Dynamic Routing and Spectrum Assignment based on the Availability of Consecutive Sub-channels in Flexi-grid Optical Networks

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***Abstract*—Using Optical Orthogonal Frequency Multiplexing (O-OFDM), variable bandwidth channels can be created in Elastic Optical Networks (EON). This allows the use of spectrum more efficiently by allocating integral multiple of basic bandwidth slots to the lightpath requests. Consequently, such networks are also called flexible grid optical networks. It also add a constraint of keeping all the allocated slots together when decide the routes for the requests. This constraint called the contiguity constraint, makes the routing and spectrum algorithms more challenging. In any network, the lightpath requests will arrive and depart dynamically, and will invariably lead of spectrum fragmentation, and hence network will have reduction in maximum possible utilization due to increased blocking probability. In this paper, we have presented an improvised RSA algorithm which leads to lesser fragmentation. It is evident from the results that the presented RSA algorithm uses adaptive parameters to reduce the blocking probability as well as fragmentation compared to other algorithms reported in recent past.**

I. Introduction

With the innovations continuously improving the performance of networks' endpoint devices, there is a continuous need to improve the communication networks' capacities to meet the resulting demands. All-Optical networks are the mostly used means to increase the capacity in backbone networks. The signal that traverses from the source to the destination node in these networks, remains in the optical domain. These networks contain routing nodes interconnected by optical fiber links. The resources used in these links can be either fixed-width wavelength slots or flexible spectrum slots. Fixed width wavelength slots are based on the Dense Wavelength Division Multiplexing technique. The bandwidth of each channel within the network link, is fixed as either 50 GHz or 100 GHz according to ITU-T G.694.1 [1] specifications. High data-rates connections for above 400 Gbps are not possible in these networks. At the same time, a very low data-rate lightpath requests will lead to bandwidth wastage.

Using Optical- Orthogonal Frequency Division Multiplexing (O-OFDM), the channel size can be further reduced to 12.5 GHz to alleviate the above problems. The O-OFDM adds flexibility to the optical network by permitting the variable connection bandwidth in multiples of 12.5GHz. Such networks are called the Flexi-grid Optical Network [1]. With flexibility, multiple adjacent channels can be used together to accommodate high data-rate connection demands.

One of the research problems in optical networks is Routing and Resource Assignment (RRA). The routing of a lightpath request is basically finding an end-to-end path between source and destination nodes, and it can be performed using a suitable algorithm. Resource assignment is basically finding out the link resources following the resource allocation constraints. Routing and Resource Assignment for a lightpath request is generally an NP-hard problem. It is called Routing and Wavelength Assignment (RWA) in Fixed-grid networks[2], and Routing and Spectrum Assignment (RSA) in Flexi-grid networks. RWA has only path continuity constraint. Due to flexibility, the Flexi-grid adds contiguity constraints to the RSA problem. This additional constraint and the fluctuating traffic increase blocking of lightpath requests in the flexi-grid network.

There exists various RRA algorithms in the literature [5], [7]–[10], [12] that envisage to reduce the blocking of arriving lightpath requests. However, most of the earlier work considered Routing and Resource Allocation as two separate problems. In these works, a fixed parameter e.g., distance (in kms), hops etc is used for deciding the optimal route.

In this paper, we consider adaptive parameter (one which changes with network conditions) for RRA in circuit-switched optical networks. The resources are allotted at the time of connection setup and released only when the connection is dismantled. We propose algorithms for Routing and Resource Assignment which aims to minimizes the spectrum fragmentation (explained in Section II) in the network links and blocking of the lightpath requests.

The rest of the paper is organized as follows. The basic concept of Routing and Resource Allocation is explained through examples. In Section III, related works are reviewed

[1]Optical Orthogonal Frequency Division Multiplexing based Elastic Optical Networks

[2]Wavelength Division Multiplexing based Optical Networks

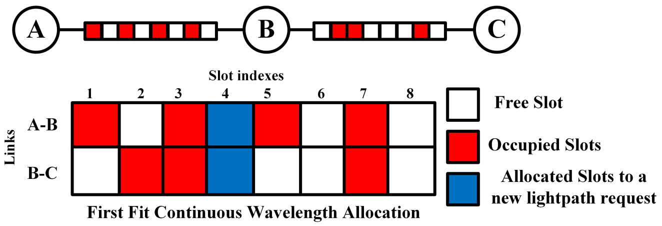


Fig. 1: Wavelength Assignment Constraints: Continuous Slot Assignment. A new lightpath request arrives from A-B-C. The slot indexes 4 and 8 are available but the slot index 4 is assigned as it available at the lower index (First Fit).

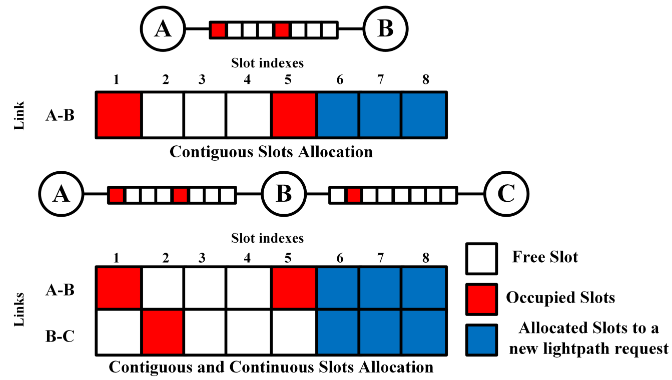


Fig. 2: Spectrum Assignment Constraints: Contiguous and Continuous Spectrum Slots Assignment. Three slots connection assignment. A new lightpath request arrives from A-B-C. The slot indexes 6, 7, and 8 is assigned as it satisfies the requirements.

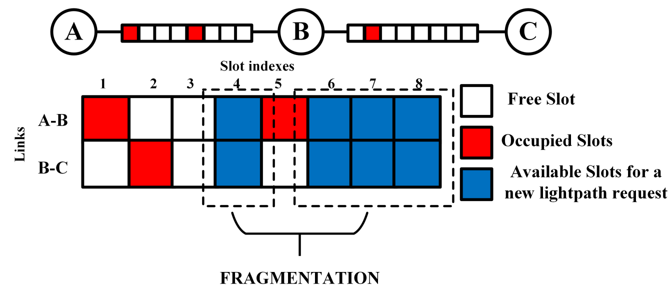


Fig. 3: Spectrum Fragmentation.

and problem statement of the paper is stated. Section IV, the problem is explained with the help different proposed algorithms. The numerical results are shown for two networks in Section V where different network settings are used to check the performance of the proposed algorithms.

II. Routing and Resource Assignment (RRA)

If we consider an N node optical network and suppose each node has N - 1 transceivers[3], then each node pair can be connected by a dedicated lightpath if there are adequate resources Nevertheless, such a solution will result in high implementation cost and may not lead to best utilization of the available resources.

To reduce the network cost, the traffic demand should be routed using minimum transceivers, wavelengths and need switches with a lesser number of ports [2]. Thus, the objective of Routing and Resource Allocation is to route and allocate resources to the lightpath requests while using minimum resources and accommodating maximum lightpath requests.

In real scenario, the RRA problem is sub-divided depending upon the type of multiplexing and switching techniques - Routing and Wavelength Assignment (RWA) and Routing and Spectrum Assignment (RSA).

However, there are a few constraints for wavelength or spectrum assignment, which need to be satisfied as explained below:

- **Wavelength Continuity Constraint:**The wavelength index for a lightpath request must be same throughout the path as shown in fig. 1.
- **Spectrum Contiguity Constraint:** The assigned spectrum slots indexes for a lightpath request must share boundary with each other as shown in fig. 2.
- **Spectrum Continuity Constraint:** The assigned continuous spectrum slots indexes for a lightpath request must be same throughout the path as shown in fig. 2.
- **Non-Overlapping Resources Constraint:** The assigned indexes to different requests cannot overlap with one other. It is consequence of capability of a slot to carry one signal at a time.

One of the problem due to the spectrum assignment constraints is *"Spectrum Fragmentation"*. It can be explained with the help of an example shown in fig. 3. A lightpath request for four slots arrives from the source node A to the destination node C. Although the four slots are available but they cannot be allocated, as we have to follow spectrum assignment constraints. It leads to the blocking of the lightpath request. If a spectrum converter is present at each node, the fragmentation can be mitigated, but converters are expensive to deploy. Also, in the literature, various defragmentation algorithms have been proposed to reduce the spectrum's fragmentation periodically. Though it is also possible to use suitable RSA algorithms to minimize it during the network operation. The defragmentation whenever invoked disrupts the existing traffic in the network for the period required for reconfiguration, which leads to another inefficiency in network performance.

The RRA problem can be further classified into *offline RRA* where the lightpath requests are known in advance and *online RRA* in which the lightpath requests arrive and released as time progresses. The later scenario is more realistic in nature. In this paper, we are considering online RRA without any periodic defragmentation. The RRA problem is further subclassified based on whether the static or adaptive parameters are considered for routing. The static parameters for routing are independent of the changes within the network; while the adaptive parameters for routing change continuously with the change in the network conditions. In this paper, our primary

[3]transmitters (lasers) and receivers (photodetectors)

focus is on Routing and Spectrum Assignment for flexible grid optical networks.

III. Related Work

In [3], Jinno *et al.* proposed the spectrum sliced elastic optical path network. The OFDM-enabled technology facilitates the allocation of a group of frequency slots (FSs) to each lightpath request according to the required bit rate. They provided a scalable network architecture using bandwidth variable-wavelength cross-connects (BV-WXC) and bandwidth variable transponders (BVT). [6] and [11] give an overview of Elastic Optical Network and the related design issues.

Issue of finding a suitable routing and resource assignment algorithm lies at the very core of the EON design. It is supposed to achieve efficient spectrum utilization while accommodating maximum number of lightpath requests. In [5], [7]–[10], [12] the problem of Routing and Spectrum Allocation in Flexi-grid networks is explained. In these papers, various heuristics for RSA have been proposed to tackle the problem of lightpath request blocking. The solution to the problem has been attempted by using a number of methods like employing different routing schemes, devising spectrum assignment algorithms based on cost of path, and by distance-adaptive modulation level manipulation.In [4], the modulation format as another dimension for manipulating the bandwidth in different sections of a lightpath, is introduced in the Elastic optical network. The authors in [15] proposed heuristics for Dynamic routing and spectrum (re)allocation, where the allocated lightpath requests are re-allocated optical spectrum to make room for new lightpath requests. A few research works [9], [22] also consider multipath routing for RSA in EON to accommodate more lightpath requests or to reduce the blocking probability.

One of the main problems due to contiguity and continuity constraint in the Flexible grid Optical Network is Spectrum Fragmentation. In [17], the authors have extensively studied the various forms of fragmentation. The survey paper presents various types of fragmentation metrics and the de-fragmentation strategies. Also, RSA strategies based on fragmentation metric without any de-fragmentation have been discussed. In [18], the authors have presented a path-based method to calculate fragmentation level and then employing it in RSA decision making. The works [19], [20] further explored fragmentation-aware routing and spectrum allocation, considering both contiguity and continuity aspects. Various parameters of the spectrum in the network links are observed and based on their state the routing decision is made. These parameters may or may not directly affect the fragmentation level. The contiguity of the spectrum slices is one of the most prominent indicators of fragmentation level. [21] gives an analytical model of fragmentation in the optical spectrum for two-service.

Many of the above research works consider static parameters such as fixed distance and hops[4] for routing of lightpath requests from source to destination to solve the problem of blocking and fragmentation. Some of them consider the adaptive parameters also for Routing and Spectrum Assignment. [23]–[25] uses relative cost parameter (e.g. link congestion), which changes with the network status while performing Routing and Spectrum Assignment for incoming lightpath requests. For various cases, the algorithms have been analyzed. The algorithm selects the route/spectrum set with the least relative cost. [26] computes the link-state based on Chromatic Dispersion and Optical Signal to Noise Ratio (OSNR). This link-state is used for routing purposes. Another adaptive parameter that has been discussed in the literature is crosstalk [27]–[29]. The crosstalk occurs within the multi-core fibres and has a bearing on Routing, Core and Spectrum Assignment in Spatial Division Multiplexed Elastic Optical Networks. In [30], the author covers the problem of spectrum de-fragmentation in crosstalk aware RCSA.

One of the adaptive parameter that can be effective for RSA is consecutive spectrum slots present on each link of the network. This can be used for routing purposes in conjunction with the above discussed literature work. In the present work, our objective is to find a suitable route and suitable spectrum slots for the incoming lightpath requests using an adaptive parameter, called link spectrum consecutiveness. In this paper, we are considering a dynamic traffic scenario and applying adaptive routing and spectrum assignment. The same problem can be extended for Routing, Core and Spectrum Assignment. However, we are not considering multiple cores within the fiber in the current work. We are attempting to utilize spectrum as efficiently as possible for single core Flexible grid Optical Networks. Therefore, we are assuming no crosstalk issues.

IV. Routing and Spectrum Assignment based on the Availability of Consecutive Slots

We represent an optical network as a graph *G(V, E)* where G is defined as a set of optical vertices[5] V, indexed by v and set of optical fiber edges[6] E, indexed by e. Each edge is connected to a pair of vertices e.g., $(i, j) \in E$, where i and $j \in V$. Each edge $e \in E$ has usable bandwidth, B_e. The B_e is partitioned into multiple spectrum slots in order to use it efficiently. We define a bitmap, Δ_e (sequence of 1s and 0s) on an edge $e \in E$ to model availability status of the spectrum slots. The cardinality of the possible spectrum slots on an edge e, $|\Delta_e|$ is represented with eq. 1

$$|\Delta_e| = \Big\lfloor \frac{\text{Total Usable Bandwidth}(B_e)}{\text{Grid Size}} \Big\rfloor, \tag{1}$$

Suppose each edge has same set (F) of spectrum slots (f_s), then the bitmap for an edge can be represented as $\Delta_e = [f_1, ..., f_{|F|}]$ where f_s can be either 0 or 1 depending on the condition whether the s^{th} frequency slot is busy or free respectively. Therefore, the bit s in Δ_e is represented as,

[4]independent of the network conditions

[5]nodes

[6]links

$$\Delta_e[s] = \begin{cases} 1, & \text{if } s^{th} \text{ slot on edge } e \text{ is free,} \\ 0, & \text{if } s^{th} \text{ slot on edge } e \text{ is occupied,} \end{cases} \tag{2}$$

The slot availability status can be easily propagated for a destination through the neighbours by simply performing AND operation of current status with the slot availability status in the next link to neighbour.

In this paper, the Routing and Spectrum Assignment uses the availability of consecutive spectrum slots for routing. It makes it a joint RSA problem. If a lightpath request with required slots is available, the spectrum slots are allocated and lightpath is established; otherwise, the request will be blocked.

Suppose if the fibers are deployed between pair of nodes in a network at different time instants, the bandwidth of some of the fiber links/edges may be different, subject to technological advancements. Let the bitmap of edge 1 is Δ_{e_1} and edge 2 is Δ_{e_2} and suppose $|\Delta_{e_1}| > |\Delta_{e_2}|$. This is the case of non-uniform bandwidth, hence, the bitmap sequence, on the edges of the network. ($|\Delta_{e_1}| - |\Delta_{e_2}|$) slots) are zero-padded in Δ_{e_2} to make uniform size of bitmap sequences for all the links in the network. However, the zero-padded bit sequence remains unavailable for use by lightpath requests independently of the network conditions. Now, $\Delta_e[s] = 0$ in eq. 2, when s^{th} slot on edge *e* is occupied or unavailable.

The availability bitmap for a path p, Δ_p can be achieved by intersecting or Bit-wise ANDing of bit maps on all the constituent edges of path p as shown by eq. 3

$$\Delta_p = \{\Delta_p[l]\} = \{\bigcap_{i=1}^{L} \Delta_{e_i}[l]\} \tag{3}$$

Eq. 3 is for both the cases of uniform and non-uniform bandwidth provisioning on the edges in the network. Here, L is the number of hops for path p.

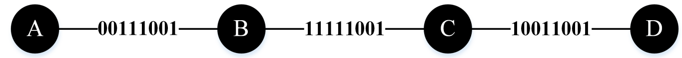
A. Examples: Equal and Unequal number of slots on the links in a network

1) Consider a uniform network with three link lightpath (p) *A-B-C-D* as shown in fig. 4a. Each link on a path has 8 slots. The slot value is represented with 1s and 0s based on the availability status. The values of Δ_{e_1} for edge 1 is 00111001, Δ_{e_2} for edge 2 is 11111001, and Δ_{e_3} for edge 3 is 10011001. Therefore,

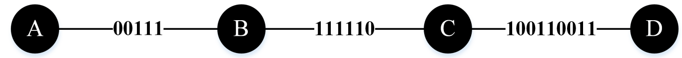
$$\Delta_p = \{\bigcap_{i=1}^{3} \Delta_{e_i}\} = 00011001$$

2) Now consider that the bandwidth on the links can be different as shown in fig. 4b. The values of Δ_{e_1} for edge 1 is 00111, Δ_{e_2} for edge 2 is 111110, and Δ_{e_3} for edge 3 is 100110011. The cardinality of available slots on edge 1, $|\Delta_{e_1}|$, is 5 on edge 2, $|\Delta_{e_2}|$, is 6, and on edge 3, $|\Delta_{e_3}|$, is 9 i.e., $|\Delta_{e_1}| < |\Delta_{e_2}| < |\Delta_{e_3}|$. The cardinality of edge 3 is the highest so there is no zero-padding for it; however, zero-padding is needed in edge 1 and edge 2. After zero-padding, the cardinality $|\Delta_{e_2}|$ changes to $|\Delta_{e_2}| + (|\Delta_{e_3}| - |\Delta_{e_2}|)$, and $|\Delta_{e_1}|$ changes to $|\Delta_{e_1}| + (|\Delta_{e_3}| - |\Delta_{e_1}|)$. The difference part is zero-padded to the edge 1 and edge 2 slots. Therefore, the Δ_{e_1} for edge 1 is 001110000, and Δ_{e_2} for edge 2 is 111110000, and

$$\Delta_p = \{\bigcap_{i=1}^{3} \Delta_{e_i}\} = 000110000$$



(a) Uniform spectrum slots on links, and



(b) Non-uniform spectrum slots on links.

Fig. 4: Examples show a lightpath request with three links and their spectrum status.

B. Lightpath representation and Parameters Notations Used

In a network *G(V, E)*, if a lightpath request arrives with a required bandwidth of B^r for an s-d pair, then the cardinality of the required contiguous spectrum slots on any choosen path is computed with the eq. 4.

$$|\Delta^r| = \left\lceil \frac{\text{Required Bandwidth}(B^r)}{\text{Grid Size} * m} \right\rceil + \text{GB}, \tag{4}$$

where m is the number of bits per symbol (modulation level) used depending on the path length of the lightpath. In this paper, we are using Grid size of 12.5 GHz and BPSK modulation format i.e., the modulation level $m = 1$. Also, we are also considering an additional guard band (GB) such that no two lightpaths interfere if they are placed next to each other.

C. Notations Used in the Algorithms

- $G(V, E, \{\Delta_e\})$: An optical network represented as graph G is defined as a
  V: set of optical vertices[7] *V*, indexed by *v*,
  E: set of optical fiber edges[8] *E*, indexed by *e*, and
  Δ_e: sequence of 1s and 0s on an edge $e \in E$ to model the availability status of the spectrum slots.
- $LR(s, d, \{\Delta^r\}, k)$ is a Lightpath Request where
  s is the source node, $s \in V$,
  d is the destination node, $d \in V$,
  Δ^r is the bitmap of required contiguous and continuous spectrum slots from s to d, and
  k is an positive integer. It is the maximum number of paths to be computed by RSA.
- Δ_p is the bitmap of available spectrum slots in path p from s to d.
- (u, v) is the edge joining the pair of vertices (nodes), where u is the starting (head) node and v is the ending (tail) node.

[7]nodes
[8]links

D. *Proposed Algorithms*

In this paper, we proposed three algorithms for routing of lightpath requests using adaptive parameters.

1) Type I: Routing and Spectrum Assignment based on Consecutive Slots (RSACS): The Type I RSACS algorithm selects the path from the set of available paths. In this algorithm, whenever a new lightpath request $LR(s, d, \{\Delta^r\})$ arrives, the algorithm traverses from the source node to its neighbouring nodes and so on, based on the available spectrum slots. If the sufficient contiguous spectrum slots are not available through a node, the search through the link leading to insufficient slots is terminated. The search continues through the other links to find all the paths with minimum required contiguous slots. The process continues until we reach the destination node. At the end of algorithm, we will find all the paths from source node to the destination node with the available contiguous slots. The best path among all the found paths having the required number of contiguous slots, is allocated to the lightpath request based on the first-fit spectrum assignment as shown in Algorithm 1. The algorithm computes set of paths with at least one slot available. The set of k (where k is a positive integer) possible paths are computed using CANDIDATEPATHS() function (Algorithm 2). The paths which have slots greater or equal to the required slots are selected. On the basis of first-fit, the slots are chosen from the set of slots present on the selected path.

Although for single-path routing, this algorithm has high time complexity, it is useful for doing multipath routing as the source node has the details of all the paths with available spectrum slots. If there are no paths with required available slots, the source node can select multiple paths whose combined available slots are greater than or equal to the required slots. Though, the feasibility to split the transmitted signal into multiple streams should exist for this scenario. In this way, we can reduce the blocking of the lightpath requests.

2) Type II: Routing and Spectrum Assignment based on Consecutive Slots: Algorithm 3 is Type II: Routing and Spectrum Assignment based on Consecutive Slots. It is another way of routing using consecutive spectrum channels. Each node checks the contiguous required slots with the slots present after Bit-wise ANDing of the bitmap of path from source node and the bitmap of the link from the current node to the neighbouring node. If the current node is the destination node, that path will be considered for RSA. But, if the required slots are not available from source to the current node, then no path is feasible via current node. In this method, routing reduces the computational time as we need not compute all the candidate paths. Instead, we get the best candidate path for Routing and Spectrum Assignment. The role of function CANDIDATEPATH() (Algorithm 4) changes and it return the only best candidate path using ISFEASIBLE() function. ISFEASIBLE() (Algorithm 5) which checks the required slots Δ^r at each node, if available, then passes the information to the adjacent nodes for route discovery further.

This way of routing is best suited for single path routing and independent of k.

Algorithm 1 Type I: RSACS

Input: $G(V, E, \{\Delta_e\})$, $LR(s, d, \{\Delta^r\}, k)$
$AllPath \leftarrow$ list of candidate paths from s to d using CANDIDATEPATHS($G(V, E, \{\Delta_e\})$, s, d, k) ▷ Algorithm 2
if $AllPath$ is not empty **then**
    for all the candidate paths in $AllPath$ indexed by i **do**
        if $|\Delta^i| >= |\Delta^r|$ **then**
            Return $BestPath = AllPath(i)$ ▷ First one in the AllPath() which satisfy the constraint is picked. There can be other ways of choosing if more than one option are there.
        else
            $i++$
        end if
    end for
    if $BestPath$ is empty **then**
        Block the request
    end if
else
    Block the request
end if

3) Type III: Routing and Spectrum Assignment based on Consecutive Slots and Shortest Path: The Algorithm 6 is Type II Routing and Spectrum Assignment based on Consecutive Slots with additional Shortest Path Constraint. The method for computing path is same as used for Algorithm 3 except in this instead of multiple paths from a node only one candidate path is maintained from a node to source s in CANDIDATEPATHS function (Algorithm 4). Based on the distance, the shortest path is chosen for Routing and Spectrum Assignment.

This method is the reverse process of k-shortest path algorithm. This is also used for single path routing.

V. NUMERICAL RESULTS

The k-shortest path (k-sp) algorithm found the route on the basis of path containing least number of hops or shortest distance (km or miles). After that it checks whether the required slots are available or not. This method might require extra computation. Therefore, we proposed algorithms in which the routes are found on the basis of contiguous and continuous spectrum available and compare their performance with k-shortest path algorithm and shortest path algorithm.

A. *Performance Metrics*

The performance of the proposed algorithms is evaluated on the basis of blocking of the incoming requests, blocking of the incoming required slots, and the spectrum utilization with the gradual increments of demand rate (in Gbps):

- **Blocking Probability**: It is defined as the ratio of total number of blocked connections to the total number of arrived connections.

Algorithm 2 CANDIDATEPATHS()

function CANDIDATEPATHS($G(V, E, \{\Delta_e\})$, s, d, k)
  $AllPath$ = [ ] ▷ Contains the list of all the paths possible with available slots, at the end of the algorithm
  $Path = [s]$ ▷ A path is an ordered list of nodes with neighbouring node having link between them.
  while $Path$ is not empty **do**
    tmp = [ ]
    for all paths in *Path* indexed by i **do**
      $u = Path(i).end$ ▷ u is the end node as of now for the i^{th} path entry
      $\{v\} = \text{ADJ}(u))\backslash Path(i)$ ▷ ADJ function returns set of all neighbours of u excluding the one already on $Path(i)$, $\backslash$ sign is for excluded elements. All nodes in the i^{th} path are excluded
      if $\{v\}$ is not empty **then**
        for all nodes in $\{v\}$ indexed by j **do**
          $\Delta_i \leftarrow \Delta_i \cap \Delta_{(u,v(j))}$
          if $\text{SUM}(\Delta_i) \neq 0$ **then** ▷ SUM function gives the number of available slots in $Path$, p. Only $(Path(i), v(j))$ should not be considered if sum is zero.
            if $v(j) == d$ **then**
              $AllPath = AllPath + [Path(i), v(j)]$ ▷ add the $[Path(i), v(j)]$, as another path from s to d.
              if $size(AllPath) == k$ **then**
                Return: $AllPath$
              end if
            else
              $tmp = tmp + [Path(i), v(j)]$ ▷ add the path $[Path(i), v(j)]$ to tmp path storage.
            end if
          end if
        end for
      end if
    end for
    $Path = tmp$ ▷ All new paths learnt are stored in $Path$
  end while
  Return: $AllPath$
end function

Algorithm 3 Type II: RSACS

Input: $G(V, E, \{\Delta_e\})$, $LR(s, d, \{\Delta^r\}, 1)$
$AllPath \leftarrow$ A candidate path (k = 1) from s to d using CANDIDATEPATHS($G(V, E, \{\Delta_e\})$, $LR(s, d, \{\Delta^r\}, 1)$) ▷ Algorithm 4
if $AllPath$ is not empty **then**
  $BestPath$ = $AllPath(1)$
  Return $BestPath$
else
  Block the request;
end if

Algorithm 4 CANDIDATEPATHS() $\rightarrow$ Path with contiguous slots $\geq \Delta^r$

function CANDIDATEPATHS($G(V, E, \{\Delta_e\})$, $LR(s, d, \Delta^r)$, k)
  $AllPath$ = [ ]
  $Path = [s]$
  while $Path$ is not empty **do**
    tmp = [ ]
    for all paths in *Path* indexed by i **do**
      $u = Path(i).end$
      $\{v\} = \text{ADJ}(u))\backslash Path(i)$
      if $\{v\} \neq []$ **then**
        for all nodes in $\{v\}$ indexed by j **do**
          $\Delta_i \leftarrow \Delta_i \cap \Delta_{(u,v(j))}$
          if ISFEASIBLE((Δ_i, Δ^r)) == TRUE **then**
            if $v(j) == d$ **then**
              $AllPath = AllPath + [Path(i), v(j)]$
              if $size(AllPath) == k$ **then**
                Return: $AllPath$
              end if
            else
              $tmp = tmp + [Path(i), v(j)]$
            end if
          end if
        end for
      end if
    end for
    $Path = tmp$
  end while
  Return: $AllPath$
end function

Algorithm 5 ISFEASIBLE()

function ISFEASIBLE((Δ_a, Δ_b)) ▷ ISFEASIBLE function checks the contiguous slots Δ_b is available in Δ_a
  if Δ_b in Δ_a **then**
    Return: TRUE
  else
    Return: FALSE
  end if
end function

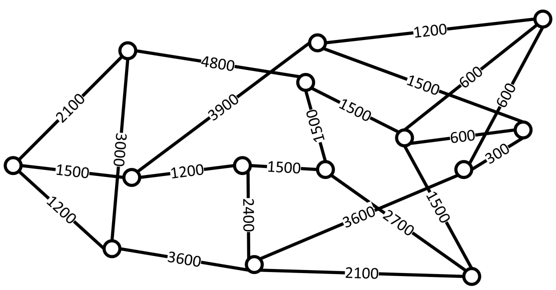
- **Bandwidth Blocking Probability**: It is defined as the ratio of the total amount of incoming bandwidth or slots blocked to the total amount of bandwidth or slots required for all the connections.
- **Spectrum Utilization**: The ratio of total bandwidth or slots used to the total bandwidth or slots in the spectrum.

B. Network Settings

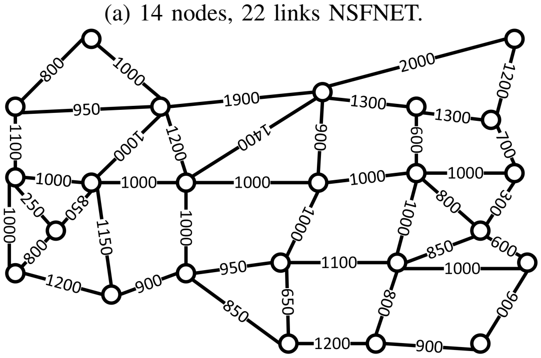
To evaluate the efficacy of our proposed algorithms, we operated a set of simulation experiments using MATLAB

Algorithm 6 Type III: RSACSSP

Input: $G(V, E, \{\Delta_e\})$, $LR(s, d, \{\Delta^r\}, k)$
$AllPath \leftarrow$ list of candidate paths from s to d using CANDIDATEPATHS($G(V, E, \{\Delta_e\})$, $LR(s, d, \{\Delta^r\}, k)$) ▷ Algorithm 4
if $AllPath$ is not empty **then**
  for all the candidate paths in $AllPath$ indexed by i **do**
    Select the shortest path (distance in km) from all paths listed in $AllPath$ and store in *BestPath*
    Return: *BestPath*
  end for
else
  Block the request
end if



(a) 14 nodes, 22 links NSFNET.



(b) 24 nodes, 43 links USNET.

Fig. 5: Networks Topologies used.

R2019b. The simulations are done for 1,00,000 requests for multiple iterations. The performance of proposed algorithms - Type I: RSACS, Type II: RSACS and Type II: RSACSSP in Flexigrid Optical Networks, are evaluated on the 14-nodes 22-links NSFNET with an average degree of all the vertices [9] is 3.0, and 24 nodes 43 links USNET with an average degree of all the vertices is 3.5 as shown in fig. 5. We assume the fiber bandwidth to be 4 THz on each link of the network. Using O-OFDM technology, the whole bandwidth is divided into 12.5 GHz parallel channels. Therefore, there are 320 spectrum slots on each link of the network, calculated using eq. 1. The traffic demands for all the lightpath requests on each node pair are uniformly distributed. The bandwidth required for each lightpath is chosen randomly between 1 and B, where different 'B' values are used as a parameter in simulations. In this paper, the values of B are 100 Gbps[10] and 200 Gbps[11]. For spectrum allocation, we are also considering an additional guard band (GB). The value of GB is considered 1[12].

The use of static traffic for simulation does not show the effectiveness of the algorithms proposed, and we are dynamically generating lightpath requests, i.e., considering dynamic traffic scenarios. The incoming lightpaths can be set up and released upon request. These are equivalent to setting up and releasing circuits in circuit-switched networks. The incoming lightpath requests arrive with an exponentially distributed time with the average inter-arrival time of $\frac{1}{\lambda}$ seconds and take an exponentially distributed holding time average of $\frac{1}{\mu}$ seconds before release. The offered load (ρ) in Erlang(E) is given by

$$\rho = \frac{\frac{1}{\mu}}{\frac{1}{\lambda}} = \frac{\lambda}{\mu} \tag{5}$$

The performance of the k-shortest path (k-sp) algorithm depends on the number of shortest paths k for pathfinding. On the other hand, the pathfinding for our proposed algorithms also depends on the availability of the spectrum slots. The value of k chosen for pathfinding is 10 for k-sp, Type I and Type III algorithms. At the same time, the shortest path and Type II algorithms are independent of the value k. The performance parameters are computed based on the observations made after reaching the steady-state condition (approximately three times the average holding, i.e., $3 * \frac{1}{\mu}$).

C. Simulation Results

The path finding algorithms used for comparison with the proposed algorithms are shortest path and k-shortest path algorithms. Fig. 6 shows the performance of algorithms in terms of blocking of the incoming lightpath requests whereas fig. 7 is for the blocking of incoming spectrum slots and fig. 8 is for utilization of the spectrum slots. Fig. 6, 7 and 8 plots are for NSFNET network where the value of k is 10 and the incoming demand rate is 100 Gbps.

Fig. 6 and 7 plots the blocking probability of five pathfinding techniques with first-fit spectrum allocation policy. Intuitively, as the value of the offered load increases, the blocking increases, as shown in fig. 6. The performance of consecutive slots-based pathfinding algorithms is better than shortest path algorithms. Additionally, for low loads, the Type I and Type II algorithms outperform existing algorithms. Also, the Type III and k-shortest path algorithms processes are the same, except in Type III, the adaptive parameter is used first and then static parameter for routing. The performance of the

[9] a.k.a. nodal degree, $n_d = \frac{2E}{V}$

[10] 8 spectrum slots, if the grid size is 12.5 GHz

[11] 16 spectrum slots, if the grid size is 12.5 GHz

[12] For 100Gbps, Δ^r = 8 + 1 = 9. Similarly, for 200Gbps, Δ^r = 16 + 1 = 17.

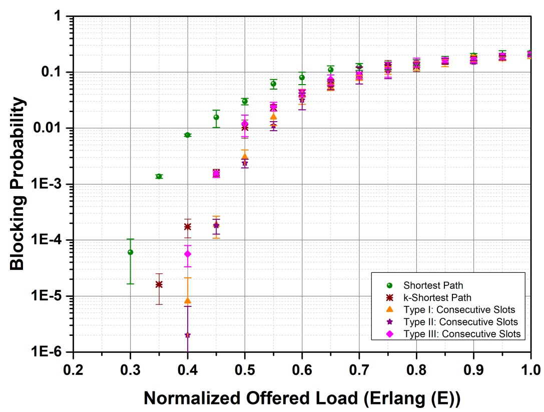


Fig. 6: Blocking Probability Vs Offered Loads for NSFNET with a demand rate of 100 Gbps.

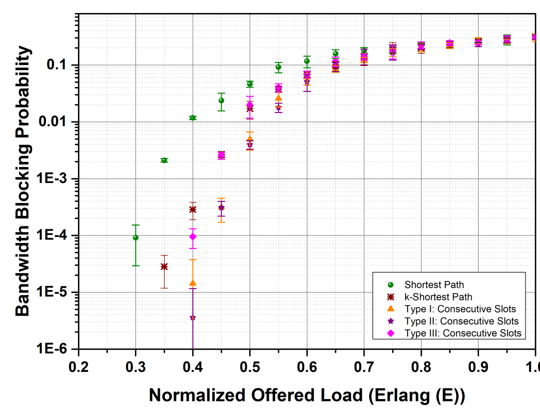


Fig. 7: Bandwidth Blocking Probability Vs Offered Loads for NSFNET with a demand rate of 100 Gbps.

Type III algorithm is better than the k-shortest path algorithm for lower loads. Intuitively, this is because the shortest path algorithm finds the route from source to destination based on the distance, not the spectrum slots available. Therefore, if the spectrum slots are not available at the spectrum assignment, that path gets blocked. In this case, other paths might have required spectrum slots; therefore k-shortest algorithm is expected to perform better. Whereas the Type II algorithm finds the path based on required spectrum slots, the path gets blocked at the routing time if the spectrum slots are not available. In this, all the possible paths are checked where spectrum slots are available. Nevertheless, after the 0.45 offered load, the blocking performance is almost the same.

In contrast, Type II and shortest path algorithms' time complexity is almost the same as both the algorithms are independent of the value of k. However, the performance of Type II is far better than the shortest path for lower and intermediate load conditions. The shortest path algorithm has the worst performance of all the algorithms.

Fig. 8 compares the performance in terms of spectrum utilization. The blocking of the connections for lower loads is almost negligible; therefore, the spectrum utilization values are random and low. But as the offered load values increase, there is a higher spectrum utilization for the k-shortest path and the proposed algorithms. One of the main reasons for higher blocking of connections and lower spectrum utilization for the shortest path is the unavailability of the spectrum slots present in a fragmented state. In contrast, for other cases, the fragmentation is lower.

Fig. 9, 10 and 11 plots are for NSFNET network where the value of k is 10 and the maximum incoming demand rate is 200 Gbps. For higher demand rates, the blocking keeps increasing as the probability of availability of required spectrum slots becomes lower than that for 100 Gbps. The comparison is the same as that of the demand rate of 100 Gbps. The spectrum performance is also the same, i.e. the spectrum utilization of

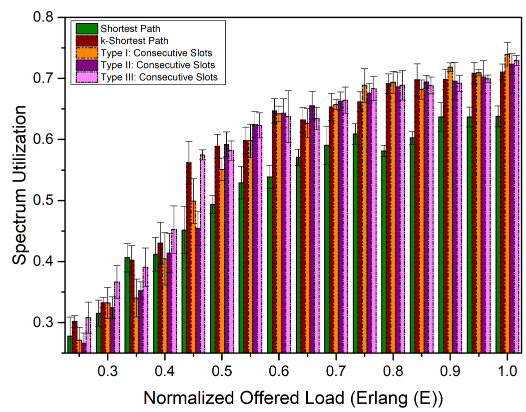


Fig. 8: Spectrum Utilization Vs Offered Loads for NSFNET with a demand rate of 100 Gbps.

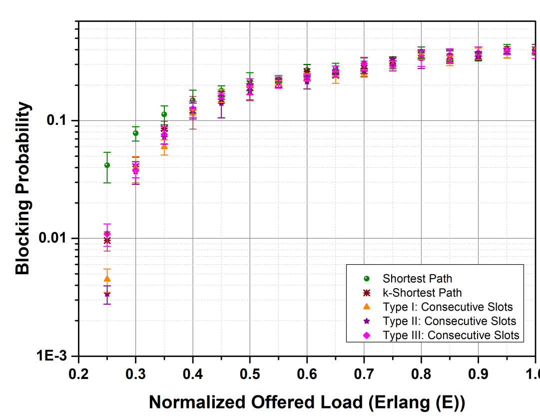


Fig. 9: Blocking Probability Vs Offered Loads for NSFNET with a demand rate of 200 Gbps.

Parameters	Shortest Path	*k*-Shortest Path	Type I	Type II	Type III
Path finding	On the basis of distance or hops	On the basis of distance or hops	On the basis of available slots	On the basis of available slots	On the basis of available slots and hops
Time Complexity	$O(V.E)+O(\Delta.E)$	$O(k.V.E)+O(\Delta.E)$	$O(k.V.E.\Delta)+O(\Delta.E)$	$O(V.E.\Delta)+O(E)$	$O(k.V.E.\Delta)+O(E)$
Blocking of the request after path finding	If the required spectrum is not available, request can be blocked	If the required spectrum is not available, request can be blocked	If the required spectrum is not available, request can be blocked	No blocking	No blocking

TABLE I: Comparison of Algorithms used for Routing and Spectrum Assignment. Here, V is the set of vertices, E is the set of edges, Δ is the set of spectrum slots, and k is the maximum number of paths to be computed by RSA.

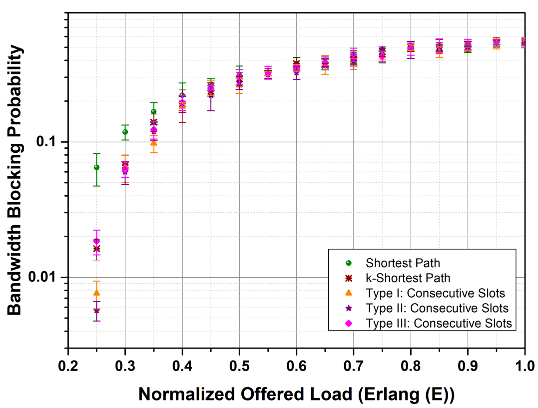


Fig. 10: Bandwidth Blocking Probability Vs Offered Loads for NSFNET with a demand rate of 200 Gbps.

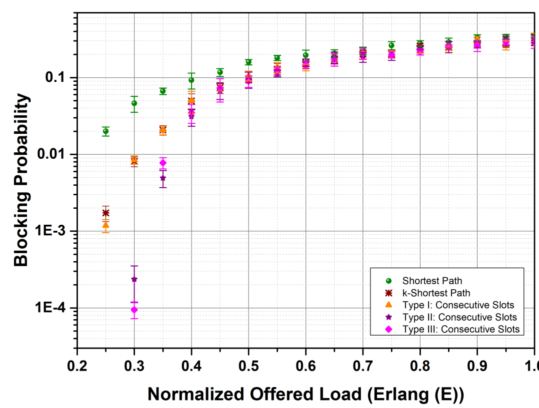


Fig. 12: Blocking Probability Vs Offered Loads for USNET with a demand rate of 100 Gbps.

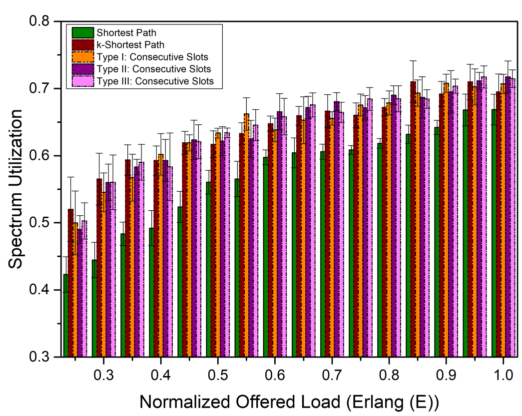


Fig. 11: Spectrum Utilization Vs Offered Loads for NSFNET with a demand rate of 200 Gbps.

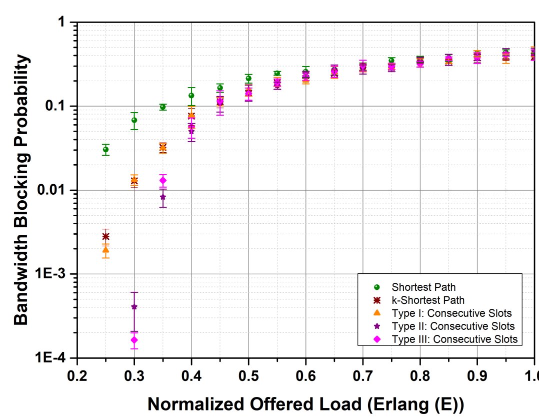


Fig. 13: Bandwidth Blocking Probability Vs Offered Loads for USNET with a demand rate of 100 Gbps.

the shortest path is the worst. Whereas, other four algorithms' spectrum utilization performance is almost the same.

Fig. 12, 13 and 14 plots are for USNET network where the value of k is 10 and the incoming demand rate is 100 Gbps[13]. This observation is for large networks with 24 nodes and 43 links. The blocking performance of the lightpath requests and spectrum slots changes as compared to NSFNET. In USNET, the Type III algorithm outperforms the other strategies. Intuitively, since for large-sized networks, the path length is an important parameter along with the spectrum slots. Also, the lower the path length, the lesser is the fragmentation within the network.

The blocking performance of the algorithms is almost the

[13] 16 spectrum slots, if the grid size is 12.5 GHz

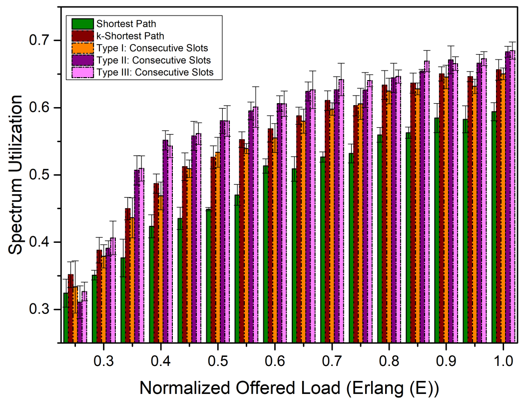


Fig. 14: Spectrum Utilization Vs Offered Loads for USNET with a demand rate of 100 Gbps.

same after 50% of the offered load. For lower loads, the performance metrics of the shortest path algorithm perform worst, whereas the performance of the k-shortest path and Type I algorithm is the same. The Type II algorithm is also better for USNET. The spectrum utilization performance is better for Type II and Type III algorithms. From different performance comparisons, the Type II algorithm outperforms in terms of blocking and complexity. Also, we know a priori blocking, i.e., at the routing time, so there is no need for spectrum assignment in this algorithm.

One of the reasons for changing the routing schemes is to lower fragmentation within the spectrum slots. Since we are not using any de-fragmentation strategy as it interrupts the active lightpath requests. Therefore, lowering the blocking of the lightpath requests results in lesser spectrum slots fragmentation.

VI. Conclusion

The routing and spectrum assignment is a tedious process in Flexible grid Optical Networks. The main reason is dynamic arrivals and departures of the lightpath requests and contiguity constraint, resulting in fragmentation within the spectrum of the network. In this chapter, instead of using static parameters for RSA, we used adaptive parameters, i.e., consecutive spectrum slots for routing. The consecutive spectrum slots keep changing with the network conditions. We performed the detailed analysis under different demand rates for NSFNET and USNET. The performance of the proposed algorithms is better than the existing strategies in terms of lower blocking of the lightpath requests. One of the reasons is the lower fragmentation of the spectrum slots. We performed a detailed analysis of the proposed algorithms. The Type II algorithm outperforms in terms of blocking as well as time complexity.

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