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Abstract*—The swift escalation in internet traffic due to diverse bandwidth starving applications and innovative concepts of modern technologies such as Elastic Optical Networks (EONs) and Software-defined networking (SDN) demands a dynamic and flexible optical network architecture both at the control and data plane. Characteristically, the flexibility in EONs is achieved by the emerging SDN-enabled sliceable bandwidth variable transponders (SBVTs) that support multiple optical carriers' simultaneous generation. These generated multiple optical carriers can operate different lightpaths using slice-ability or combined into a single high-rate super-channel. In this perspective, one of the major issues in EON is Routing and Spectrum Allocation (RSA). Typically, in EON, RSA is a spectrum management and Non-deterministic Polynomial-time hardness (NP-hard) problem in which network resources mainly bank on the applied ordering strategy. This article proposed a novel heuristic algorithm, Minimum Hops with Least Slot Spectrum (MHLS), to accommodate maximum traffic requests with better spectrum utilization. The proposed algorithm aims to minimize block requests, block traffic, and the total number of spectrum slots used in the network. The MHLS exploits Dijkstra-shortest-path and SDN-enabled SBVTs for RSA problem. The performance evaluation of MHLS is accomplished on the entire USA network.

***Keywords*—Elastic Optical Network, Off-line routing, Routing and Spectrum Allocation.**

I. Introduction

In the last few decades, extensive growth in the global internet traffic of the core optical networks is observed. According to the CAGR index (Compound Annual Growth Rate) from [1], an annual growth of 6% is expected between 2018 and 2023. In addition, the nature of the traffic is changing, becoming more dynamic and less predictable [2]. This is mainly due to bandwidth-intensive application implementations and emerging concepts of IoT (Internet of Things). This prompted the network operators to use the maximum remaining capacity of the currently available network architecture. In order to directly use the remaining capacity optimally or to better forward traffic requests on the existing infrastructure, the data transport layer must reach the maximum capacity. The key technology for the optimal use of data transport is Dense Wavelength Division Multiplexing (DWDM) transmission technology.

Conventional fixed-grid DWDM-based optical networks typically have 50 GHz spectrum spacing systems under the International Telecommunication Union (ITU) standards. According to this ITU standard, the C band (1530 nm - 1565 nm) is divided into the fixed spectrum slots of 50 GHz, as shown in Fig. 1a. This non-granular distribution of the spectrum results in inefficient scaling performance to meet the growing demand for internet traffic. The dynamics and randomness of traffic patterns throughout the network result in a mismatch between the required spectrum and the assigned spectrum in DWDM fixed-grid network systems. The 400 $Gbps$ spectrum width in the standard modulation format is too wide to fit into the 50 GHz ITU fixed grid as it will likely overlap the 50 GHz grid boundary. These restrictions lead to inefficient use of the spectrum and are likely to reduce usage performance with increasing data rates further. A more fine granular approach to frequency (spectrum) slicing is being taken to overcome this bottleneck in fixed-line systems, and fixed-grid systems have evolved into flex-grid network systems. An optical network based on flex-grid systems is equipped with adaptive transceivers and network elements (NE) to offer flexibility according to traffic requirements. Such a combination of adaptive transceivers and NE enables the next generation optical network known as EON and enables service providers (SPs) to efficiently handle the continued growth in traffic volume [3]. According to the ITU-T standard, the EONs follow the flex-grid and offer fine granularity in the spectrum distribution of 25 GHz, 12.5 GHz, and 6.25 GHz [4] as shown in Fig. 1b. This granular EON approach helps in the efficient and scaled allocation of frequency resources based on actual traffic requirements. Flexibility in EONs is generally achieved by dividing the spectrum into flexible slots and allocating it, taking traffic requirements into account This granular approach of EON helps in improving the spectrum utilization according to actual traffic requirements [5].

As DWDM evolves towards EONs and the advantages of flexibility, there are also some new challenges. The most important of these is the optimized spectrum management, the RSA. RSA in EON is analogous to Routing and Wavelength Allocation (RWA) in DWDM. RSA is an NP-hard problem [6], [7] that is the tight coupling between RSA and RWA. In

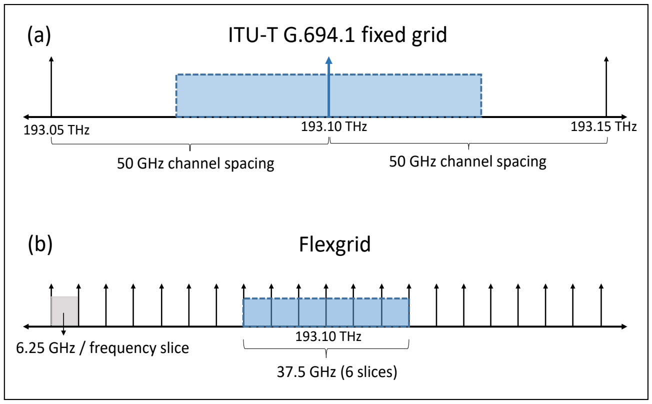

Fig. 1: (a) Fixed DWDM grid (50 GHz channel spacing), (b) flexible-grid (6.25 GHz spacing between central frequencies)

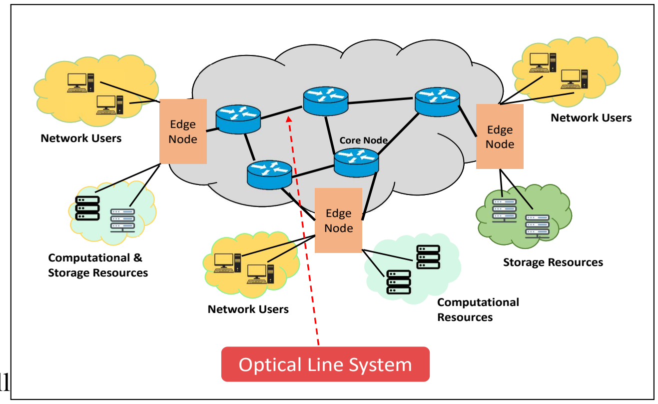

Fig. 2: Architecture of Optical Network

RSA, the main goal is to route traffic over the spectrum so that minimal resources are used to meet a given traffic requirement. RWA takes into account the continuity constraint, but RSA also takes into account another contiguity constraint of the spectrum slots on the routing path. RSA plays an essential role in the design and operation phases of EONs, especially when it comes to the performance of the network in terms of spectrum efficiency. In recent years, RSA has drawn a lot of researchers' attention and developed various algorithms. RSA operational scenario divides it into two types: RSA offline and online. RSA offline (static), where traffic requirements and network topology are known in advance, while RSA online (dynamic) processes traffic requests in a real-time. Various integer linear programming (ILP), meta-heuristic and heuristic models have been proposed to solve RSA problems. The main goal of all research work is to use network resources and efficiently meet maximum traffic requirements. The RSA concept described by Jinno [6], in which frequency resources are allocated based on distance. In [7], the authors formulated an ILP model to minimize spectrum use in EONs and proposed a method for resolving RSA. In work [8], the authors describe the dynamic RSA in the optical network with a flexible network comprehensively taking into account traditional routing algorithms such as fixed routing, Fixed Alternative Routing (FAR), and alternative routing. In [9], the authors also deal with the dynamic RSA scenario, in which the author took into account four known heuristic algorithms in the RWA problem and used them to solve the RSA problem. Several authors have used different meta-heuristic techniques to address the NP-hard RSA problem in EON. In [10], the author proposed an intelligence search algorithm known as the Evolutionary Algorithm for spectrum assignment. The authors in [11] have proposed a Delayed Spectrum Allocation (DSA) technique for scheduled traffic inquiries to solve the RSA problem in EON.

In contrast to the already work done, this paper proposes a new heuristic algorithm, Minimum Hops with Least Slots Spectrum (MHLS), to solve the offline RSA problem in EONs. The proposed MHLS algorithm is implemented together with the SBVT Flex-Optical Carrier Source Module (OCSM), as it offers better hardware and resource utilization in the [12] device. The synergistic use of MHLS and Flex-OCSM offers a practical improvement in spectrum usage compared to existing benchmark algorithms. The proposed algorithm runs on the actual network topology (USA) to validate its performance.

II. Overview of Optical Transport Network

An Optical Transport Network (OTN) is a set of optical network elements (ONEs) connected by fiber links with the traffic request being added/dropped, or forwarded. Typically fiber links are distributed bidirectionally with a single fiber in a fiber pair for each direction, as shown in Fig. 2. Amplifiers are placed after a specific span using the erbium-doped fiber amplifiers (EDFAs) technique or Raman amplification, or optionally both used in combination. In the current state-of-the-art optical network, ONE connected by fibers is usually indicated as an OLS, and a specific controller, with the property of adjusting the operating point of each amplifier, traverses with the path and spectral load given at the input of each span of fiber. Also, add/drop services for transport or routing layers are provided using Reconfigurable Optical Add/Drop Multiplexers (ROADM) technology. According to ITU-T recommendations, a spectral utilization technology such as DWDM can use the fixed or flexible spectral grid that characterizes the spectral slots of both grid architectures. LPs are deployed using the flexible grid architecture, where LPs are the set of feasible links between node-to-node based on the traffic demands. A Polarization Division Multiplexing (PDM) is used for each distributed LP to propagate each source to its required destination. In transmission phase, LPs experience various propagation problems such as additional amplifier noise such as Amplified Spontaneous Emission (ASE), ROADM filter effects and fiber propagation. In addition, it was shown in detail that the propagation of the fiber from an uncompensated optically coherent transmission system changes the QoT of the controlled lightpaths by introducing phase and amplitude noise [13]–[16]. This introduced phase noise is effectively catered for by the receiver's DSP moduleby utilizing a carrier phase estimation algorithm. This specific set of noise can only be taken into account for communications with a very high symbol rate designed for short distances [16]. In contrast, amplitude noise, which is typically referred to as No-Linear Interference (NLI), continuously degrades performance. It is Gaussian noise that adds-up with the receiver's ASE noise.

Finally, when LP is given to the destination from a particular source, the ROADM effects cause the degradation of all previously traversed OLSs to accumulate, with each crossed OLS adding a certain amount of ASE and NLI noise. In addition to the effects of ROADMs, each LP suffers from the cumulative impairments of all previous OLSs, each with a certain amount of ASE and NLI noise. Overall, a network can be represented as a weighted graph (G), where G = (V,

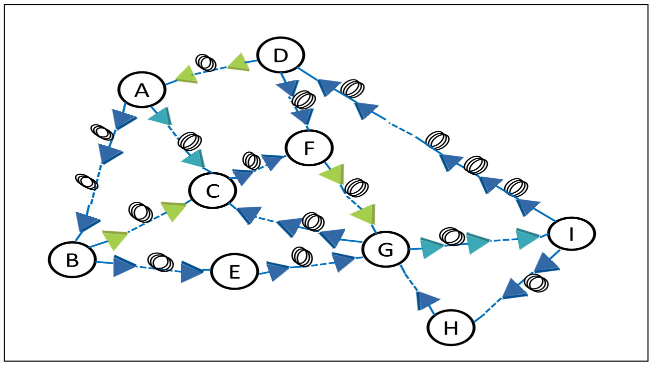

Fig. 3: Optical Transport Network

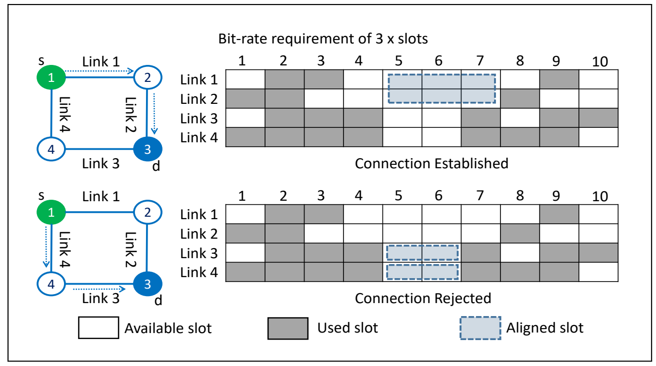

Fig. 4: Example of continuity and contiguity constraint

E) corresponds to the specific topology concerning the above scenario. The vertices (V) are nodes of the ROADM network, whereas the edges (E) are the OLS, as shown in Fig. 3.

III. RSA PROBLEM IN EON

This section focuses on modeling an offline RSA problem within EON with offline traffic requests subject to continuity and continuity. Firstly, we discuss the basic concept of RSA and then formulate the model.

A. Basic Concept of RSA

Typically, RSA is a fundamental problem at the network level, especially in the design and operational phases of EON. RSA is analogous to RWA in conventional optical WDM based networks. The methodology of creating light paths (LPs) for every source-destination request by choosing a feasible path and allocating the desired wavelength is known as the RWA problem [17]. In this kind of optical networks where there is no wavelength converter, the same wavelength must be assigned for all the intermediate hops in the end-to-end path of a request. This characteristic is also known as the wavelength continuity constraint. The major distinction between RSA and RWA is based on the elastic optical network's (EON) ability to utilize flexible spectrum allocation to accommodate the required data rates. In RSA, a connection is assigned a series of contiguous spectrum slots instead of the RWA wavelength in WDM-based networks with a fixed network. These assigned spectrum slots must be placed close together to meet the spectrum contiguity constraint. If there are not enough contiguous slots available on the requested path, the connection request can be divided into smaller requests. Each of these smaller requirements would then need fewer contiguous slots on the sub-carrier. In addition, the continuity of these spectrum slots should be ensured in a manner similar to that required by the wavelength continuity constraint. RWA problem in WDM based optical networks is an NP hard problem and this has been researched well over last two decades. The RWA problem can be reduced to the RSA problem since the number of wavelengths is equal to the number of spectrum slots in each fiber link. If RWA requests a wavelength along the LP, this corresponds to a slot requirement for a spectrum along the LP in the RSA problem. In other words, the RWA problem has a solution if and only if the constructed RSA problem has a solution. From the discussion above, we can therefore say that the RSA problem is an NP-hard problem [18], [19]. Although RSA is a challenging problem, it can be simplified by breaking it down into two separate sub-problems: (i) the routing sub-problem and (ii) the spectrum allocation sub-problem [20].

B. Problem Statement

In our work, the offline RSA problem is taken into account and can be formally specified as follows:

- ***Given:***
  - EON is represented by a connected graph $G = (V, E)$, where V is the set of nodes (locations) and E is the set of fiber links connecting two nodes.
  - Optical spectrum characteristic (i.e. spectrum width, frequency slot width and set of modulation formats), with the flexible grid represented by an ordered set of frequency slots.
  - D Set of offline traffic requirements that has to be met. The tuple s, d, t is provided for each request, where s and d are the source and the destination and t is the bit rate of the requested traffic in Gb/s
- ***Constraints:***
  Two important constraints come into play during the spectrum allocation phase:
  - *Continuity:* The traffic requirement requires two or more frequency slots, and these frequency slots must be optically adjacent.
  - *Contiguity:* The same index of frequency slots assigned to a traffic request must be available on all links of the LP path [21].

  The abstraction of contiguity and continuity constraints of frequency allocation is demonstrated using an example. For this reason the network segment is shown in Fig. 4. For example, suppose a connection request requires a bit rate equal to three slots for RSA from source node 1 to destination node 3. The connection request cannot be made using the path $1 \to 2 \to 3$ $(link1 - link2)$ because links of $1 \to 2 \to 3$ have only two contiguous slots and no three adjacent continuous slots available, so continuity and contiguity constraints are not met at the same time. However, both continuity and contiguity constraints are met synergistically if the connection uses path $1 \to 3 \to 4$ $(link4 - link3)$ and spectrum slots 5, 6, and 7.

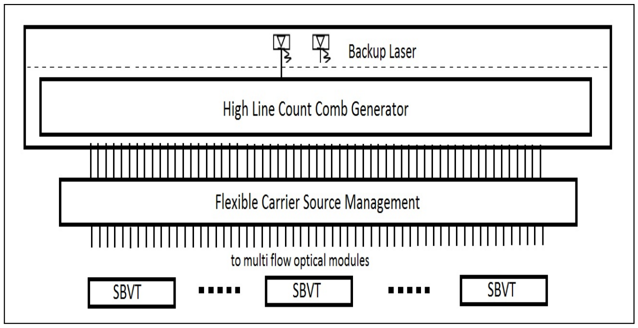

Fig. 5: Flex-OCSM Centralized Laser Source Architecture

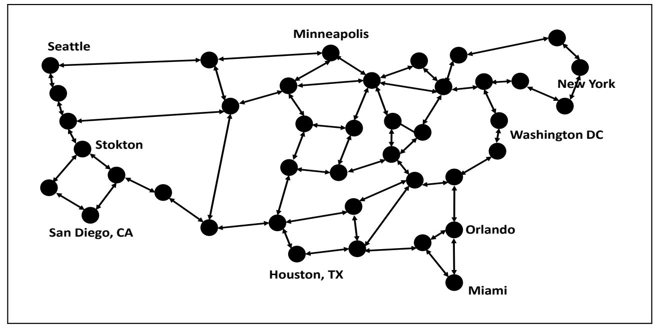

Fig. 6: USA network topology

- ***Objectives***
  - Minimize the total amount of Blocked Requests in the network
  - Minimize the total amount of Blocked Traffic (Gb/s) in the network
  - Minimize the total amount of Used Slots in the network
- ***Input Parameters***
  - Network Topology: Number of nodes V and links E
  - Traffic matrix and Paths
  - D Set of traffic request matrix. For each demand, the tuple s, d, t is given
  - P Set of pre-computed paths, index p
- ***Output***
  - The *RSA* is the output for each demand in matrix D

IV. NETWORK MODEL

In the present work we consider the Internet Protocol (IP) on an EON. A connected graph G = (V, E) represents the physical topology, where V represents the nodes (different locations) and E represents the physical connections between the nodes in the network. The nodes are equipped with IP routers and cross-connectors with variable bandwidth (B-OXC). Each E from $s \rightarrow d$ is represented by physical length $L_{s\rightarrow d}$ denoted in km and is bi-directional i.e. $L_{s\rightarrow d}$ = $L_{d\rightarrow s}$. Every traffic requirement of $s \rightarrow d$ is fulfilled with LP. The traffic demand is essentially accommodated by the use of LPs, which may require more LPs depending on various network parameters. In this case, LPs at source and end nodes are generated and managed by transponders with variable bandwidth (SBVT). In [12], a detailed comparison on the selection of SBVTs is discussed. In view of the results in [12], the current simulation environment has adopted Flex-OCSM as SBVT. Flex-OCSM offers better utilization in terms of the number of hardware and in-device resource utilization than multi-laser SBVT (ML-SBVT) and multi-wavelength SBVT (MW-SBVT). The basic architecture of Flex-OCSM is shown in Fig. 5. The maximum transmission capacity of SBVT is $X_{\text{max}} = 400Gb/s$ and the maximum connection capacity of the spectrum (C-band) is $SL_{\text{max}} = 4THz$. The optical spectrum on the network is divided into narrow 12.5 GHz slots, and each link consists of 320 slots. We assumed an empty slot as a guard band. LPs are correlated with the M modulation format and the FS frequency slots. Where M is defined by the optical reach and the traffic request t of V s $\rightarrow$Vd. Tab. I reported on the details of the modulation format examined in this work. LPs are created for long-distance links with low data-rates or short-distance operations with high data-rates. It all depends on the choice of modulation level. The number of FS connected to LP is linked to a specific traffic request t and the data rate Z. Our network model consists of LPs that meet the traffic requirements specified in the network. LPs are set up for a specific traffic requirement by choosing the most appropriate M and FS numbers based on the distance in km and the required bit rate in Gb/s. Finally, each LP slot's allocation is carried out, considering all constraints (*continuity, contiguity, and guard band*).

In addition, two greedy heuristic algorithms are considered in our network design phase: Direct-Lightpath Establishment (DLE) and Traffic Grooming Algorithm (TGA). Both algorithms were originally proposed in [22]. During the design phase, the DLE only defines the direct LP, which depends on the traffic requirements, while the TGA uses the capacity of the already existing LPs to design the network. The output of our proposed heuristic MHLS algorithm and the other benchmark algorithms such as First Fit (FF), Most Sub-Carrier First (MSF) and Longest Path First (LPF) are successively used as input parameters for the design of the network under consideration, i.e. algorithms DLE and TGA. The performance analysis of our proposed algorithm *MHLS* and the benchmark algorithms (FF, MSF, LPF) is carried out on this network system model, taking into account various network topologies and traffic scenarios.

TABLE I: Details of the available modulation formats [23]

Modulation Level	BPSK	QPSK	8QAM	16QAM	32QAM	64QAM
Transmission Rate [Gb/s]	12.5	25	37.5	50	62.5	75
Optical Reach [km]	4000	2000	1000	500	250	125

V. PROPOSED MHLS TO SOLVE RSA

Typically, a heuristic algorithm is used to obtain practical and sub-optimal solutions to large network problems in a reasonable time. Order strategies play a key role in achieving efficient and cost-effective use of network resources. This section explains in detail the proposed MHLS heuristic algorithm. To evaluate performance, we are considering some traditional algorithms and call them the benchmark algorithm. These algorithms are First Fit (FF), Most Sub-Carrier First (MSF)

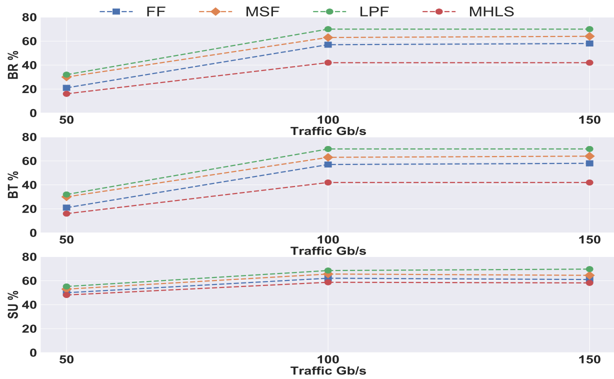

Fig. 7: USA network homogeneous traffic analysis

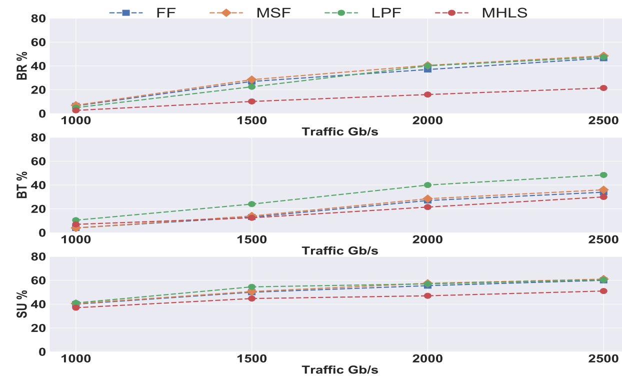

Fig. 8: USA network heterogenous traffic analysis

and Longest Path First (LPF).

$$FS_{s\to d} = \frac{t_{s\to d}}{\mathcal{Z}_{s\to d}} \tag{1}$$

$$\mathcal{N}_P = FS_{s\to d} \times \mathcal{H}_{s\to d} \tag{2}$$

The MHLS heuristic was developed with two main general

Algorithm 1 Minimum Hops with Least Slot Spectrum

Require: *Total number of slots required by given $s \to d$ in network*
Ensure: *Physical Topology Graph $\mathcal{G}$ with $\mathcal{V}$ number of nodes*
1: Input $\mathcal{D}_{s\to d,t} \forall (s,d,t) \in \mathcal{V}$
2: Output Ψ
3: **for all** $\mathcal{D}_{s\to d,t} \in \mathcal{D}$ **do**
4: $OR_{s\to d}$ = calculate_optical_reach;
5: $\mathcal{H}_{s\to d}$ = calculate_hops($OR_{s\to d}$);
6: $M_{s\to d}$ = find_modulation_level ($OR_{s\to d}$);
7: $\mathcal{Z}_{s\to d}$ = find_data_rate ($M_{s\to d}$);
8: $FS_{s\to d}$ = Slot_calculation ($\mathcal{Z}_{s\to d}$);
9: $\mathcal{N}_{\mathrm{P}}$ = $FS_{s\to d}$ × $\mathcal{H}_{s\to d}$;
10: **end for**
11: Sort the $\mathcal{N}_{\mathrm{P}}$ in the ascending order;
12: Ψ = sorted $\mathcal{N}_{\mathrm{P}}$;
13: **return** Ψ;

points in mind. The first is the total number of hops $\mathcal{H}$ and the second is the total number of FS slots for each traffic request on the network. In algorithm MHLS, the input parameter is $\mathcal{D}$, which represents the set of offline traffic demands that needed to be fulfilled. For each demand from the respective source to the destination, required traffic bit-rates in Gb/s is known. Well, the main function of the MHLS, is for each t request from $s \to d$ (Line 1), first calculates the optical reach (OR) for the respective s and d (Line 4). Then $\mathcal{H}$ is calculated (Line 5) using $Dijkstra - shortest - path$ algorithm and OR for given traffic request t. MHLS, find an appropriate modulation level M for the given traffic request with the help of OR and required bit-rates (Gb/s) (line 6). A suitable selection of the M plays a vital role in achieving the spectrum resources' efficient use. Transmission Data rate $\mathcal{Z}$ is calculated after selecting M (Line 7). After the calculation of $OR, \mathcal{H}, M$ and $\mathcal{Z}$, slots FS calculation is performed (line 8). For a given s and d, FS are calculated with the help of equation (1). After calculating all these parameters, a new parameter is being introduced $\mathcal{N}_{\mathrm{P}}$ (Line 9), which is the product of two parameters FS and $\mathcal{H}$ as shown in equation (2). Equation (2) helps us find the total number of slots required by given s and d in the network. The same steps will be repeated for the entire traffic matrix $\mathcal{D}$ (line 3-9). After that, sorting is done in the ascending order of the $\mathcal{N}_{\mathrm{P}}$ (line 11) and save as output in matrix Ψ (line 11). The proposed algorithm MHLS is reported in Algo. 1, combines two parameters $\mathcal{H}$ and FS, then sort it in ascending order and then sequentially served to our design network. Results reflect that the proposed *MHLS* minimize Blocked Requests (BR), Blocked Traffic (BT) and Slots Used (SU) in the network as compared to other considered benchmark algorithm.

VI. Results and Performance Analysis

This section compares the simulation results of the proposed MHLS algorithm and the benchmark algorithms (FF, MSF and LPF). In the FF algorithm, the traffic request (s, d, t) is first sorted in descending order of the traffic bit-rates (Gb/s) and then served one after the other. In the MSF algorithm, FSs are first calculated for each traffic request and then sorted in descending order based on the number of frequency slots requested. Traffic requests that have requested a maximum of FS are processed first in the correct order. In the LPF algorithm, OR is first calculated for each traffic request according to Dijkstra's algorithm, and then the traffic is provided as OR in descending order. The performance of the proposed MHLS is analyzed based on dynamic network parameters such as the variable number of nodes, the node degree, the optical range and the type of traffic (heterogeneous traffic and homogeneous traffic). In this way we can show which algorithm performs better in minimum blocked requests (BR), blocked traffic (BT) and spectrum-slots used(SU) in the network.

The physical network topology of USA considered in this work is shown in Fig. 6. The considered topology consists of 40 nodes, 116 bi-directional links and has a node degree of 2.9. For the network topology under consideration, the variable nature of the traffic is tested, homogeneously and heterogeneously. In the heterogeneous case, the traffic is randomly distributed over the links, so that the network has an average of traffic per node. First, traffic matrices are created by setting each traffic request equal to a uniformly generated number in the range [0: 1] and then scaling these values in order to achieve a certain average target traffic per node. With homogeneous traffic, the traffic is evenly distributed over the network links. We consider 50 Gb/s, 100 Gb/s and 150 Gb/s of homogeneous traffic per node and 1000 Gb/s, 1500 Gb/s, 2000 Gb/s and 2500 Gb/s of heterogeneous traffic average per node. The performance parameters considered in this work are BR, BT and SU.

The performance of MHLS is analyzed based on the real and large network topology. In this way we can understand which algorithm is superior for real and large network scenarios. In this scenario, two types of traffic were considered, namely homogeneous and heterogeneous. The Detailed comparison of homogeneous traffic (50 Gb/s, 100 Gb/s and 150 Gb/s) scenario is depicted in Fig. 7, for homogeneous traffic. First, for 50 Gb/s traffic performance of the different algorithm is observed: for MHLS, BR & BT is around 16.2% and SU is 45%. For FF: BR and BT is 21.1% and SU is 48%, while for MSF: BR and BT is 25.3% and SU is 56.2%. For LPF: BR and BT is 36% with SU 58.1%. Results for BT and BR improves for higher traffic. For traffic of 150 Gb/s , MHLS facilities 12.7%, 20% and 26 % more traffic requests with 7%, 9.3% and 12.3% less spectrum used as compared to FF, MSF and LPF respectively.

For heterogeneous traffic profile, results are demonstrated in Fig. 8.It is observed that the algorithm MHLS can accommodate $\approx$ 24%, 27% and 25 % more number request and 6%, 8% and 10 % more traffic with saving 10%, 11.1% and 11.5 % spectrum as compared to others approaches (FF, MSF, LPF). This proves the distinction of MHLS among all other approaches. Arranging the traffic request under the MLHS algorithm proves to be more efficient even in a more complex network and traffic scenarios, i.e., a network with a more significant number of requested frequency slots having a large number of node links.

VII. Conclusion

Network operators are facing continuous growth in the volume of Internet traffic around the world. Due to this increase in data traffic, they must utilize the existing capacity of the optical networks already installed to the full. In this context, EON emerged as a candidate capable of extracting residual capacity using the option to meet demanding traffic requirements in terms of diversity and spectrum.

An important issue that arises during the design and operation phases for EON is RSA. To take advantage of EON, an efficient RSA algorithm is essential. This article proposes a novel heuristic MHLS algorithm in combination with Flex (OCSM) SBVT that can take into account the maximum number of traffic requests and minimize the total amount of block traffic and frequency slot usage. To evaluate the performance of MHLS, simulations are carried out for a real USA network topology with different traffic scenarios. In addition, a comparison with some conventional algorithms (FF, MSF and LPF) is presented for analysis purposes. Promising results are being achieved, showing that MHLS outperforms all reference algorithms to maximize traffic demand adaptation and save a significant amount of spectrum.

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