect to average EDFA lifetime increase using SP for different traffic loads.

different scenarios using EFOADE-IoE method with respect to the average EDFA lifetime increase using SP method. We compute the average lifetime increase of EDFA based on EDFA occupancy model presented in [13, 19]. SP method shows the highest EDFA occupancy, thereby offering the lowest EDFA lifetime increase. EFOADE (25,5) shows the lowest EDFA occupancy, thereby showing the highest increase in EDFA lifetime increase. EFOADE (100,100) and EFOADE (50,100) show intermediate average EDFA occupancy as some fibers are not used to reduce PC due to relaxed restriction in α, β values, thus reducing the overall average EDFA occupancy. Among all EFOADE-IoE based scenarios with EDFA occupancy threshold equal to 100%, EFOADE (25,100) offers the most stringent active-sleep switching frequency restriction, resulting to more lightpaths being occupied in fiber and increasing the overall average EDFA occupancy. Thus, EFOADE (25,100) shows the lowest improvement on lifetime increase of EDFA. EFOADE (100,100), EFOADE (50,100) and EFOADE (25,5) show 9% to 15% improvement in average EDFA lifetime increase compared to SP based scenario.

V. Conclusion and Future Works

In this study, we propose an AG based EDFA active-sleep mode transition frequency and EDFA occupancy aware dynamic traffic provisioning for energy-efficient IP-over-EON (EFOADE-IoE) heuristic. The proposed heuristic provisions traffic demands with due consideration to improving energy-efficiency, even though it does not violate the predefined upper thresholds of active-sleep mode switching frequency and EDFA occupancy. Simulation result shows that EFOADE-IoE heuristic improves energy-efficiency, average EDFA occupancy and average EDFA lifetime compared to SP method. However, the proposed method increases blocking probability compared to SP method. Among EFOADE-IoE based scenarios, EFOADE (100,100) shows the lowest blocking probability and PC, whereas EFOADE (25,5) offers the highest average EDFA lifetime. It is intuitive that, learning of traffic pattern and predicting future traffic will help taking more informed decision for dynamic traffic provisioning. It will be an interesting research area to explore different time-series deep learning algorithms in this context. We also plan to study setting up lifetime-aware energy-efficient IP-over-EON along with optimal regenerator placement for static network traffic in future.

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