A Novel Hop-distance Sensitive Approach to Elastic Optical Networks RSA Algorithms

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Abstract: Elastic optical networks (EON) allow great flexibility through finer spectrum allocation granularity when compared to traditional WDM solutions. Their improved spectrum efficiency makes them a promising solution for next-generation backbone and metropolitan networks. Distant connections in elastic optical networks that are routed through multiple hops suffer from increased bandwidth blocking probability (BBP), in contrast to easier formulation of more direct connections. Traditional BBP as a metric fails to capture this phenomenon. In this work, a normalization of BP to the connection's hop distance is proposed and a novel low complexity algorithm is presented that takes this new metric into consideration. Simulation results show that the proposed scheme improves network performance and fairness with no deterioration of BBP, when compared to the FirstFit RSA algorithm.

1 INTRODUCTION

Globally, the IP traffic in telecommunication networks has risen at unprecedented levels, expanding annually at an average rate of 24%, according to Cisco Global - 2021 Forecast Highlights (Cisco, 2016). Not only do the number of users increase, but also new, bandwidth starving applications such as voice over IP, video on demand, high- definition video and gaming (Beletsioti et al., 2016).

Traditionally, optical technologies based on Wavelength Division Multiplexing (WDM) (e.g (Kyriakopoulos et al., 2018b), (Beletsioti et al., 2018)), which use the conventional fixed grid of 50 GHz and 100 GHz for backbone and metro networks (Simmons, 2014) respectively, have been used to accommodate the requested traffic demands. However, today's extremely high traffic needs threaten to make the traditional WDM technologies inadequate. Nevertheless, Elastic Optical Networks (EON) in conjunction with OFDM scheme is assumed to be a promising technology coping with the increasing and more diverse traffic demands (Gerstel et al., 2012), (Kyriakopoulos et al., 2018a).

EONs offer flexibility in how to allocate just the appropriate bandwidth capacity to the connections and are considered the network solution for backbone and next generation metropolitan networks. In flexible grid technologies the spectrum is split into slots of 6.75 GHz, 12.5 GHz or 25 GHz. These frequency slots (FS) are then combined to create channels, which are not overlapping due to OFDM's orthogonality condition (Vizcaíno et al., 2012), in order to serve custom sized bandwidth requests and adapt to the dynamic and heterogeneous nature of their arrivals during network's operation.

The main focus of routing and spectrum allocation assignment EON algorithms (RSA) is that connections are required to satisfy both the continuity and contiguity frequency constraints (Chatterjee et al., 2018). Under high traffic loads, requests between distant nodes may suffer increased blocking rates due to the fact that these constraints need to be satisfied

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across multiple links.

Our work demonstrates the fairness problem that multihop connections face. Satisfying the continuity and contiguity constraint over longer distances becomes increasingly harder, when compared to establishing connections comprising of only a few hops. To this end, we propose a new metric in this paper, the *normalize to hop-distance Bandwidth Blocking Probablity* (*normalized_BBP*), that takes connection hop-distance into consideration and its effect on network performance.

A similar fairness issue is highlighted in (Rosa et al., 2015), where it is shown that bandwidth consuming connections are characterized by higher blocking probability. Finding larger continuous groups of unoccupied FSs is hard; contiguity exacerbates the situation. Light bandwidth requests are more probable to fit in the spectrum and experience lower probability of blockage.

Another work that takes interest into connection distance is (Chatterjee and Oki, 2016). Low index FSs are affected by dispersion less than high index ones, meaning that long distance lightpaths suffer more quality-of-transmission degradation when placed in a high index FS. By taking this phenomenon into consideration, the number of FSs per connection can be minimized, leading to improvements for the network performance. Our work takes a different approach since it utilizes connection hop-distance instead of the actual lightpath length.

A low complexity, effective RSA solution that is used in many works is the FirstFit (FF) algorithm (Zheng et al., 2010), (Ning and Shen, 2012). Our proposed method, called HopWindows (HW), improves upon FF by taking hop-distance into consideration. In Section 2 the motivation for this work is further explained. Section 3 provides a detailed description on the operations of the HW algorithm. Finally, in Section 4 the performance evaluation of our method is presented. It is shown, that the proposed method can achieve improvements from 5% up to 36% when compared to FF against the *normalized BBP* metric, for a variety of underlying topologies (metro-mesh, backbone and metro-ring).

2 MOTIVATION

One of the most commonly used metrics employed when investigating the performance of elastic optical networks is bandwidth blocking probability (BBP) and is calculated as:

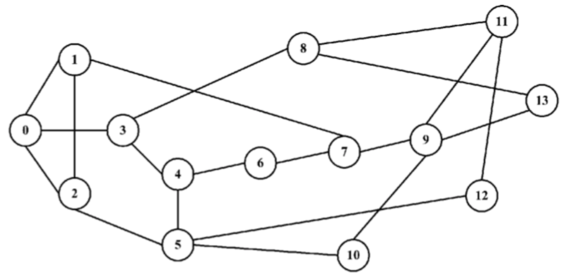

Figure 1: Optical backbone network NSFnet, with 14 nodes and 21 links (Shen and Tucker, 2009).

$$bbp = \frac{\sum bandwidth\_blocked}{\sum total\_bandwidth\_generated} \quad (1)$$

This metric is undeniably useful, but doesn't reflect the total reality, especially concerning connections comprising many hops. Depending on the underlying routing algorithm, one or more paths are available betweeen a pair of nodes. Node connections that can only be established over more than one intermediate nodes are called high-hop connections. Node pairs that are neighbors or require only one other intermediate nodes are low-hop connections. Minimum hop distance (*conn_min_hops*) is considered in our method and refers to the minimum hop length of all allowed paths between two nodes. Neighbor nodes have a minimum hop distance of one.

Elastic optical networks allow great flexibility and increased bandwidth utilization, however connections are required to satisfy both the continuity and contiguity frequency constraints. Since high-hop connections require free overlapping frequency slots over multiple links, they suffer from higher blocking probability.

This phenomenon can be observed when BBP is analyzed per minimum connection hop distance. Indicatively, in our simulation of First Fit performance for the NSFnet topology in Section 4 (Figures 3 and 5), average BBP of all connections for 150 Erlangs may be 0.06, however BBP for connection with $conn\_min\_hops = 1$ and 2 is 0.001 and 0.0487 respectively, while BBP exponentially increases in the cases of $conn\_min\_hops = 3$ and 4, to 0.10 and 0.215 respectively.

3 PROPOSED SCHEME

3.1 HopWindows Scheme

The proposed HopWindows (HW) algorithm is described in Algorithm 1. Similarly to the FirstFit method (Zheng et al., 2010), when a new connection request is generated, the k shortest paths between

Algorithm 1: HopWindows.

```
1  New Connection

   Input  : conn_min_hops: minimum number
            of hops for this connection
            Paths[i]: k3 shortest paths
            Paths[i][max_util]: Percentage of
            FSs in path that are occupied
            Paths[i][len]: number of hops for
            this path
            Paths[i][free_slots]: available FSs
            on path
            masks[conn_min_hops]: limit FS
            according to the mask

2  foreach path ∈ Paths do
3        ▷ Find a path that fits this connection
4      if path[max_util] > 50% then
5            ▷ This path is at risk of congestion
6          if path[len] > conn_min_hops + 1
            then
7              continue
8          else
9              apply masks[conn_min_hops] on
                path[free_slots]
10     if connection fits in path[free_slots] then
11                ▷ Apply firstfit for this path
12         return path
   Output: Select Path | Reject connection
```

source and destination are examined for unoccupied FSs, that are continuous and contiguous. Those free FSs are stored in the array $path[free\_slots]$.

The critical step of HW is Line 4, where the proposed method is differentiated from the simple FF method. In the case of HW, the maximum path utilization is calculated. Each link in that path will have a different degree of utilization, and *maximum path utilization* refers to the utilization of the most "filled" link in that path. If *maximum path utilization* is higher than a threshold, then that path contains a link that is either a network bottleneck, or simply, the network offered load is sufficiently high and that path is already congested. Our investigation suggested that using 50% for that threshold produces good results.

The next step, when HW mode is enabled for that connection path, is to examine if the current path is longer than the shortest in hops from all paths. This check preemptively disables connections from establishing "circular" paths and is integral part of our proposed method. A side benefit of this rule, is that connections may select a longer but less occupied path,

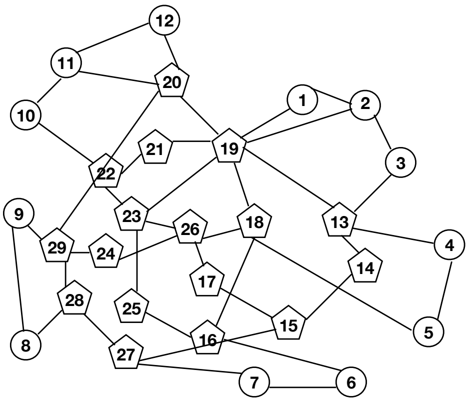

Figure 2: Mesh based metropolitan network with 29 nodes and 41 links (Antoniades et al., 2004).

resulting in a simple load balancing of the network links.

If the connection is allowed to proceed to Step 9, then a mask is applied to the $path[free\_slots]$. The form of the mask depends on the minimum hop distance of the source - destination pair, thus a different mask is enforced in the case of neighboring nodes, than in the case of N hop-distant nodes. The enforcement of this mask further limits the allowed FSs for this connection. For example, the meaning of a mask like $mask[1] = [0, 100]$, is that neighboring nodes (with hop-distance = 1) are allowed to only use FSs with index from 0 to 100, disallowing FSs with index larger than 100. Practically, this limitation may force some 1-hop connections to be rejected, but reserves bandwidth for high hop connects that are underperforming.

After the mask rule is applied to the $path[free\_slots]$, the algorithm attempts to place the connection to the leftmost slot of continuous FSs that can fit it, similarly to how FF operates. If the connection fails to fit, the algorithm examines the next available path or the connection is denied. In that case the connection is "blocked".

3.2 Selecting the Hop-distance Masks

A critical component of our method is the form of the masks utilized in the proposed method. Our analysis through simulation demonstrates that masks are unique to each topology employed. There is no generic rule set that can satisfy multiple and diverse scenarios, such as those examined in Section 4. Our suggestion to this problem is to diverge to a good solution by pre-processing.

In order to find a good mask for our proposed method, a new metric is introduced that our divergence technique attempts to reduce, which is called

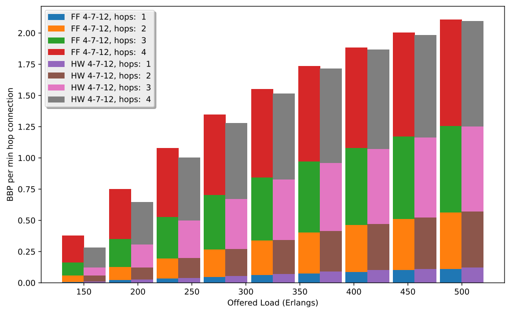

Figure 3: Blocking probability per connection hop distance. For each load value, the left bar represents FirstFit and right the HW method. BBP is represented as bar high. Lower sections of the bars represent the blocking probability of low hop-distance connections. HW improves upon BBP, while the largest benefit is on high hop-distance connections.

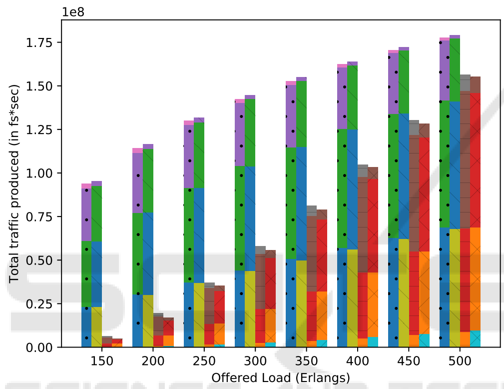

Figure 4: Total network traffic load analysis. The dotted bar represents the FF successful connections, the slashed bar the HW successful connections, bars with horizontal lines the FF blocked connections and the crossed bar the HW blocked connections. Lower sections of the bars represent the traffic of lower hop-distance connections. HW achieves more successful 3-hop and 4-hop connections.

normalized_bpp and is calculated as:

$$normalized\_bbp = \frac{\sum bandwidth\_blocked \cdot min\_hops}{\sum bandwidth\_generated \cdot min\_hops} \quad (2)$$

In *normalized_bpp* bandwidth block probability is weighted against the minimum connection distance. Our rationale behind this parameter, is that long hop distance connections occupy more FSs in more links, when compared to more direct connections. If network performance is examined only against BBP, then a scheme that bans all long connections would superficially perform better. In such a network, if offered load is sufficiently high, then multiple short connections could be established in the place of a single long connection. The BBP performance would seemingly improve, while in reality, if we apply this scheme to NSFnet, then all east coast to west coast connections are disabled.

This metric is an attempt to alleviate the unfairness problem that is present in EONs, when high hop-distance node pairs struggle to establish connections, even when the network is superficially operating with low blocking probability. Utilizing *normalized_bpp* leads to not only improved network performance, but also slightly decreases the fairness problem. Ignoring this parameter can lead to the undesired result of rejecting high hop connections and artificially improving BBP, since then, more low hop connections would be established. Comparing schemes against *normalized_bpp* can give additional insights to network performance, since it takes the effect of connection hop distance into consideration. Our results in Section 4 demonstrate that our approach not only improves upon this *normalized_bpp* metric, but the benefits can be even observed in the BBP metric (Figures 5 and 6).

Algorithm 2: Calculate masks.

Input : *topology*: contains the network topological information
$simulation(masks, topology)$: will run a simulation and returns the *normalized_bbp*
$Masks[conn\_min\_hops]$: limit FS according to the mask
max_fs: maximum FS index

```
masks[i] = [1, max_fs]                    ▷ neutral masks
norm_bbp = simulation(masks, topology)

while True do
    foreach mask ∈ Masks do
        mask[2]–                          ▷ decrease mask
        new_norm_bbp =
          simulation(mask, topology)
        if new_norm_bbp > norm_bbp then
            continue                      ▷ no improvement
    if the foreach run once without
      improvement then
        break
```

Output: The $Masks[i]$ used in Alg. 1

The algorithm that calculates the mask is detailed in Algorithm 2. In order to design masks that minimize *normalized_bbp*, first a baseline is calculated by using neutral masks for all hop-distances. The neutral mask is in the form of $mask[i] = [1, maxfsindex]$, where i is all possible minimum hop distances for the network's nodes. Running a simulation for each topology using those neutral masks produces a baseline *normalized_bbp*. Then, while the simulations show that this will improve *normalized_bbp*, each hop distance's mask is constantly decreased, until we have solution. The masks used for each topology in Section 4 are calculated using this method.

4 PERFORMANCE EVALUATION

4.1 Network Topologies Employed

In order to assess the performance of our approach a simulation environment was implemented to test our proposed algorithm HW versus the FF algorithm. In order to demonstrate the benefits of our proposed algorithm in both elastic backbone and next-generation metropolitan networks, three topologies were examined. The backbone network we included in our simulation is NSFNET (Shen and Tucker, 2009), which consists of 14 nodes and 21 links (Figure 1). A mesh based network (Antoniades et al., 2004), which consists of 29 nodes and 41 links (Figure 2), and a ring topology of 16 nodes are also examined, as representatives of elastic optical metropolitan networks.

As will be demonstrated in the rest of this Section, our proposed method achieves different gains depending on the underlying topology. The benefits in the case of NSFnet and ring topology are in the region of $10-30\%$ in low offered loads, while in the case of the metro-mesh topology, the highest gain achieved is 5.5%. Compared to the FF scheme, our method never underperforms. As our results show, the worst case performance of HW is at least on par with the FF method.

4.2 Simulation Parameters

Following the standard settings used in most of the corpus of EONs, the main characteristics of our simulation are the following:

- Each link in the network consists of two unidirectional fibers. Each fiber contains a maximum of 160 Frequency Slots (FS). This value is typically used in previous works, and is irrelevant to conclusion we derive from our results.
- The source and destination nodes of a traffic request are uniformly selected.
- The traffic load is dynamically generated and calculated as λ / μ (Erlang). The interarrival connection rate λ is constant and equal to 1. The connection duration parameter μ follows a negative exponential distribution.

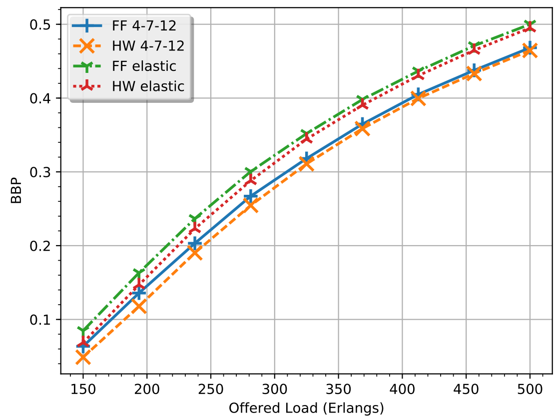

Figure 5: Bandwidth blocking probability for the NSF network topology. The proposed method can even improve upon the BBP metric.

- In our implementation of the FF scheme, the parameter $k = 3$ for the K-shortest path algorithm.
- The connection load follows one of the two rules: *elastic* and *4-7-12*. In the case of *elastic*, the connection load is in the range of $[2, 15]$ FSs, including guard-band, while the rule *4-7-12* describes the scenario of three distinct services with requirements of 4 FSs, 7 FSs and 12 FSs, including guardbands (Qiu et al., 2016). In both cases, the load of newly generated connections is chosen uniformly from the allowed values. Similar results are observed for both traffic profiles. The average connection load for the *elastic* traffic is 8.5, while in the case of *4-7-12* is 7.666. This range of *elastic* is purposely selected so that the result lines of both *elastic* and *4-7-12* in Figures 5-8 are meaningfully near but not overlapping with each other.
- The simulation ends when simulation time reaches 10e5 time units.

4.3 Simulation Results

Even though our method primarily focuses on improving the normalized BBP metric, the improved network operations can even be of benefit to the more commonly used BBP metric, as can be seen in Figure 5, leading to gains up to 5.5%. When performance is compared against the normalized BBP parameter (Figure 6), the gains are more pronounced reaching up to 36% for low offer load, though gains diminish with high loads (Table 1). The topology used in both of those experiments is the NSFnet (Figure 1). The mask employed for this topology, only limits the 1-hop distance connections to 149 FSs. This group of experiments demonstrates that our method

Table 1: Numerical results comparison for FF and HW for NSFnet.

Erlangs	150	200	250	300	350	400	450	500
FF elastic *normalized_bbp*	0.105	0.215	0.309	0.39	0.455	0.507	0.55	0.587
HW elastic *normalized_bbp*	0.0832	0.192	0.295	0.376	0.441	0.497	0.541	0.577
gains percentage	26.5	11.4	4.9	4	3	1.95	1.81	1.81
FF 4-7-12 *normalized_bbp*	0.08	0.181	0.273	0.352	0.419	0.47	0.51	0.55
HW 4-7-12 *normalized_bbp*	0.058	0.155	0.257	0.336	0.405	0.461	0.50	0.54
gains percentage	36.4	16.79	6.2	4.82	3.58	2.03	1.97	1.34

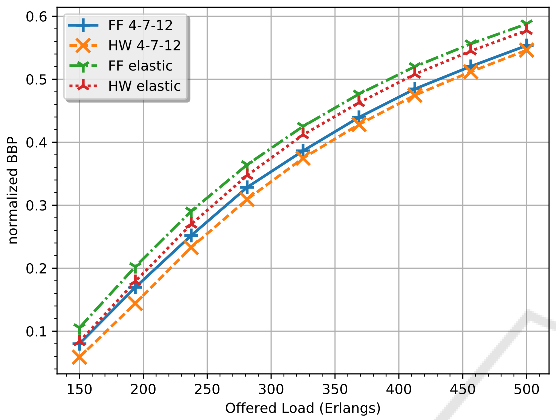

Figure 6: Normalized bandwidth blocking probability for the NSF network topology.

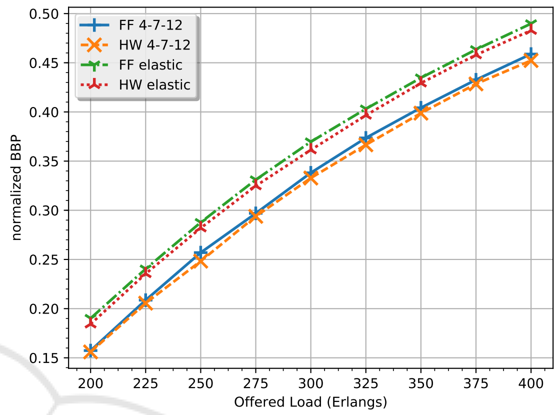

Figure 7: Normalized bandwidth blocking probability for the metro network topology.

will improve the performance of a typical backbone network, when compared to the FF algorithm. Similar improvements are observed in both the *elastic* and *4-7-12* traffic profiles.

The NSFnet topology is also used in the results displayed in Figures 3 and 4. Those Figures give a detailed image on BBP per N-hop connection for the former and on the amount of successful/blocked connection per N-hop connection for the latter. Those results demonstrate both the unfairness that high-hop connections face and the improvements HW achieves. Those improvements are more pronounced in comparably "low" offered loads, which are also the most interesting, since a real world scenario will operate within those ranges of low BBP (a network with 50% BBP is unresponsive and unrealistic).

Similar results are achieved in both the cases of the mesh based network (Figure 2) and the ring topology of 15 nodes. In both of those topologies, the mask algorithm limits bandwidth for the 1-hop and 2-hop connections. In the case of the mesh network (Figure 7), 1-hop connections are limited to 113 FSs and 2-hop connection are limited to 149 FSs, while larger hop connections are allow to use the whole bandwidth. The maximum hop-distance is 6. In the case of the ring network (Figure 8), 1-hop connections are limited to 137 FSs and 2-hop connections to 125 FSs. In this topology, the maximum hop-distance is

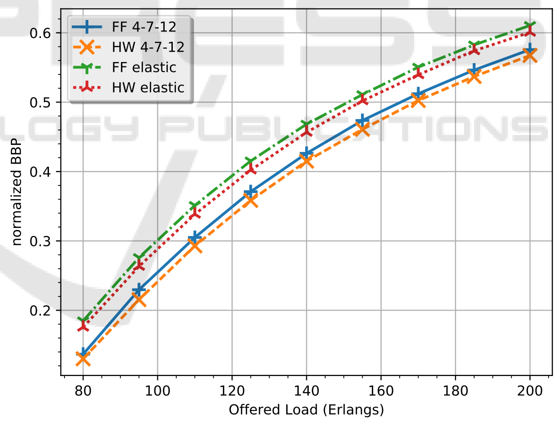

Figure 8: Normalized bandwidth blocking probability for the ring network topology.

8. Our experiments show that the ring topology benefits more than the mesh topology when utilizing the proposed algorithm.

5 CONCLUSIONS

In this work we propose the utilization of the new metric *bandwidth blocking probability normalized to connection hop distance*, or normalized BBP. Our analysis and the new, weighed probability metric shed light on the intrinsic problem that multihop connections face in elastic optical networks. High hop connections are harder to satisfy the continuity and contiguity constraints of elastic optical networks, leading to unfairness and performance deterioration.

Our proposed algorithm achieves up to 10% gains in BBP when compared to the FirstFit scheme, by limiting low-hop connections in certain paths and by preemptively blocking non-shortest-hop connections when the path utilization is high. Our low complexity algorithm leads to performance improvements that are shown to be without negative trade-offs.

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