

Class-based First-Fit Spectrum Allocation with Fragmentation Avoidance for Dynamic Flexgrid Optical Networks

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Abstract

A novel Class-Based First Fit (CBFF) spectrum allocation policy is proposed for dynamic flexgrid optical networks. The effectiveness of the proposed CBFF policy is compared against the First Fit (FF) policy for single-link and network scenarios. Throughput is shown to be consistently improved under the proposed CBFF policy with throughput gains of up to 15%, compared with the FF policy for the network scenarios we studied. The reduction in bandwidth blocking probability with CBFF with respect to FF increases as the link capacities increase. Throughput gains of CBFF compared with FF are more significant under alternate routing as opposed to fixed routing.

Keywords: Flexgrid optical networks, spectrum allocation, first fit, connection blocking probability, bandwidth blocking probability

1. Introduction

Current state of the art optical transport networks employ Dense Wavelength Division Multiplexed (DWDM) transmission with per-wavelength capacities of 10, 40, or 100 Gbps [1],[2]. Optical cross-connects (OXC) with or without wavelength conversion route the optical signal from one end point to another in DWDM networks, hence referred to as Wavelength Routed Networks (WRN), and the path followed by the optical signal in WRNs is called an Optical Path (OP). The International Telecommunication Union (ITU) currently employs a fixed wavelength grid which divides the available optical spectrum into fixed 50 GHz spectrum slots (or frequency slots). Fixed modulation formats and rigid and coarse wavelength level granularity have

been identified as the main drawbacks of current fixed grid DWDM networks [2],[3],[4],[5]. A recent paradigm, called Elastic Optical Networks or Flex-grid Optical Networks (FON), has recently emerged as a solution addressing the issues that DWDM-based WRNs raise. FONs rely on the flexgrid scheme where the available optical spectrum is divided into frequency slots that have finer spectral width compared to fixed grid; potential alternatives for the slot width are 6.25 GHz, 12.5 GHz, or 25 GHz [6]. The actual benefit of the flexgrid stems from the Liquid Crystal on Silicon (LCOS) devices by which adjacent slots can be joined together to form a multi-slot spectral block that can be dedicated to a single OP [7]. Moreover, different modulation formats, as opposed to a single standard one, can be used for different OPs in FONs. Realization of FONs using BV-Ts (Bandwidth Variable Transponder) and BV-OXCs has been demonstrated in the SLICE network using Orthogonal Frequency Division Multiplexing (OFDM) [3].

In WRNs, Routing and Wavelength Assignment (RWA) problem is involved in finding a route and assigning a wavelength for the OP. When the OXCs lack wavelength conversion capability, the so-called Wavelength Continuity Constraint (WCC) ensures that the assigned wavelength needs to be the same on each link of the OP. The WCC constraint is replaced with the Spectrum Continuity and Contiguity Constraint (SCCC) for the Routing and Spectrum Allocation (RSA) problem in FONs. The SCCC dictates that the frequency slots dedicated to a particular OP need to be not only the same for all links along the OP (continuity constraint) but contiguous in spectrum as well (contiguity constraint). In the off-line RSA problem which is used in the design and planning stages of flexgrid networks, RSA applies to all connection requests at the same time, i.e., static traffic scenario. The off-line RSA is known to be NP-complete [8],[9]. In [8], the authors propose a heuristic algorithm to find a sub-optimal solution to the RSA problem whereas alternative simulated annealing- and ant colony optimization-based methods are proposed in [5] and [10], respectively. The reference [6] proposes Integer Linear Programming (ILP) formulations for the RSA problem with reduced problem complexity.

In the on-line RSA problem, connection requests arrive at the system one at a time and RSA applies to one single connection request only, i.e., dynamic traffic scenario. In this on-line version of the problem, OPs are also allowed to be torn down occasionally. The on-line RSA problem applies to dynamic FONs where connections are added and terminated, but also a solution to on-line RSA can also be used as a heuristic for the off-line RSA problem. Al-

ternatively, a carrier may use off-line RSA in the network planning phase but until the next time the network will be re-planned, incremental changes are addressed by the on-line RSA algorithm. On-line RSA implementation can either be centralized or distributed [11]. In centralized control, the mechanism we envision in this paper, a single controller maintains a detailed, global, and unique view of the network topology and the available spectrum on each link. When requests arrive, it is the responsibility of the controller to find routes and contiguous spectral blocks to meet the incoming request and provision the optical path [12]. For distributed control, Internet Engineering Task Force (IETF) is currently working on a distributed control plane for FONs and in particular the flexgrid extensions to existing signaling protocols [13],[14].

Fragmentation of optical spectral resources is a well-known consequence of on-line RSA algorithms. Similar to fragmentation in hard disk drives, once new connections are added and existing connections are terminated, the free spectrum eventually becomes interspersed (or scattered). Horizontal fragmentation refers to a scenario where a spectral block may not be available on all links of a path for a request although individual links may have sufficient bandwidth [15],[16]. On the other hand, vertical fragmentation arises when the idle spectral resources on individual links turn out to be scattered making it hard to find large contiguous spectral blocks to be allocated to large demands [15]. It has been observed in the above-mentioned studies that the blocking probability (BP) of connection requests with larger number of slots are generally much higher than those with fewer-slot requests which stems from both types of fragmentation. Fragmentation is therefore not only detrimental to overall blocking performance but also to fairness among different types of requests. There are two types of fragmentation avoidance algorithms: reactive and proactive. Reactive defragmentation policies are triggered once the spectrum becomes heavily fragmented [17],[18],[19]. On the other hand, proactive fragmentation avoidance has the advantage over reactive defragmentation schemes that it does not require reconfiguration of existing connections which may cause disruption for live connections [16]. The focus of this paper is on proactive fragmentation avoidance.

Some simulation examples demonstrating fragmentation are presented in [7]. For different quantification methods of fragmentation, we refer the reader to [17], [20],[21],[22]. A number of Spectrum Allocation (SA) policies have been discussed in [21] for dynamic flexgrid networks. The First-Fit (FF) policy, inspired from the FF algorithm devised for the wavelength assignment

problem in WRNs [23],[24], places the incoming request in the first available spectral block starting from the low end of the spectrum. The Exact-Fit (EF) algorithm of [21] places the incoming request in the first available spectral block that exactly matches the request. The EF algorithm is computationally more intensive than FF and results are given in [21] only for the single-link case. A spectrum-consecutiveness-based spectrum allocation policy with increased computational complexity is proposed in [22] which is shown to reduce blocking probabilities compared to FF. For other proposed spectrum allocation policies in the context of dynamic flexgrid optical networks, we refer the reader to [16],[17],[20].

Connection requests in flexgrid networks belong to different classes with different spectral requirements. For example, assuming 6.25 GHz slot width, a 10 Gbps connection requests a spectral block comprising 1 slot only and a 100 Gbps connection requires a contiguous spectral block of 8 slots, both connections using QPSK modulation [25]. This multi-class scenario resembles the multi-service circuit-switched network studied in [26], however it is also very different due to the SCCC. The multi-class nature of the spectrum allocation problem has already been addressed in various studies. The reference [27] proposes the FF-LF (First Fit or Last Fit) policy where high modulation format connections use FF for spectrum allocation; otherwise LF policy is used allocating resources from the high end of the spectrum. A similar SA policy is proposed in [28] where individual classes are further classified using a threshold-based classifier into two super-classes, namely high data rate and low data rate super-classes, and FF (LF) is used for requests of low (high) data rate super-classes. In [29], again a number of super-classes are defined on the basis of the granularity of spectrum bandwidth required for different demands. For example, demands with bandwidth requirements of 2, 4, and 8 frequency slots are mapped to one super-class whereas those with 3, 6, and 9 slots may be mapped to the other super-class in [29]. Then, spectrum partitions are allocated for each super-class. When a demand arrives, resources will first be checked in the designated partition but the other subspaces will also be checked when needed. A similar idea is studied in [15] where classification is done on the basis of data rate only and the spectrum is sliced into K partitions. To cope with the unfairness problem, high data rate demands are allowed to access more partitions than relatively low rate demands. In particular, the lowest (highest) data rate demand is allowed to access one (all) partition(s). The spectrum allocation policy therefore employs admission control for low rate demands and is non-work-conserving,

i.e., some demands are denied despite availability of bandwidth. In [15], proper partitioning of the spectrum is needed so as to ensure high spectral efficiency and/or fairness among super-classes.

In this paper, we propose a work-conserving Class-Based First-Fit (CBFF) spectrum allocation policy involving potentially more than two traffic classes. Moreover, hard partitioning of the spectrum is not required in CBFF. Instead, the incoming request is placed by CBFF in the first available spectral block when the search starts from an outset assigned to the class the request belongs to. The search continues in a zig-zag fashion with alternating search direction. We also propose a load balancing-based heuristic for choosing per-class outsets which is practical to implement. The degree of freedom in using different outsets for each class for performance improvement is the basis of the proposed CBFF policy. Being as computationally simple as its ancestor FF, and inheriting the horizontal fragmentation avoidance feature of FF, CBFF gives rise to notable performance gains in terms of bandwidth blocking probability with respect to FF which are shown in several single-link and network scenarios using simulations.

The organization of the paper is as follows. The FF and CBFF policies are described in detail in Section 2. In Section 3, we present simulation results to demonstrate the effectiveness of the proposed SA policy CBFF using Poisson connection request arrivals and exponentially distributed connection holding times. The scenarios we consider are i) single-link scenario, ii) NSFNET topology, iii) Pan-European network topology. The policies under consideration are i) FF policy, ii) CBFF policy. For routing purposes, we study i) fixed routing with one shortest path ii) alternate routing using two shortest paths. Finally, we conclude.

2. Class-Based First-Fit Spectrum Allocation

We envision a flexgrid optical network where nodes are interconnected by links comprising N contiguous frequency slots, numbered from 0 (the frequency slot at the left end of the spectrum) to $N - 1$ (the frequency slot at the right end of the spectrum). The parameter N is representative of the link capacity. A spectral range or block $[a, b]$, $0 \leq a \leq b \leq N - 1$ is a contiguous subset of the entire spectrum consisting of all the slots $a, a + 1, \dots, b - 1, b$. Clearly, the spectral range $[0, N - 1]$ corresponds to the entire spectrum. A spectral block of size h with the lowest end slot being a is characterized with the spectral range $[a, a + h - 1]$. We have K classes of requests numbered

from $k = 0$ to $K - 1$. A class- k connection requests n_k contiguous slots to be allocated to that connection. For the sake of convenience, we assume $n_0 < n_1 < \dots < n_{K-1}$. Let n denote the vector of per-class requests, i.e., $n = \{n_0, n_1, \dots, n_{K-1}\}$. If there exists a spectral block comprising n_k contiguous frequency slots and which is available on all links along a path upon a new request, then the connection is accepted (i.e., work-conserving) and one of such free blocks is allocated to the connection. Otherwise, the connection is blocked leading to a non-zero connection blocking probability. If there are multiple free blocks that can satisfy the request, an SA policy chooses one from the existing alternatives so as to maximize a certain performance metric. In multi-hop scenarios, the situation is more challenging since a spectral block needs to be free on all the links of the OP that the connection is to use. Not only a desired spectrum allocation policy is to avoid fragmentation on individual links, but it should also give rise to spectral blocks that are free on all links.

In CBFF, each class k is associated with a search outset m_k which is a real number satisfying $0 \leq m_k \leq N - 1$. The distance of a spectral block $[a, b]$ to outset m_k is defined to be $|0.5(a+b) - m_k|$. For a new class- k request with outset m_k and with request size n_k , CBFF chooses a free spectral block closest in distance to the outset m_k . If there are two such spectral blocks, any of the two can be chosen. Alternatively, the block that is closer to the lower end may be chosen, or one of the two blocks may be chosen at random with incremental impact on overall performance. The CBFF algorithm for a new class- k request for link capacity N , class outset m_k , and class request size n_k is formally given in Algorithm 1 for n_k . In Algorithm 1, \bar{m}_k is obtained by rounding m_k to the nearest integer and \tilde{m}_k is the fractional part of m_k . Note that, depending on whether n_k is odd or even, the evolution of the algorithm is slightly different.

Note that the FF policy reduces to $m_k = 0$ for all k since in FF, all connections use the same outset 0. The computational complexity of the general CBFF is similar to that of FF with the exception that the search is unidirectional over the entire spectrum in FF whereas for $0 < m_k < N - 1$, the search direction alternates in CBFF as described in Algorithm 1. However, whenever a free spectral block is found during the search, both FF and CBFF allocate the first free spectral block without having to continue the search as would be the case in EF-type spectrum allocation.

The choice of the particular outset values for each class is key to the success of CBFF. We denote the outset vector of per-class outsets by m ,

Algorithm 1 The pseudo-code for the CBFF spectrum allocation policy

```
1: procedure CBFF( $N, n_k, m_k$ )
2:   if  $n_k$  is even then
3:      $m_k \leftarrow m_k + 0.5$ 
4:   end if
5:    $\bar{m}_k \leftarrow \text{round}(m_k)$ 
6:    $\tilde{m}_k \leftarrow$  fractional part of  $m_k$ 
7:   if  $n_k$  is odd then
8:      $\Delta \leftarrow (n_k - 1)/2$ 
9:   else
10:     $\Delta \leftarrow n_k/2$ 
11:  end if
12:   $a_1 \leftarrow \max(0, \bar{m}_k - \Delta)$ 
13:  if  $\tilde{m}_k \geq 0.5$  then
14:     $a_2 \leftarrow \max(0, a_1 - 1)$ 
15:  else
16:     $a_2 \leftarrow a_1 + 1$ 
17:  end if
18:  if  $a_1 \geq 0$  and  $a_1 + n_k - 1 \leq N - 1$  then
19:    Check the availability of the spectral block  $[a_1, a_1 + n_k - 1]$ . If
    available, allocate the spectral block and exit.
20:  end if
21:  if  $a_2 \geq 0$  and  $a_2 + n_k - 1 \leq N - 1$  then
22:    Check the availability of the spectral block  $[a_2, a_2 + n_k - 1]$ . If
    available, allocate the spectral block and exit.
23:  end if
24:  if  $\tilde{m}_k \geq 0.5$  then
25:     $a_1 \leftarrow a_1 + 1, a_2 \leftarrow a_2 - 1$ 
26:  else
27:     $a_1 \leftarrow a_1 - 1, a_2 \leftarrow a_2 + 1$ 
28:  end if
29:  if ( $a_1 < 0$  or  $a_1 + n_k - 1 > N - 1$ ) and ( $a_2 < 0$  or  $a_2 + n_k - 1 > N - 1$ )
then
30:    Block the request and exit
31:  end if
32:  Goto Step 18
33: end procedure
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i.e., $m = \{m_0, m_1, \dots, m_{K-1}\}$. As opposed to FF, the CBFF policy uses different subsets for each class $m_k \neq m_l$ if $k \neq l$. In particular, the proposed CBFF policy imposes the following. We propose $m_0 = 0$ for class 0 and $m_{K-1} = N - 1$ for class $K - 1$. In the latter case, for a connection belonging to class $K - 1$, we search for a free spectral block toward the low end of the spectrum but starting from the high end of the spectrum. For a class- k connection request $0 < k < K - 1$, the subset m_k is such that $0 \leq m_k \leq N - 1$ and moreover $m_{k+1} \geq m_k$.

Typically, the per-class subsets need to be positioned as far from each other as possible. In case we do not have a-priori knowledge on the input traffic distribution, one possibility is to uniformly place the remaining subsets other than 0 and $N - 1$ in the interval $[0, N - 1]$. In a three-class system, this policy reduces to positioning the class-1 subset m_1 at the mid-point, i.e., $m_1 = (N - 1)/2$. However, other choices are possible if we would know a-priori how the incoming traffic is distributed amongst the traffic classes. For this purpose, let us assume that connection requests arrive at the link with rate λ_k in units of requests/time unit (TU) and the mean holding time of the accepted connections is $1/\mu_k$. We do not strictly relate TU to any actual time unit in this study. Following the notation of [30], the intensity of traffic introduced by class- k connection requests in Erlangs is denoted by α_k :

$$\alpha_k = \frac{\lambda_k}{\mu_k}. \quad (1)$$

The overall traffic intensity in units of slots is denoted by α :

$$\alpha = \sum_{k=0}^{K-1} n_k \alpha_k. \quad (2)$$

Assume that this traffic is offered to a single flexgrid optical link with capacity N . In this case, the link load ρ is the ratio of the overall traffic intensity to capacity:

$$\rho = \frac{\alpha}{N}. \quad (3)$$

The contribution of class- k traffic to the overall link load is denoted by

$$\rho_k = \frac{n_k \alpha_k}{N}, 0 \leq k \leq K - 1. \quad (4)$$

For $K > 2$, we propose the following heuristic based on the idea of balancing the load across the spectral blocks between successive per-class subsets. In

this case, the offered load between successive outsets m_i and m_{i+1} equals to $\frac{\rho_i}{2} + \frac{\rho_{i+1}}{2}$ if neither of the points is the left or right end of the spectrum. Mathematically, we have

$$\frac{m_1 - m_0}{\rho_0 + \frac{\rho_1}{2}} = \frac{m_2 - m_1}{\frac{\rho_1}{2} + \frac{\rho_2}{2}} = \dots = \frac{m_{K-1} - m_{K-2}}{\frac{\rho_{K-2}}{2} + \rho_{K-1}} \quad (5)$$

Since $m_0 = 0$ and $m_{K-1} = N - 1$, we have $K - 2$ unknowns with $K - 2$ linearly equations, the solution of which gives the remaining per-class outsets. Although this outset selection mechanism appears to provide relatively good results for the single-link case, its extension to the network case involving multiple links is not straightforward. This difficulty stems from different ρ_k values for different links in the same network. In the current paper, we propose to use a single outset vector for all the links in the network based on the entire network demand distribution among multiple classes of connections. Other possibilities are left for future research.

To motivate CBFF, we present the following 3-class example with $N = 14$ frequency slots in Fig. 1. We assume the request vector $n = \{1, 2, 4\}$. For CBFF, we use the outset vector $m = \{0, 6.5, 13\}$. We concentrate on a single flexgrid optical link that is offered with connection requests with the following order: class-0, class-1, class-0, class-1, class-0, class-1, class-2, class-0. The occupancy diagram for the optical link after all connection requests are accepted for both FF and CBFF spectrum allocation policies are presented in Fig. 1. The vertical fragmentation problem is evident for FF: when any two class-0 connection requests are to depart, no room will be freed for forthcoming class-1 connections. Similarly, if two class-1 connections decide to leave, there would not be any free spectral block for forthcoming class-2 connection requests. This problem is less problematic with CBFF. If any two successively-arrived class-0 requests decide to leave the link, a spectral block would be freed for a forthcoming class-1 request. Similarly, the departure of the first two successively-arrived class-1 connections would free room for a class-2 request. Therefore, CBFF favors classes with larger slot requirements in comparison with FF. While doing so, CBFF is work-conserving; if there is a free spectral block for an incoming request, then the request will always be admitted by choosing one of the free blocks. This is in contrast with non-work-conserving spectrum allocation policies which perform admission control to potentially increase the system throughput. However, it is clear that vertical fragmentation problem can only be mitigated, but not totally avoided, by CBFF. Assume now that the following sequence of events take

place: i) slots 6-7 released, ii) slot 6 occupied by a class-0 demand, iii) slots 4-5 released, iv) slots 8-9 released, v) a class-2 demand arrives and it is blocked because there is not a free spectral block of four contiguous slots out of the the five available slots. A detailed simulation study will be presented in the next section to quantify the benefits of CBFF relative to FF in terms of reducing the overall bandwidth blocking probability in more general single-link and network scenarios.

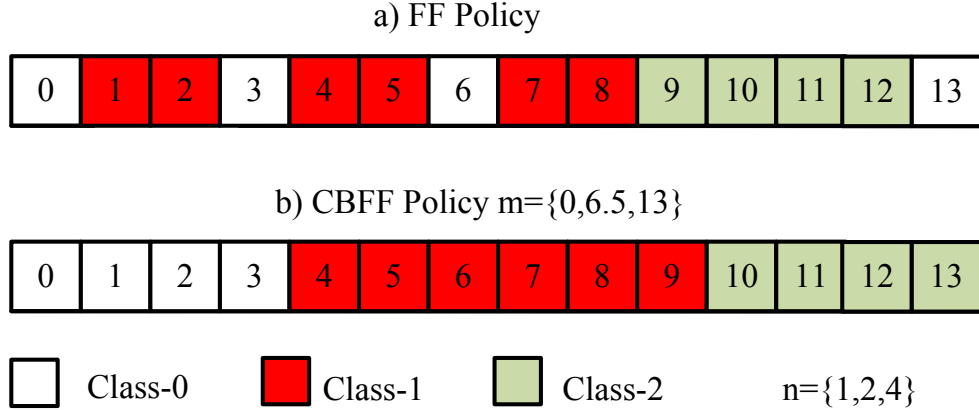


Figure 1: Illustration of the FF and CBFF spectrum allocation policies for a 3-class numerical example.

3. Numerical Results

For studying the performance of CBFF, we use the following three network topologies:

- a) Single optical link,
- b) NSF network topology [31],
- c) Pan-European network topology [32].

For the routing problem, we use

- i) Fixed Routing (FR) in which one minimum hop path only, called the primary path, is used to establish an OP using Dijkstra's algorithm [33],

- ii) Fixed Alternate Routing (FAR) is used in which a secondary minimum hop path is used as an alternative to the primary path using Yen's algorithm [34]. A free spectral block is first searched for the primary path. If not found, the search procedure is repeated for the alternative path.

The spectrum allocation policy is either FF or CBFF. We also assume exponentially distributed connection holding times with parameter $\mu_k = \mu$ for all classes of connections. For the performance measures of interest, we need the following definitions. The total number of connection requests during a simulation run of duration D for class- k is denoted by R_k . The number of blocked connection requests out of R_k requests is L_k . The per-class connection blocking probability is denoted by P_k :

$$P_k = \frac{L_k}{R_k}. \quad (6)$$

The bandwidth blocking probability P_B is defined as the ratio of total blocked bandwidth to the total requested bandwidth, both quantities in units of slots:

$$P_B = \frac{\sum_{k=0}^{K-1} n_k L_k}{\sum_{k=0}^{K-1} n_k R_k}. \quad (7)$$

3.1. Single Optical Link

In the first numerical experiment, a single optical link is studied. We assume Poisson connection request arrival rates denoted by λ_k for class- k . We also denote by λ the vector of connection arrival rates, i.e., $\lambda = \{\lambda_0, \lambda_1, \dots, \lambda_{K-1}\}$. An Equal Intensity (EI) scenario refers to one where all arrival rates are identical, i.e., λ_j is fixed for all $j, 0 \leq j \leq K-1$. On the other hand, an Equal Load (EL) scenario refers to one where the contribution of each class to the overall load is identical, i.e., $\lambda_j n_j$ is fixed for all $j, 0 \leq j \leq K-1$. We set $\mu_k = 1$ for all traffic classes in all examples pertaining to the single link case and we generate 10^7 overall requests for each simulation run.

In the first numerical example, we fix $N = 400$, $K = 3$, $n = \{2, 3, 7\}$ and $\rho = 0.9$. When CBFF is used, the two outsets m_0 and m_2 are set to zero and 399, respectively, but the outset for class 1 is allowed to vary in order to validate the effectiveness of the proposed heuristic for m_1 given in Eqn. (5). For this purpose, we plot the bandwidth blocking probability

P_B obtained with CBFF as a function of the outset m_1 in Fig. 2 for the EI and EL scenarios. FF result is also provided as a reference for both scenarios. As conjectured, the choice of m_1 is crucial for performance when CBFF is used and it is clear that there is an optimal value for m_1 at which P_B is minimized. The load balancing heuristic given in Eqn. (5) dictates the choices of $m_1 = 116.3750$ and $m_1 = 199.5$ for the EI and EL scenarios, respectively, which appear to be located very closely to the optimum values of m_1 obtained with simulations. We repeat the same experiment this time with $n = \{1, 4, 10\}$ in Fig. 3 while all other parameters are fixed for which we draw similar conclusions. The heuristic of Eqn. (5) leads us to the choices of $m_1 = 79.8$ and $m_1 = 199.5$ for the EI and EL scenarios, respectively, which again appear to be very close to the optimum values of m_1 obtained via simulations. Note that for both examples of Figs. 2 and 3, the choice of $m_1 = 0$ corresponds to a FF-LF spectrum allocation policy for which classes 0 and 1 use FF whereas class 2 uses LF. On the other hand, the choice of $m_1 = 399$ corresponds to the other FF-LF policy for which classes 1 and 2 use LF whereas class 0 employs FF. Therefore, CBFF not only outperforms FF but also the only two possible FF-LF policies for a 3-class link.

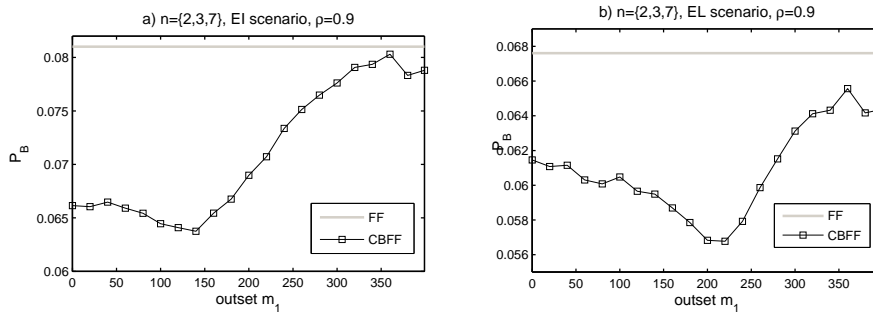


Figure 2: Bandwidth blocking probability P_B for the single optical link with CBFF as a function of m_1 when $N = 400$, $K = 3$, $n = \{2, 3, 7\}$ and $\rho = 0.9$: a) EI scenario, b) EL scenario. P_B obtained with FF spectrum allocation policy is also given as a reference for both scenarios.

In the final numerical example concerning a single optical link, we study the impact of the number of classes K and the capacity N of the optical link on CBFF performance. We try the following three cases for both EI and EL scenarios for the case $\rho = 0.85$:

- i) $K = 2$, $n = \{1, 8\}$,

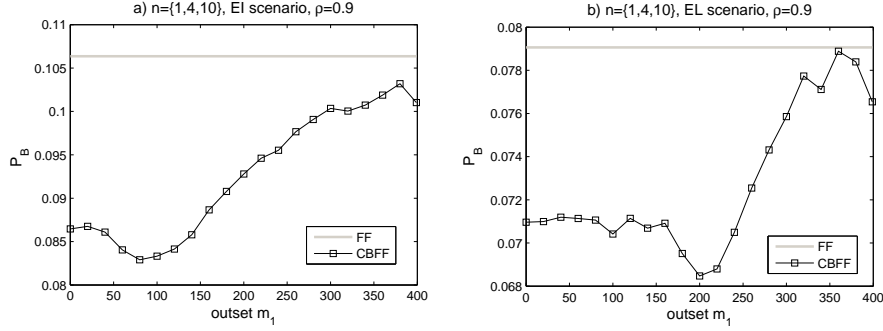


Figure 3: Bandwidth blocking probability P_B for the single optical link with CBFF as a function of m_1 when $N = 400$, $K = 3$, $n = \{1, 4, 10\}$ and $\rho = 0.9$: a) EI scenario, b) EL scenario. P_B obtained with FF spectrum allocation policy is also given as a reference for both scenarios.

- ii) $K = 3$, $n = \{1, 4, 8\}$,
- iii) $K = 4$, $n = \{1, 2, 4, 8\}$.

We plot the bandwidth blocking probability as a function of N in Fig. 4 using CBFF and FF. We have the following observations:

- The performance advantage of CBFF over FF is more emphasized for lower number of classes. This advantage appears to reduce as K increases. However, CBFF always outperformed FF in all the studied cases.
- The reduction in bandwidth blocking probability using CBFF relative to FF increases when N increases. Therefore, CBFF is relatively more advantageous for relatively higher capacity optical links.
- Performance advantage of CBFF is more apparent in the equal intensity case for which the load introduced by classes with larger number of slots is more dominant relative to other classes with fewer slot requests.

3.2. NSF Network and Pan-European Network Topologies

We now extend the simulation study for the performance evaluation of CBFF to multi-hop networks. We use two well-known network topologies given in Figures 5 and 6. The NSF topology has 14 nodes and 21 links [31] whereas the Pan-European network has 18 nodes and 35 links [32]. We fix $N = 128$ and $K = 3$ for all the examples in this section. We set $\mu_k = 0.01$

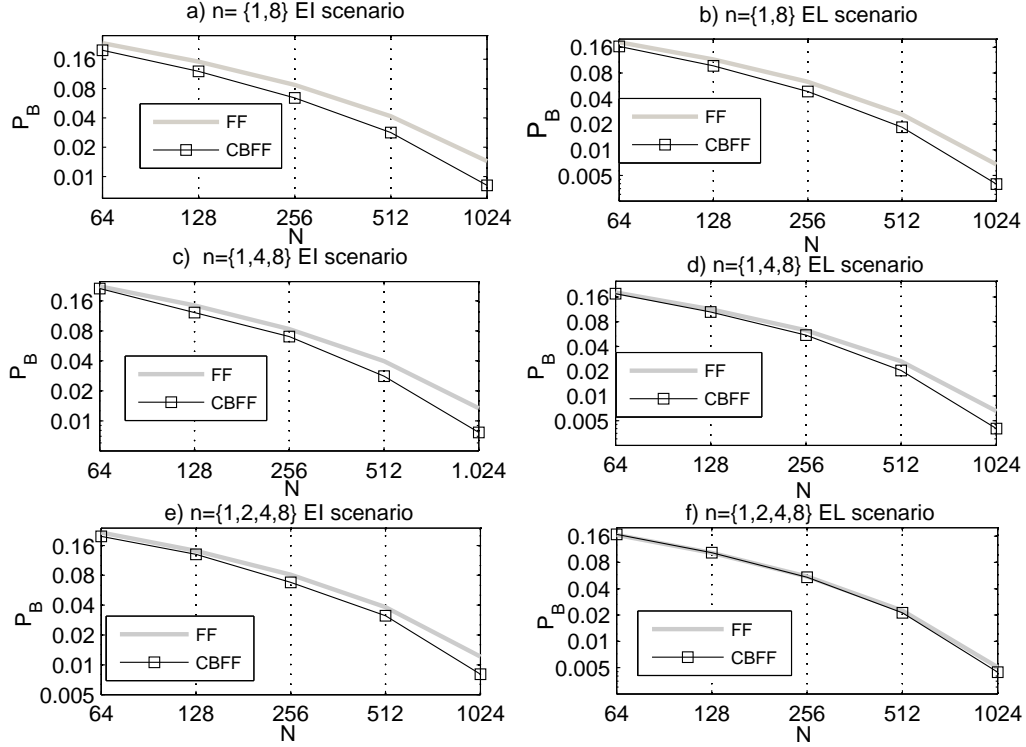


Figure 4: Bandwidth blocking probability P_B for the single link case as a function of N for $\rho = 0.85$ under CBFF and FF for six different scenarios.

for all three classes. The connection request vector is set to $n = \{1, 4, 10\}$ and we assume traffic between each pairs of nodes. For both topologies, the connection arrival rate vector λ is the same for all source-destination pairs of nodes and is characterized with a single traffic parameter σ which is varied in the range $[0.001, 0.009]$. We study five different traffic profiles for both topologies described in Table 1. The overall traffic rate (in units of slot requests/TU) offered to a source-destination pair is fixed at 15σ for all the five traffic profiles. When CBFF is used, the load balancing heuristic (5) is employed to find the class-1 outset m_1 but we round this value of m_1 to the nearest integer in which case it is possible that there may be two spectral blocks at the same distance from the outset m_1 one of which is chosen at random for this example.

In order to provide more insight on the effectiveness of CBFF against the FF policy, we introduce the so-called throughput, denoted by $T(P_B)$ which

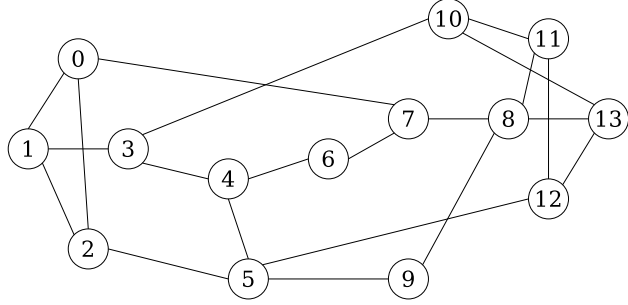


Figure 5: NSF Network Topology.

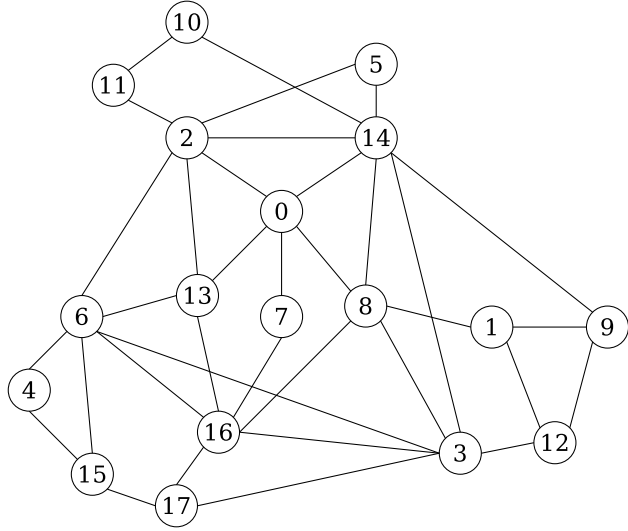


Figure 6: Pan-European Network Topology.

is the rate of traffic (in units of slots/TU) that is carried, averaged over all source-destination pairs, while not exceeding a certain desired bandwidth blocking probability P_B . The percentage increase in throughput ($\Delta_T(P_B)$) defined below is indicative of the gain in using CBFF relative to FF when a desired bandwidth blocking probability of P_B is realized:

$$\Delta_T(P_B) = 100 \frac{T^{CBFF}(P_B) - T^{FF}(P_B)}{T^{FF}(P_B)}. \quad (8)$$

The gain in throughput achieved by CBFF relative to FF under these five traffic profiles is given for both topologies in Table 2 when the desired bandwidth blocking probability P_B is allowed to vary in the range $10^{-3} - 10^{-1}$.

Table 1: Traffic profiles used for the NSF and Pan-European network topologies.

Traffic Profile	Arrival Vector λ
TP-1	$\{\sigma, \sigma, \sigma\}$
TP-2	$\{5\sigma, \frac{5}{4}\sigma, \frac{1}{2}\sigma\}$
TP-3	$\{\frac{9}{2}\sigma, \frac{9}{8}\sigma, \frac{3}{5}\sigma\}$
TP-4	$\{\frac{9}{2}\sigma, \frac{15}{2}\sigma, \frac{9}{20}\sigma\}$
TP-5	$\{6\sigma, \frac{9}{8}\sigma, \frac{9}{20}\sigma\}$

CBFF outperforms FF for all the traffic profiles with up to 15% gains in throughput. CBFF appears to be more effective with FAR than with FR. CBFF seems to benefit more from the flexibility provided by alternate routing when compared with FF. We also observe that the throughput gains with CBFF are higher for lower target bandwidth blocking probabilities. The performance improvement with CBFF is maximum for TP-1 in the Pan-European network scenario with FAR routing policy. We present detailed simulation results in Fig. 7 for this particular scenario.

Table 2: Gain in throughput by CBFF relative to FF under the five traffic profiles for the NSF and Pan-European network topologies for FR and FAR when P_B is varied in the range $10^{-3} - 10^{-1}$.

Traffic Profile	Network Topology	Routing Policy	Throughput Gain $\Delta_T(P_B)$
TP-1	NSF	FR	12.18 - 9.27
TP-2	NSF	FR	6.03 - 3.98
TP-3	NSF	FR	5.25 - 4.27
TP-4	NSF	FR	6.31 - 4.07
TP-5	NSF	FR	7.08 - 3.16
TP-1	NSF	FAR	12.59 - 10.47
TP-2	NSF	FAR	6.31 - 4.35
TP-3	NSF	FAR	5.13 - 4.47
TP-4	NSF	FAR	5.25 - 4.17
TP-5	NSF	FAR	6.76 - 3.31
TP-1	Pan-Eur.	FR	12.30 - 10.23
TP-2	Pan-Eur.	FR	11.75 - 2.00
TP-3	Pan-Eur.	FR	6.47 - 3.55
TP-4	Pan-Eur.	FR	6.31 - 2.00
TP-5	Pan-Eur.	FR	5.01 - 2.00
TP-1	Pan-Eur.	FAR	14.79 - 11.22
TP-2	Pan-Eur.	FAR	7.59 - 3.55
TP-3	Pan-Eur.	FAR	7.08 - 4.17
TP-4	Pan-Eur.	FAR	6.17 - 3.55
TP-5	Pan-Eur.	FAR	6.31 - 2.40

We observe that the per-class blocking probability for class-2 is substantially reduced with CBFF allowing more class-2 connections to be accepted into the FON while being work-conserving. Consequently, the other two classes are affected slightly adversely in terms of increased per-class blocking probability. However, the overall bandwidth blocking probability is reduced when CBFF is employed. Since the gap among the per-class blocking probabilities gets to shrink with CBFF, we also conclude that CBFF improves fairness among traffic classes in terms of blocking probabilities.

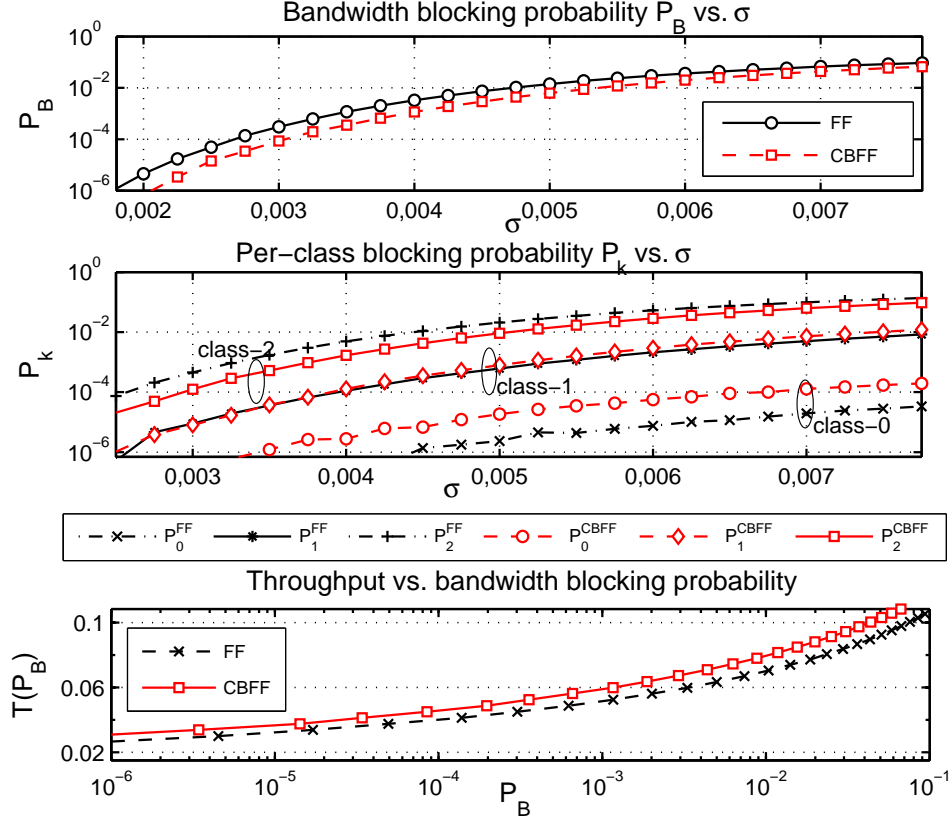


Figure 7: Simulation results for the Pan-European network topology for TP-1 with CBFF and FF under FAR routing: a) Overall bandwidth blocking rate P_B as a function of traffic parameter σ b) Per-class blocking probability P_k as a function of σ c) Throughput T as a function of P_B .

4. Conclusion

A novel class-based first fit spectrum allocation is proposed for dynamic flexgrid optical networks. When compared with the conventional first fit algorithm, the proposed policy is shown by simulations to reduce the bandwidth blocking probability and increase the throughput in single- and multi-hop scenarios. The proposed policy is especially effective in network scenarios with relatively higher link capacities. The simplicity of the proposed spectrum allocation scheme is another advantage.

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