An Iterative Optimization Approach for Routing, Modulation, and Categorical Spatial Bandwidth Block Allocation to Improve Network Performance for Dynamic Traffic in Elastic Optical Networks

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Abstract—In this work, we have proposed an iterative optimization model for allocating spectral resources in optical networks. The proposed model gives spatial routes and spatial bandwidth allocations in optical networks with variable data-rates, modulation schemes, and optical reach adaptation. We have also proposed an algorithm which allocates continuous and contiguous block of frequency slots (FS) between transponders which forms bandwidth partitions. The primary objective of the bandwidth partition is to reduce spatial fragmentation. The integrated approach includes the routing information from using the optimization model and the categorical spectrum allocation from using the proposed algorithm. The integrated approach has been used for dynamic traffic to improve network performance in terms of bandwidth blocking, link utilization, and fragmentation metrics. It has been shown that the FS utilization (FSU) and link utilization (LU) largely increase in the proposed integrated scheme with 80% LU compared to shortest path first (SPF) routing with LU as low as 20%. Similarly, the standard deviation between FSU in the proposed scheme is approximately 5% compared to 25% in other schemes which shows that the FSU sufficiently increases in the integrated approach.

Index Terms—Resource allocation, elastic optical networks, spatial fragmentation, network partition, iterative optimization.

I. INTRODUCTION

ENSE wavelength division multiplexing (DWDM) based systems with a capacity of 40 Gbps were earlier deployed in optical networks before 2012 to support high data rate traffic [1]. It was extended to 100 Gbps with QPSK deployment in 2013 and was again extended to 200 Gbps with 16QAM, 150 Gbps with 8QAM, and 100 Gbps with QPSK in 2015 [1]. Since 2020, network interfaces are available to support network traffic at 400 Gbps with 16QAM, 300 Gbps with 8QAM, and 200 Gbps with QPSK [2], [3], [4]. However, the behavior of network traffic is rapidly changing and it is becoming more dynamic [5]. Networks are facing new challenges with an objective to achieving high efficiency, more flexibility to adapt with dynamic data rates, and scalability to maintain network performance [6]. Elastic optical networking (EON) is becoming the most favorable candidate to address the network challenges with its ability to allocate heterogeneous bandwidths to lightpath demands.

In EON, the entire spectrum is divided into a large number of narrow bandwidth channels with bandwidths equal to 12.5 GHz [7], [8], [9] which are called frequency slots (FS). In EON, multiple FS’s may be allocated to establish a lightpath between the two end nodes. However, these FS’s must be closed neighbors with each other which is called contiguity [10]. EON utilizes optical orthogonal frequency division multiplexing (O-OFDM) in which the frequency bands are orthogonal to each other. It is flexible to adapt signal modulations including quadrature phase shift keying (QPSK), 8/16/32/64 quadrature amplitude modulation (QAM), and binary PSK (BPSK) [6]. A higher modulation scheme has more number of bits and requires smaller bandwidths to transmit information signal. However, the optical reach of a higher modulation scheme is lower due to lower optical signal-to-noise ratio (OSNR) and higher bit-error-rate (BER) [11]. This means that the higher order modulation schemes will provide faster data rates at the cost of higher BER, lower OSNR, and lower optical reach. In EON, optical interfaces can dynamically adapt data rates according to the modulation format, optical reach, and the amount of data to be transmitted between end nodes.

Routing and spectrum allocation (RSA) is a popular research area in EON to allocate limited resources in an optimal way [12], [13]. In RSA, a lightpath is established between the two transponders through a selected route and allocating contiguous and continuous FS’s to support traffic demand. The later is termed as the continuity constraint such that similar indexed FS’s must be assigned during lightpath establishment on all links along the fiber path. The other is termed as the contiguity...
Routing subproblem may either be static or dynamic to support static or dynamic lightpath requests respectively. For dynamic traffic and network operation, shortest path first routing with \( k \) paths using the Dijkstra’s algorithm are mostly utilized. However, these paths are computed offline which are utilized for dynamic network operation. Hence, \( k \) SPF routing may over-utilize resources on some links while under-utilize other resources. Therefore, it degrades network performance for dynamic traffic. There are algorithms [14], [15] which are adaptive in nature and compute paths between transponders at the time of lightpath establishment to support dynamic network operation. Adaptive routing [16], [17] tries to establish lightpaths between transponders using link-state information and using all possible routes between transponders. Therefore, it provides lower bandwidth blocking probability compared to \( k \) SPF routing at the cost of lightpaths set up times. These algorithms are highly time consuming and require extensive support to continuously update information of routing tables at the transponders. Finally, adaptive routing suites well centralized implementation with common network information compared to the distributed approach.

Spectrum (i.e., FS) allocation (SA) subproblems in EON are mostly dynamic and are utilized for online traffic. A continuous and contiguous band of FS’s are allocated using SA algorithms to lightpath requests after finding suitable routes between transponders. These SA algorithms include first-fit, last-fit, random-fit, first-last-fit, and exact-fit algorithms [18], [19], [20]. In the first-fit, a contiguous band of slots with minimum possible indexes and satisfying the continuity constraint are allocated to a lightpath request. The number of allocated slots depends on the adapted modulation scheme. The last-fit is a reversal to the first-fit scheme or algorithm in which a contiguous band of slots with maximum possible indexes and satisfying the continuity constraint are allocated to a lightpath request. First-last-fit is a mix strategy in which the spectrum is allocated using SA schemes to lightpath establishment on a path subject to different constraints including spectral and spatial fragmentation. Vertical fragmentation is called spectral fragmentation which occurs in a single fiber link. Horizontal fragmentation is called spatial fragmentation which occurs along a selected path between transponders [22]. The spectral and spatial fragmentation in an EON is demonstrated in [23]. Furthermore, it is reported in [24] that partitioning may improve lightpath establishment probability and hence, will reduce the amount of bandwidth blocking in a network. However, the number of partitions should be minimized to improve the performance [22]. There are different fragmentation measurement metrics which include external fragmentation metric (EFM) and access blocking probability metric (ABPM). The time complexity of EFM is lowest as it focuses on the maximum size of contiguous slots in spectral fragmentation and spatial fragmentation. However, the time complexity of ABPM is higher and it will find whether the spectrum is completely fragmented or not. Both metrics will return values between 0 and 1. A 0 indicates no fragmentation in a link (spectral fragmentation) or a path (spatial fragmentation) which shows the initial condition of a link or a path. Similarly, a 1 indicates that a link or path is completely fragmented which will highly reduce network performance.

Spectral and spatial fragmentation management schemes in a network include reactive fragmentation as well as proactive fragmentation [25], [26]. These are also called defragmentation approaches. Reactive fragmentation schemes are used after lightpaths are established using hitless methods. Hop returning, push-pull returning, and make-before-break schemes are all hitless methods which are briefly explained in [26]. Proactive defragmentation methods are utilized during lightpath establishment time for dynamic traffic by taking into account resource information on different paths between transponders. The information is processed before lightpath admission and establishment on a path subject to different constraints including EFM, ABPM, and contiguity ratio.

Optimization problems are generally formulated in literature for static lightpath establishment in EON. However, traffic nature has highly changed in the recent past with higher traffic growth driven by dynamic cloud, video, and IoT applications. Optimization models are formulated with an objective to establish maximum static lightpaths between transponders which are constrained by the network resources. There are few optimization models [12], [13], [27], [28] which are formulated with static traffic and their results are utilized for routing purpose for dynamic traffic. However, the routing information changes in these models with changes in network traffic load (Erlang) as the lightpath establishments are subject to traffic loads (Erlang). For higher traffic loads (Erlang), resources must be increased to make the models feasible to support higher traffic [29]. However, increasing network capacity with associated hardware and software deployment is a costly and time consuming process. Furthermore, it will require sufficient time to deploy new capacity and associated resources. Therefore, the incremental approach for scaling networks with deploying more resources with pace of increasingly traffic demand will lead to unnecessary infrastructure and cost. It is a network challenge to optimize the available network resources before the next network upgrade subject to the elastic characteristics of the network, technology used in EON, optimizing modulation
schemes for adapting higher data-rates based on transponders locations, and the distance/hops between the transponders. We therefore, proposed an iterative based optimization model which is further explained in Section II.

In this work,

1) we have considered network partitioning problem to optimize the network performance. We have design an iterative based optimization problem for network partitioning and routing. According to our latest information, there is no work available in the literature related to the application of iterative optimization in EON.

2) Furthermore, proactive defragmentation approach is used in this work such that routes between transponders are precomputed with adapted modulation scheme in the optimization model. Therefore, different bandwidths are allocated to end pairs which are based on the adapted modulation scheme and their optical reach.

3) The outcome of the proposed optimization model is to minimize link loading by adapting higher modulation scheme with higher data-rate transmission and allocating minimum numbers of FS’s between transponders. The outcome of the proposed optimization model includes the routing information and the amount of bandwidth allocation between transponders.

4) The proposed algorithm processes the data-sets from the optimization model and categorically allocates spatial contiguous FS blocks. This also specifies the indexes of the contiguous band of FS’s according to the allocated bandwidths along the optimized routes.

5) We utilize the set of integrated output information from the optimization model and the algorithm for dynamic traffic and networking to improve efficiency of EON in terms of average bandwidth blocking probability, average EFM, average ABPM, and link and FS utilization.

The rest of the paper is organized as follows. Section II include the proposed iterative based optimization model along with all traffic, network, and decision variables. It also include the proposed algorithm which arranges the optimization results into a set of paths and contiguous band of FS’s to be utilized for dynamic networking. In Section II, we have also discussed the performance parameters. In Section III, we have carried out extensive simulations and presented the findings of this work. Finally, section IV concludes this work.

II. OPTIMIZATION MODELS

A. Stage 1: Preparing Parameters for the Optimization Model

The network, traffic, and path parameters as well as different variables are given below.

- **Network parameters:**
  
  \( \mathcal{N} \): Represents a set of wavelength selective switch (WSS) nodes geographically located in a network.
  
  \( \mathcal{C} \): Set of frequency slots (FS) per fiber such that \( \mathcal{C} = \{1, 2, 3, \ldots, \Delta\} \). An FS represents a frequency channel having bandwidth equal to \( \delta_{\text{channel}} = 12.5 \text{ GHz} \). |\( \mathcal{C} \)| represents the size of the set \( \mathcal{C} \) in which \( \Delta \) is the maximum index of a FS.
  
  \( \mathcal{L} \): Set of directed fiber links which carry traffic in one direction between neighbor nodes.

- **Path parameters:**
  
  \( S \): Set of all possible source-destination (s-d) pairs in a network with a number equal to \( N(N-1) \).
  
  \( c_l \): The cost of using a FS channel on a link \( l \). In the hop based routing, it has a value setted equal to 1. In the distance based routing, this represents the actual distance of a fiber link \( l \).

- **Variables:**
  
  \( \Delta f_s \): Numbers of FS allocation to an s-d pair \( s \).
  
  \( \Lambda_l \): Total number of FS allocated on link \( l \).

- **Decision variables:**
  
  \( \alpha^p \): Represents bandwidth allocation in numbers of FS’s to an s-d pair \( s \).

  \( \Delta f \): An iterative integer value with a lower bound equal to 1 and an upper bound equal to |\( \mathcal{C} \)|. The proposed optimization problem iteratively starts with the lower bound. It stops when the proposed integer linear problem (ILP) becomes feasible and gives an optimal solution. We have observed that its value, which makes the problem feasible, remains unchanged for the same network. Noting its value will reduce the numbers of iterations to only one time execution for the same network.

B. Stage 2: Programming the Optimization Model

Objective function:

\[
\text{minimize} \sum_{l \in \mathcal{L}} c_l \Lambda_l + \sum_{s \in S} \Delta f_s \quad (1)
\]

Subject to:

\[
\Lambda_l = \sum_{p \in \mathcal{P}_l} \alpha^p, \forall l \in \mathcal{L} \quad (2)
\]

\[
\sum_{p \in \mathcal{P}_l} \alpha^p \leq |\mathcal{C}|, \forall l \in \mathcal{L} \quad (3)
\]
Finally, the integer constraints are given in (7)–(9).

\[ \alpha^p \in \mathbb{Z}^+, \forall p \in \mathcal{P} \]  
\[ \Delta f^s \in \mathbb{Z}^+, \forall s \in \mathcal{S} \]  
\[ \Lambda_l \in \mathbb{Z}^+, \forall l \in \mathcal{L} \]  

The objective function of the optimization problem in (1) is to minimize the cost of using FS’s on all links in a network as well as to optimize FS allocation to each s-d pair s. This will help in optimizing a route between end WSS nodes by adapting higher modulation scheme with more bits to carry information and to allocate minimum FS’s to each s-d pair. This is explained as follows.

Equation (2) gives the link cost in terms of bandwidth allocation in numbers of FS’s. These FS’s are allocated to an s-d pair s along a path p. Therefore, the link cost includes the sum of FS’s allocation on all paths which is using a link l.

Equation (3) shows that the sum of FS allocation on any link l must not exceed the available numbers of FS’s on that link. Moreover, it is important to note that path based FS allocation is considered in (3) so that same band of FS’s will be allocated to each s-d pair s on all links along the path which satisfies the continuity.

Equation (4) represents numbers FS allocation to an s-d pair s. For a demand request equal to 100 G, BPSK with modulation index \( k^s = 1 \) will require only 2 bits and 4 FS with \( \delta_{\text{channel}} = 12.5 \text{ GHz} \) for transmission. Similarly, QPSK with \( k^s = 2 \) will require 4 bits and 2 FS to carry the information between end nodes. Finally, 8 QAM with \( k^s = 3 \) will require 8 bits and only 1 FS to carry the information between end nodes. However, in case of giving preference to the lightpath distance instead of number of hops in the shortest path calculation/consideration/computation, the constraint in (5) will be considered instead of the constraint in (4) which will give similar information of allocating FS’s for each modulation scheme. In (5), if length of SPF \( s \leq 1000 \text{ km} \), then 8 QAM with 8 bits and 1 FS will be adapted by an s-d pair s. Similarly, if 1000 km < length of SPF \( s \leq 2000 \text{ km} \), then QPSK with 4 bits and requiring 2 FS’s will be adapted by an s-d pair s. Finally, for a transmission distance between 2000 km and 4000 km, BPSK with 2 bits and 8 FS’s will be adapted by an s-d pair s to satisfy the bandwidth demand.

The constraint in (6) is explained as follows. We have considered s-d pairs with uniform demand requests equal to 100 G. Therefore, BPSK with 2 bits will require more FS compared to QPSK with 4 bits and 8 QAM with 8 bits. In other words, for 100 Gbps bandwidth demand, BPSK will require 4 FS, i.e., 4 FS \( \times 12.5 \text{ GHz} \) (channel width) \( \times 2 \text{ bits} = 100 \text{ Gbps} \). Similarly, QPSK will require 2 FS, i.e., 2 FS \( \times 12.5 \text{ GHz} \) (channel width) \( \times 4 \text{ bits} = 100 \text{ Gbps} \). Finally, 8 QAM will require 1 FS, i.e., 1 FS \( \times 12.5 \text{ GHz} \) (channel width) \( \times 8 \text{ bits} = 100 \text{ Gbps} \). In all cases, 12.5 GHz represents the channel width of a FS. Similarly, BPSK has highest optical reach compared to other schemes. Therefore, 100 G bandwidth demand requires 1 FS using 100 G 8 QAM (i.e., 8 bits) transmission with lowest optical reach. A similar bandwidth demand requires 2 FS using 50 G QPSK (i.e., 4 bits) transmission with an optical reach up to 2000 km. Finally, 100 G bandwidth demand requires 4 FS using 25 G BPSK (i.e., 2 bits) transmission with an optical reach up to 4000 km.

C. Stage 3: Programing an Algorithm to extract/sort Useful Information

In this Section, we have proposed an algorithm which takes into account the information from the optimization model and allocates contiguous blocks of FS’s with continuity constraint. The procedure to extract the necessary information and allocation of FS bands is given in Algorithm (1). In Algorithm (1), sd-path-used is a list which will keep track of sd-paths such that resources will be allocated only once to the path in the list. link-optimal-values represents numbers of FS slots allocation to optical links from the optimization problem. This list will be sorted in descending order with respect to the number of hops. The sorted list will be used to group links according to FS numbers. The set sd-path-values keeps the list of all tuples of sd pair \( \forall s \in \mathcal{S} \) and a path for sd pair. The value of \( \alpha^p \) is obtained from the optimization problem which shows the number of FS’s allocated on route \( p \) according to the modulation used.

In the set paths-through-links, paths are grouped according to the link-path-cluster-size. The links-from-opt-problem represents a set of lists of tuples including link \( l \forall l \in \mathcal{L} \) and paths from the optimization problem which are utilizing link \( l \). The dbr-path-sort keeps list of paths utilizing link \( l \). The paths in the list are sorted in descending order according to the number of hops. This will ensure allocating FS slots first to the longest routes to minimize contiguity and continuity issues of FS slots allocation due to horizontal or spatial fragmentation. Shortest routes with higher modulation formats, better data rates, and minimum FS requirements will face minimum horizontal fragmentation. Therefore, FS contiguity requirement will be addressed more efficiently. Finally, path-slots-info is a set of tuples with path information and list of contiguous FS slots allocated along the path. The resources in the path-slots-info as well as the routing information from the optimization problem will be used for dynamic network operation.

D. Stage 4: Performance Parameters

In this Section, we have discussed several performance measurement metrics for evaluating the performance of EON for dynamic traffic in this work. These metrics include average network external fragmentation metric (EFM), average network ABPM, average network contiguity, average network bandwidth blocking probability (BBP), average standard deviation of FS utilization for the EON, and network link utilization. These are explained as follows.

1) Average Network EFM: This parameters gives the information about maximum available spatial FS block size along a
Algorithm 1: Algorithm

Input: link-optimal-values; optimal-set-of-paths
Output: path-slot-info
/* [] \rightarrow list, {} \rightarrow set */
sd-path-used = []
link-path-cluster-size = link-optimal-values
sd-path-values = [(sd.path, value(α̃))], ∀s ∈ S, ∀path ∈ optimal-set-of-paths[s]
paths-through-links = {c : [∀l ∈ L | link-optimal-values[l] = c], ∀c ∈ link-path-cluster-size}
links-from-opt-problem = {l : [path transiting link l; ∀ path ∈ optimal-set-of-paths | l ∈ path] ∀ l ∈ L}
for link-size in link-path-cluster-size do
  for link in paths-through-links[link-size] do
    dbr-path-sort =
    links-from-opt-problem[link]
    for path in dbr-path-sort do
      if path not in sd-path-used then
        sd-path-used.append(path)
        Find continuous-FS-slots
        Find sd = (path[0][0], path[len(path)-1][1])
        Find contiguous-FS-slots in continuous-FS-slots with values
        \geq sd-path-values[(sd.path)]
        // Numbers of contiguous-FS-slots will be equal to numbers of FS slots allocated from the optimization problem.
      end
    end
    path-slots-info = {((path, contiguous-FS-slots))}
  end
end

route [30]. It is given in (10) in which \(x_i\) and \(y_i\) represent available block of maximum contiguous spatial FS’s and available number of all spatial FS’s along a route for arrival \(i\).

\[
\text{EFM} = \frac{\sum_{v \in \text{arrivals}} \left( 1 - \frac{x_i}{y_i} \right)}{\text{total arrivals}}
\] (10)

Fig. 1. Spectral fragmentation in links \(L_{1,2}, L_{2,3},\) and \(L_{3,4}\).

2) Average Network ABPM: Average network ABPM can be used to estimate spatial fragmentation for dynamic traffic in a network. It is given by a mathematical expression in (11) [12], [30]. The value of average network ABPM ranges from 0 to 1 and shows spatial fragmentation. A 0 indicates the initial condition of FS along a route between the transponders. Similarly, a 1 indicates that the FS’s along a route between the transponders is mostly fragmented and not available for the demanded band of FS’s.

\[
\text{ABPM} = \frac{\sum_{v \in \text{arrivals}} \left( 1 - \frac{\text{available FS blocks}}{\text{demanded slots}} \right) \left( \sum_{\text{path transiting link l}} \frac{\text{available FS blocks}}{\text{demanded slots}} \right)}{\text{total arrivals}}
\] (11)

Consider three links \(L_{1,2}, L_{2,3},\) and \(L_{3,4}\) between nodes \(n_1, n_2, n_3,\) and \(n_4\). The spectral fragmentation in each link is given in Fig. 1. Let we consider two incremental lightpath requests \(s_1\) and \(s_2\) between \(n_1\) and \(n_3\) and between \(n_1\) and \(n_4\) respectively. Let \(s_1\) use QPSK modulation and requires 2 FS’s. Similarly, let \(s_2\) use BPSK modulation and requires 4 FS’s to setup lightpath between the end nodes. The spatial fragmentation over the path for \(s_1\) is represented by path\(^{1,3}\). Similarly, the spatial fragmentation over the path for \(s_2\) is represented by path\(^{1,4}\). In the first case, we consider the whole bandwidth of fiber links to calculate the values of ABPM as follows.

\[
\text{ABPM}^{\text{path}^{1,3}} = 1 - \frac{\left\lfloor \frac{2}{2} \right\rfloor}{\left\lfloor \frac{12}{2} \right\rfloor} = 1 - \frac{1}{6} = 0.5
\]

Similarly,

\[
\text{ABPM}^{\text{path}^{1,4}} = 1 - \frac{\left\lfloor \frac{4}{4} \right\rfloor}{\left\lfloor \frac{12}{4} \right\rfloor} = 1 - 0 + \frac{1}{3} = 0.667
\]

This means that the ABPM values on the spatial fragmented optical paths path\(^{1,3}\) and path\(^{1,4}\) are 50% and 66.7% for a
represents the numbers of all FS’s on − to carry the information over the path path to FS = max are allocated on ⌊ Δ indicates that has two states which is either 1 or 0. A 1 indicates the L. Δ in a using indicates that all values of FS on links in a network are max using δ SFFS. (13) indicates that FS utilization on ∀ to FS 1 indicates maximum utilization = L 1 and its utilized value. LU is a are 50% each for a demand and path are allocated on − means spatial Fig. 2 with different colors. FS spectral bandwidth into two categories which is shown in 42x419 as follows. BPSK scheme. In this case, we calculated the values of ABPM FS 3, 2, 4 FS and 4 FS using QPSK and BPSK modulation schemes respectively. In the second case, we split the demand of 2 FS and 4 FS using QPSK and BPSK modulation schemes respectively. In Fig. 2 with different colors. FS1 to FS4 are allocated on L1,2 and L2,3 to carry the information over the path path1,3 using QPSK. Similarly, FS3 to FS12 are allocated on L1,2, L2,3, and L3,4 to carry the information over the path path1,4 using BPSK scheme. In this case, we calculated the values of ABPM as follows.

\[
\text{ABPM}^{\text{Path1,3}} = 1 - \frac{[\frac{3}{2}]}{[\frac{3}{2}]}
\]
\[
\text{ABPM}^{\text{Path1,3}} = 1 - \frac{1}{2} = 0.5
\]

Similarly,

\[
\text{ABPM}^{\text{Path1,4}} = 1 - \frac{[\frac{3}{2}]}{[\frac{3}{2}]}
\]
\[
\text{ABPM}^{\text{Path1,4}} = 1 - \frac{1}{2} = 0.5
\]

This means that the ABPM values on the spatial fragmented optical paths path1,3 and path1,4 are 50% each for a demand of 2 FS and 4 FS using QPSK and BPSK modulation schemes respectively. This means that splitting the bandwidth of the fiber links into different categories improve ABPM values. This is due to the fact that FS’s are allocated and released in pairs in the same category. Hence, the probability of availability of contiguous FS’s is good compared to allocating different sizes of FS’s in a shared category. Therefore, resources in a shared category makes the spatial band of FS’s more fragmented.

3) Average Network Contiguity: The mathematical formulation for finding the average network contiguity (ANC) is adapted from the work in [31] which is given in (12). SFFSp has two states which is either 1 or 0. A 1 indicates the availability of a free FS and a 0 indicates that a FS is busy. The value of spatial route contiguity ranges from 0 to 1. A value 1 indicates that all available FS’s are contiguous and close neighbors with each other. Alternatively, a value 0 indicates that the available FS’s on a spatial route (if any) are not contiguous and close neighbors with each other.

4) Average Network BBP: The statement of average network BBP is adapted from the work in [15]. It is given in (13) as a ratio between the bandwidth of lightpath requests which could not be established successfully to the total bandwidth of lightpath requests. The later includes the bandwidths of successfully established and blocked lightpath requests.

\[
\text{BBP} = \frac{\sum_{i \in \text{Lightpaths blocked}} \Delta f^i}{\sum_{i \in \text{All lightpath requests}} \Delta f^i}
\]

5) Average Standard Deviation of FS Utilization: An average value of standard deviation of FS utilization δ(FSU) in a network is given in (14).

\[
\delta(\text{FSU}) = \delta \left( \forall i \in \mathcal{L} \max F S I_{l} \right)
\]

In (14), FSI denotes the maximum index of a FS which is utilized on a link. Similarly, L represents the numbers of all FS’s on a link l. Finally, (−) represents the standard deviation of a list of values which has a value in the range from 0 to 1. A value δ(−) = 0 indicates that all values of FS on links in a network are same. Similarly, a value δ(−) = 1 indicates that FS utilization on some links is extremely low while on other links, FS utilization is extremely high. Finally, the value δ(−) = 0.5 indicates that some links in a network are frequently utilized compared to others.

6) Network Link Utilization: The value of network link utilization (LU) in a network for link l is given in (15). In (15), (l, maxFSIL) is a tuple with link l and its utilized value. LU is a ratio of the maximum index of a FS which is utilized on a link l to the maximum value of FS’s on that link. The values of LU are in the range 0 to 1. A value = 1 indicates maximum utilization and a value = 0 indicates minimum utilization of a link l.

\[
\text{LU} = \forall i \in \mathcal{L} \left\{ \left( l, \frac{\text{maxFSI}_l}{\text{L}_l} \right) \right\}
\]

III. RESULTS AND DISCUSSION

In this section, we have analyzed the performance of the proposed integrated model for dynamic networking. The integrated model includes the results from the optimization model which is followed by the proposed algorithm to allocate resources between transponders in groups. The integrated approach will give routing information, spectral capacity allocation on each link in terms of FS’s, and spatial capacity allocation between transponders along the route with their modulation schemes. In simulations, we have used first-fit spectrum allocation scheme.
for FS allocation with the routing information from the optimization model. We have also considered lightpaths with variable data rates and bandwidth requirement arriving to a network with Poisson’s distribution. However, traffic is considered to be uniformly distributed. The mean holding time of lightpaths to stay in the network follows exponential distribution with the mean holding time equal to 1 time unit. In general, we have simulated different scenarios in two different networks for 1 million lightpath requests to get steady state results. We have used two networks (net1 and net2) to evaluate the performance of the proposed approach. Networks net1 and net2 have 11 and 14 nodes each which are shown in Fig. 3 and Fig. 4 respectively. Moreover, net1 has 50 directed links while net2 have 64 directed links.

In the first stage, we get all related information sets from the optimization problem using GLPK solver with Python Linear Program Module (PuLP) [32]. Let us consider network net1 with all input parameters for the optimization model which are given in section II. After solving the optimization model, we extracted the information related to the link cost for the link $l = (1, 9)$ in net1, paths utilizing the link $l$, and capacity allocation on routes utilizing link $l$. These values of different parameters are given in Table I which are extracted using the programming syntax in algorithm 2, algorithm 3, and algorithm 4. Similarly, we use the proposed algorithm to allocate block of contiguous spatial FS’s along the optimized routes and using all other information from the optimization problem. The contiguous FS allocation on different routes in Table I are given in Table II using the proposed algorithm.

| Link      | Link Capacity |
|-----------|---------------|
| (1, 9)    | 160 FS’s      |
| path      |               |
| (1, 9)    | ((1, 9), (9, 8)) |
| (1, 9)    | ((1, 9), (9, 8), (8, 11)) |
| (1, 9)    | ((3, 1), (1, 9)) |
| (1, 9)    | ((6, 2), (2, 1), (1, 9)) |
| capacity of path and adapted modulation | 40 FS’s / QPSK |
| ((1, 9), (9, 8)) | 20 FS’s / 8QAM |
| ((1, 9), (9, 8), (8, 11)) | 60 FS’s / BPSK |
| ((3, 1), (1, 9)) | 20 FS’s / BPSK |
| ((6, 2), (2, 1), (1, 9)) | 20 FS’s / BPSK |
| ((6, 7), (7, 8), (8, 9)) | 60 FS’s / BPSK |

| s-d pair | Modulation | FS allocation on Path |
|----------|------------|-----------------------|
| (1, 11)  | BPSK       | [(FS_index_v index ∈ [1, 2, ..., 60])] |
| (1, 11)  | BPSK       | [(FS_index_v index ∈ [1, 2, ..., 20])] |
| (6, 9)   | BPSK       | [(FS_index_v index ∈ [61, 62, ..., 80])] |
| (6, 9)   | BPSK       | [(FS_index_v index ∈ [1, 2, ..., 60])] |
| (1, 8)   | QPSK       | [(FS_index_v index ∈ [81, 82, ..., 120])] |
| (3, 9)   | QPSK       | [(FS_index_v index ∈ [121, 122, ..., 140])] |
| (1, 9)   | 8QAM       | [(FS_index_v index ∈ [141, 142, ..., 160])] |
Algorithm 2: Using Python Programming for Extracting Information of Paths Through Link.

1: paths-through-link = {}
2: \( \forall l \in L \):
3: temp-link = []
4: for sd in sd-pairs:
5:  for path in optimized-paths[sd]:
6:   if \( l \in \text{path} \):
7:     temp-link.append(path)
8:   paths-through-link[\( l \)] = temp-link

Algorithm 3: Using Python Programming for Extracting Information of Bandwidth (Capacity) Over a Path: Value(\( \alpha_{\text{path}} \)) is Python Syntax using PuLP to Give Cost of a Variable.

1: sd-path-value = dict(((s,path),value(\( \alpha_{\text{path}} \))) \( \forall s \in S \) and \( \forall \text{path} \in \text{optimized-paths}[s] \))

Algorithm 4: Using Python Programming for Extracting Information of Link Cost Values.

1: link-cost = dict(((l,[])) \( \forall l \in L \))
2: \( \forall l \in L \):
3:  for temppath in paths-through-link[l]:
4:   link-cost[l].append(sd-path-value(((temppath[0][0],temppath[len(temppath)-1][1]),temppath))
5: link-values = dict(((l, sum(link-cost[l]))) \( \forall l \in L \))

scheme highly reduces the amount of BBP values compared to the existing SPF routing and alternate routing. It should be noted that the integrated approach is using approximately equal number of routes compared to SPF routing and half number of routes compared to alternate routing. Similarly, the total link cost in the proposed scheme is minimum in both net1 and net2 compared to the existing schemes. The routing and s-d pair informations for both net1 and net2 are compared in Table III and Table IV respectively.

In Fig. 6, we have calculated the average ABPM values for different traffic loads (Erlang) in both networks. The proposed integrated approach has lower average ABPM values compared to SPF routing and alternate routing. This shows that the spatial fragmentation decreases in splitting the available spectrum into a number of limited subgroups. This increases the availability of idle spatial FS along a route. Therefore, reduces the amount of BBP values compared to SPF routing and alternate routing. In both SPF routing and alternate routing, the complete spectral FS on links are shared among the s-d pairs which sufficiently increases the values of ABPM. Therefore, it also increases spatial fragmentation along the routes. In Fig. 6, the values of average ABPM increases with the network traffic load (Erlang) in all cases. Hence, spatial fragmentation increases with an increase in the network traffic load (Erlang).

In Fig. 7, we have calculated the average EFM values for different traffic loads (Erlang) in both networks. We have observed that the external fragmentation in the proposed scheme is also less compared to the existing schemes. It can be observed that the

| Algorithm | s-d pairs | Number of routes | Network link cost (in numbers of FS) |
|-----------|-----------|------------------|-------------------------------------|
| SPF routing | 110 | 110 | 8000 |
| Alternate routing | 110 | 220 | 8000 |
| proposed scheme | 110 | 123 | 6440 |

| Algorithm | s-d pairs | Number of routes | Network link cost (in numbers of FS) |
|-----------|-----------|------------------|-------------------------------------|
| SPF routing | 182 | 182 | 10204 |
| Alternate routing | 182 | 364 | 10204 |
| proposed scheme | 182 | 204 | 8368 |
EFM values in alternate routing is more compared to SPF routing and the proposed scheme. This is due to the fact that traffic will be diverted to the underutilized links on the second route between the transponders to use the idle resources. Therefore, it will reduce the availability of a block of maximum contiguous spatial FS’s to utilize idle resources on these routes.

In Fig. 8, the average contiguity in the proposed scheme is less compared to other schemes. This is due to the fact that the complete spectrum is divided into a number of limited subgroups. Therefore, the availability of a maximum block of spatial FS’s along the network routes is lower compared to spectral bandwidth without partitions.

In Fig. 9, the values of \( \delta(FSU) \) are shown for different traffic load (Erlang) values in net1 and net2. It has been observed that for lower values of network traffic load (Erlang), \( \delta(FSU) \) is higher in SPF \((k = 1)\) routing which shows that FS's on some links are highly utilized and on other links, it is loosely utilized. This trend continues for SPF \((k = 1)\) routing for all traffic load (Erlang) values as BBP will increase sufficiently in the highly utilized links for higher traffic. This will make a bottleneck for other links to carry higher traffic. Hence, these under-utilized links will not carry traffic to increase FSU. The proposed scheme has the lowest values of \( \delta(FSU) \) for all traffic values compared to SPF \((k = 1)\) routing and alternate \((k = 2)\) routing. This trend shows that FSU on all links is approximately equal as the standard deviation of FSU in both networks for all traffic values remains within the range 5%. This further shows that link utilization in both networks are balanced. For alternate \((k = 2)\) routing with lower traffic, the value of \( \delta(FSU) \) is approximately equal to the value of \( \delta(FSU) \) for SPF \((k = 1)\) routing. This is due to the fact that alternate routing may use only one route due to lower traffic. However, as the network traffic increases, alternate routing utilizes the available resources on second route in case of unavailability of idle resources on primary route. Therefore, \( \delta(FSU) \) decreases slightly and approaches to the values obtained in the proposed scheme. Hence, \( \delta(FSU) \) decreases in alternate routing for higher traffic loads (Erlang) due to increase in \( (FSU) \) over all links in the network.

In Fig. 10 and Fig. 11, FS with same utilization in net1 and net2 are grouped together in different subgroups. These subgroups are called bins. It has been observed in both SPF routing and alternate routing that few groups are utilized very often compared to others. Similarly, few bins are utilized least frequently. This is possible as we have integrated SPF routing and alternate routing with first-fit spectrum allocation scheme. Therefore, the FS with minimum indexes will be highly utilized compared to the others.
in a shared spectrum. Similarly, the FS with maximum indexes are utilized slowly. The high and low utilization of few bins in SPF routing and alternate routing are reduced in the proposed scheme in which the complete spectrum is divided into limited numbers of spatial bandwidths. These spatial categories of FS blocks are dedicated on each path for each s-d pair. Therefore, first-fit scheme will utilize the starting minimum index of each subgroup. It is also increasing the frequency of utilization of FS with higher indexes.

In Fig. 12 and Fig. 13, network links with similar utilization are grouped together into bins. It has been observed that the proposed scheme has the highest link utilization. The lower bound of link utilization in the proposed scheme is greater than 65% and 80% for net1 and net2 respectively. The SPF routing has the lowest link utilization with few links under utilized. Alternate routing increases link utilization compared to SPF routing. However, the highly utilized links in this case also becomes a bottleneck for carrying additional traffic on other paths.

Finally, we have plotted the simulation time in Fig. 14 in both networks for different traffic values in all cases. It has been found that the proposed scheme has an improved lightpath setup time compared to other schemes. This is due to the dedicated bounded spatial blocks with fewer FS compared to searching for idle FS in a completely shared set of resources. It is expected that the proposed scheme will also improve bandwidth blocking due to delayed information sharing and signaling between the network nodes.

IV. CONCLUSION

In this work, we have proposed an integrated scheme for dynamic traffic which works in three phases. In the first phase, an optimization formulation is programmed which is solved using an iterative procedure to minimize the network cost. The optimization model gives routing information according to the adapted optical reaches. The objective of the optimization problem is to reduce the network cost by adapting to higher modulation schemes with higher data-rates and minimum bandwidth requirements between transponders. The second phase utilizes the routing and spectral bandwidth allocation such that spatial blocks of FS are allocated between transponders with continuity and contiguity.
constraints. These spatial FS blocks along with the routing information are utilized for dynamic traffic in the third phase. It has been shown with the support of simulation results that the spatial partitions improves the network performance in EON. Average ABPM and EPM decreases in the integrated proposed scheme compared to SPF routing in different networks which shows the availability of FS blocks to support further traffic.

Therefore, the FS utilization and the link utilization in different networks increase to support dynamic traffic in the proposed scheme. The standard deviation of FS utilization in different networks is approximately 5% compared to the existing schemes. FS utilization is approximately 25% to 30% in SPF ($k = 1$) routing. For alternate routing, the standard deviation of FS utilization is 25% to 30% initially for lower network traffic.

![Fig. 10. Bins (of similar sizes) of FS with different indexes verses number of times FS is utilized using different routing schemes in net1.](image1)

![Fig. 11. Bins (of similar sizes) of FS with different indexes verses number of times FS is utilized using different routing schemes in net2.](image2)
However, as the network traffic load (Erlang) increases, the FS utilization approaches to the level of the proposed scheme which shows that the alternate routing diverts traffic to the under-utilized links to improve link and FS utilization.

In practice, online routing is more time consuming in searching a feasible or optimal route between pair nodes with bounded constraints. Moreover, the time utilization in practical networks will increase with taking more number of routes. There are studies available on RSA / RMSA in dynamic EON which allocates routes between end pairs during the lightpath setup [33]. However, in network operation, the existing dynamic models will take more setup time to search a route with given constraints during lightpath establishment compared to the proposed approach in this work. A comparison of simulation time between...
the existing SPF routing, alternate routing, and the proposed scheme in this work is shown in Fig. 14. The routing tables are computed offline in all cases which are utilized for lightpath establishment in network operation stage. This means that the setup time will further increased to search for an optimal route in online routing compared to the reported schemes during a lightpath establishment. Therefore, the existing dynamic models are available and have been studied in the literature. However, there may be practical complications in implementing them for the dynamic network operation.

Furthermore, it is a known fact that the blocking will also occur due to signaling protocols/outdated information in online routing by utilizing shared pool of network resources. Hence, the blocking does not happens only due to unavailability of resources to establish a lightpath. It also occurs due to outdated signaling between end pairs while utilizing shared network resources. The matter is out of scope of this work and we have not studied it. However, the proposed scheme with dedicated resources allocation between end pairs will further eliminate the blocking probability with outdated signaling issue. Unlike the proposed scheme, existing online routing schemes will consider additional signaling protocols in network operation at the cost of additional connection establishment time. Alternatively, it may not consider the signaling protocols in network operation at the cost of additional network blocking probability due to outdated signaling information between end pairs in a network.

This shows the novelty and uniqueness of our proposed work.

**APPENDIX**

It is to note that a network may be operated under 2% to 5% blocking threshold level. In our case, our proposed scheme maintains the threshold level compared to the SPF blocking. However, unlike the first case (COST239 network – net1), the proposed scheme does not reduce the amount of bandwidth blocking probability in net2 in Fig. 5 further to achieve lower values compared to alternate routing scheme. However, it achieves other gains in terms of network cost, link blocking probabilities, fragmentation gain, and execution time compared to the existing SPF routing and alternate routing schemes. To demonstrate this statement, we consider equal link costs to evaluate the performance of all algorithms. This means that the number of FS’s on each link is symmetric and fixed to 160 FS’s in each case so that the network cost becomes equal in all three scenarios. Further more, the proposed algorithm is modified such that it first uses the integrated approach as explained in Section III. However, if a lightpath fails to establish using the
integrated approach, it further utilizes the routing information with first-fit heuristic to utilize the unused resources. This means that the resources outside the established tunnels are also utilized between end pairs. The scenario is simulated with 1 Million connection requests. This reduces the amount of bandwidth blocking probability at the price of network cost as shown in Fig. 15. Further, we also plotted the simulation time in Fig. 16 which is slightly increased compared to the proposed algorithm in Section III. However, the simulation time in the proposed algorithm remains largely below the existing SPF routing and the alternate routing algorithms.

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