Adaptive Flag-Based Signaling for Distributed Spectrum Assignment in Elastic Optical Networks

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***Abstract*—The emergence of flexible frequency grids and distance adaptive modulation transmission methodologies in Elastic Optical Networks (EONs) necessitates novel and efficient Routing and Spectrum Assignment (RSA) and signaling mechanisms to support them. In this paper, we propose an adaptive flag-based signaling mechanism for distributed spectrum allocation to maximize lightpath connection establishment by lowering Blocking Probability (BP). Our numerical results indicate significant improvement in the rate of success in establishing dynamically arriving connections. We also proposed an enhanced adaptive approach based on hop count with data driven learning to further reduce the BP in connections.**

***Index Terms*—Elastic optical Networks, Flexible spectrum grid, control plane design, Routing and spectrum allocation, Resources contention handling, GMPLS.**

I. INTRODUCTION

Elastic Optical Networks (EONs) were introduced to support the ongoing huge heterogeneous traffic demands beyond 100 Gb/s, by providing efficient spectrum usage [1-2]. Routing and Spectrum Allocation (RSA) plays a key role in EON design and operation [3]. For effective usage of such elastic spectrum, Orthogonal Frequency-Division Multiplexing (OFDM) is employed [1], where the spectrum is divided into Frequency Slots (FSs) of 6.25GHz or, 12.5GHz according to the ITU-T grid. Each EON connection is assigned a flexible number of contiguous FSs along its path depending upon the connection's transmission rate and distance. Current Wavelength Division Multiplexing (WDM) networks employ 50 GHz channels with an inflexible frequency grid, which leads to wasted guard bands for connections that need multiple wavelengths and for connections that need less than the full 50 GHz channel. The main enabling technologies in EON are the bandwidth-variable transponders that enable variable granularity, along with distance adaptive transmission by means of changing the level of modulation format instead of the usage of WDM single-line-rate transponders. Subsequently, Bandwidth-Variable Optical CROSS-Connects (BV OXCs) are used. They are responsible for multiplexing/demultiplexing/ switching operation with the above features to route the lightpath to the destination [4]. To establish a lightpath, a connection request needs to be optically accommodated by finding a path and reserving resources. As current optical networks operate under a circuit switching architecture, this requires a dedicated path along with exclusively reserved bandwidth for each connection. In WDM technology, classical Routing and Wavelength Assignment (RWA) was used. RSA is more challenging than RWA since more constraints have to be met [5]. RSA can be solved by adhering to its constraints and assigning the shortest path with the required available resources (i.e. a set of frequency slots instead of a single wavelength throughout the path). The huge heterogeneous traffic due to evolving Internet-based technologies can induce contention in the underlying optical infrastructure. A resource collision problem can significantly affect the network performance by unnecessarily blocking some connections that could otherwise be accommodated by prudent resource allocation and signaling mechanisms. Hence, an efficient scheme of managing resources is very crucial for future EONs.

To solve the spectrum assignment and contention issues during the connection set-up process in EONs, we propose an extension to resource management based on distributed signaling Generalized Multi-Protocol Label Switching (GMPLS) RSVP-TE [6]. We propose an adaptive flag-based algorithm to lower Blocking Probability (BP) by means of reducing resource contention during the connection set-up process. We then further refine this algorithm with the guidance of a detailed numerical performance analysis. We note that despite the recent interest in applying Software Defined Networking (SDN) paradigm (e.g. OpenFLow protocols) in optical networks, [7] envisions that a traditional embedded control-plane based on GMPLS will continue to be in place even in optical networks that utilize SDN due to factors and performance requirements specific to optical networks. These factors include vendor proprietary frame formats, different granularity of grooming functions, proprietary modulation/encoding and Forward Error Correcting (FEC) schemes, and stringent recovery time constraints [7]. Additionally, with the current experimental results, SDN is still not mature for large scale and complex optical networks [8]. Numerous recent works explored RSA methodologies in EONS [9-12, 27]. However, finding a universally optimal solution for all traffic mixes is infeasible due to heterogeneous traffic and the dynamic fluctuations of the network state.

In this paper, we present two main contributions. First, a distributed Spectrum Assignment (SA) algorithm called *Flag-Based SA* (FBSA) with *Aggressiveness Window* (*AW*) is proposed. The main objective is to overcome reservation collision in distributed GMPLS that is caused by signaling delay and lack of global knowledge. Fortunately, this can be averted by applying our flag based approach, which acts as a collision awareness mechanism. Based on our comparative analysis of network performance with existing and conventional methods presented in the section VI, we provide the second contribution

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of this work, which is the introduction of enhancements to the flag-based spectrum assignment algorithm, namely the *Adaptive Flag-Based* and *Adaptive ID-Based* approaches, which are implemented based on a data driven scheme. The trained data is an analyzed form of network statistics which can be collected from network components (i.e. OXCs).

Prior work in resource collision awareness has been conducted [13] for WDM, which selects the wavelength with a minimum weight calculated by the algorithm. However, considering a different weight for each wavelength will not be desirable for our case because of the RSAs continuity and contiguity constraints. Another interesting scheme related to RSA [14,15] is one that assigns a collision vector to FSs based on collision probability, whereas our approach enhances the BP based on anticipated intelligence from learning. We also implemented some simulation experiments by other researchers [16] to compare spectrum efficiency of RSA polices.

II. CONTROL PLANE AND SIGNALING PROTOCOLS

A. GMPLS Control Plane

Distributed GMPLS, inherited from MPLS, is a control plane that is responsible for signaling protocols, connection management, and path computation [17]. A network can have a centralized or distributed control plane in order to manage, serve and deliver connection requests. We employed a distributed controller since most of the current core and transport large-scale networks use a distributed GMPLS controller that has been investigated to be employed in EONs [18, 19]. The main drawback in the distributed GMPLS controller over a centralized controller is that it suffers from collisions in reserving resources due to signaling latency [16]. This contrasts with a centralized controller, wherein the connection has global knowledge to handle the contention with a price of longer latency due to the need for a logical communication with the centralized controller.

B. Signaling Protocols

To establish a lightpath, an efficient signaling protocol is necessary to ensure successful transmission. Backward Reservation Protocol (BRP) with the RSVP-TE [20] is a protocol that sends a *probe* (*PROB*)[1] message along the forward paths in order to collect information regarding the FSs availability; then, the destination returns a *reservation* (*RESV*) message to the source in order to reserve the required resources to satisfy the connection lightpath establishment. If no available resources are found a Negative ACKnowledgment (*NACK*) message is sent to the sender and the connection is regarded as blocked. Another protocol is Forward Reservation Protocol (FRP) that sends a reservation message to the destination to reserve the required resources. Both BRP and FRP are typically accomplished by means of control packets exchanged before any data transfer. A number of spectrum allocation algorithms are used along with the signaling protocol to form the priority order of selecting frequency slots from the spectrum. Spectrum allocation chooses the required number of contiguous FSs along the determined route. A straightforward and well–known spectrum allocation policy is the First-Fit (FF) [21-23] which selects the first available set of contiguous FSs that can satisfy the connection. Another well-known policy is the Random-Fit (RF), which selects a set of contiguous FSs in a random manner. For path selection policies, we used the shortest path routing based on the number of hops in our simulation while our spectrum assignment scheme is flexible enough to be paired with any routing algorithm. The current issue in conventional spectrum allocation policies is that they suffer from high BP due to contention and spectrum fragmentation.

III. FLAG BASED SPECTRUM ASSIGNMENT

Flag-Based Spectrum Assignment (FBSA) is implemented with the BRP scheme, which was proposed as a reservation protocol that sends a *PROB* message in the forward direction and reserves resources in the backward direction to avoid over–reservation [18]. RSVP-TE uses a label request as the *PROB* message in the forward direction and generalized label assignment *RESV* in the backward direction. The general mechanism of FBSA with the BRP scheme as illustrated in Fig.1 is as follows: for each frequency slot, a flag, F_{ij}, is applied for frequency slot Fs_i on a link *j*. F_{ij} represents the number of connections *PROBing* Fs_i at time instance *T* as they search for enough contiguous FS. When there is a connection arrival, C_k, the source node sends a *PROB* message to collect information about available FSs while regarding the flag status as a reference signal along the forward direction. The flag helps a connection steer away from resources already probed by other connections that are attempting to be established. If Fs_i is available, then C_k flags Fs_i. C_k can flag up to *N* available slots, where *N* is used to serve as an *Aggressiveness Window* (*AW*). The *AW* is the number of allowed frequency slots to be probed at a time[2]. When the connection probes a frequency slot F_{ij}, it increases the F_{ij} value by one. Since many connections may search the same frequency slots within very close intervals, F_{ij} can act as a traffic regulator. We used the first-fit policy so that when a connection arrives, it tries to probe the first available slot with a flag value less than the pre-set threshold, Th_j. After experimenting with different values of Th_j, we fixed it to unity[3]. This means a FS is disregarded if and only if it has been probed by a previous connection on the same fiber. The flag value is stored in a vector at each OXC. If the *PROB* message reaches the destination, and the *RESV* message returns in the backward direction, the value of F_{ij} is decremented by one for all unused FSs while updating the status on all links of the path.

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[1] The (*PROB*) message includes a set of frequency slot indices that may serve as the starting frequency slot for the arriving demand. It will *PROB* along the shortest path.

[2] For now, it is set to one tenth of the total number of slots

[3] It could be argued that the *Th* of unity is equivalent to RESV in FRP protocol. Yet, with F_{ij}, the greediness of probing more FSs can be controlled and the connections can have some freedom with the possibility to choose from the probed frequency slots in addition to the flagged frequencies as *Th* can be adjusted for a given link. See the section VI for different *Th* performance.

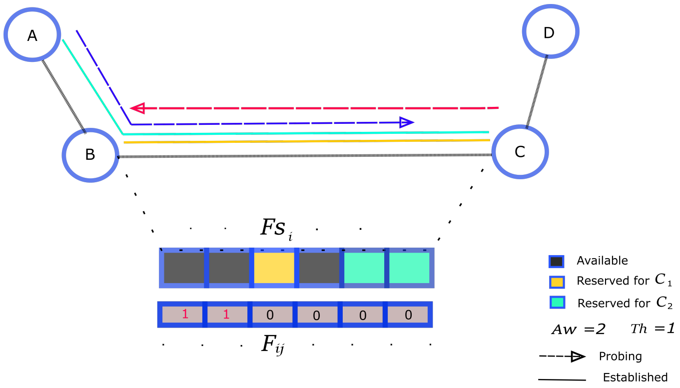


Fig. 1. Spectrum assignment with flagging. It is clear that the *blue* connection can overcome the collision with the *red* connection because of F_{ij}.

IV. SIMULATION FRAMEWORK AND ASSUMPTIONS

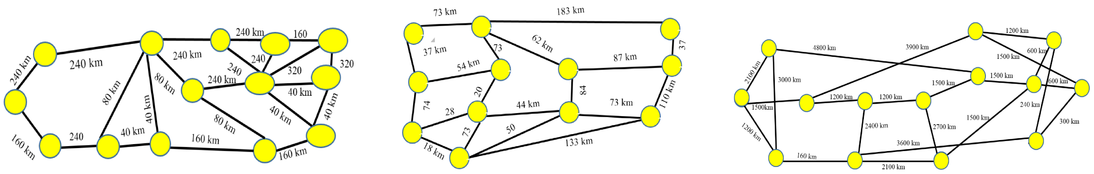
In this section, the simulation setup, assumptions, and metrics are explained. The work is evaluated by implementing simulations using an event-driven C++ EON simulator. The considered topologies to evaluate the proposed algorithm are (Fig. 2.a) 14-node Japanese network, (Fig. 2.b) 12-node Finland core topologies, and the NSF network (Fig. 2.c). Poisson distribution is considered for dynamic connection requests with an arrival rate of λ and average holding time $1/\mu$, which follows an exponential distribution. This is a commonly used traffic model in optical networks, including GMPLS-based connection establishment studies for elastic optical networks such as in [3,14,15,18]. The range of loads simulated for each network topology is selected in line with those reported in the literature for target low and high blocking rates. The connections are uniformly distributed between each source-destination pair with bit rates that are also uniformly distributed between 1 and 100 Gb/s. We assume that each fiber link has a spectrum bandwidth of 2 THz, and the slot spectrum width is 6.25 GHz. Hence, each fiber link will have 320 frequency slots (since no guardbands are considered). Both 4-QAM and 16-QAM OFDM are used as modulation formats for distance adaptive transmission: 16-QAM is assumed when the optical reach is less than 600 km and 4-QAM is used when optical reach is more than 600 km in order to maintain the physical layer requirements [24]. The main reason to assume only two modulation schemes is to assess the algorithm with low and high spectra efficiency. A tunable transceiver is used to meet this adaptation. The lightpath setup delay is assumed to be 5 μs/km for the propagation delay on each fiber, OXC operation delay is 2 ms, and RSVP-TE message processing delay is set to 1 ms. We assumed that flag processing delay is negligible. The holding time is fixed at ($1/\mu$ = 1s) and when the holding time expires, the allocated bandwidth for connection lightpath establishment is released. We simulated 10,000 connection requests for each network topology. For routing, a shortest path was chosen by Dijkstra algorithm with the least number of hops. We conducted all experiments by averaging 10 simulations to reduce simulation errors. All used network simulation parameters are summarized in Table. I.

TABLE I
PARAMETERS SELECTED FOR SIMULATIONS.

Spectrum Width	6.25 GHz
Data rate of each request	1-100 Gb/s
Number of slots on each link	320
Spectral efficiency	1- 4 bps/Hz
Bandwidth of each link	2 THz
Number of Connections Simulated	10000
Processing Delay at OXC	2 m sec
Data Transmission Duration	5 μsec
RSVP messages processing	1 m sec
Propagation Delay between links	5 μsec/km

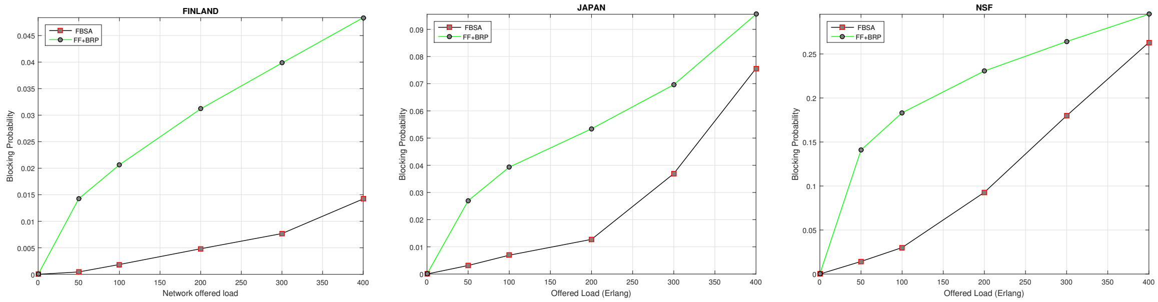
V. DISCUSSION AND FBSA PERFORMANCE

In this section, we present the results to evaluate the performance, scalability, and trade-offs, and to discover the limitations of the flag-based algorithm. Furthermore, in Section VI we discuss the proposed enhancement to FBSA, and observe additional results from the implementations of these improvements. The results for the three topologies are exhibited in Fig. 3. The figures show the BP versus traffic load for each simulated network. We observe that the numerical results show the FBSA achieved lower BP in comparison with conventional signaling in the three tested network topologies, since resource contention is reduced when a number of connections arrive in a specific interval. This occurs when some connections are in the probing mode and the others are in the reserving mode within very close intervals. The contention is averted by the awareness that the flag initiates. For the Japan topology, the FBSA scheme gains the smallest connection BP below (0.3%) for offered load of around 50 Erlangs, which is a decrease of 98% of the BP compared to the conventional one. For the Finland topology, the flag-based approach achieves a BP of 0.09% when the network offered load is less than 50. Comparing the two topologies, the Japan topology shows a higher BP. This is true because of the longer distance, which implies a longer propagation delay that can outdate the probe message. For the NSF topology, the flag approach gains 99% success rate at an offered load of 50 Erlangs. As we can observe from the results, the BP increases while increasing the arrival rate because that increases the possibility of resource scarcity and resource collision. Figure 3.c, where we evaluate the BP for the NSF topology indicates the flag-based approach gains huge improvement for low BP intervals. The results of our multiple simulations allow us to investigate the possible reasons for blocking: the main reason can be attributed to resource scarcity because of the higher arrival load with higher holding time, $1/\mu$, which means that more connections stay in the system with longer periods to consume resources, thus reducing the possibility of spectrum reuse. Another reason is spectrum fragmentation that can accumulate over time. Fragmentation is a critical problem in the spectrum allocation process that arises when available slots are scattered and cannot be used due to the contiguity constraint [3]. Fragmentation has been well studied and could be overcome by not choosing shortest path but, rather, selecting the path based on the degree of fragmentation [25-27].



(a) Japan (b) Finland (c) NSF

Fig. 2. Network topologies



(a) (b) (c)

Fig. 3. BP vs. traffic load for FBSA

VI. Performance Evaluation of FBSA

THE IMPACT OF NETWORK SETTINGS AND CONSTRAINTS

A network with a large geographical extent, as in typical core optical networks, may face huge challenges such as latency, resource scarcity, and peak traffic. The increase in users' demands and machine-to-machine traffic have also led the traffic to be more dynamic in size and direction. We have evaluated the challenges that networks may face, which also provides an evaluation of the performance of our algorithm.

A.The Effect of Traffic Load

As any core optical network may have a traffic surge, we increase the traffic arrival rate up to 1000 connections/s. As a result, more connections will arrive in very small intervals that can be comparable to the average end-to-end delay. Subsequently, more collisions are expected to occur, which can induce more blocked connections. For the Finland network, as shown in Fig. 4, the FBSA approach outperforms the conventional one in certain offered loads (up to 700 Erlangs). However, at an offered load of around 800 Erlangs, the flag-based approach degrades its performance. For the Japan network, as shown in Fig. 4, the performance starts to degrade at a load of 600 Erlangs. This is because of the flag discontinuity phenomena. It is also an indicator that the aggressiveness of the flagging method may be ineffective when more connections arrive in close intervals. Another reason for higher blocking is spectrum fragmentation since, when more connections arrive and depart with different intervals, they leave scattered available space which might not be used due to continuity and contiguity constraints. A possible solution can be an adaptive algorithm that can change its behavior based on network status.

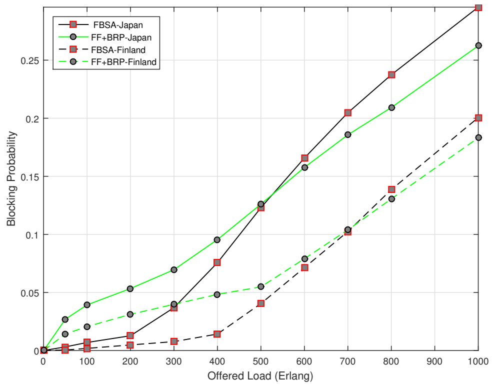


Fig. 4. Blocking probability vs. traffic load for Japan and Finland.

B.The Effect of Setup Delay

Setup delay is the time from a connections arrival until the lightpath is fully established. Setup delay is generally caused by the propagation delay, message processing delay, and OXC operation delay. We increased the network latency in order to investigate the performance by setting the same parameters in Table-1 and changing the processing delay of the OXC from 2 ms to 200 ms and the RSVP message processing time from 1 ms to 10 ms. Figure 5 indicates that as the latency increases more connections are blocked. We observe high BP because connections experience longer latency in the system. Yet, our approach still outperformed the conventional scheme.

C.The Effect of Resource Scarcity

With ever increasing traffic, the consumed bandwidth of the currently deployed optical fiber may reach its limit. Even though EON offers high spectrum utilization, at some point in time the network can face severe resource scarcity. In our simulation, we evaluate this issue by fixing the arrival rate to

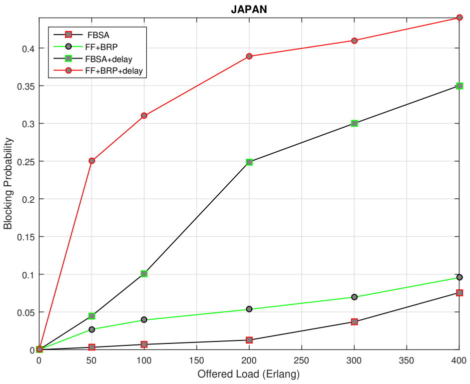


Fig. 5. Blocking probability for Japan with delay

100 connections per second and varying the fiber bandwidth from 125 GHz up to 2 THz. Analyzing the results for the Japan topology as shown in Fig. 6, we observed that the flag-based approach achieves the lowest BP. As the bandwidth increases, we can approach zero blocked connections.

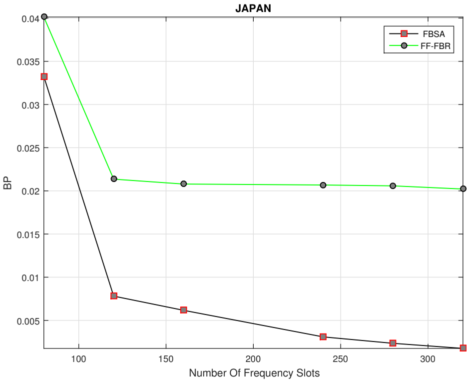


Fig. 6. Blocking probability for Japan with different bandwidth.

Conversely, the conventional approach does not benefit from the increased bandwidth since the connection looks for the first available slots and it may lose them because of the probed message betrayal. Hence, it will not use the remaining available slots. Fig. 7 shows the earlier argument that, as the bandwidth is reduced but the arrival rate increases, both curves coalesce and the system cannot be optimized due to resource scarcity.

D.THE EFFECT OF SUBCARRIER WIDTH

As stated earlier, EONs can offer finer granularity. Each subcarrier can have multiple of 6.25 GHz or 12.5 GHz instead of 50 GHz. We have conducted investigations under both scenarios. The 6.25 GHz offers more spectrum utilization. However, it might induce more physical layer challenges such as the need for the sharp optical filters. The result is shown in Fig. 8. This result indicates that both scenarios follow the same trend when the offered load is reasonable but, as the offered load exceed 200 Erlangs, the 6.25 GHz scheme offers a better success rate; hence, lower BP is seen because it meets users data rates as it only assigns as small spectrum width as needed.

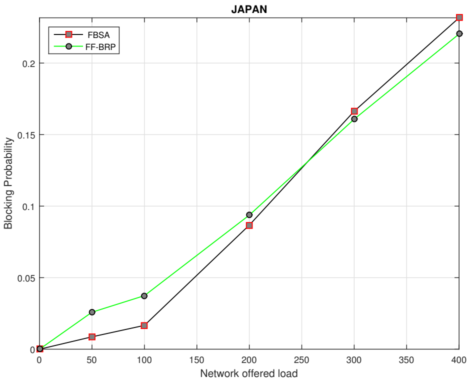


Fig. 7. Blocking probability for Japan with resources scarcity.

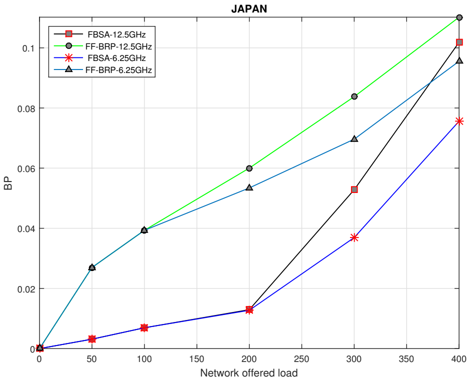


Fig. 8. Blocking probability for Japan with different slot width.

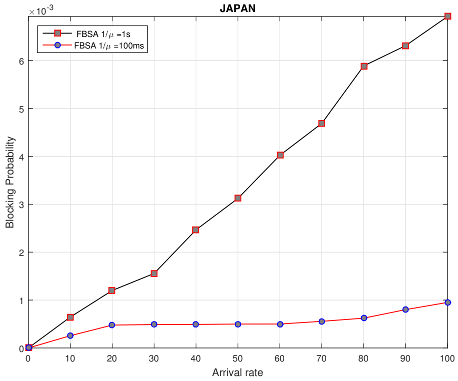


Fig. 9. Blocking probability for Japan with different holding time.

E.THE EFFECT OF HOLDING TIME

Holding-time is a key factor in a client's services. It is the time taken by a demand to stay active while occupying the network resources. By setting the average holding time, $1/\mu$, to 100 ms, and increasing λ from 1 to 100, we can see from the behavior of the proposed scheme as indicated in Fig. 9 that lower holding time considerably reduces the lightpath BP because the connection will stay for a shorter period of time, since it allows spectrum reuse and also the flag discontinuity can be reduced. It should be noted that both the connection setup time and the holding time, for many connection services, is deterministic and should be known in advance [30].

F.The Effect of Traffic data rate

The exponential growth of Internet heavy technology has led to traffic that reaches up to 100 Gb/s and beyond. The current deployed traffic data rate is around 100 Gb/s. We have changed the traffic data rates from 1 Gb/s to 200 Gb/s and compared the results to 100 Gb/s. The numerical results in Fig. 10 illustrate that the BP increases as the traffic data rate increases since more frequency slots will be demanded with each connection request. However, the FBSA keeps the BP as low as 0.2% when the network offered load around 30 Erlangs for both 50 and 100 Gb/s.

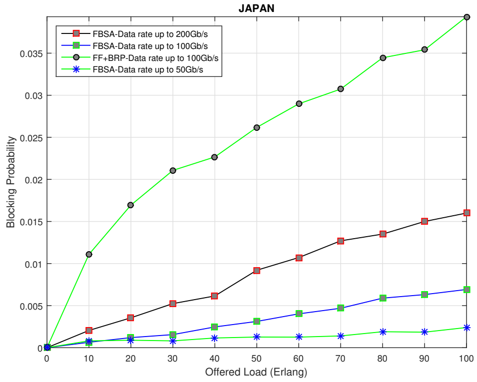


Fig. 10. Blocking probability for Japan with different data rates.

G.The Effect of threshold

The flag-threshold value represents the number of connections that can probe the similar FSs during the signaling operation. While we changed the threshold from 1 to 3, we observed that, as expressed in Fig. 11, the optimal threshold is unity which indicates the absolute property for the first arriving connection. Hence, it allows the second arrival connection to look for different adjacent spots in the spectrum in order to avoid collision. However, when the resources become limited, it is advisable to set freedom of flagging to be adaptive.

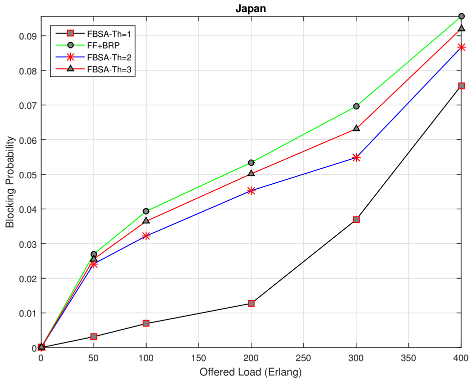


Fig. 11. Blocking probability for Japan with different threshold.

VII. ENHANCEMENTS AND EVALUATION OF ADAPTIVE SPECTRUM ASSIGNMENT

In Section V, we observed that FBSA can improve blocking performance over conventional spectrum allocation by creating contention awareness. After conducting a performance evaluation under different network conditions as shown in the section VI, we observed that the FBSA can be impacted by factors such as the network delay, bandwidth, and offered load. As a result, we developed an enhancement to the algorithm that can further improve the rate of success under such conditions that challenged the FBSA.

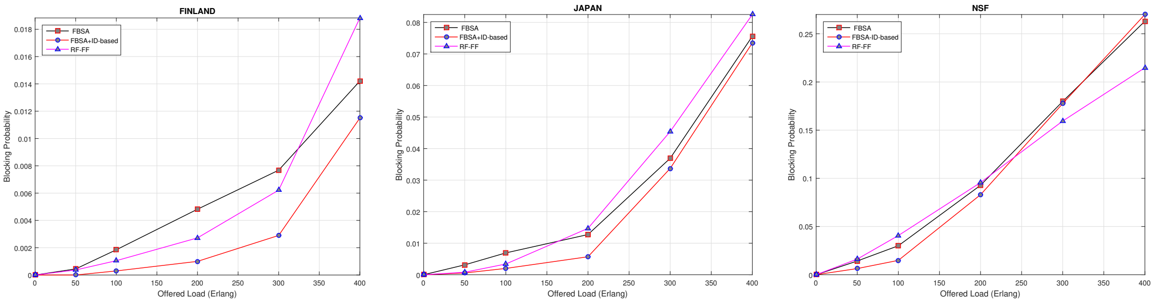
A. *The ID-Based Approach*

In this section, we used a different mechanism to look for FSs in the available spectrum. As each connection request arrives with a source, s_{id} and a destination, d_{id} along with a required data rate r, i.e. $C_k(s_{id},d_{id},r)$, a connection's *ID* can be assigned in regard to its arrival-based $C_k(s_{id},d_{id},r,ID)$. Therefore, we can differentiate between the connections that might encounter a collision based on the arrival's *ID*. The mechanism of the algorithm is as follows: if a connection has an odd *ID*, it will look for the spectrum from the far end with highest indexed FS, whereas if the *ID* is even it will look for FSs from the lowest indexed end of the spectrum. In this manner, collisions can be reduced as the load is distributed on the spectrum within short intervals. A similar approach has been investigated in [28, 29]. However, in [28], the algorithm varies its approach based on the modulation formats and not on the *ID*.

We incorporated this approach into our flag-based spectrum allocation algorithm. This approach can reduce the flag-discontinuity since it increases the likelihood of slot alignment. Flag-discontinuity is an apparent issue in a First-Fit flagging scheme because slots are flagged but may not be used due to continuity constraints. The numerical results in Figs. 12 show that, the FBSA ID-based approach with flag, substantially outperforms the conventional approach with flag for the Finland and Japan topologies. This indicates the possibility of collision reduction along with fragmentation reduction since the resources are taken based on equally fairness. However, only a slight BP improvement is observed for the NSF topology shown in Fig. 12.c, and the performance is somewhat similar between 300 and 400 Erlangs because of the huge physical topology and load.

B. *FBSA and FBSA-ID Vs Random fit-First fit*

In this section, we compare our algorithm with previous work known as First Fit-Random Fit (RF-FF), which was firstly proposed for WDM [16]. The RF-FF is an algorithm that uses mixed spectrum allocation policies. It selects the algorithm based on the possibility of a collision. The mechanism of the algorithm is as follows: when a connection tries to reserve a wavelength, it checks a counter of the outgoing link, which might signal for a collision. If a collision is detected, it will use a Random-Fit policy; otherwise, it uses First-Fit, while reserving in the backward direction. For comparison, we implemented the algorithm in our EON simulator with additional adherence to RSA constraints. As we can see in Figs. 12, our FBSA with the ID-based achieves the lowest connection blocking for all cases. However, RF-FF achieves



(a) (b) (c)

Fig. 12. BP vs. traffic load for FBSA compared with RF-FF and FBSA-ID

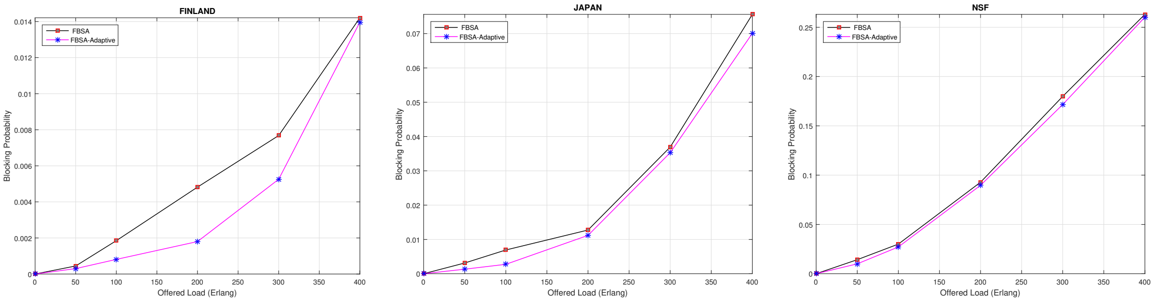


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Fig. 13. BP vs. traffic load for FBSA compared with adaptive FBSA

better performance than FBSA for very low loads. Additionally, for the NSF topology, RF-FF outperforms other schemes with higher load due to flag-discontinuity. With higher load, the RF-FF shows fluctuating unstable performance as it starts to degrade with the increase of the offered load since the randomization approach can increase spectrum fragmentation. Hence, the FR-FF might be a good policy only for WDM but not a good candidate for EON.

C. Adaptive FBSA

The optimal parameters such as *Th* and *AW* of the FBSA algorithm is traffic dependent, as the previous results illustrate that the load has an impact on its performance. While the network traffic load can be heavier from time to time, an adaptive algorithm is required to alter its behavior based on the traffic and the BP of the system.

The algorithm must be trained for specific network and offered loads based on network traffic engineering statistics (i.e. from OXC). For any traffic load, x_i, the network produces a blocking probability, BP_i. We can tune the *AW* to gain the lowest BP by conducting multiple of simulations similar to a Monte Carlo approach, so that training data is generated. Hence, a set of (x_i,BP_i,AW) is called a training set. In the training list, it is important to keep the *AW* such that :

$$AW_i = \arg\min_{AW} BP(x_i, AW) \tag{1}$$

Subsequently, after collecting enough samples of training set, we can train a decision tree model to predict the *AW* for future unseen traffic. It is intuitive to predict that when there is a high BP in a region of the network, the *AW* should be set low since a higher blocking refers to higher load. However, it may depend on the current distribution of the spectrum. Based on trained data, we can predict the most suitable *AW*. The scheme is implemented by means of a lookup table which, for each traffic load/blocking probability interval, selects the best fit *AW*. The numerical results shown in Fig. 13 display promising improvement with the adaptive FBSA compared to the static FBSA in the Finland topology.

The results for the simulated topologies demonstrate the benefits from the adaptive method. Figure 13.a shows that Finland topology experienced higher successful connection rate of 99.998% around traffic load of 200 Erlangs. For the Japan topology (Fig. 13.b), also gained benefit but lower than Finland with only a BP decrease of 12.26% at 200. For the NSF topology, the result improved very slightly with a decrease of 3.36% at 200 Erlangs as shown in Fig. 13.c.

We next have closer look at lower load behavior as in Figure 14. Fig. 14.c, the NSF network, illustrates a slight improvement between offered loads of 30-100 Erlangs whereas for Finland as displayed in Fig. 13.a shows higher improvement. For Japan, it lowers the blocking probability more significant between 10-100 offered loads as shown in Fig. 13.b.

D. Adaptive FBSA based on hop count

We extended the proposed algorithm to be more efficient based on the fact that for a connection that traverses fewer links[4], the possibility to meet the spectrum continuity constraint increases. Hence, an approach that sets the *AW* from a few predetermined values based on hop count is predicted to

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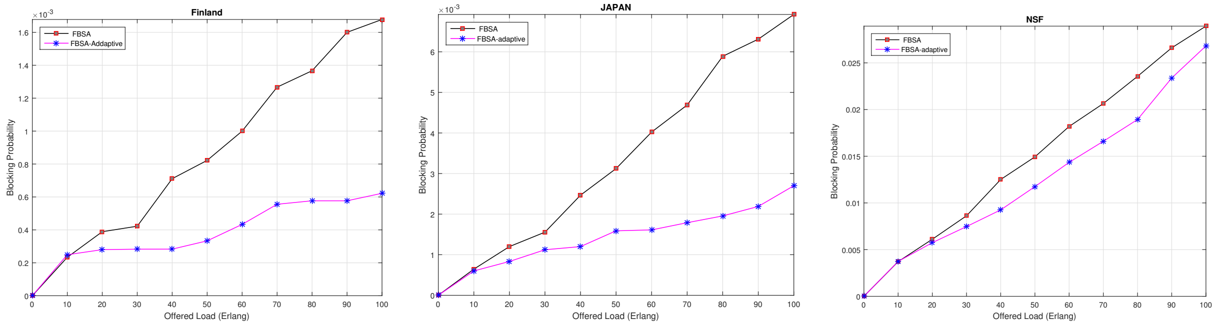
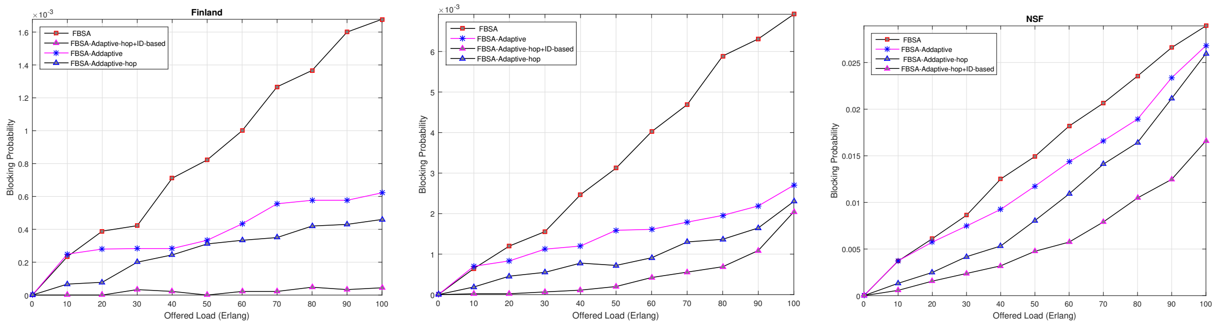
[4] With the help of a shortest path algorithm.



(a) (b) (c)

Fig. 14. BP for FBSA and adaptive FBSA for lower load. The full range is shown in Fig. 13.



(a) (b) (c)

Fig. 15. BP for FBSA, adaptive-FBSA, Adaptive-FBSA-ID, and Adaptive-FBSA-ID-Hop

be smarter with the proposed flagging scheme. The mechanism of the algorithm is as follow: For any i, and j, let Fs_{ij} and AW denote the frequency slot i and the control aggressiveness window on link j, respectively. For a connection, C_k looking for Fs_{ij}, the algorithm checks if the connection travels with the fewest number of hops (fewer than 3), then, it sets AW to the lower level. If the connection travels between 3 or 4 hops, it sets the AW to the medium level, and for more than 4 hops the aggressiveness window should be the highest, which means more slots will be flagged in order to satisfy the continuity constraint. These sets of conditions, along with the traffic load settings, are represented by a decision tree. The lower, medium, and upper levels of the AW are determined for each connection by the preceding training for estimated traffic, BP, and network conditions that is conducted by Monte Carlo approach. The results shown in Fig. 15 are typical since flag-discontinuity will be reduced due to the connection being *smarter* with the flagging and learning. The numerical results for an adaptive hop based algorithm illustrate considerable reduction in BP compared to the adaptive method without a hop count consideration. Furthermore, the adaptive ID-based hop based approach outperforms all other schemes, as we can see in Figs. 15 as it may reduce fragmentation. For the Japan topology, the algorithm lowers the blocking probability to 6.6* 10^{-5} when the offered load is below 40 Erlangs; this is a very promising value compared to the other schemes. In the Finland topology, the blocking probability is ($4.4*10^{-5}$) in an adaptive scenario for loads below 90 Erlangs. For the NSF topology, the adaptive approach reduces the blocking probability approximately to 0.5% for a load of 50 Erlangs.

VIII. CONCLUSION

In this paper, the adaptive FBSA is developed to improve network performance by lowering spectrum contention in the distributed allocation process for EONs with GMPLS. The proposed algorithm considerably outperforms the traditional first-fit policy by means of a smart enhanced algorithm in non-homogeneous traffic pattern and network environment. A study of the network conditions and settings was conducted that indicates the algorithm needs to adapt to different traffic demands in order to meet the user requirements. The results showed that the proposed method can achieve higher lightpath establishment success rates by adapting to the current network conditions and by avoiding frequency slots that have been already probed by other connections. Thus, the probe message alone is not reliable since it might be out-of-date after some delay. The results also indicate that the flag-based algorithm may be used without adaptiveness, thereby, eliminating the need for training but at the cost of performance sensitivity to network setting and conditions. For future work, our data driven approach can be extended by including more training features such as modulation formats, data rate, the overall delay, current spectrum fragmentation levels, previous flag stats, and link number. All attributes can be fed to a deep learning framework to predict suitable FSs for a given connection. A thorough comparative study of our approach with centralized schemes will also be an interesting future work.

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