A vectored fragmentation metric for elastic optical networks

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Abstract

When circuits are set up and dismantled dynamically in elastic optical networks, the link spectrum becomes fragmented. The fragmentation limits the available path choices and may lead to significant blocking of connection requests. The fragmentation can be link fragmentation due to non-contiguity of available spectral resources on individual links or path fragmentation due to non-continuity of available spectral resources on the paths of the connection requests. The study of fragmentation and its management is essential to operate the networks efficiently. This paper proposes a vectored fragmentation metric for characterizing the fragmentation, which includes both types of fragmentation. We discuss the characteristics of this metric considering different network scenarios, where connection requests arrive and depart dynamically. To establish the functionality of this metric, we also test the utility of the metric in fragmentation management cases. We compare the different link-based fragmentation metrics and a path-based fragmentation metric with our Adapted vectored fragmentation metric to understand the efficacy of the proposed measure. We find the vectored fragmentation metric to be effective in this study.

Keywords Elastic optical networks · Fragmentation metric · Spectrum fragmentation · Fragmentation management

1 Introduction

The colossal bandwidth availability in the core optical fiber networks has fueled innovations and the development of applications that use the available bandwidth. It is further fueling the bandwidth demand around the globe. According to the Cisco Annual Internet report (2018–2023), nearly two-thirds of the global population will have access to the internet, and mobile connectivity by 2023 [1]. Over several decades, there has been intensive research to seek various technological advancements in optical networks to cater to expected bandwidth demand. Elastic Optical Networks (EONs) are one such recent advancement in the last decade. They have emerged as a possible way of moving ahead from traditional Wavelength Division Multiplexed (WDM) networks toward more efficient and possibly more economical networks.

WDM networks allocate fixed bandwidth channels of 25 GHz or 50 GHz to any incoming bandwidth demand requests. In a WDM network, if a bandwidth request of 5 GHz1 arrives at an ingress node, the network has no option but to allocate a 50 GHz optical channel, leading to wastage of spectral resources. The idea of EONs is conceived to resolve this limitation. In EONs, the lowest bandwidth that a single optical sub-channel can fulfill with 100% efficiency is 12.5 GHz [2]. Thus, the same 5 GHz request will get only 12.5 GHz allocated in an EON. Finer bandwidth allocation granularity allows more efficient use of spectral resources and increases the available capacity to cater to more bandwidth demand. References [3, 4] discuss the enabling technologies for EON at the hardware (transceivers and switches) and network-level (resource allocation schemes) and layout the essential requirements for their implementation.

EON defines a spectrum slice as a basic sub-channel unit. In order to cater to a large bandwidth demand, integral multiples of the basic spectrum slice unit, or Frequency Slot Unit [5] (FSU), are allocated in a given spectrum. A group of spectrum slices (SS) is called the spectrum slot (SL). Consequently, the wastage of spectrum is reduced drastically compared to the WDM networks.

The allocation of a contiguous group of SS, i.e., SS, on the arrival of connection requests is carried out by Routing and Spectrum Assignment (RSA) strategies. RSA problem

1 In terms of spectral grid requirement.
ensures that the connection request is set up on an appropriate path while satisfying bandwidth requirements from the source to the destination and complying with the spectrum assignment constraints. In EON, broadly, there are two RSA constraints [6]. The spectral contiguity constraint dictates that the allocated slices should form a continuous band in the link spectrum. The spectral continuity constraint makes sure that the same SS are allocated throughout the path. However, the optimization techniques for RSA have additional constraints to resolve contention between demands for a common resource, [7]. The spectrum non-overlapping constraint makes sure that two connection requests cannot share the same SS if their paths are not link-disjoint.

However, these constraints and the dynamic nature of incoming traffic lead to another problem, i.e., Spectrum Fragmentation, where sometimes, even sufficiently available spectrum cannot be allocated [8]. The fragmentation could bring significant degradation in network performance.

This paper investigates the fragmentation level indication methods to use the available spectrum slices efficiently in EONs. A brief overview of this paper is as follows:

1. We propose a vectored fragmentation metric (VFM) indicating the fragmentation level in the network considering both link-fragmentation and path-fragmentation.
2. The various factors contributing to the proposed metric are identified.
3. We check the utility of the proposed fragmentation metric in different network traffic scenarios.
4. We also compare the proposed fragmentation metric with other fragmentation metrics, both link-based (external [9], compaction-based [10], and Shannon entropy-based [9]) as well as path-based (Wasted-Unused-Free Ratio) [11].

The rest of the paper is organized into four sections. In Sect. 2, we discuss spectrum fragmentation, its challenges, and other related issues. Section 3 discusses the proposed vector fragmentation metric, with formulation, example, and applications. Section 4 presents the assessment of the proposed fragmentation metric using simulation. Section 5 concludes the paper with general observations and future challenges in the study of vectored fragmentation metric.

2 Background: spectrum fragmentation and related issues

When the connection requests arrive and depart in a highly dynamic manner, and there is a strict imposition of spectrum assignment constraints, there arises an inefficiency called spectrum fragmentation. This is due to a lack of continuity and contiguity constraint fulfillment by available SS present in the links of candidate paths. The fragmentation brings in spectrum inefficiency and further degrades the network performance (increased blocking probability of connection requests). We identify two types of fragmentation- the one due to the non-continuity of available resources on a path and the second one due to the non-contiguity of available resources on a link [12].

Consider the scenario as shown in Fig. 1a–c. If the spectrum slot satisfying the constraints is available, the connection request is provisioned and set up as in Fig. 1b. However, in Fig. 1c, a connection request for two slices from node N1 to node N4 cannot be set up. More than two slices are available in each of the individual links, i.e., A, B, and C, and still, due to spectrum assignment constraints, the request cannot be satisfied.

In the fragmented network spectrum, the connections with shorter hops and requiring fewer SS are more likely
to get through than the requests with more SS requirements. This leads to unfair treatment toward connections requesting a large number of SS over longer hops. Also, the time to find spectral resources increases, and there is no surety of whether connection requests will be provisioned. The fragmentation can also lead to poor utilization of network spectral resources and network management resources.

To better understand the problem and find the remedial approaches for fragmentation, studying the factors causing or affecting the fragmentation in the network spectrum is imperative. A few works with Markov Chain (MC) model tried to characterize the fragmentation in the network by using single-channel and super-channel services [13, 14]. The blocking probability results show how the single-channel requests rob the spectral resources from super-channel requests, and more super-channel requests are blocked than the single-channel requests. Both the studies assert and prove that when the networks are fragmented, it brings unfairness to heterogeneous service types. Most of the subsequent studies have been centered around fragmentation management approaches.

There are two approaches to managing fragmentation based on whether periodic defragmentation is performed or not, i.e., defragmentation or non-defragmentation. In the non-defragmentation approach, the objective is to operate the network to keep the fragmentation at a minimum level. It is employed before the onset of the fragmentation and strategizes to avoid the severe effects of fragmentation on future connection requests. However, the non-defragmentation approach cannot guarantee the 100% fragmentation-less operation of the network, though the existing connections in the network are not disturbed, and this approach is lower in cost in terms of operational and capital expenditure [9]. Also, if a network gets into a fragmented state, whether it comes out of it on its own at the earliest needs to be ensured by the algorithms. The main techniques in this approach are spectrum partitioning [15], multipath [16], and multigraph [9].

The spectrum partitioning strategy divides the network spectrum into smaller blocks, and different spectrum assignment policies are employed to achieve the desired performance. The authors in [16] have used pre-assignment, post-assignment, and fragmentation measuring metrics together with multipath routing to control the fragmentation and lower the blocking probability for incoming requests.

In the defragmentation approach, existing connections are reorganized to set up new connections whenever the network is in a fragmented state. Connection rearrangements aggregate the spectral gaps. The rearrangement is basically of the current paths and SS. The defragmentation approach may or may not bring interruption in the existing connections when rearrangement is going on, [17, 18]. Some of the techniques are re-optimization, make-before-break, push–pull ([19]), and hop-tuning, [8, 9].

The defragmentation techniques are more reliable in alleviating the fragmentation but are computationally complex. Identifying a suitable instant to initiate defragmentation is a challenge in itself. There are two approaches to address this issue, reactive and proactive defragmentation. As the name suggests, reactive defragmentation responds to the degradation of some performance metrics, like a sudden increase in the rate of blocked connection requests. The proactive defragmentation triggers the rearrangements periodically, [20], or when some fragmentation indicators cross a predefined threshold value, [10]. The non-defragmentation approach cannot guarantee the 100% fragmentation-less operation of the network; therefore, defragmentation methods are more reliable in pacifying the fragmentation.

Fragmentation management based on either defragmentation or non-defragmentation is a complicated and costly process. Therefore, it is crucial to efficiently monitor the fragmentation level and take appropriate measures at the right time to manage the fragmentation. One needs to quantify the level of fragmentation to trigger the management approaches. [12, 21, 22] discuss the fragmentation-aware RSAs to accommodate the connection requests only if they do not lead to fragmentation in the future. Different spectrum allocation strategies are discussed in the above schemes to achieve maximum request acceptance even in the presence of fragmentation. The important aspect in all of the above fragmentation management approaches is the use of fragmentation metrics in finding a route or appropriate resources.

Some of the link-based fragmentation metrics which exploit the spectrum status in links have been discussed in [9, 10, 23]. Some of these measures are - the external fragmentation [9], the Shannon entropy-based measure [9], the Access Blocking probability-based measure [9], the utilization entropy [23], the high-slot mark [23] and the spectrum compactness [10]. The metrics discussed in the cited works give an abstract treatment to the fragmentation measure. They tend to ignore some crucial aspects of spectrum status, e.g., small fragments. A few of these metrics cannot differentiate between different spectrum scenarios.

The works in [24–26] use link-based contiguity ratios as fragmentation metrics to evaluate different spectrum allocation policies (first-fit, random fit, smallest fit, exact fit, least used, most used, first-last fit and first-last-exact fit). They evaluate the performance in terms of blocking probability of the connection requests.

Some of the proposed fragmentation measures are dependent on connection requests and paths requested by them. Pederzolli et al. [11] have proposed a path-based fragmentation metric. The authors use the Wasted-Unused-Free ratio as the metric in the RSA to find path-slots combination.
for a connection request, which should result in a lower overall fragmentation level and accommodation of more future connection requests. So, inappropriate path selection is a precursor to fragmentation, if any. While this metric captures fragmentation due to continuity and contiguity, it is path/connection request specific.

In [27], Bonani et al. presented the network-level metrics, using the link consecutiveness aspect in all the links at specific observation periods (time-weighted) to decide on a network’s fragmentation level. They also gave the idea of unfairness, i.e., high bandwidth requests are more likely to get blocked due to fragmentation at higher loads.

Following the above studies, we present a novel two-dimensional fragmentation metric in EON, VFM, which gives an absolute value for the fragmentation status for the whole network.

3 Vectored Fragmentation Metric (VFM)

Blocking of a connection can happen due to the unavailability of contiguous bandwidth slices in one or more links forming the path over which connection is to be set up. It will happen due to improperly managed RSA. While considering a metric to quantify fragmentation level in the spectrum, we would like to have a single metric that can represent the fragmentation level considering both contiguity and continuity aspects.

Based on earlier studies, we enumerate as follows a few cases in which a useful fragmentation metric should be able to identify (Fig. 2), [28].

1. All slices are free (no fragmentation)
2. All slices are busy (no fragmentation)
3. Free slices are contiguous (no fragmentation)
4. All free slices are unusable (absolute fragmentation)
5. Free slices can have varying number of fragments and size of fragments in the different spectrum scenarios (relative fragmentation), e.g. in Fig. 2e both link spectrum has five free slices but the first one is more fragmented than the second one.

We formulate a vectored fragmentation metric that provides a single absolute value for the fragmentation level while taking care of all the above scenarios. The proposed metric considers the fragmentation in individual links (α-component) and the fragmentation over some paths (β-component). For the α-component, we find maximum contiguous SS over individual links. For the β-component, we find the maximum number of continuously available links for each spectrum slice. Operationally, we can assume a centralized network controller that interacts with all the nodes to gather all the links’ status and set up the paths for the arriving connection demands. As it has the entire links’ status, it is expected to make better decisions [29]. The central controller can determine the VFM using the individual links’ status and continuity of available slices across the specified paths.

We can define α- and β-components as follows:

- α-component is covering the fragmentation due to non-contiguity of total available SS in individual links across the whole network, and
- β-component is the fragmentation of spectrum indices due to the non-continuity of available SS on the links of representative paths in the network.

3.1 Formulation of metric

The VFM is the fragmentation indicator that is denoted using $\nu$. It is the resultant of α- and β-components. For the α-component, the maximum contiguous SS in a link are taken up against the total available SS in the link. Ideally, if all the available SS form a single contiguous slot, there is no fragmentation. Multiple SS scattered in the link spectrum in a dis-contiguous manner is the main cause of fragmentation. An important assumption considered in using the metric is that at least one spectrum slice is available in the network spectrum/links of the network. Also, the β-component checks the continuity of all SS individually on the path links, i.e., the component decides on the non-continuity aspect of fragmentation from individual slice indices’ point of view.

Multiple selective paths are used to check the continuity of each slice index over all the links in each path. A minimum number of paths are chosen so that minimum link repetition is there and the status of all the links is covered. Then, the continuity of links for all the spectrum slice indices (available in at least one of the links on the path) is used. The maximum number of continuous hops where SS (of a particular index) are available is taken against the total available (unused) hops/links for that spectrum slice over the whole path. The individual components ($\alpha$ and $\beta$) and the fragmentation indicator ($\nu$) are defined as follows (Eqs. 1–3):
\[ \alpha = \frac{1}{|EL|} \sum_{i=1}^{EL} \frac{CG_i}{SS_i} \]  
\[ \beta = \frac{1}{|P|} \sum_{i=1}^{P} \frac{1}{E_i} \sum_{j=1}^{E_i} \frac{CN^i_j}{AS^i_j} \]  
\[ \text{VFM} = v = \sqrt{\alpha^2 + \beta^2} \]

here \( L \) is the set of links in the network, and \( EL \) is the set of links with at least one empty (available) spectrum slice. The \( SS_i \) is the total number of available SS in the \( i \)th link, and \( CG_i \) is the maximum number of contiguous SS available on the \( i \)th link. \( P \) is the set of multiple paths covering all the links in the network, specified for the path continuity aspect, and \( H_p \) is the number of hops on \( p \)th path in set \( P \). \( E_i \) is the total number of spectrum slice indices in the network spectrum with at least one empty spectrum slice anywhere on the \( i \)th path. Next, \( AS^i_j \) is the number of hops where slices on \( j \)th index are free in the \( i \)th path, and \( CN^i_j \) is the maximum number of continuous hops with available \( j \)th SS in \( i \)th multi-hop path. \( TSS \) is the total number of SS in the network (includes both available and occupied).

This formulation calculates the fragmentation level in the network spectrum using the available SS. If there is no available SS, then no fragmentation exists. We emphasize choosing selective paths out of all possible path combinations for \( \beta \)-component as it ensures that we get a network-wide \( \beta \)-component with less computational overhead. The \( \beta \)-component is not specific to any particular connection request, but the selected paths represent continuity information of many paths.

The candidate paths (all active or previously used paths) are given priority for inclusion in \( P \) used in \( \beta \)-component calculation following a Path Preference Policy (PPP). The PPP selects the paths from candidate paths that are most prone to fragmentation (longest) while covering all the links. PPP uses a link and path parameter to check the repetition of the route direction and links, respectively, in the candidate paths with the already selected \( P \) paths to reduce the calculation overhead.

- PPP starts the path selection with the longest paths, more vulnerable to degradation due to fragmentation.
- Repetition in path is the similarity of current path ‘\( p \)’ with paths in \( P \). PPP selects the path with minimum repetition.
- Repetition of the link indicates the common links in path ‘\( p \)’ compared with links of paths in \( P \). PPP should choose the path with a minimum repetition of the links.

As per our understanding, in place of using all the possible path combinations, we try to use a few longest paths, which are essentially the most actively used routes, and are most prone to fragmentation and contribute maximum to \( \beta \)-component at an abstract level.

The maximum and minimum values of the \( \alpha \) and \( \beta \) components can be found using the worst and best case scenarios. If \( TSS \) is the total number of SS and \( H_p \) is the number of hops in the selected paths, the range of \( \alpha \)-component is \( \left[ \frac{2}{TSS}, 1 \right] \). The range of \( \beta \)-component is \( \left[ \frac{2}{H_p}, 1 \right] \) if \( H_p \) is even, and \( \left[ \frac{2H_p}{2(H_p^2-1)}, 1 \right] \) if \( H_p \) is odd.

The lower limit of the range is calculated by considering a worst-case scenario, as shown in Fig. 3. In the worst-case scenario, each link in the network exhibits Fig. 2 case (d)’s spectrum status, with slices available alternatively in a link as well as in a path. As shown in Fig. 3, a single available slice is the maximum contiguous slot size in each of the links and also in the path(s). This scenario has only half of the available resources. We also get a highly fragmented scenario over a path if the maximum continuous slice over a single path is 1 for a spectrum index ‘\( i \)’, even if half of the resources on that path are available. If such a case exists for all the spectrum slice indices, we get a worst-case scenario for the \( \alpha \) and the \( \beta \). The best-case scenario is when all the available SS resources are available continuously and contiguously.

### 3.2 Example of fragmentation level calculation

In Fig. 4, we have a 4-nodes 5-links network, with its network spectrum status. All the white blocks represent empty or available SS. In this spectrum scenario, the occupancy level is 50%.

In the example, for the calculation of \( \alpha \)-component, the average ratio of maximum contiguous slot size to total available SS is considered. In \( \beta \)-component calculation, a single longest path is taken into account, covering most of the source-destination pair routes. For continuity calculation, we considered a single path traversing all links in a 3-1-4-5-2 direction; hence \( P = 1 \). All the spectrum slice indices have
at least one available slice in the given path, so $E_i = 8$. In the example, we calculate the fragmentation level using VFM and a Link-based External Fragmentation Metric (L-EFM).

The L-EFM considers the largest contiguous slot’s size ($CG_i$) and total available SS ($SS_i$) in links, $i \in L$, to decide the fragmentation level [9]. It is the most basic metric with less complexity. It also tends to ignore fragmentation due to smaller fragments present in the spectrum. The L-EFM formulation is given in Eq. (4).

$$L - EFM = 1 - \frac{1}{N} \sum_{i=1}^{L} \frac{CG_i}{SS_i}$$  \hspace{1cm} (4)

In this example, the network spectrum utilization is 50%, which means that half of the total SS is used. L-EFM for this network is 0.35. The $\alpha$ and $\beta$ contribution is 0.6533 and 0.75 respectively. The $\nu$ or the VFM value is 0.9944. If the $\nu$ (VFM) value is closer to $\sqrt{2}$ (or $\nu_{norm}$ Normalized Vectored Fragmentation Metric (NVFM) is closer to 1), then fragmentation in the network spectrum is not significant. The corresponding NVFM value is around 0.547844. It means that a moderate fragmentation is present in the spectrum. While comparing the VFM with other link-based fragmentation metrics, we use the Adapted form of VFM (AVFM), i.e., $1 - \nu_{norm}$. Using AVFM ensures that the same meaning as L-EFM is conveyed effectively; a low metric value means a lower level of fragmentation and vice versa. The AVFM value in this network is 0.452156 ($1 - \nu_{VFMD}$).

The network spectrum utilization and its relationship with fragmentation level in the system could be an interesting finding. However, a direct relationship between the two is improbable because the occupied spectrum’s arrangement also plays a part. The fragmentation level can vary for the same network spectrum utilization values when observed in steady-state conditions in the real-time traffic scenario.

We compare theoretical aspects of the VFM and the other metrics reported in the literature. The comparison allows us to put vectored fragmentation metric in perspective. The comparison is based on some of the essential characteristics and the complexity of the metrics. Table 1 compares link-based metric, path-based metric, and the vectored metric using some key features such as the ability to identify fragmentation scenarios and the time complexity. The VFM can outperform link-based metrics for fragmentation estimation at the network level with an additional computation cost but still less than the cost of the path-based fragmentation metric.

We conducted a simulation study of the adapted form of the vectored fragmentation metric (AVFM). The results are presented in the next section, and compared with the link-based fragmentation metrics (external-fragmentation metric, compaction-based, entropy-based [9]), and a path-based fragmentation metric.

The AVFM evaluation estimates the degree of fragmentation. It is further used in fragmentation management approaches. We use a threshold-based approach to trigger the fragmentation management or rearrangement of active connections in the network.

### 4 Results and discussion

To study our proposed metric, we consider three networks: Net-A with 7-nodes 12-bidirectional links, NSF network with 14-nodes 21-bidirectional links, and German network with 17-nodes 26-bidirectional links shown in Fig. 5. Each network link has 320 SS (with 12.5 GHz spectrum slice width), providing 4 THz of bandwidth in the C-band. We generate connection requests (or demands) on every node using the Poisson distribution ($\lambda$) and the holding time with exponential distribution ($\mu$). The normalized traffic load range is using the $(L_{max}/L_{ave})$ formulation. We consider a uniformly distributed SS requirement by connection requests, ranging between 1 and 16. We assume no waveband conversion scheme at any intermediate node. We use the Shortest Path-First Fit technique to provide the first contiguously available SS to connection requests. The PPP selects 12, 20, and 22 paths on an average for $\beta$-component calculation in Net-A, NSF network, and German network, respectively. The single points on the plots are an average of 500000 connection requests over 20 iterations. We obtained all the results with a 95% confidence interval.

First, we study the general characteristics of the proposed metric using different network traffic dynamics. We use the AVFM, A-Alpha ($1 - \alpha$), and A-Beta ($1 - \beta$) to study the fragmentation level. After that, we compare the network performance using several link-based and path-based metrics with AVFM when the metric is used to trigger fragmentation management in a dynamic traffic scenario.

![Fig. 4 An example for calculation of vectored-fragmentation metric with 50% occupancy](image)
### Table 1 Comparison of fragmentation metrics

| Characteristics                                                      | Link-based | Path-based | Vectored |
|---------------------------------------------------------------------|------------|------------|----------|
| Identifies fully fragmented scenario (Fig. 2d)                      | No         | No         | Yes      |
| Identifies zero fragmentation scenario (Fig. 2a, b and c)           | Yes        | Yes        | Yes      |
| Differentiates between fragmentation scenarios (Fig. 2e)            | Some of them | Yes        | Yes      |
| Time Complexity                                                     | Lowest among others | High $O(S.L)$ [28] | Moderate $O(2.5L)$ |
| General Observations                                                | 1. Ignores small fragments | 1. Specific to a path of the connection request | 1. Covers all available spectrum slices |
|                                                                   | 2. Can be relative or absolute | 2. Can be relative or absolute | 2. Absolute |
|                                                                   | 3. Covers only contiguity aspect | 3. Covers contiguity and continuity aspect specific to connection request | 3. Can covers both contiguity and continuity aspect independently. |
|                                                                   | 4. Defines fragmentation aspect in terms of spectrum compactness as well | 4. Calculates fragmentation in all path combinations for better accuracy but increasing computational complexity | 4. Calculates fragmentation in selective path combinations for better accuracy and reduced computational complexity. |
|                                                                   | 5. External, Entropy-based, Compaction-based, Highest-slot mark, Access-blocking probability | 5. Wasted-Unusable-Free Ratio metric | |

S is the total number of spectrum slices, L is the total number of Links, and G is the total number of permissible granularity of connection requests.
4.1 Analysis of Adapted Vectored Fragmentation Metric as a fragmentation indicator

The objective of the AVFM analysis in different traffic scenarios is to establish its utility. The AVFM should be able to reflect the network spectrum state in the form of fragmentation level. Fragmentation level depends on the network spectrum status, which depends on the network traffic dynamics. The traffic dynamics can vary as the average arrival rate, the average holding time, or heterogeneity in the SS requirement of the incoming connection requests. The observations are taken in the network’s steady-state, i.e., in the period after the six times the average holding time from the start of the simulation. The network is observed to reach steady-state roughly in this period.

In Fig. 6, we first evaluate how fragmentation levels vary with the connection holding time for the given arrival rate. We considered four arrival rates (\( \lambda = 5 \) per time units (t.u), \( \lambda = 10 \) per t.u, \( \lambda = 25 \) per t.u, and \( \lambda = 50 \) per t.u), and the holding time varies from one to ten t.u. We observed that overall AVFM increases with the increase in the load, i.e., increasing holding time and arrival rate. Net-A’s steady-state fragmentation level is around 0.75 for a higher arrival rate (\( \lambda = 50 \)), which is 7.5 times more severe than the fragmentation at a lower arrival rate (\( \lambda = 5 \)) while having the same holding time (1 t.u.). NSFNET and German network (Fig. 6b–c) also exhibit similar behavior; however, the networks converge to maximum AVFM level (0.6) much faster in these two networks. When the holding time and arrival rate are both less, the network shows a lower fragmentation level because the utilization of the spectrum slices is also less (only 20–30% of the available spectrum slices are busy).

Next, we observed the AVFM level for different arrival rates for holding times (HT). We considered three holding times (HT=0.1 t.u, HT=1 t.u, and HT=10 t.u) and average arrival rates between 5 and 50 connections per unit time (t.u.). In Fig. 7a–c, we observe that the fragmentation level increases with the arrival rate when the holding time is 0.1 t.u and 1 t.u. When the holding time is short, the release of connection requests is speedy, and AVFM is comparatively low, whereas when the holding time for connection requests is longer, the AVFM level is high, and a further high arrival rate can worsen the situation.

In Fig. 8a–c, we considered four different arrival rates (\( \lambda = 5 \), \( \lambda = 10 \), \( \lambda = 25 \), and \( \lambda = 50 \)), each one with increasing holding times to create varying load conditions. We observed that AVFM value increases with the traffic load. Net-A’s maximum steady-state fragmentation level is around 0.6, i.e., 60 percent fragmentation, for
the normalized load of up to 1. In NSFNET and German network (Fig. 8b–c), the steady-state AVFM value varies from 0.55 to 0.6 from 0.4 to 1 normalized load. We observe that the steady-state AVFM value does not change for a fixed load. So, varying the arrival rate and holding time for a fixed load will result in the same fragmentation level.

We also observe that the maximum permissible slot size or granularity range of the incoming connection requests (MaxDemand) affects the fragmentation level (Fig. 9a–c). We consider three MaxDemand values, 4, 8, and 16. The higher granularity range (MaxDemand 8 and 16) indicates more fragmentation (AVFM) compared to the scenario of the MaxDemand 4, as the arriving connection requests are more diverse and leave the spectrum more disorganized. We observed this behavior in all three network topologies. However, at a very high traffic load, the AVFM may fall due to the unavailability of network slices. It might be because of more connection requests of smaller granularities being accommodated (Fig. 9b–c). The high heterogeneity of the demands combined with higher arrival rates indicates a more fragmented network spectrum.

Next, in Fig. 10a–c, we observed how the influence of A-alpha and the A-beta as fragmentation level indicators vary for different network topologies. In Net-A, at low load traffic, A-beta is dominant than the A-alpha (A-alpha/A-beta < 1) for normalized traffic load of up to 0.5. The A-beta influences the Net-A more at lower traffic load, which has lower spectrum occupancy. The crossover point is when A-alpha becomes more than A-beta. For Net-A, the crossover point occurs at around 0.52. It is shown in Fig. 10b–c that A-alpha is the dominant component for a wide range of the normalized traffic loads. One of the reasons could be the number of paths considered in PPP, and the uniform type of connection arrivals. At high traffic load, more SS are occupied, and hence the fragmentation of available SS is less. It implies that link fragmentation is more prominent than the path fragmentation when majority of the spectrum slices in the links are occupied. In this case, the blocking of the connection requests for multi-hop paths would be due to the unavailability of spectrum resources rather than fragmentation. The chances of single-hop connection paths being accommodated are more in such cases.

In Fig. 11, AVFM, A-alpha and A-beta are plotted against the network spectrum slices utilization (NSSU) for three different networks. One can observe that AVFM, A-alpha, and A-beta are all smaller for smaller and higher NSSU values. They all achieve their maximum value somewhere between the NSSU value of 0.4 to 0.9.

AVFM is a composite function of A-alpha and A-beta; it always has a higher value than A-alpha and A-beta. A-alpha achieves its peak at a higher value of NSSU as compared to A-beta. It indicates that contiguity fragmentation is significant at higher NSSU while continuity fragmentation is significant at lower NSSU. One can also observe that continuity fragmentation is prominent in the network topology where the network diameter is larger. Network diameter is the maximum of the minimum hop distance among all possible node pairs. Contiguity fragmentation is dominant for all networks, especially at higher utilization.

4.2 Analysis of AVFM as a fragmentation indicator in fragmentation management approach

In this section, we use the fragmentation metrics to trigger the defragmentation process, after which the available SS are more contiguous and continuous for future connection requests. We use a green-field approach while defragmentation, where the new resources are assigned to all the active connections. The link-based metrics used in triggering the defragmentation process are link-external fragmentation metric (L-EFM) [9] in Eq. (4), the compaction-based fragmentation metric (Com-FM) [10] in Eq. (5), and the
entropy-based fragmentation metric (Ent-FM) [9] in eq.6. We have also used a path-based fragmentation metric (Path-FM) [11] in Eq. (7), to compare with the proposed metric.

\[
\text{Com - FM} = \frac{\text{Max. used SSI} - \text{Min. used SSI} + 1}{\text{Total used SSI} \times \text{Available Blocks}}
\]

(5)

where SSI is Spectrum Slice Index.

\[
\text{Ent - FM} = - \frac{\text{Used/Unused SS}}{\text{Total SS}} \log \frac{\text{Used/Unused SS}}{\text{Total SS}}
\]

(6)

\[
\text{Path - FM} = \frac{\text{Wasted SS} + \text{Unused SS}}{\text{Total SS} \text{ on the path}}
\]

(7)

where Wasted SS are unavailable on the links as per constraints, and Unused SS cannot be used for few connection requests.

We take two dynamic traffic scenarios: Case-I, where the probability of arrival of all connection requests is uniform, and Case-II, where the likelihood of the arrival of connection requests with longer hop paths is more than the shorter hop paths (considering only the shortest path between source-destination pair). We compare the network performance of different fragmentation level indicators using the blocking ratio as a primary parameter. Blocking ratio (BR) is the ratio of blocked requests to total arrived requests during the simulation time. A connection request is generally blocked if continuous and contiguous resources are unavailable on the selected path. We also observe the percentage of the defragmentation time with respect to total observation time when using the different metrics (Table 2).

The triggering of the defragmentation is a threshold-based event. Considering the worst fragmentation case in all the links of the network, i.e., Fig. 2d, we normalized the fragmentation levels and decided on a 50% threshold value for initiating defragmentation. The different defragmentation processes using different fragmentation metrics are AVFM-DF, L-EFM-DF, Com-FM-DF, Ent-FM-DF, and Path-FM-DF. We compared the BR of the networks when using the threshold-driven defragmentation and when there was no defragmentation (No-DF).

Figure 12a–c shows the BR as a function of normalized traffic load for the three networks with case-I traffic type. We observe that our proposed metric performs better than the other metrics significantly. The blocking ratio increases with the increase in the network traffic load. We can observe in Fig. 12a, for Net-A, that AVFM-DF has less than 1% blocked requests for the considered traffic load range. The L-EFM-DF, Com-FM-DF, and Ent-FM-DF have a maximum of 10%, 2%, and 3% blocked requests, respectively. Path-FM-DF has a maximum of 4% blocked requests. In Fig. 12b–c, AVFM-DF has only a maximum of 0.9% and 0.1% of blocked requests in NSFNET and german networks, respectively.

The network spectrum has fewer contiguously and continuously aligned SS in the no-DF scenario. Therefore, there is more blocking of the connection requests. We conclude that AVFM can better manage the fragmentation than other metrics in the Case-I traffic type for the considered load range.

In another case, Fig. 13a–c, we plot the BR for the Case-II traffic type as a function of traffic load. In the Case-II
traffic type, there are more connection requests with longer path lengths than connection requests with shorter path lengths. In Fig. 13a for Net-A, AVFM-DF and Path-FM-DF have a maximum of 12% connection requests are blocked. The connections with longer paths are more vulnerable to blocking and prone to fragmentation. Therefore, we see overall increased blocking in the case-II traffic type. The L-EFM-DF, Com-FM-DF, and Ent-FM-DF may not be able to identify the severity of the continuity fragmentation in the longer paths. Hence, they have more blocked requests than the path-based metrics even after performing defragmentation. In Fig. 13b–c, we can clearly see the advantage of using multi-dimensional metric over the link-based and path-based metrics. The AVFM-DF keeps the maximum number of blocked connections under 1% in NSF and under 7% in the German network for higher load values. The link-based defragmentation (L-EFM-DF, Com-FM-DF, and Ent-FM-DF) has better performance than the no defragmentation in the system but worse than the Path-FM-DF and AVFM-DF in both the networks. Overall, AVFM has a better performance gain than the link-based metrics and the Path-FM-DF when considering the Case-II traffic type.

Table 2 shows the percentage of the total time dedicated for defragmentation operation ($T_d = \frac{\sum t_{ef}}{t_{om}} \times 100$). The defragmentation time considers the total processing time taken by the individual defragmentation process ($t_{ef}$). Defragmentation frequency (N) is essentially the number of times the defragmentation is triggered per observation time. The most sensitive fragmentation metric would trigger the defragmentation more frequently. The defragmentation processing time is the time taken to rearrange the active connections. The processing time may depend on the traffic load (number of active connections) and the defragmentation frequency. We have considered the low traffic load (normalized traffic load ≤ 0.5) and high traffic load (normalized traffic load > 0.5) for Case-I and Case-II traffic types in Table 2 for different defragmentation cases.

We observed that both the AVFM-DF and the Path-FM-DF take a significant time for the defragmentation processes. But, the $BR$ of the Path-FM-DF is greater than the AVFM-DF. The L-EFM-DF and Com-FM-DF take the least defragmentation time in most cases, and their $BR$ performance is also not good. It could be due to the inability of the L-EFM and Com-FM metrics to identify the severity of the continuity fragmentation. The ENT-FM-DF has the longest defragmentation time out of all link-based metrics’ defragmentation processes. In this particular case, the metric identifies the fragmentation in the spectrum much later. In ENT-FM-DF, most of the defragmentation time is utilized in rearranging the connections. So, even with low defragmentation frequency, there is significant defragmentation time and higher $BR$ than the AVFM-DF and the Path-FM-DF. We can
conclude here that the AVFM-DF, which uses the AVFM as a fragmentation indicator, gives better BR performance, but at the cost of time, which is still less than the other path-based metric.

The results show that our metric AVFM improves the network’s performance in both traffic types (Case-I and Case-II). The AVFM metric captures the fragmentation level accurately with changing traffic dynamics. Also, it performs better than other considered metrics when used for fragmentation management.

5 Conclusion

To the best of our knowledge, there has not been any other proposal for a vectored metric using the resultant of both continuity and contiguity aspects for network-level fragmentation in elastic optical network spectrum. In this work, we have proposed a vectored fragmentation metric to estimate the degree of fragmentation in a network. This work has assessed a vectored fragmentation metric’s (AVFM) ability to capture fragmentation levels using continuity ($\beta$) and contiguity ($\alpha$) in real-time network scenarios. Both $\alpha$ and $\beta$-component can be accepted as a measure of fragmentation individually. The connectivity of multiple contiguous slices over a path in $\beta$-component is not considered. Thus, it is a 1st level metric, as it takes into account only a single slice index for the evaluation of continuity constraint fragmentation. The representation of the fragmentation for single slice connection requests also represents a worst-case scenario for applications with large bandwidth requirements.

We observed that the fragmentation level evolves with time and network spectrum status. In the AVFM, continuity ($\beta$) and contiguity ($\alpha$) contribute significantly to the overall fragmentation level. We also observed that continuity fragmentation (A-beta) is more than contiguity (A-alpha) at a low traffic load. The A-alpha surpasses it at some crossover point as load increases. The other network characteristics like arrival rates, holding times, and the connection requests’ granularity range may also significantly affect the fragmentation levels. We also consider the effectiveness of the AVFM in actual defragmentation initiating scenarios. The threshold-based defragmentation using AVFM outperforms the other metrics, considering the blocking ratio of the arriving connection requests as performance parameters.

In future work, we plan to investigate the effectiveness of the proposed vectored fragmentation metric in the joint Routing and Spectrum Provisioning (RSA) strategies. It can be used in optimizing routing decisions and slot selections to efficiently use spectral resources. The individual components of the vectored fragmentation metric can be molded or weighted to act as application-specific indicators in different traffic scenarios.

Data availability Supporting data can only be made available to bona fide researchers subject to a non-disclosure agreement. Details of the data and how to request access are available from Anjali Sharma at the Indian Institute of Technology Kanpur.

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