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Proactive Spectrum Defragmentation Leveraging Spectrum Occupancy State Information

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ABSTRACT One of the main obstacles to efficient resource usage under dynamic traffic in elastic optical networks (EONs) is spectrum fragmentation (SF), leading to blocking of incoming service requests. Proactive spectrum defragmentation (SD) approaches periodically reallocate services to ensure better alignment of available spectrum slots across different links and alleviate blocking. The services for reallocation are commonly selected based on their properties, e.g., age, without detailed consideration of prior or posterior spectrum occupancy states. In this paper, we propose a heuristic algorithm for proactive SD that considers different spectrum fragmentation metrics to select services for reallocation. We analyze the relationship between these metrics and the resulting service blocking probability. Simulation results show that the proposed heuristic outperforms the benchmarking proactive SD algorithms from the literature in reducing blocking probability.

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Keywords: Elastic optical networks, fragmentation metric, proactive spectrum defragmentation

1. Introduction

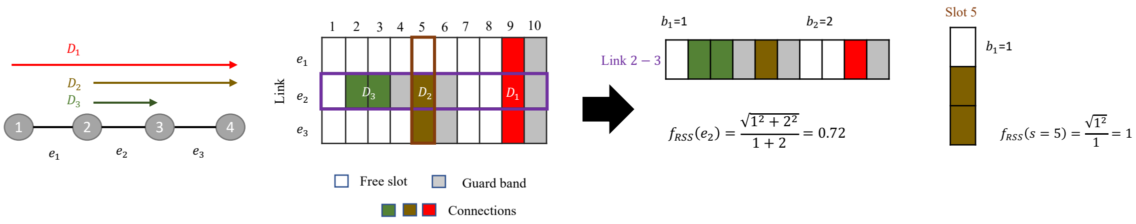
In dynamic elastic optical networks (EONs), arrivals and departures of service requests exacerbate spectrum fragmentation (SF), which refers to the misalignment of free spectrum gaps across the different links and the capacity required by incoming service requests. Spectrum fragmentation degrades the network resource usage efficiency and may aggravate the service blocking ratio (SBR) [1]. To reduce the negative impact of SF on network performance, spectrum allocation is consolidated to minimize the presence of unusable gaps in a process known as spectrum defragmentation (SD). SD aims at reducing the number of spectral gaps, increasing the size of remaining gaps and improving their alignment across the links in an effort to enhance spectrum grid utilization and minimize SBR [2]. However, SD also incurs a reconfiguration overhead which might be undesirable for network operators due to its associated costs. Therefore, the selection of services for reallocation should be carefully considered to enhance efficiency of SD.

In general, SD schemes can be classified as proactive or reactive [3]. Proactive SD is executed periodically or when a particular metric of interest crosses a given threshold. Reactive SD schemes are initiated on-demand, e.g., upon failure to accommodate an incoming service request. Proactive SD, which is in the focus of this work, was studied in [4], where the authors proposed heuristic algorithms to mitigate SF by periodically reallocating a given number of services. The algorithms select services for reallocation based on various service attributes, such as their age, required number of slots, and path length. For example, the older-first (OF) approach prioritizes services that have been active for the longest time, while the longer-lasting-first (LLF) approach selects services with the greatest remaining holding time.

While the existing approaches reduce the SBR [4], they only consider service attributes and disregard the impact of spectrum occupancy at the network level on spectrum usage efficiency. In this paper, we present a heuristic algorithm for proactive SD which utilizes network- and service-level spectrum occupancy information, gauged by two different SF metrics, to identify the most suitable services for reallocation. We conduct a comprehensive performance evaluation of the proposed algorithm and compare it to existing heuristic algorithms from the literature, demonstrating that the algorithm outperforms prior service-attribute-driven algorithms.

2. The Proposed SD Algorithm Based on Spectrum Occupancy State Information

Various metrics have been introduced in the literature to measure SF in EONs, helping network operators to monitor and optimize the utilization of optical spectrum resources [5]. Our proposed defragmentation method utilizes two SF metrics, i.e., the number of cuts (NoC) [6] and the root of sum of squares (RSS) [7]. To illustrate how these metrics are calculated, Fig. 1 presents a snapshot of a subset of three network links, denoted as e_1 to e_3, and each link has the capacity of 10 spectrum slots. Figure 1a illustrates the current state of the network with three established services, denoted as D_1 to D_3. The spectrum allocation state of each link is shown in Fig. 1b. One spectrum slot is used as guard band between adjacent services on a link. The notation includes the following parameters: e is the index of a link, E is the total number of links, s is the index of a spectrum



(a) (b) (c)

Figure 1: A simple example with a subset of three network links supporting three services (a). The spectrum occupancy state (b). Calculation of the root of sum of squares (RSS) metric values for link e_2 and slot 5 (c).

slot on a link, S is the total number of available slots on each link, b_i is the size of the i^{th} free spectrum block, and B is the number of free spectrum blocks.

Figure 1c illustrates the calculation of the value for the RSS metrics for link e_2 and slot number (5) (highlighted with frames). RSS can be calculated for a link, a spectrum slot, and for the network as a whole. RSS for link e, known as spectral fragmentation, is denoted by $f_{RSS}(e)$ and defined in Eq. (1). Analogous calculation for a slot s is referred to as spatial fragmentation and denoted by $f_{RSS}(s)$. Network-wide RSS, denoted by F_{RSS}, is calculated as the average of the spectral and spatial RSS values for all links and slots, expressed in Eq. (2).

$$f_{RSS}(e) = \frac{\sqrt{\sum_i^B (b_i)^2}}{\sum_i^B b_i} \tag{1}$$

$$F_{RSS} = \frac{\sum_s^S f_{RSS}(s)}{S} + \frac{\sum_e^E f_{RSS}(e)}{E} \tag{2}$$

The NoC metric is computed for a service, expressing the number of links along the service's path with available lower-indexed slots adjacent to the slots occupied by the service. In the example, service D_1 occupies slot 9, so the adjacent, lower-indexed slot 8 is checked to calculate the NoC. Slot 8 is free on all three links included in the path of D_1, so the value of NoC is equal to 3 for this service. For D_2, the value of NoC is equal to 1 since slot 4 is occupied on link e_2 and free on link e_3. In general, the NoC values are proportional to the level of fragmentation (e.g., a higher average value of NoC over all services indicates stronger fragmentation), while the opposite is true for the RSS metric (i.e., a higher value of RSS indicates weaker fragmentation).

Our proposed SD algorithm works by proactively triggering SD cycles, e.g., with a certain period or upon exceeding a performance indicator threshold value. The pseudo-code of an SD cycle is given in Algorithm 1. The basic idea of the approach is to reconfigure connections whose reallocation brings the greatest benefits in terms of the spectrum fragmentation metrics, and to compact the active services at the lower end of the spectrum. The algorithm takes as input the set of active services that are also candidates for reallocation D, the maximum number of services to be reallocated N, and the SF metric of interest T.

In each SD cycle, the algorithm chooses the best services to be reallocated by computing the reallocation score (RS) for each active service using the spectrum occupancy information. First, for each service D_i, the algorithm checks whether or not it is possible to re-allocate D_i to a lower-indexed spectrum slot than the current one (line 6). If multiple spectrum gaps are available, the one with the lowest starting index is selected, referred to as First-Fit void capable. The service is considered eligible for reallocation if there exists a void at the lower end of the spectrum (line 7). The algorithm then calculates the RS value for service D_i as the difference between the SF metric in the current spectrum state ($F_{current}$), and in a state where the service is hypothetically allocated to the target spectrum slot (F_{target}). If the metric of interest is RSS, the current and target values are computed using Eq. (2). If NoC is considered, the $F_{current}$ and F_{target} refer to the two corresponding values of NoC for D_i. Based on the target SF metric, the algorithm tries to select the reallocation option with a bigger (for RSS) or lower (for NoC) value of the metric (lines 8-11). In the next step, the algorithm checks if the RS is greater than the best score found so far (line 12) and saves the best candidate service, denoted as D_s (lines 13-14). After computing the RS values for all services, the selected service D_s is reallocated, the counter of the number of moved services is incremented, and the list of existing services is updated (lines 15-18). If no service is selected for reallocation, or if the number of moved services reaches N, the SD cycle terminates.

3. Simulation Settings

The performance of the proposed algorithm is evaluated via simulations of a dynamic traffic scenario for two network topologies: the NSFNET (14 nodes and 22 links) and the German network (50 nodes and 88 links). Each link in both topologies supports 320 spectrum slots. Service requests are generated using a Poisson process, and traffic loads are adjusted to achieve approximately 0.1% to 1% SBR for the scenario without SD for each

Algorithm 1: The spectrum defragmentation (SD) cycle

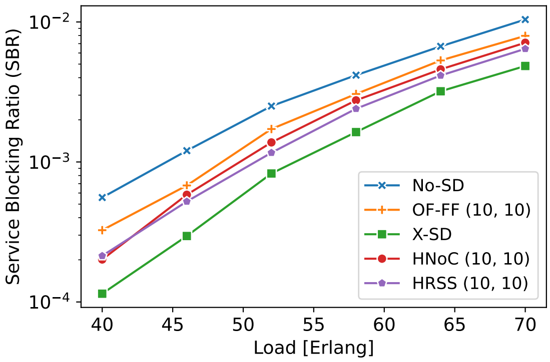
Input: D, N, $T \in [RSS, NoC]$
$Moved \leftarrow 0$;
while $D_s \neq \emptyset$ ***or*** $Moved < N$ **do**
  $RS_{best} \leftarrow 0$;
  $D_s \leftarrow \emptyset$; `// service selected for reallocation`
  for *each* D_i *in* D **do**
    Check the spectrum on all links along its path and find the First-Fit void capable
    if *void is found* **then**
      if T *is* RSS **then**
        $RS_d(i) \leftarrow F_{target}(i) - F_{current}(i)$
      else if T *is* NoC **then**
        $RS_d(i) \leftarrow F_{current}(i) - F_{target}(i)$
      if $RS_d(i) > RS_{best}$ **then**
        $RS_{best} \leftarrow RS_d(i)$
        $D_s \leftarrow D_i$
  if $D_s \neq \emptyset$ **then**
    Move the selected service
    $Moved \leftarrow Moved + 1$
    Update D

topology. 80% of the service requests are long-lived, with an average holding time of 25 time units, and the remaining 20% have an average holding time of 12.5 time units. An exponential distribution is assumed for the holding time of the services. The bit rate for service requests is 100 Gbit/s for 50%, 200 Gbit/s for 30%, and 400 Gbit/s for the remaining 20%. We use BPSK, QPSK, 8-QAM, and 16-QAM modulation formats with maximum reach length of 10,000 km, 2,000 km, 1,250 km, and 625 km, respectively, and slot capacity of 12.5 Gbit/s, 25 Gbit/s, 37.5 Gbit/s, and 50 Gbit/s. The modulation format with the highest spectral efficiency, determined by the transmission reach of the signal, is chosen. Each request is served using the following routing, modulation, and spectrum assignment (RMSA) scheme: the shortest available path among five pre-computed shortest paths and the first fit available slots, satisfying the continuity and contiguity constraints. The SD algorithm is run periodically after the departure of a pre-defined number of services, referred to as the SD period. The proposed algorithm is developed in the Optical RL-Gym framework [8].

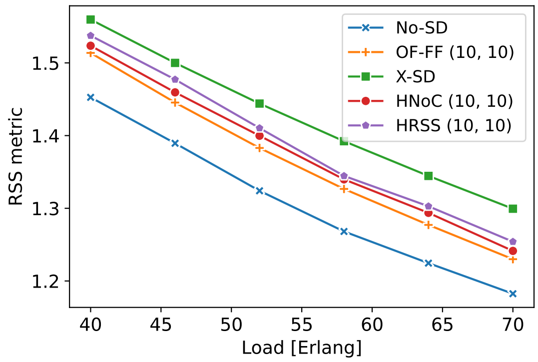
Two versions of the proposed heuristic algorithm are analyzed: the one that uses the NoC metric is referred to as *HNoC*, and the one that uses RSS is called *HRSS*. In order to evaluate the performance of the proposed algorithms, a comparison is made with three heuristic algorithms, namely *older-first first-fit (OF-FF)*, *exhaustive spectrum defragmentation (X-SD)*, and *No-SD*. *OF-FF* uses service age as the criterion to determine the set of services for reallocation and first-fit (FF) spectrum assignment policy to find new slots. It is used for benchmarking purposes as it has shown excellent performance in terms of SBR [4]. *X-SD* is simulated to establish an approximate lower bound on the value of SBR by reallocating an unlimited number of services upon each service departure and using FF spectrum assignment policy to find new slots. Note that in this approach, service blocking occurs due to a lack of resources which cannot be prevented by any proactive SD scheme. Finally, the *No-SD* approach represents network performance in the absence of SD. Different configuration parameters are tested and yield analogous results. We choose to report on the configuration with the SD period and the number of service reallocations both equal to 10.

4. Results

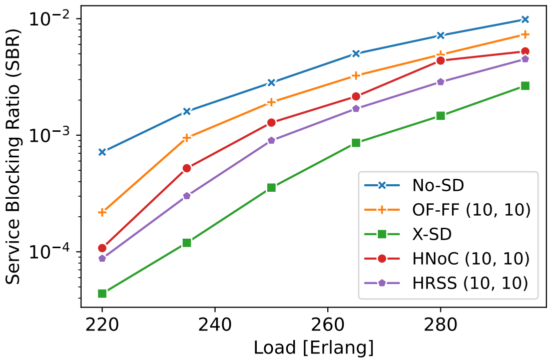
Figure 2 depicts the performance of the considered SD strategies for the NSFNET and German network, highlighting the benefits of the proposed algorithms. As shown in Figs. 2a and 2c, *No-SD* and *X-SD* perform the worst and the best in terms of the SBR for both networks, respectively. For NSFNET (Fig. 2a), *X-SD* achieves 57% lower SBR than *No-SD*, demonstrating the maximal potential gain that can be attained by a sequential proactive SD algorithm under the considered settings. The difference in SBR between *X-SD* and *No-SD* is 77% for the German topology, indicating a stronger impact of SF on this network. Here, the ability of the *HRSS* algorithm to select suitable services for reallocation becomes more crucial, resulting in a better overall performance in the German compared to the NSFNET network. Namely, in the German topology, *HRSS* outperforms *No-SD* and *OF-FF* in terms of SBR by 62% and 44% on average over all loads, respectively. In NSFNET, the *OF-FF* scheme yields a 26% lower SBR than *No-SD*, while *HNoC* and *HRSS* reduce SBR by 36% and 43%, respectively. The *HNoC* and *HRSS* approaches outperform the *OF-FF* by 16% and 25%, respectively. This confirms the benefits of using occupancy state information in the process of selecting services for reallocation. When it comes to the two considered metrics, RSS seems to be a better contender than NoC for decreasing SBR, which can be supported by 14% better performance of the *HRSS* algorithm than *HNoC* on average.



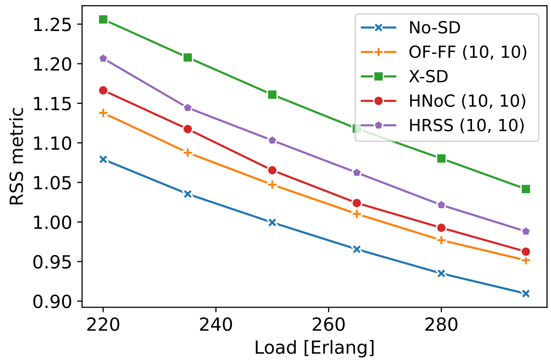
(a) Service blocking ratio (SBR) for NSFNET topology



(b) Root of sum of squares (RSS) metric for NSFNET topology



(c) Service blocking ratio (SBR) for German topology



(d) Root of sum of squares (RSS) metric for German topology

Figure 2: Performance of the SD schemes: (a) and (b) NSFNET topology, (c) and (d) German topology.

To obtain a deeper insight into the network performance, Figs. 2b and 2d show the values of the network RSS metric for different scenarios of the two topologies. The RSS metric shows inverse correlation with the SBR values depicted in Figs. 2a and 2c, respectively. In other words, a network with greater fragmentation (indicated by a lower RSS value) tends to have a higher SBR. Also, the figures indicate that the value of the RSS metric decreases as the load increases, which shows there is stronger fragmentation for the higher loads.

5. Conclusion

This paper presents a heuristic algorithm for proactive spectrum defragmentation (SD) that utilizes spectrum occupancy information, measured by the number of cuts (NoC) and root of sum of squares (RSS) metrics, to select the most suitable services for reallocation. Simulation results demonstrate the effectiveness of the proposed algorithm in reducing SBR compared to older-first first-fit (OF-FF) algorithm by up to 44%.

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