ABSTRACT

IMPROVING LIGHTPATH ESTABLISHMENT IN ELASTIC OPTICAL NETWORKS

by Amer Al Baidhani

Optical Networks are an effective means for faster and reliable communications. Because of the dramatic increase in bandwidth demand, Elastic Optical Networks (EONs) have been introduced as a future solution. This technology provides efficient spectrum utilization. Thus, the Routing and Spectrum Assignment (RSA) problem has arisen as the key design in EONs. This thesis shows that Spectrum Assignment can be improved by means of reducing resource contention. The major objective of this thesis is to maintain connectivity using a proposed flag-based algorithm. The study will analyze RSA with different traffic patterns and network topologies, settings and constraints. Furthermore, an adaptive approach based on learning is proposed to overcome such networks conditions, and challenges.
IMPROVING LIGHTPATH ESTABLISHMENT IN ELASTIC OPTICAL NETWORKS

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CHAPTER 1

INTRODUCTION

1.1 Overview of Optical Networks

Optical networks are utilized to enable reliable and faster communications for data transfer between any endpoints. An optical network is built from optical fibers as links which carry light through very narrow glass cylinders and optical devices at the nodes. Optical network components include switches such as Optical Cross-Connects (OCX), Reconfigurable Optical Add/Drop Multiplexers (ROADM), transponders, amplifiers, and regenerators. Optical networks offer huge bandwidth, longer distance transmission with very small delay, and high SNR compared to RF communication. As result, it is expected that optical networks will be the dominant method for telecommunications for future communications systems. Optical fibers offer higher bit rate of data transfer and they are able to transmit data over kilometers at more than a few megabits per second [1]. Much of the achievement for the current huge bandwidth utilization over optical fibers may be attributed to Wavelength Division Multiplexed (WDM) technology [2]. In conventional WDM technology, each connection request is assigned to a wavelength via a Routing and Wavelength Assignment (RWA) algorithm. Yet, the rigid nature of WDM technology limits the network utilization efficiency because of the fixed-sized spectral bandwidth. This restriction initiates poor spectrum utilization as the demand’s bit rate varies dynamically. Thus, WDM suffers when used in heterogeneous traffic [3-4]. Because of the emergence of new technologies such as ultra-high definition video streaming, huge social media usages, machine to machine communication, and Cloud computing, traffic is increasing exponentially and the traffic bandwidth demand is expected to be around 606 Tb/s in 2018 [5]. Consequently, the need for a new technology that has the ability to handle bandwidth-hunger is required. Recent research trends focus on developing efficient use of optical network resources and gaining more effective and elastic spectrum utilization. This promising solution is known as Elastic Optical Networks (EONs) and has been proposed to handle spectrum waste and achieve adjustable data rate in order to sustain diverse granularity of network demands [6].
1.2 Objective

The objective of this master’s thesis is to develop an algorithm for managing spectrum allocation in EONs. A key point of this work is to manage, efficiently, the available resources to satisfy a user’s requirements, maximize resource utilization, and minimize the blocking probability. This thesis will show that the blocking probability of connection establishment is not only influenced by the network bandwidth, topology, or traffic pattern, but also by the protocol and algorithm that is implemented to solve RSA. Different traffic scenarios and topologies will be simulated to verify the effectiveness of the proposed algorithm. Furthermore, we will compare the proposed scheme with other current algorithms to prove the superiority of our scheme. Correspondingly, we will present further enhancements for the algorithm based on learning named the adaptive flag based algorithm.
CHAPTER 2

FLEXGRID OPTICAL NETWORK SCHEME

2. Elastic Optical Networks

The need for high-speed networks with huge bandwidth capacity is crucial because of the rapid
growth in technology that lends itself to the importance and domination of optical networks.
Hence, EONs are promising candidates to solve this issue, since they offer efficient utilization of
the optical resources [6]. Unlike WDM networks, EONs use small channels known as frequency
slots (FS) that employ Orthogonal Frequency Division Multiplexing (OFDM) [6]. In conventional
WDM, spectrum bands have 50 or 100 GHz spectral space and every band is able to adapt one
wavelength [7]. However, EONs are proposed to utilize either slots of 6.25 GHz or 12.5 GHz
spectral width so that spectrum is better utilized [6]. Spectrum efficiency is gained because of the
use of OFDM technology which employs overlapped subcarrier slots [8 -11]. To ensure efficient
spectrum utilization, EONs use OFDM, distance adaptive modulation techniques, and Bandwidth
Variable Transponders (BVTs). BVTs fulfill the traffic demand by producing an optical signal
with an appropriate modulation level. When the modulation level and the spectrum needs are
known, a lightpath is established and routed through Bandwidth Variable Wavelength Cross-
Connects (BV WXCs), shown in Fig. 1; then, the end-to-end optical path is created [11].
EONs also ensure better accommodation of multiple data rates, separation and accumulation of
spectral resources [12]. The main advantage of EON over WDM is spectrum utilization since no
concept of a wavelength line rate or a bandwidth grid exist. Rather, every request is assigned to
its spectrum need to meet its required rate [6]. Figure 2 illustrates the difference between WDM
and EON from a spectral perspective. This thesis deals with a problem that is called Routing and
Spectrum Allocation (RSA). RSA is a NP-hard problem that requires some constraints,
specifically the contiguity constraint and the continuity constraint [13]. In RSA, the demand of
the connection request is being assigned to a number of required frequency slots by means of the
OFDM transponder [14-15]. When there are not enough resources to fulfill a connection request,
the connection request will be blocked as illustrated in Fig. 3.
Figure 1: Bandwidth variable wavelength cross-connects [15]

Figure 2: Spectrum utilization of EON vs WDN [16]

Figure 3: Blocked connection and resource scarcity
2.1 Bandwidth Variable Transponders Based on OFDM

The Bandwidth Variable Transponder (BVT) is the main enabling technology in EON. The key advantage of BVTs is their ability to adapt to different data rates by adjusting the modulation format and bandwidth occupancy depending on the optical reach. The BVT supports distance adaptive transmission, minimizes the use of regenerators, and gains effective usage of the spectrum.

2.2 Frequency Slots (FS) in the Spectrum

Each OFDM-subcarrier represents a frequency slot. For flexibility, a slot width has been proposed to be multiple of 6.25 GHz [6]. Accordingly, networks with 1 THz Bandwidth will correspond to 160 slots. The idea of a frequency slot is to divide the spectrum into small segments so that a number of them can be assigned to a connection depending on the bit rate of that connection without a huge guard band.

2.3 Spectrum Efficiency

The spectrum gains efficiency because of OFDM. To increase the spectrum efficiency with a small distance around 600 km, a higher modulation level can be used; for instance, 16-QAM [17]. Lower level modulation formats can be considered when the optical reach is longer (typically more than 1000 km). Distance-Adaptive (DA) spectrum allocation can be conducted to allocate a different number of frequency slots (sub-carriers) for the connection request with the same rate depending on the feature of their path (short or long) [18]. A connection request can use adaptive modulation levels each with a different spectral efficiency since each OFDM sub-carrier can be modulated separately using QAM, BPSK, or QPSK with different bits per symbol and spectral efficiency as described in Table 1 [17-19]. The choice of the modulation level and technique is also can be considered in RSA and it is known as the Routing, Modulation Level, and Spectrum Allocation (RMLSA), which is one of the scopes of this thesis.
Table 1: Modulation format and optical reach in EON [20]

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>Optical Reach (km)</th>
<th>Spectral efficiency (bps/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>9600</td>
<td>1</td>
</tr>
<tr>
<td>QPSK</td>
<td>4800</td>
<td>2</td>
</tr>
<tr>
<td>8-QAM</td>
<td>2400</td>
<td>3</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1200</td>
<td>4</td>
</tr>
</tbody>
</table>

2.4 Routing and Spectrum Allocation

RSA is used to find a route and allocate a spectrum for an incoming connection demand. RSA is regarded as a critical issue in EONs. Different algorithms have previously been proposed to solve this problem. There are constraints that make it more challenging as described below in Fig. 4.

- **Spectrum continuity**: In this constraint, for each connection request, the same number of frequency slots of the spectrum need to be assigned in every link along the path as shown in Fig. 5a.
- **Subcarrier contiguity**: Frequency slot segments that are assigned to the same connection request have to be neighbored to each other as shown in Fig. 4.b.
- **Frequency slot capacity**: Every link along the path requires a specific number of frequency slots, \( N \), to be assigned and the number of slots is equal to \( N \) on all links.
- **Non-overlapping spectrum assignment**: The assigned spectrum slices have to be orthogonal in order to prevent interference. Figure 4.c shows that, when two demands have the same link(s), the non-overlap constraint in the frequency domain holds.
The RSA problem in EONs is categorized into two classes: 1) Static: offline RSA, where the traffic and topology are static and already known, and given in terms of capacity needed; 2) Dynamic: online RSA has unknown and random demands. Integer Linear Programming (ILP) has been used to optimize the offline RSA. This thesis will solve and consider the online RSA problem because it is more accurate, though also more difficult. In online RSA, at each time interval, a new connection request with a different bit rate arrives in a random manner (Poisson distribution). This new connection needs to be accommodated to $n$-frequency slots. If there is a scarcity of resources, the connection request cannot be accommodated and it will be blocked; after $t$-intervals the resources can be highly fragmented. As a result, the blocking probability is a significant metric to verify the algorithm’s effectiveness. RSA can be solved in one step by performing the routing and allocation simultaneously, or in two steps by solving the routing first and the spectrum allocation secondly. The second approach will be considered in this thesis, since it is easier to decompose into two sub-problems: first perform Dijkstra’s shortest path algorithm for routing and then apply different spectrum allocation algorithms.
2.5 Spectrum Allocation (SA) Algorithms

Different algorithms were developed for searching and allocating a connection request to a number of slots in the spectrum. The key point of a useful algorithm is to minimize the Blocking Probability (BP) without excessive time and cost (computation complexity).

a. First Fit:

First Fit (FF) is a well-known and commonly used method [21] since it increase the possibility of finding contiguous frequency slots. This algorithm tries to allocate the connection for a number of available frequency slots that has the lowest index. When it cannot accommodate the demand, the next slot will be inspected. This tool has lower computation cost and it does not need global knowledge.

b. Random Fit:

In Random Fit (RF) style, the slots will be assigned randomly in order to lessen multiple connections looking for the same slot. This algorithm works well in WDM as a naive algorithm that assign an available wavelength blindly, whereas using it in EON, leads to fragmentation that causes higher blocking probability according to [22].

c. Random Fit – First Fit:

Random Fit – First Fit (RF – FF) is a mixed algorithm that was proposed in WDM technology to prevent collisions [23]. The mechanism of the algorithm is as follow: when a connection tries to reserve a wavelength, it checks a counter of the outgoing link, which might signal a collision. If a collision is detected, it will use RF; otherwise it uses FF, while reserving on the backward direction.

d. Flag based Algorithm:

This algorithm is proposed for the thesis and used for Backward Reservation Protocol. We applied a flag with zero values to all frequency slots. Each time a connection accommodates any frequency slot, the flag of this particular slot is increased by one. After each update - new interval, the flag vector is stored within the outgoing OXC. When the connection tries to probe (Backward Reservation scenario), it checks the flag value with a specific threshold; if the flag value is greater than the threshold, it will disregard that slot and search for a different one. When the connection reaches the destination and has been serviced, the flag value will be incremented by one in the
backward path. This scheme is expected to lower the BP since it prevents more than a specific number of connections to conflict with the same spot. The main objective of this algorithms is to minimize optical resource contention, as this leads to minimizing the system BP.

To illustrate the BRP-flag-based procedure for one of the scenarios of resource collision, we first consider that a connection, say 1 – 4, arrives as in Fig. 5. It chooses the shortest path, which is link 1-3 and 3-4. Then, it sends a probe message to look for free slots; we assume it finds a free number of slots (typically, successful probing does not guarantee a successful connection since there is a time delay between probing and reserving). Subsequently, the flag value is increased for that link with a freedom of flagging only the $n$ available slots ($n$ is used to be the tenth of the number of the slots); in this case, the probe message is on its way to the destination while the second connection 1 - 6 arrives and probes. Since the 1-3 link has a flag reference for a connection that might take this particular slot, the new connection will disregard the flagged slot and search for the next available slot. At this time the connection 1-4 has just reached its destination with the probe message and it tries to reserve it by using the First-Fit policy; it reserves the first one according to the probe message. Now, connection 1-6 reaches its destination and tries to reserve the required slots. The effectiveness of the flag is that if it did not disregard the flagged slot on link 1-3, a contention could have occurred. When the connection reaches the destination, the algorithm decrements the flag value. After the probing process is over, the flag value is decremented. Then, both connections stay with a holding time, $t$. Finally, the 4-3 connection arrives and looks for the available slots with the same scenario. It might be predicted that the flag-based method has better performance as the arriving rate increases, accordingly. However, we may not be so optimistic when the arrival rate is very high because many factors can play into the performance such as, Topology, propagation delay, and fiber bandwidth. As result, an event driven simulation can provide a better understanding of the latter issues.
Figure 5: Illustrative Example of Flag-based Connection

<table>
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<tr>
<th></th>
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<th>flag</th>
<th>slots</th>
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<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
</tr>
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<td>5</td>
<td>0</td>
<td>0</td>
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<table>
<thead>
<tr>
<th>Connection</th>
<th># of slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4</td>
<td>1</td>
</tr>
<tr>
<td>1 - 6</td>
<td>1</td>
</tr>
<tr>
<td>4 - 3</td>
<td>2</td>
</tr>
</tbody>
</table>
3. Control Plane

In networks with very dynamic traffic demands, it is necessary to design an efficient control and management scheme. To establish a lightpath between source and destination, a signaling protocol is needed to allocate resources in order to send data. The control plane provides connection supervision and supports restoration services. The control plane of an optical network is separated from the data plane, which is in charge of managing the network resources. Currently, two kinds of controller architecture could be employed: an optical network centralized controller or a distributed controller. In this work, a distributed controller is used since most current large scale networks employed it and it is compatible with recent vendors’ equipment [24].

The Generalized Multi-Protocol Label Switching (GMPLS) is a control plane that has been chosen for this work and it has a Resource Reservation Protocol with Traffic Engineer, RSVP-TE [25]. As shown in Fig. 6, practically, to manage the network, the GMPLS controller is distributed through all OXCs. The general mechanism of distributed GMPLS is as follows: when a connection request arrives, GMPLS creates a generalized label request that travels through the intermediate nodes, assigns new labels for the path to the destination that is followed by a generalized label assignment that travels back in order to manage the resource reservation. In distributed and dynamic networks, there is no guarantee that resources accessibility on each link will be available for all connection requests because of contention. To study this issue, several reservation schemes have been proposed in previous studies [26].

Figure 6: distributed GMPLS controller [27]
3.1 Forward Reservation Protocol (FRP):

Forward Reservation Protocol (FRP) is one of the resource reservation protocols. In this protocol, the sender sends a RESerVation (RESV) message and the available resources are temporarily reserved along the forward direction through all links on the path to the destination depending upon whether or not there are enough resources available. When there is no recourse to accommodate the reservation, a FAILure occurs and a FAIL message is sent to the source. There is no promise that the same selected slots will be available throughout all links (contiguity constraint). The disadvantage of this scheme is that the number of slots are over-reserved for an amount of time (greedy algorithm), which may prevent other connections from allocating those slots for an amount of time. This scheme releases the frequency slots and reserves only the required amount after the connection has arrived at the destination. After a particular holding time, a ReLeaSe (RLS) message is sent to free all FS. Figure 7 describes the message types sent using FRB scheme.

Figure 7: Forward reservation scenario messages [28]
3.2 Backward Reservation Protocol (BRP):

Another resource reservation protocol is the Backward Reservation Protocol (BRP). In this scenario, a control packet is sent as PROBe (PROB) message packet to the destination without reservaing any resources rather than carrying information about availability of the resources. Then, the destination node reserves and sends a RSVE message to the source relaying the probe message. If no resources are available, a Negative ACKnowledgment (NACK) is sent to the source to inform it to retransmit or that a failure occurred. The drawback with this method is that the resource may no longer be available when the probe message has reached the destination and it exhibits latency compared to the FRP. After a particular holding time, a RLS message is sent to release all FS. The illustration in Fig. 8 demonstrates the BRP mechanism.

![Diagram of Backward Reservation Protocol]

Figure 8: Backward Reservation messages [28]
CHAPTER 4

SIMULATION AND ASSUMPTIONS

4.1 Simulation

Designing a network simulation tool is crucial in optical network research as it serves researchers in validating and assessing new proposed algorithms. Under feasible assumptions, we can study a specific technology and evaluate the performance of these algorithms. We have developed an EON simulation for validating the work. The earlier version of optical network simulator was firstly designed by a former member of our research group [29]. The simulator can simulate a FF RSA algorithm and provides performance metrics that include blocking probability and network bandwidth occupation. In the simulation, each demand and connection request arrives randomly with a Poisson distribution at a rate of $\lambda$. The number of FS on each link is regarded as a system resource, while each arrival and departure is considered an event. A number of connections arrive in a parallel manner within time intervals at rate $1/\lambda$. Each demand request is routed on its shortest path by implementing Dijkstra's algorithm. The request carries information about the source node, the destination node, distance, and the bandwidth (the number of frequency slots required to be transferred from the source node to the destination). During the simulation, the connections are not allowed to modify their bit rate, which was decided randomly over the range of 1 to 100 Gb/s. After the path has been found and the distance has been realized, a DISTANCE-ADAPTIVE (DA) algorithm is used so that the destination node configures the modulation format and the bandwidth for that demand according to Eq. (1) [30].

$$\text{Number of slot} = \frac{\text{Requested bit rate of the connection}}{\text{(Spectral Efficiency} \times \text{Slot width})} \ldots (1)$$

The FF algorithm is used for spectrum allocation. The simulation was coded using C++ and it uses open source openGL to present the Graphical User Interface or GUI. The FF policy is applied for spectrum allocation. This research proposes a flag-based spectrum allocation algorithm to be included with the FF policy. The current contribution includes: debugging, modification to the simulation by implementing the flag-based approach, RF-FF, odd-even algorithms, maintenance...
for the GUI, multi-platform compatibility; forward and backward reservation schemes enhancement, path’s distance, delay, modulations schemes, and additional topologies.

4.2 Assumptions and Simplification:

- Each demand is generated based on a Poisson process and the holding time of each connection request takes an exponential distribution
- The connection arrives and then will be released after a holding time once it reaches the destination
- Each demand is generated with three attributes source, destination and requested bit rate
- The demand’s bit rate for each request is distributed using a uniform random-generator between 1-100 Gb/s
- A 16-QAM was used for a distance less than 600 km and 4 QAM for a length longer than 600 km
- The spectrum spacing and the total number of subcarrier slots per channel are considered with 6.25 GHz width
- No optical regenerator and link protection on all paths are considered
- If the connection fails, no retransmit is generated as it is regarded as blocked
- No traffic grooming was applied
- No guardbands are considered
CHAPTER 5

DISCUSSION AND RESULTS

In this chapter, the evaluation and result of the work are presented, including the chosen topologies, the metrics, and the simulation results. In our simulations, the performance of the proposed flag-based algorithm is compared with conventional algorithms and protocols. The results will aim to evaluate performance, scalability, trade-offs, and to discover challenges of the algorithm. The performance of the proposed FF flag-based algorithm is evaluated through discrete event simulation. The most well-known core network topologies, NSF, Japan, and Finland, will be used accordingly to evaluate the performance of the work since they differ in the following parameters: distance, number of link and nodes. To produce the simulation results, the 12-node and 19-link Finland topology (see Fig. 9) will be selected as a typical network topology along with parameters in Table-2. Each link will have 320 slots; thus; each link uses 2 THz of the optical spectrum, since one slot represents 6.25 GHz. Bidirectional connections between Sender-Receiver nodes are assumed. The shortest distance is calculated based on the least number of hops between source and destination.

Figure 9: 12-node Finland core topology
Table 2: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Spectrum Width</td>
<td>6.25GHz</td>
</tr>
<tr>
<td>Data rate of each request</td>
<td>1-100 Gb/s</td>
</tr>
<tr>
<td>Number of slot on each link</td>
<td>320</td>
</tr>
<tr>
<td>Spectral efficiency</td>
<td>1-4 bps/Hz</td>
</tr>
<tr>
<td>Bandwidth of each link</td>
<td>2 THz</td>
</tr>
<tr>
<td>Number of Connections Simulated</td>
<td>10000</td>
</tr>
<tr>
<td>$T_o = $ Processing Delay at OXC</td>
<td>2 m sec</td>
</tr>
<tr>
<td>$T_b = $ Data Transmission Duration</td>
<td>5 µsec</td>
</tr>
<tr>
<td>$T_m = $ RSVP messages processing</td>
<td>1 m sec</td>
</tr>
<tr>
<td>$T_p = $ Propagation Delay between each link</td>
<td>5 µsec/km</td>
</tr>
</tbody>
</table>

5.1 First Fit Backward Reservation vs. Flag-Based

The performance of the algorithm is evaluated in term of blocking probability versus network offered load which is $(\lambda / \mu)$. We will vary the arrival rate from 1 to 1000 connection/s while keeping the holding time unity. For each simulation, the number of simulated connection requests is 10,000 along with Table-1 parameters. The first 1000 connections were disregarded from our calculation in order to reach a steady state. It can be seen from Fig. 10 that the blocking probability of the flag-based for Finland topology provides significant improvement with lowest probability — we see an improvement averaging at least 99% in the overall request blocking probability for low arrival rates and up to 70% with high arrival rates. More essentially, it is even effective with an extremely low arrival rate below 1 connection/s. The proposed scheme decreases the probability as the arrival rate increases. This is feasible due to the flags that were applied to the network resources, since this method lowers resource contention and acts as traffic regulator. We observe the higher probability of a non-flagging scheme due to the possibility of losing a frequency slot
after probing, since the probe message might be outdated after reaching a destination. As a result, many of connections will have to search for another FS when an FS is already flagged.

![Figure 10: BRP result Finland Topology](image)

It is clear that the proposed algorithm efficiently lowers the blocking probability during the busy hour traffic scenario by around 200-400 Erlangs. For all simulation tests, the flag-threshold was fixed to 1 (the threshold represents the upper value that a connection can probe a frequency slot on a link). When a connection tries to allocate a FS while the flag threshold value equals the flag value of a specific FS, the connection will be required to look for another slot with a lower flag value to avoid a collision. To minimize our simulation error, the results are repeated 10 times with different seeds and then averaged. In order to gain detailed insight into the algorithm’s behavior, we use different topology network sizes. The NSF topology (Fig. 11) is the second test that has 14-nodes and 21 links with longer distances between each link.
The results shown in Fig. 12 prove the value of our work, since our flag-based approach considerably increases the successful rate of lightpath establishment. NSF is a valuable network to test because it has a bulky topology (that is, it contains massive link distances). Comparing the BP for the NSF and Finland topologies, the connection delay set up is longer. Thus, we can predict that conflicts may occur during resource reservation. We note that the flag-based approach for NSF achieved higher successful rates by approximately 70%-99% with respect to the conventional signaling scheme. However, the BP at higher loads is still noticeable; this is due high latency, fragmentation, and lack of resources when the arrival rate is high.
To further study the performance of the proposed algorithm, we investigated the Japanese topology displayed in Fig. 13. The results in Fig. 14 demonstrate that the BP can also be lowered with a flag scenario due to the intelligence that the algorithm provides to the incoming connection. The proposed approach achieved the lowest connection blocking probability, less than (~0.15%) for low offered load below 50.

Figure 12: BRP result for NSF Topology

Figure 13: 14-node Japan core topology [20]
Figure 14: BRP result for Japan Topology

Figure 15: BRP result for Japan Topology lower load
As we can see from the latter results, the flag-based approach can improve the success rate performance more substantially in the NSF topology when compared to both the Japan, and Finland topologies. This is because of the size of each network and the long distances that a connection request needs to traverse because the flag value can better reduce contention while higher delay is present. However, in some scenarios, the flag value might also be uninformative due to spectrum fragmentation. We can have a closer look at lower offered load as shown in Fig. 15 where the results indicates blocking probability still appears. According to our observations, this could be due to one or both of two reasons: fragmentation and/or flag discontinuity. Since fragmentation causes available frequency slots to be scattered around the spectrum, they may become unusable. The problem with flag discontinuity is that the connection flags the frequency slot but ends up not using it.

### 5.2 First Fit FRP vs BRP vs. Flag-Based

In this section, FRP, BRP and flag-based approaches will be compared in regards to the blocking probability with different network topologies and traffic patterns. For a network, connection blocking probability can be triggered by one of three scenarios: the first scenario is because of a lack of network resources; the second scenario is due to algorithm aggressiveness, i.e., over-reservation; the third scenario is due to BP for the FRP in the Finland topology is the highest. This is because the FRP is greedy and over-reserved the FS (resources are reserved but may not be used). For BRP, the probability increases as the arrival rate increases; this is due to the fact that the probe information might be outdated due to the signaling delay. Hence, the most beneficial scheme with the lowest BP is the flag-based because of collision-intelligence and less aggressiveness.

It is obvious from Fig. 16 that the performance of the FRP is drastically worse than the performance of BRP. Let us consider different topologies: the NSF result is shown in Fig. 17; the BP of the FBR scheme suffers with extreme connection failure, and the BP reaches up to 35% while the offered load is around 50 Erlangs. For high offered loads, the blocking of connections is around 70% due to the over reservation constraint; however, the BRP-flag offers advantage that is highly successful with regards to the BP with the improvement in performance of more than 20%. For the Japan topology, Fig. 18 indicates the same clues that the previous topologies implied. The BP
surges as the arrival rate increases because of protocol aggressiveness and inadequate network resource capacity. Therefore, the FRP signaling protocol is not optimal as for robust traffic.

Figure 16: Blocking Probability for Finland using FRP vs BRP

Figure 17: Blocking Probability for NSF using FRP vs BRP
5.3 Network Challenges and Settings

To further investigate the performance of the proposed algorithm, we evaluate and analyze networks settings and challenges that network may face.

5.3.1 The Effect of Traffic Load

Network load becomes more dynamic in size and direction with the new bandwidth usage surge. During the peak times of high traffic intensity, the networks are prone to degradation in performance. As it is very clear from our previous series of the simulation results, the blocking probability increased as the traffic increased. The arrival rate increases during busy hour traffic; this means more demands tends to arrive in parallel (arrive almost within the same intervals). The results related to Finland topology, illustrated in Fig. 19, show the proposed scheme achieved the lowest BP. However, the proposed approach starts to degrade at offered loads of more than 700 Erlangs (with extremely high arrival rate) indicating that the aggressiveness of the flagging method may be ineffective when more connections arrive.

The result for Japan topology is presented in Fig. 20. It also implies that the flag-based approach starts to be ineffective when the offered load approaches 600 Erlangs. This is because of the
aggressiveness of the flagging method (the resource is flagged but might not be used); as a result, we are losing the adaptivity of flagging. Alternatively, when the threshold value is varied, we can observe in Fig.21 that the blocking rate at higher loads does not degrade. Hence, this is another indication for the need for an algorithm to be adaptive.

Figure 19: Blocking Probability for Finland using BRP

Figure 20: Blocking Probability for Japan using BRP
5.3.2 The Effect of Setup Delay

Setup delay starts when the connection arrives at the lightpath configuration. Setup delay is generally caused by propagation delay, message processing delay, and OXC operation delay. For any network, the latency is a significant element in degrading performance, since it can have an impact on the quality and reliability of the system. In the case of high latency, more connections might be blocked. To justify this, we use the same parameters in Table-2 while changing the processing delay of the OXC from 2 ms to 200 ms and RSVP message processing time from 1 ms to 10 ms. It is clear that longer setup time results in higher BP. Under extreme latency conditions, the numerical experiments in Fig. 22 show that the flag-based scheme minimizes the BP, since it provides a successful rate between 70%-99% with respect to the conventional BRP. As latency increases, the possibility of a probe message to be outdated increases that means the probability of selecting a FS that is no longer available rises. We can conclude that our proposed scheme outperforms the BRP even with the extreme delay. We varied the set up delay since the setup delay cannot be guaranteed to be deterministic due to the processing times of different size loads and different times of hardware component processing.
5.3.3 The Effect of Resources Scarcity

Even though optical networks offer huge bandwidths for lightpath establishment, with the ongoing increasing demand and future traffic, networks may face resource scarcity. We examine this situation by setting the arrival rate to 100 connections per second and varying the fiber bandwidth from 125 GHz up to 2 THz. From Figs. 23-24, we see that the performance of our flag-based methodology outperforms the conventional scheme. However, as the arrival rate increases to 400 with a fiber bandwidth of 1 THz, we observe that the flag-based degrades as the BW reduced. It is clear from the results that the performance curves coalesce as the load increase. This is quite reasonable since, at peak rush hour with not enough bandwidth, there are resource scarcity issues and nothing can be done to optimize the performance. Furthermore, we set the arrival rate at 100 connections per second and varied the bandwidth. Our numeric experimental results, shown in Fig. 25, indicate that the flag-based BP approaches ~0% while increasing the bandwidth. Yet, the conventional signaling scheme does not benefit from the resource availability because of high possibility of collision.
Figure 23: Blocking Probability for Japan with 160 frequency slots

Figure 24: Blocking Probability for Finland with 160 frequency slots
5.3.4 The Effect of Subcarrier Width

OFDM subcarrier width represents the frequency slot spacing in EONs. In flex-grid networks, the slot width can be a multiple of 6.25 GHz according to the ITU standard [27]. It is noted that a fiber with a bandwidth of 2 THz that uses the 6.25 GHz scheme, will correspond to 320 frequency slots, and using 12.5 GHz band-width slot will correspond to 160 total slots. We have examined both scenario. Figure 26 displays the results for slots of 6.25 GHz and it shows that this slot size is promising to support higher data rate than the slotting scheme of 12.5 GHz. This is due the wasted guard band in a 12.5 GHz scheme. We observe that the BP decreases as the slot width shrinks. However, as spectrum spacing get smaller, more physical layer challenges occur (i.e., sharp optical filters are needed and channel nonlinearities can come into play). More importantly, our approach, the flag-based method, largely outperforms others in both scenarios of the above slotting scheme.
5.3.5 The Effect of Traffic Data Rate

Currently, the traffic data rate has been impacted by the new technologies with bandwidth growth such as the Internet of Things (IoT) communication and social media bandwidth usage. This growth is turned into an offered load traffic per node which can range from 1 Gb/s up to 200 Gb/s. The traffic data rate load varies in optical networks and it is unequally distributed. This can cause unbalanced resource assignments. To produce fair simulation results, we varied the offered traffic per node as uniformly distributed between 1 to 200 Gb/s. As illustrated in the Fig.27, the BP increases, since more frequency slots are consumed. Our approach achieved lower BP especially with low bit-rate requests. If we reduce the data rate for each request to 50 GHz, our observed results indicate that the success rate increases, since less frequency slots will be required for each request. If we look closely at lower traffic around 100, we can see the advantage of our approach when compared to the conventional methodology even though the data rate is comparably high.
5.3.6 The Effect of Threshold

The threshold is the limit that the slot can be probed by an incoming connection. It can be argued that the threshold value of unity is equivalent to RESV message in FRP approach. However, using the flag-based scheme, the flagging procedure can be less/more aggressive in selecting FSs and it can have some freedom with the possibility to choose from the probed frequency slots in addition to the flagged frequencies. The results in Fig.28 indicate that the blocking of connections starts to decrease when the threshold is applied. We can see that the hard flagging of unity is the optimal choice since the connection can ensure that the flagged resources will be assigned at a cost of bandwidth consumption.
5.4 Results for Flag-Based odd-even approach

In this section, the two algorithms - first-fit flag-based and even-odd flag-based approaches - will be compared along with the conventional signaling scheme. Using the odd-even approach, the connections will be distributed on the spectrum based on their ID, namely an odd or even ID will be assigned to the connection as they arrive in sequence. A connection that arrives with an even message-ID needs to search for a resource from the far-end of the spectrum. An odd ID will search for resources from the beginning of the spectrum. A similar approach with conventional signaling was discussed in [31-32]. Additionally, we implemented the algorithm in the EON simulator with the idea of improving the performance of our flagging scheme. As is shown in Figs. 29-32, the flag-based odd-even approach outperforms the flag-based version. The BP of the connections analysis for 100 Erlangs is the lowest and always under 2% for NSF, 0.3% for Japan, and 0.1% for Finland. This indicates that the traffic load is equally distributed on both sides of the spectrum within very short intervals. We note that this can increase collisions-awareness. When adopted, this approach for this scenario can apply a fair load distribution on each side of the
It is clear that the conventional FF policy provides the worst performance compared to the two proposed policies.

**Figure 29:** Blocking Probability for Finland with odd-even approach

**Figure 30:** Blocking Probability for Japan with odd-even approach
Figure 31: Blocking Probability for NSF with flag vs flag odd-even

Figure 32: Japan topology under low load with flag vs flag odd-even approach
5.5 Results for Random Fit vs First Fit (RF-FF)

In order to accurately evaluate our algorithm, we compare it with other existing similar algorithms. The discussions in Section 3.1 indicated that RF-FF chooses random or first fit scheme depending on the condition of the collision scenario. To provide fair results, we implemented the algorithm in our simulation environment. The numerical results for the three tested topologies are stated in Figs. 33-35. The RF-FF shows better performance with lower load than the flag-based, yet not better than flag even-odd approach. The RF-FF performance starts to degrade around 200 Erlangs. Therefore, an RF-FF approach is not a proper choice for EONs compared to WDM implementation since it depends on a randomization approach that can lead to higher fragmentation that can greatly degrade the performance when the offered load increases with the dynamic nature of the traffic.

![Graph showing blocking probability for different algorithms](image)

Figure 33: Blocking Probability for Japan with different algorithms

For the Finland topology, we see the same trends as in the Japan topology. This suggests that RF-FF is not a robust algorithm especially in the cases with higher load.
We observed an interesting result with the NSF topology as shown in Fig. 35. In this case, the algorithm indicates the reverse trend when comparing to the previous two topologies. One possibility is due the fact of the huge propagation delay in NSF.
5.6 Adaptive Flag based algorithm

Due to the vast ongoing dynamic traffic, the flag-based approach needs to adapt to different traffic conditions and network requirements. As we conducted our comprehensive performance analyses of our proposed algorithm, it can be seen that the algorithm need to be further enhanced. First, the algorithm requires a training data sequence for a specific network with concurrent offered loads based on traffic engineering statistics (i.e., from OXC), in order to have the desired data for future predictions. Subsequently, the flag aggressiveness decision is adapted based on regression of the earlier trained data by implementing a decision tree with a lookup table. Flag aggressiveness is the maximum number that the connection can use to flag a probed FSs. In our earlier section, we developed the flag algorithm that authorizes the connection to accommodate the FSs depending on the flag status. Now, let us apply the adaptive approach to the earlier algorithms by conducting a set of multiple simulations in order to observe the best fit threshold aggressiveness for a specific traffic load. We adjusted the flag aggressiveness by conducting a number of simulation, while storing the optimal flag aggressiveness for a specific traffic load. The results for the proposed adaptive algorithm, as shown in Figs. 36-40, proved to be satisfactory compared to the raw approach. Furthermore, the adaptive approach is significantly more efficient with lower load. For the adaptive method, we also observe a slight improvement when the traffic load is light. We have set an adaptive aggressiveness window based on blocking probability/traffic load. The idea of aggressiveness is tied to the maximum number of frequency slots that a connection can flag. When there is high blocking probability in a region of the network, the aggressiveness factor should be low, since higher blocking connections infers a higher load o that the flagging process can be less aggressive. However, the difference arises when the mean observed blocking probability over a period of time is quite low; in this case, a connection should be quite aggressive in term of flagging. Thus, we have to train each selected topology in order to observe the optimal threshold for each aggressiveness factor. Figure 36 shows the results for our adaptive approach in the Finland network with regards to fixed flagged aggressiveness. After the training scenario, it can be seen that we gain a reasonable improvement with lower load and slightly improvement with higher loads.
Figure 36: Blocking Probability for Finland with adaptiveness

Figure 37: Blocking Probability for Japan with adaptiveness
Figure 38: Blocking Probability vs low load for Japan with adaptiveness

Figure 39: Blocking Probability for NSF with adaptiveness
We note that, with very high load, there is a trade-off between being less aggressive at a price of more connections having collisions in the signaling process. Hence, it appears that the results of the algorithm cannot be further optimized. For the NSF network, we gain very slight improvement since there is difficulty in compromising between long propagation delay and aggressiveness.

![Blocking Probability for NSF with adaptiveness](image)

**Figure 40:** Blocking Probability for NSF with adaptiveness

### 5.7 Adaptive Flag Based Algorithm Based on the Number of Hops

As some of the connections traverse over fewer links, we can increase the possibility of satisfying the spectrum continuity constraint by adapting to such a network condition. This method is expected to add more intelligence with the help of flagging and utilizing the shortest path. The algorithm can be described as follow: for any $i$, and $j$, let $S_i$ and $Aw$ represent the frequency slot and the aggressiveness window, respectively, for a connection $j$ looking for slot $i$. The procedure of the algorithm sets the $Aw$ to the lower bound when the connection requires a fewer number of hops with lower data rate. However, if the connection travels between 3 or 4 hops, it sets the $Aw$ to a medium bound; then, when the connection traverses many intermediate nodes, for more than 4 hops, say, the aggressiveness is set to the highest bound; that means more slots will be flagged.
in order to satisfy the spectrum continuity constraint. The lower, medium and upper bounds are predicted to a connection by conducting a training data session for estimated traffic network conditions with the mini hop counts and lowest data rates which are implemented as a decision tree. This approach can lead to an intelligent decision by only flagging FSs as needed. Therefore, the flag discontinuity will be reduced due to connections being established based on a smarter flagging criteria that learns from previous decisions. It is clear, from Figs. 41-43, that the adaptive hop based approach outperforms the raw adaptive method. Moreover, the adaptive odd-even approach achieves the highest success rates when compared to all previous methods as stated in the numerical results. Figure.41 shows the result for the Japan network, which indicates clearly that our new methods further reduce the blocking probability to $6.6 \times 10^{-5}$ when the offered load is below 40 Erlangs. Furthermore, Fig. 42 shows the that BP for the Finland topology approaches zero in the scenario with adaptive odd-even based on hop count for loads around and below 20 Erlangs; however, we note that we still obtain slight improvement between 30 and 50 Erlangs with adaptivity without the hop count being employed. For the NSF network, the results in Fig. 43 indicate that the adaptive approach lowers the BP approximately by factor of 1.5. However, the simulations show a very slight improvement (averaging at most 0.01 decrease in overall request BP for the range of the arrival rates) with higher loads.

Figure 41: Blocking Probability for Japan with different adaptiveness
Figure 42: Blocking Probability for Finland with adaptiveness

Figure 43: Blocking Probability for NSF with adaptiveness
We can observe that the adaptiveness of the algorithm that conducted depending on the number of hops and traffic density is the best approach, since it achieves the lowest BP as shown by our early numerical results. This makes reasonable sense because traveling within more hops requires more efforts to maintain the validity of the spectrum continuity constraint. In addition, from the physical layer perspective, traveling over longer distances induces more noise and physical challenges. Hence, efficient modulation formats are used, which offer high spectrum efficiency.
CHAPTER 6

SUMMARY AND FUTURE WORK

In this proposal, a flag-based algorithm is designed to manage resource allocation in Elastic Optical Networks. EONs provide significant flexibility for spectral resource usage because of the employment of an OFDM technique. While current trends tend to employ flex-grid optical networks, management of the resource assignment plays a critical role in designing, operating, and planning of such a network. The RSA problem has been solved by the proposed signaling scheme that is targeted to minimize blocking probability at the network level. In this work, we also have compared the performance of our proposed scheme with other conventional protocols under different parameters and topologies. The simulation results demonstrate significant improvement in the probability of success for different traffic arrival patterns. The results indicate that designing and planning a vital control plane is not only influenced by the lack of resources, but also by the signaling scheme, latency, physical impairment, and traffic pattern. An adaptive approach is proposed after conducting a comprehensive study of network setting and challenges that indicates the need for flagging methods to be adaptable. The study of high traffic rates demonstrated that flag performance degrades because of the lack of resources and global knowledge. Hence, the need for a centralized controller is necessary for long term consideration. Our algorithm provides low cost with simple computation demands, since it is an extension to the software of the current distributed GMPLS control plane.

For our future work, we also aim to implement a Software Defined Network (SDN) and study the challenges and trade-offs of the centralized controller. Such a SDN should offer further flexibility and enhance the overall network performance. An adaptive routing with restoration may be included with the algorithm to further reduce the network blocking probability. Fragmentation minimization also can be further overcome by developing a fragmentation-awareness algorithm. A deep learning approach can be conducted to, not only adapt the flag aggressiveness window, but to determine the base slot for the connection and the route that can result in less network congestion and spectrum fragmentation.
REFERENCES


