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Energy-efficient Virtual Optical Network Embedding Over Mixed-Grid Optical Networks

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***Abstract*—To cop with the exponential growth of network traffic nowadays, migration from fixed-grid to flex-grid technology in the backbone optical networks (ONs) gains broader attention. On the other hand, virtual optical network embedding (VONE) emerges as the potential solution to communicate between remote organizations and share physical network resources simultaneously. However, the methodology to analyze and optimize VON over mixed-gird networks is still an open problem. Consequently, the analysis of different migration strategies from fixed-grid to flexible-grid networks is also unknown. In order to cope with the aforementioned problem, this paper proposes an online VON resource allocation model over mixed-grid ONs. The proposed model uses a simulated annealing (SA)-based heuristic algorithm to embed VON connections over mixed-grid ONs by performing node and link mapping. The performance of the proposed heuristic is evaluated over NSFnet network in terms of blocking ratio and total power consumption for different migration strategies and spectrum allocation policies. Simulation results indicate that blocking ratio and power consumption is minimum when *increasing flexible island-based migration strategy* is favoured over other two considered migration strategies.**

***Index terms* – Mixed-grid, virtual optical network embedding (VONE), mixed-grid optical networks, power consumption, simulated annealing.**

I. Introduction

The exponential development of internet traffic due to the industrial internet and large-scale commercialization of 5G lead to rapid increase in number as well as volume of high data rate applications. Efficient handling of this traffic demand requires high-bandwidth backbone network to allow Tb/s class of transmission [1]. Traditional dense wavelength division multiplexing (DWDM)-based optical networks (ONs) cannot provide this Tb/s class of transmission due to its inherent fixed-grid technology and significant amount of spectrum wastage [2], [3]. A promising solution to increase the capacity of backbone ON is to switch from fixed-grid to flex-grid technology and adopt orthogonal frequency division multiplexing (OFDM)-based elastic optical networks (EONs) [2], [3], [4]. EONs provide a number of advancement over DWDM-based optical networks in terms of spectrum utilization which ensure increased scalability in the network with available limited spectrum resources [5], [6].

The key problems to switch from fixed-grid to flex-grid technology in ONs are [2], [3]: (i) which set of nodes need to be upgraded? and (ii) how to manage the resource allocation during this migration process? In [3], several migration strategies are presented based on network topology parameters and traffic generation/ transmission and their performances are compared in terms of bandwidth blocking ratio. Creation of flexible island(s) is another strategy where a set of adjacent fixed-grid nodes are upgraded in each step and results an island of flex-grid nodes [3]. The initial flexible island formed at the first step of upgradation can be increased in each later step, or a new flexible island can be formed in each step. This gradual migration from fixed-grid to flex-grid technology is suitable to limit the capital expenditure (CapEx), but complexes the resource allocation problem due to coexistence of fixed-grid and flex-grid nodes in the ONs. The work presented in [3] consider gradual migration by developing the flex-grid island by accommodating optical cross-connects at the junction nodes. Short-term, middle-term, and long-term migration plannings were considered to minimize the CapEx in ONs. On the other hand, managing blocking probability and minimizing total power consumption are the key parameters need to be considered while designing online resource allocation model in mixed-grid ONs. In [7], an online resource allocation model is presented in mixed-grid ONs to minimize the the blocking ratio by adopting several on-demand path selection and spectrum allocation strategies. The work in [8] considered energy-efficient resource allocation model for online traffic in IP-over-fixed/ flex-grid ONs by employing traffic grooming.

With the advancement in backbone ON to support higher volume of traffic, network ossification emerges as a major obstacle to adopt new technologies due to the lack of cooperation between internet service providers [9], [10], [11]. A potential solution to tackle this problem is to adopt network virtualization which allows different users to share the same physical infrastructure simultaneously- thanks to the concept of infrastructure as a service (IaaS). In case of optical network virtualization, multiple virtual optical network (VON) requests are embedded over a substrate (physical) ON to share the common physical network infrastructure. A VON request consists of a set of virtual nodes and a set of virtual links connecting the virtual nodes [9], [10]. Each virtual node demands a fixed amount of computing resources, and each virtual link needs to transmit an amount of traffic between the associated virtual nodes. The process to map these v-nodes and v-links of a VON request over the substrate optical network is referred as virtual optical network embedding (VONE) [9], [10].

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The works in [12], [13] consider VONE problem over DWDM-based ONs, whereas in [9], [11], [14], [15], the VONE problem is considered over EONs. In case of VONE problem over the mixed-grid ONs, both the properties of DWDM-based ONs and EONs are required due to coexistence of fixed/flexible grid nodes. Therefore, the works considered VONE for either DWDM-based ONs or EONs cannot be employed for mixed-grid ONs. In [16], an online VONE model is presented over flexible-grid ONs to minimize the bandwidth blocking ratio. However, minimization of total power consumption and effect of different migration strategies are not considered. A resource allocation model for online VONE problem over mixed-grid ONs is, therefore required, which considers total power consumption besides minimizing bandwidth blocking ratio in different migration scenarios.

To address the above issue, for the first time in this paper, we have proposed an online energy efficient resource allocation model for the VONE problem over mixed-grid ONs considering different fixed-grid to flex-grid migration strategies. The proposed model maps incoming VON requests over the substrate mixed-grid ON by performing one-to-one node mapping and corresponding link mapping. To minimize total power consumption of the substrate ON, a simulated annealing (SA)-based heuristic model is presented to perform node and link mapping. The performance of proposed SA-based heuristic is evaluated over a large network in terms of blocking ratio and total power consumption. Three migration policies are considered- increasing flexible-island, different flexible-island, and the highest degree first-based approach. Three spectrum allocation policies are considered for simulation purpose-first fit, first last fit, and best fit approaches.

The rest of this paper is organized as follows. In Section II, details of substrate mixed-grid optical network model, VON request model, and power consumption model are described with an example. Simulated annealing-based heuristic algorithm to solve the aforementioned problem is proposed in Section III. Section IV reports the simulation results of proposed heuristic over a large network, and finally, Section V concludes this work with future direction.

II. Substrate Mixed-Grid ON and VONE Model

A. Substrate Mixed-Grid ON Model

The substrate mixed-grid ON is considered as a directed graph $G(V, E)$, where V and E are the set of nodes and optical links in the substrate network, respectively [9], [10]. V_{fl} is the set of nodes upgraded from fixed-grid to flex-grid technology, and V_{fd} is the set of nodes with fixed-grid architecture such that $V_{\text{fl}} \cup V_{\text{fd}} = V$, and $V_{\text{fl}} \cap V_{\text{fd}} = \phi$. C_{fd} and C_{fl} are the computing capacity of each fixed-grid and flex-grid nodes and it is assumed that C_{fl} is n times higher than C_{fd}. If node pair (v_i, v_j) are adjacent and $v_i, v_j \in V_{\text{fl}}$, then the optical links between (v_i, v_j) are able to perform flex-grid transmission. The rest of the optical links communicate by fixed-grid transmission. W and F are the set of wavelengths and spectrum slots in each fixed-grid and flex-grid links, respectively. Each wavelength $w \in W$ has a bandwidth of S_{fd} GHz, and each spectrum slot $f \in F$ has a bandwidth of S_{fl} GHz. For the flex-grid communication, four modulation formats (MFs) BPSK, QPSK, 8-QAM, and 16-QAM are considered. Their respective transmission reaches and spectrum slot capacities are 4000 km, 2000 km, 1000 km, and 500 km, and 12.5 Gb/s, 25 Gb/s, 37.5 Gb/s, and 50 Gb/s [6], [10] [Table I].

B. Virtual Optical Network (VON) Request Model

Each virtual optical network (VON) request is represented as a tuple $< M, N, B, H >$, where M is the set of virtual nodes, N is the set of ordered pair of virtual nodes or virtual links, B is the demanded traffic, and H is the set of demanded computational capacity by the virtual nodes [9], [10].

C. Routing in Mixed-Grid ONs

The mixed-grid ON model mentioned in [7], [10] is adopted in this work, where reconfigurable optical add/ drop multiplexers (ROADMs) are placed in each flex-grid nodes allowing inter-grid communication by optical-electrical-optical (O-E-O) conversion. In case of fixed-grid transmission, strict international telecommunication union-telecommunication (ITU-T)-defined central frequencies are followed. The fixed-grid transponders and fixed-grid wavelength selective switches (WSSs) are equipped with spectrum grids of S_{fd} GHz. In case of flex-grid communication, flex-grid transponders and flex-grid WSSs can transmit as well as receive super-channel consisting multiple spectrum slots. Each flex-grid node can perform wavelength/ spectrum conversion [7], [10]. For a connection, the required number of wavelengths is computed as $\lceil \frac{B}{S_{\text{fd}}} \rceil$, and required number of spectrum slots is computed based on the distance-adaptive MF [Table I].

TABLE I: Modulation formats associated with spectrum slot capacities, optical reaches and power consumption per spectrum slot due to transponders

Modulation format	Spectrum slot capacity	Optical reach	Power consumption
BPSK	12.5 Gb/s	4000 km	112.374 W
QPSK	25 Gb/s	2000 km	133.416 W
8-QAM	37.5 Gb/s	1000 km	154.457 W
16-QAM	50 Gb/s	500 km	175.498 W

D. Power Consumption Model in Mixed-Grid ONs

The power consumption computation of a routing path in mixed-grid ON can be divided into two parts: power consumption for the fixed-grid segment(s), and the power consumption for the flex-grid segment(s). They are described as follows.

1) Power consumption model for fixed-grid segment: The power consumption model for IP over WDM ON presented in [8] is adopted in this work. An 100 Gb/s IP router at the source (destination) node consumes a power of 205 W. A 100 Gb/s WDM transponder consumes 351 W per wavelength. Power consumption due to erbium doped fiber amplifier (EDFA) is ignored in this work [8].

2) Power consumption model for flex-grid segment: The power consumption model for EON presented in [8], [17], [18] is adopted in this work. An 400 Gb/s IP router port at the source (destination) node consumes a power of 560 W. Power consumption of a sliceable transponder depends on

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transmission rate (TR) in Gb/s of the adopted MF and is given by (1.683×TR + 91.333) W [Table I]. Power consumption due to EDFA is ignored.

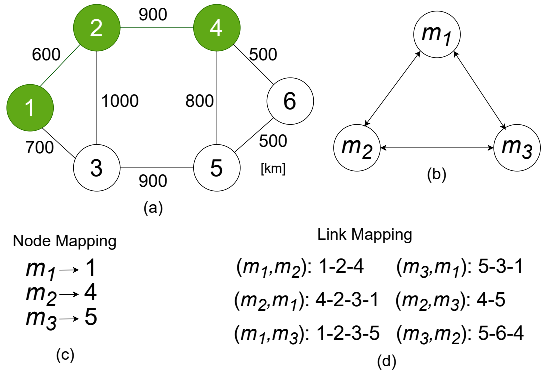

Fig. 1: An illustration of node-mapping and link-mapping of a VON request over a substrate ON: (a) a sample six-node eight-link mixed-grid ONs, (b) a sample VON request with three virtual nodes and six virtual links, (c) node mapping of the VON request over mixed-grid ONs, and (d) link mapping of the VON request over mixed-grid ONs.

E. An Illustration of the Proposed Model

The proposed model is illustrated in a six-node eight-link substrate optical network shown in Fig. 1(a) using a sample VON request shown in Fig. 1(b). Nodes 1, 2 and 4 of the substrate ON is upgraded to flex-grid nodes (marked in green colour), and the links connecting these nodes, i.e., 1-2, 2-1, 2-4, and 4-2 are able to perform flex-grid communication. The rest of the nodes are fixed-grid nodes (that is nodes 3, 5, and 6) and rest of the links communicate through fixed-grid transmission. In this example, each flex-grid link consists of 12 spectrum slots, and each of these slot has a bandwidth of 12.5 GHz. Each fixed-grid link consists of 6 wavelengths, and each of these wavelength has a bandwidth of 50 GHz. The sample VON request consists of three virtual nodes- m_1, m_2, and m_3, and each of these virtual nodes are expected to communicate with other nodes via virtual links and the demanded traffic is 100 Gb/s. A possible solution of node mapping and link mapping for this VON request over the substrate ON are demonstrated in Figs. 1(c) and 1(d).

Fig. 2 demonstrates an illustration of wavelength and spectrum slot allocation of the VON request over the substrate ON based on the setup reported in Figs. 1(c) and 1(d). From Fig. 2, three types of routing strategies can be classified based on wavelength and spectrum slot allocation as follows.

• *Flex-grid link(s) only:* The virtual link between the virtual node pair (m_1, m_2) uses path 1-2-4 (see Fig. 1(d)) where both the links are flex-grid. The path length of this flex-grid only path is 1600 km, hence QPSK can be employed and corresponding number of spectrum slot is 4. These spectrum slots are allocated in the links 1-2 and 2-4 with spectrum slot index 7 to 10, maintaining the spectrum continuity, spectrum contiguity, and non-overlapping constraints.

• *Fixed-grid link(s) only:* The virtual link between the virtual node pair (m_3, m_1) uses path 5-3-1 (see Fig. 1(d)) where both the links are fixed-grid. Two wavelengths with index two and three are allocated in those links maintaining the wavelength continuity, and non-overlapping constraints.

Spectrum Slot index	Flex-grid Links			Fixed-grid Links							Wave-length index
	1-2	2-4	4-2	2-3	3-1	3-5	5-3	4-5	5-6	6-4	
1				(m_1,m_3)		(m_1,m_3)					1
2											
3	(m_1,m_3)		(m_2,m_1)	(m_1,m_3)	(m_3,m_1)	(m_1,m_3)	(m_3,m_1)				2
4	(m_1,m_3)		(m_2,m_1)								
5	(m_1,m_3)		(m_2,m_1)		(m_3,m_1)		(m_3,m_1)		(m_3,m_2)	(m_3,m_2)	3
6											
7	(m_1,m_2)	(m_1,m_2)		(m_2,m_1)	(m_2,m_1)				(m_3,m_2)	(m_3,m_2)	4
8	(m_1,m_2)	(m_1,m_2)									
9	(m_1,m_2)	(m_1,m_2)		(m_2,m_1)	(m_2,m_1)			(m_2,m_3)			5
10	(m_1,m_2)	(m_1,m_2)									
11								(m_2,m_3)			6
12											

Unavailable   Available

Fig. 2: Demonstration of wavelength and spectrum allocation based on node-mapping and link-mapping depicted in Figs. 1(c) and 1(d).

• *Both flex-grid and fixed-grid links:* The virtual link between the virtual node pair (m_2, m_1) uses path 4-2-3-1 (see Fig. 1(d) where link 4-2 is flex-grid link and links 2-3 and 3-1 are fixed-grid links. An O-E-O conversion is required at node 4 to support this mixed-grid transmission. The length of link 4-2 is 900 km, hence 8-QAM can be employed in the flex-grid segment and corresponding number of spectrum slot is 3. These spectrum slots are allocated in link 4-2 with spectrum slot index 3 to 5. Two wavelengths (index 4 and 5) are allocated in the fixed-grid segment maintaining the wavelength continuity, and non-overlapping constraints.

The power consumption of three virtual links- (m_1, m_2): 1-2-4, (m_3, m_1): 5-3-1, and (m_2, m_1): 4-2-3-1 of the VON request shown in Fig 1(d) are computed as follows based on Fig. 2. It is assumed that only these paths are active at the given instance for power computation. (i) The flex-grid path 1-2-4 utilizes 4 spectrum slots and adopts MF QPSK. Hence, its power consumption due to IP router and S-BVT are 1120 W (560×2), 533.67 W (133.416×4), respectively. (ii) The fixed-grid link only path 5-3-1 uses two wavelengths, and its power consumption due to IP router and BVT are 410 W (205×2), 702 W (351× 2), respectively. (iii) The inter-grid path 4-2-3-1 has one flex-grid segment 4-2, and one fixed-grid segment 2-3-1. The length of the flex-grid segment is 900 km, adopted MF is 8-QAM, and power consumption due to IP router and S-BVT are 1120 W and 463.37 W, respectively. In case of fixed-grid segment, power consumption due to IP router and BVT are 410 W, 702 W, respectively. The total power consumption of this inter-grid path is approx 2.67 kW.

It is evident that if a path uses both fixed-grid and flex-grid segments, its power consumption is too high due to involvement of O-E-O conversion.

III. Proposed Simulated Annealing-based Heuristic

The key issue of SA-heu is to determine the node mapping and link mapping for an incoming VON request r over the substrate ON $G(V, E)$ so that total power consumption of the substrate network can be optimized. Simulated annealing (SA)-based meta-heuristic is employed in this work to obtain the solution for node and link mapping of the incoming request over the substrate ON. SA is a probabilistic method which starts from an initial temperature and approaches to a predefined final temperature; in each iteration the current temperature is reduced by a factor of cooling parameter. A valid random solution and its neighbour solution is generated to solve the problem in each iteration. These solutions are compared and updated in a probabilistic way to achieve the optimum solution. The basic model of SA considered in this work is described in Algorithm 1.

Algorithm 1 begins with a predefined initial temperature Γ_{ini}, assigns this temperature to the current temperature Γ_{cur}. In each iteration Algorithm 1 reduces current temperature by a cooling parameter γ. A random solution R of r in terms of node and link mapping is generated in each step based on the available resources in the substrate mixed-grid ONs. A neighbour solution R_{ngh} of R is determined and their performances are evaluated in terms of total power consumption by each of them. If R_{ngh} is better than R, then R_{ngh} is set as the current solution R; otherwise a probabilistic measurement is performed to assign R_{ngh} to R. This process continues until the current temperature is reduced to predefined final temperature Γ_{fnl}. The details of each parameter mentioned in Algorithm 1 are described as follows.

Algorithm 1 Simulated Annealing model

Input : Mixed-grid ON G, incoming connection r, initial temperature Γ_{ini}, final temperature Γ_{fnl}, cooling parameter γ.
Output : Node and link mapping of r over G.

1. Set $\Gamma_{\text{cur}} \leftarrow \Gamma_{\text{ini}}$.
2. Generate a random solution R and its neighbour solution R_{ngh}.
3. Compute $\triangle^{\text{pow}}$ based on R and R_{ngh}.
4. **if** $\triangle^{\text{pow}} < 0$ **then**
   Set $R \leftarrow R_{\text{ngh}}$.
   end
5. **if** $\triangle^{\text{pow}} \geq 0$ **then**
   Set $R \leftarrow R_{\text{ngh}}$ with a probability of $e^{\frac{-\triangle^{\text{pow}}}{\Gamma_{\text{cur}}}}$.
   end
6. $\Gamma_{\text{cur}} \leftarrow \Gamma_{\text{cur}} - \gamma$.
7. **if** $\Gamma_{\text{cur}} \geq \Gamma_{\text{fnl}}$ **then**
   Go to Step 2.
   end
8. Return R.

• *Structure of a random solution R:* A random solution R consists of two parts- set of substrate nodes to be mapped to the virtual nodes, and set of routing paths between the substrate node pairs, if corresponding virtual link exists. In case of node mapping, for mth v-node, a substrate node is randomly selected from the set of available nodes in terms of computing capacity; provided no two v-nodes are mapped in a common substrate node. For link mapping, if v-nodes m_1 and m_2 are mapped into substrate nodes i and j, and $(m_1, m_2) \in N$; a routing path is selected randomly from the set of precomputed K-shortest paths between node pair (i, j).

• *Structure of a neighbour solution R_{ngh}:* The neighbour solution R_{ngh} of a solution R is obtained by altering the node mapping of a randomly selected v-node of R. Let node $m \in M$ is selected for alteration and m is mapped to substrate node i. A new substrate nodes j is selected to replace i from the set of available substrate nodes, maintaining no two v-nodes are mapped in a common substrate node. For link mapping, the v-links with an end node m are updated accordingly in a random way.

• *Placement of a virtual link over the substrate ON:* For each routing path corresponding to a v-link of r obtained from R (R_{ngh}), the set of fixed-grid and flex-grid segments are identified. For a fixed-grid segment, number of required wavelengths are computed and they are placed maintaining the wavelength continuity, and non-overlapping constraints. For multiple fixed-grid segments, either the same or different wavelengths can be selected due to O-E-O conversion at the junction node(s). For flex-grid segment(s), length of that segment is computed and the number of required spectrum slot is determined based on distance adaptive modulation. These spectrum slots are allocated maintaining the spectrum continuity, spectrum contiguity, and non-overlapping constraints. Three spectrum allocation policies are considered: first fit (FF), first last-fit (FL), and best fit (BF), and they are employed for both fixed-grid and flex-grid segments.

• *Computation of $\triangle^{\text{pow}}$:* Power consumption of each routing path obtained from R (R_{ngh}) is computed according to the model described in Section II-D. Power consumption difference $\triangle^{\text{pow}}$ of R_{ngh} and R is computed as $\triangle^{\text{pow}} = R^{\text{pow}}_{\text{ngh}} - R^{\text{pow}}$.

The worst case computational complexity of Algorithm 1 is determined as follows. Using Yen's Algorithm [19], computational complexity to find K-shortest paths for each virtual link of r is $\mathcal{O}(NK(|E| + |V| \log |V|))$. In a selected routing path of a virtual link, computational complexity to search a set of wavelengths and/ or a set of spectrum slots is $\mathcal{O}(|E|^2|W||F|)$. Finally, Algorithm 1 executes $\frac{\Gamma_{\text{ini}} - \Gamma_{\text{fnl}}}{\gamma}$ times. Hence, computational complexity of Algorithm 1 is $\mathcal{O}(\frac{\Gamma_{\text{ini}} - \Gamma_{\text{fnl}}}{\gamma} N|E|^2|W||F| + NK(|E| + |V| \log |V|))$.

IV. Simulation Results

The performance of the proposed SA-based heuristic is evaluated in the 14-node NSFNET topology [10], where $|V_{\text{fl}}|$ is set to 6. Three migration strategies are considered: (i) for incremental flexible-island (Inc-FI)-based approach, V_{fl} is set as $\{5, 6, 7, 8, 9, 10\}$, that is- one flexible-island with six flex-grid nodes connected by flex-grid links, (ii) for different flexible-island (Dif-FI)-based approach, V_{fl} is set as $\{1, 2, 3, 11, 12, 13\}$, that is- two flexible-islands with three flex-grid nodes in each of them and they are connected by flex-grid links, and (iii) for the highest degree first-(HDF)-based approach, V_{fl} is set as $\{1, 3, 6, 9, 12, 14\}$. The value of C_{fd} is set as 500 and n is set to 2 and 3 for simulation purpose. It is assumed that each optical fiber has a capacity of 4 THz and each wavelength (spectrum slot) has a bandwidth of 50 GHz (12.5 GHz) which means $|W|$=80 ($|F|$=320). 10000 VON requests are generated and they arrives by a Poisson process with an arrival rate λ. The holding time of each connection follows an exponential distribution with the parameter μ. The

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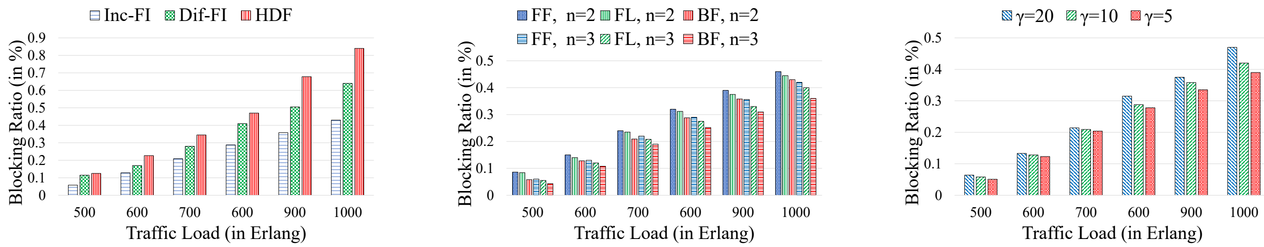
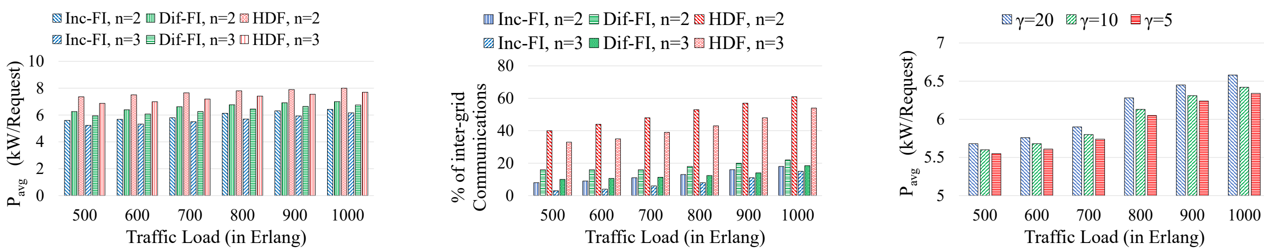


(a) (b) (c)

Fig. 3: Variation of blocking ratio in different cases: (a) for different migration strategies when spectrum allocation policy is set to best fit, (b) for different spectrum allocation policies and different values of n when migration strategy is set to Inc-FI, and (c) for different values of cooling parameter γ when spectrum allocation policy is set to best fit and migration strategy is set to Inc-FI.



(a) (b) (c)

Fig. 4: Comparison of power consumption in different aspects when the spectrum allocation policy is set to best fit: (a) average power consumption per VON request for different migration strategies and different values of n, (b) variation of the percentage of VON requests uses inter-grid communication for different migration strategies and different values of n, and (c) average power consumption per VON request for Inc-FI-based migration strategy for different values of cooling parameter γ

offered traffic load is expressed as $\frac{\lambda}{\mu}$ in Erlang by setting λ=10, and vary μ in the range [50,100] with a step of 10. The number of virtual nodes ($|M|$) of a VON request is randomly selected from the range [3, 5], and the virtual links between the virtual node pairs are randomly generated with a probability of 0.7 [16]. The computing capacity demand of each virtual node is randomly selected from the set [1, 3], and demanded traffic of the virtual links are uniformly selected from the set $\{25, 50, 75, 100, 125, 150\}$ in Gb/s. K-shortest paths are computed between each substrate node pair with K=3. The guardband is set to 2 spectrum slots for flex-grid communication. The SA parameters Γ_{ini} and Γ_{fnl} are set to 100 and 0 respectively. The value of γ is set to 20, 10, and 5 in different cases.

Fig. 3(a) plots the variation of blocking ratio (in percentage) with traffic load for considered migration strategies Inc-FI, Dif-FI, and HDF, when spectrum allocation policy is set to best fit. It is observed that blocking percentage is maximum for HDF-based approach and minimum for Inc-FI based approach. In case of Inc-FI-based approach, a set of interconnected nodes are upgraded which allows complete mapping of a VON connection over that flex-grid island, results minimum or no use of fixed-grid network elements. On the other hand, for HDF-based approach, the flex-grid nodes are not interconnected by flex-grid paths directly which results use of both fixed and flex-grid network elements while mapping a VON connection over mixed-grid ON. As the flex-grid nodes and links have higher capacity in terms of computation and bandwidth, it allows accommodation of larger number of VON connections. The blocking percentage of Dif-FI-based approach is better than HDF-based approach but worse than Inc-FI-based approach due to the same reason. Fig. 3(b) plots the variation of blocking ratio (in percentage) with traffic load for different spectrum allocation policies first fit (FF), first-last fit (FL), and best fit (BF) and for the values of n=2 and 3, when migration strategy is set to Inc-FI. As expected, blocking percentage is decreased when n=3 is favoured over n=2 for all spectrum allocation policies. The blocking ratio is minimum for best fit approach and maximum for first fit approach as well. Fig. 3(c) plots the variation of blocking ratio (in percentage) with traffic load for different values of cooling parameter γ when spectrum allocation policy is set to best fit and migration strategy is set to Inc-FI. The blocking ratio is improved when the value of cooling parameter γ is decreased i.e., the number of iteration is increased. When the value of γ is further decreased from 5, no significant improve in the blocking ratio is observed.

Fig. 4(a) plots variation of average power consumption P_{avg} (in kW) per VON request for different migration strategies for n=2 and 3. Fig. 4(b) plots the variation of the percentage of VON requests uses inter-grid communication for different migration strategies for n=2 and 3. Fig. 4(c) plots average power consumption P_{avg} (in kW) per VON request for Inc-FI-based migration strategy for cooling parameter γ=20, 10, and 5. In all these cases, the spectrum allocation policy is set to best fit (BF). From Fig. 4(a), it is observed that value of P_{avg} is maximum for HDF-based migration strategy and minimum for Inc-FI-based migration strategy. This is because of the number of O-E-O conversions performed by the connections due to inter-grid communication as reported in Fig. 4(b). In case of flexible-Island based approach, if a VON connection is entirely mapped in that flexible-Island no O-E-O conversions are required. The value of P_{avg} is larger for Dif-FI-based approach compared to Inc-FI-based approach, as size of flexible-Island is larger in the later one. This results complete mapping of higher number of VON connections than that of the previous one. Complete mapping of a VON connection in a single flexible-Island results use of only flex-grid links and usage of modulation formats with higher bit rate, which further minimizes the power consumption. From Fig. 4(c) it is observed that value of P_{avg} decreases when the value of γ decreases, which increases the number of iteration. Similar to blocking ratio, no significant improve in power consumption is observed when value of γ is decreased from 5.

From the above discussion, it is concluded that increasing flexible-Island-based migration strategy is suitable for online VONE over mixed-grid ONs to minimize the blocking ratio and total power consumption. Among the considered spectrum allocation policies, blocking ratio is minimum for best fit approach in all cases. Performance of the proposed SA-based heuristic improves with an increase in the number of iterations involved in it.

V. Conclusion

This paper proposed an online virtual optical network embedding (VONE) model over mixed-grid optical networks with the aim to optimize the total power consumption of the substrate network. A simulated annealing (SA)-based heuristic algorithm is proposed to solve this problem. The performance of the proposed heuristic is evaluated over the NSFNET network in terms of blocking ratio and total power consumption. Three types of fixed-grid to flex-grid migration strategies are considered and their performances are compared on a large network. Simulation results indicated that among the considered migration strategies, increasing flexible-island-based approach is favourable to minimize the blocking ratio and total power consumption. This is because it allows complete mapping of a VON connection over the flexible-island. Best fit-based spectrum allocation policy performed well to minimize the blocking ratio over first fit and first last fit-based approaches for all cases. The blocking ratio and total power consumption decreased for all migration strategies when computing capacity of flex-grid nodes were increased. Finally, both the optimizing parameters improved when the number of iterations performed by SA-based heuristic was increased.

Traffic grooming plays an important role in minimizing power consumption both in WDM-based ONs and EONs, and hence in mixed-grid ONs. Incorporation of survivability against single link failure and traffic grooming while performing VONE over mixed-grid ONs is left as the part of the future work.

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