Cognitive Zone-Based Spectrum Assignment Algorithm for Elastic Optical Networks

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***Abstract*—In this work, we present the Cognitive Zone-Based spectrum assignment algorithm (CZB). Our algorithm is capable of observing the network traffic and acquiring information regarding the network services, thus using it to calibrate the division of the spectrum into partitions. To achieve this, the CZB algorithm uses an upgraded version of the Static Zone-Based spectrum assignment algorithm. Our results show that CZB algorithm can indeed achieve its objective, and even improve the fairness under certain conditions. Simulations show that CZB algorithms can achieve up to 10 times better fairness under certain conditions when compared to the Spectrum Sharing First-Fit algorithm.**

***Index Terms*—Elastic Optical Networks, Fairness, Spectrum Management, Spectrum Assignment.**

I. Introduction

According to Cisco Visual Networking Index Report [1], the traffic from wireless and mobile devices will account for more than 63 percent of total IP traffic by 2021, and roughly half of that will be from Smartphones. This new traffic characteristic era represents a significant challenge to be faced by service providers since supporting this highly dynamic traffic demands a flexible and agile optical core networks [2].

In the last few years, the Elastic Optical Networks (EON) has emerged as a promising technology to fulfill this niche due to its flexibility and higher spectral efficiency [3], [4]. This added flexibility and efficiency come at the price of increased complexity and new hurdles, such as the spectrum fragmentation and unfairness among the network services [5], [6]. The unfairness problem can be especially worsened with the extra mobile traffic expected in the years to come.

Previous works proposed to tackle the unfairness problem by using a myriad of spectrum management techniques, mostly involving dividing the spectrum into partitions. The division of the spectrum is usually made following specific criteria and are classified as Dedicated Partition (DP) or Shared Partition (SP). The DP schemes work in a restrictive manner, in which the services are obliged to fit the designed partition [6], [7], whereas the SP techniques are priority-based, allowing services to be accepted outside the ideal partition [8], [9]. Some schemes work in a mixed mindset with restrictive partitions but using a spectrum range that can be shared [10]. The more complex the spectrum management technique is, more information from the network is needed to establish and manage the partitions. Most methods need knowledge about the services that may use the network [7], [9], [10], the ratio between them [6], and even the blocking probabilities [6], [8]. All information is made available as an input for the allocation algorithm, also known as Routing and Spectrum Assignment (RSA) algorithm, responsible for accepting or blocking new requests trying to access the network.

These methods require an increasing number of inputs and features to increase the accuracy of the obtained results. In this sense, an approach that reduces the complexity required is desirable. On the other hand, we find cognitive methods that can infer results from a reduced set of inputs with reduced or negligible losses. In the telecommunications context, the word cognitive evokes the ability to observe and to extract information from the network conditions, and then to use this information in a useful manner [11].

In this context, we present the Cognitive Zone-Based (CZB) spectrum assignment algorithm. Our technique is capable of observing the network traffic and acquire information regarding the services using the network. Using the acquired data, CZB infers the traffic ratio of the services and uses it to calibrate the spectrum division into partitions. Since CZB is based on an improved version of previous work [7], in this paper we also present the updates we developed in our previous Zone-Based algorithm.

The remainder of this paper is divided as follows: Section II presents the updates we made in our previous method, now called Static Zone-Based (SZB) assignment algorithm, whereas Section III shows the new CZB version of it. Section IV presents the tests and rhe results we obtained using both techniques. Finally, Section V concludes this paper.

II. An Upgrade to the Static Zone-Based Spectrum Assignment Algorithm

In a dynamic network scenario, incoming requests are established and released in an entirely random fashion. This randomness induces spectral resources to be highly fragmented, and consequently, "gaps" are unavoidably introduced leading to the so-called intra-link fragmentation, thus degrading spectrum utilization efficiency. Due to the contiguity constraint, the more fragmented is the spectrum, the harder is for new connections to be established. In a heterogeneous environment, more spectrally demanding services suffer from an increased difficulty to get requests accepted by the network when comparing to less demanding services, thus the blocking ratio is proportional to the number of resources requested. In

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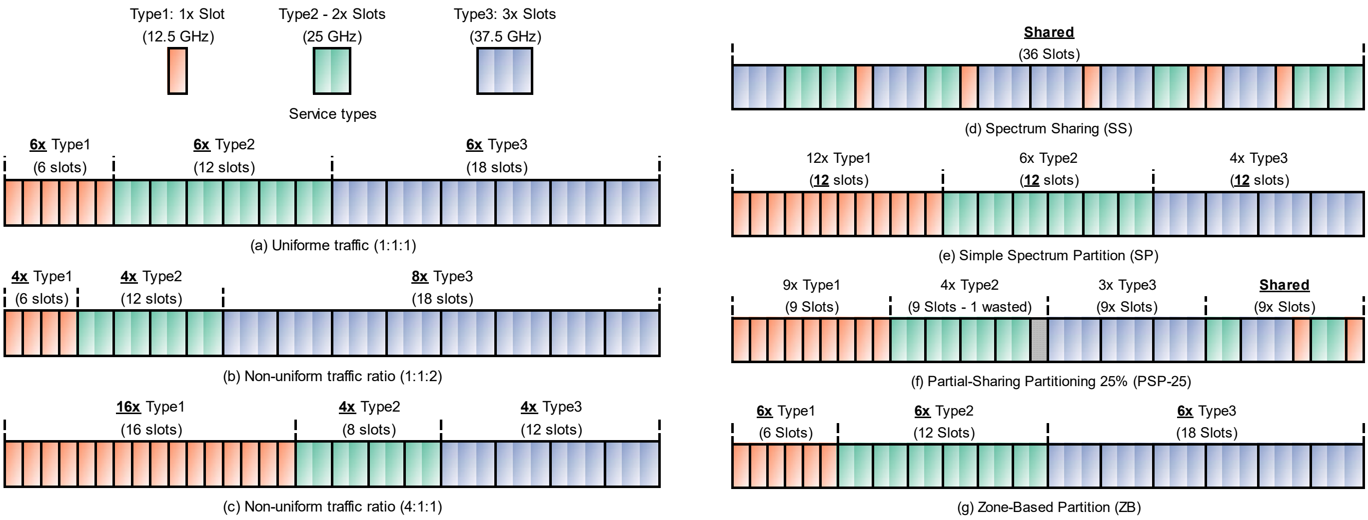


Fig. 1. Example of zone divisions configured by the proposed Static Zone-Based algorithm according to different traffic ratios: (a) Uniform traffic (1:1:1), (b) Non-uniform pattern (1:1:2), and (c) Non-uniform pattern (4:1:1). Comparison between (d) Spectrum Sharing (SS), (e) Simple Spectrum Partition (SP), (f) Partial-Sharing Partitioning 25% (PSP-25) [9], and (g) Zone-Based partitioning (ZB) [7].

this sense, the disparity of the services blocking ratios is what we call unfairness.

To mitigate the unfairness effect, in previous work [7] we proposed the first version of the Zone-Based spectrum assignment algorithm, which idea is to divide the spectrum transforming the expected heterogeneous environment in a set of smaller and homogeneous environments (i.e., partitions or zones). It pays particular attention to partition delimitation, ensuring coexistence of similar services within each partition only and ensuring each partition has the same capacity (i.e., can accommodate the same maximum number of connections at a given time). Therefore, homogeneity is guaranteed as each partition only supports connections with the same size. Such homogeneity mitigates the effects of intra-link fragmentation. Although the fragmentation is not entirely removed, this division ensures that every single fragment of the spectrum available has enough space to accommodate at least one connection, therefore not being a problem anymore. The first version of our solution achieves its objective assuming a uniform traffic pattern. Furthermore, the focus of this section is presenting an upgrade, allowing the technique to handle non-uniform traffic.

The main change of this updated version of our technique is taking the traffic pattern into account during the zone delimitation. The idea is to maintain the same maximum number of connections for each possible service type, adjusted by the traffic pattern. For example, supposing three service types are coexisting in the same network and uniform traffic; the spectrum would be divided into three zones, holding C_{max} connections each. In total, 3 C_{max} connections could exist at the same time, C_{max} connections per service type. This concept is illustrated in Figure 1. In Figure 1 (a) the zones are configured based on uniform traffic with the ratio (1:1:1) between services types, implying in the same maximum number of connections accommodated within each zone simultaneously (i.e., $C_{max} = 6$ for each service type). Figure 1 (b) illustrates how the zones are influenced by non-uniform traffic, the ratio 1:1:2 results in doubling *Type3* connections, whereas the proportion (4:1:1) implies in four times more *Type1* connections (c).

To describe the zones division we introduce the following notation:

- B_{max} : Total bandwidth available in each link (in *slots*).
- St : Set of all possible services, $St = \{St_1, ..., St_n\}$ (in *slots*).
- Tr : Set of service traffic ratio, $Tr = \{Tr_1, ..., Tr_n\}$.
- C_{max} : The maximum number of connections allowed within each zone (before traffic ratio compensation).
- Zc : Set of zones capacities, $Zc = \{Zc_1, ..., Zc_n\}$ (in slots)

The following equations define C_{max} and Zc:

$$C_{max} = \left\lfloor \frac{B_{max}}{\sum_{i=1}^{n} St_i \, Tr_i} \right\rfloor \tag{1}$$

$$Zc_i = C_{max} \, St_i \, Tr_i \tag{2}$$

Using Figure 1 (c) values as example, $B_{max} = 36$, $St = \{1, 2, 3\}$, and $Tr = \{4, 1, 1\}$, Equation (1) gives $C_{max} = 4$, and Equation (2) gives $Zc = \{16, 8, 12\}$. The value $C_{max} \, Tr_i$ gives the maximum number of connections that can coexist simultaneously at any given time for a service type St_i whereas the Zc_i represents the number of slots needed by the zone to support those connections.

Figure 1 also illustrates how the Zone-Based spectrum assignment technique compares to other related work under uniform traffic pattern. From top to bottom, first, Figure 1 (d) shows the Spectrum Sharing (SS), i.e., if connections are allocated without any spectrum management. Next, (e) shows the most straightforward way to manage spectrum, by dividing it into partitions with the same number of slots. It is called Simple Spectrum Partition (SP). The third algorithm presented in (f) is the Partial Sharing Partitioning 25% (PSP-25), that uses a shared zone that can be used as an "overflow zone" [9]. Finally, our Zone-Based method (g), which fixes the same maximum number of connections within each partition [7].

Although our Static Zone-Based algorithm (SZB) was developed to work using as less information as possible, it still needs information regarding the traffic expected in the network, more specifically, the types of services and their ratio. As shown in Section IV, when this data is available, SZB performs well and increases the fairness among the different services within the network. For the cases in which this information regarding the traffic is not available, in the next section, we present the cognitive version of our algorithm.

III. Cognitive Zone-Based Spectrum Assignment Algorithm

Spectrum partitioning techniques are *highly dependent* on the traffic pattern in the network. In cases where the nature of the network traffic is known beforehand, and the traffic does not change, it is possible to feed a partitioning algorithm with the required information it needs to work correctly. The question that naturally comes next is "what if the traffic pattern is unknown or varies over time?" In both cases, "static" algorithms (including SZB) would not be capable of establishing proper zones boundaries and would not perform according to the expected.

In this context, we present the Cognitive Zone-Based (CZB) spectrum assignment algorithm. Our technique is capable of monitoring the network requisitions received by the network controller, acquiring information regarding the services using the network. With this data, CZB infers a compatible distribution that fits the received traffic, and then using the ratio between the types of services, calls an instance of the Static Zone-Based (SZB) algorithm, providing the services types using the network (St) and their ratio (Tr) as input.

At first, it is assumed that no information regarding the network traffic is known during the algorithm initialization. Therefore, the first step of the CZB algorithm is to acquire data regarding the traffic received. However, the network can not afford to reject requisitions while waiting for the calibration of the algorithm, thus needing to attend the arriving requests. Consequently, the use of an auxiliary algorithm is necessary during this "initialization phase."

Although our method allows any spectrum assignment algorithm to be used as auxiliary algorithm during the initialization phase, after dozens of simulations performed, empirical results induced us to the conclusion that the combination of Spectrum Sharing and First-Fit algorithms (SS_FF) is a good solution, especially under lower loads. Furthermore, the First-Fit algorithm is easy to implement and has low complexity. Suppose that a network is starting its operation, and there are plenty of resources available. If the network load is low and no requests are being blocked, there is no need to use more robust algorithms, and the SS_FF is enough. Therefore it makes sense to use the Spectrum Share First-Fit algorithm as the auxiliary algorithm throughout the initialization of the CZB algorithm.

The Cognitive Zone-Based algorithm needs three inputs to work properly: the total number of slots available in each link (B_{max}), as described in Section II; the blocking threshold (blk_thr); and the size of its receiving window ($window\_size$). The blk_thr input is an integer representing the minimum number of requests that must be blocked to trigger a change in the partitions. Additionally, CZB has a "receiving window", an array of size $window\_size$ that stores data regarding the arriving requests. Figure 2 shows how the algorithm works.

As requests arrive in the network, the CZB algorithm stores in its receiving window the number of slots (num_slots) needed to fulfill each request. After $window\_size$ requisitions, the algorithm verifies if the network rejected at least blk_thr of the latest $window\_size$ requests. If not, the CZB calls the active Spectrum Assigned (SA) algorithm (SZB or the auxiliary algorithm), that returns the slot index (if available) to allocate the request. This situation happens if current zones are good enough or if the traffic load is low.

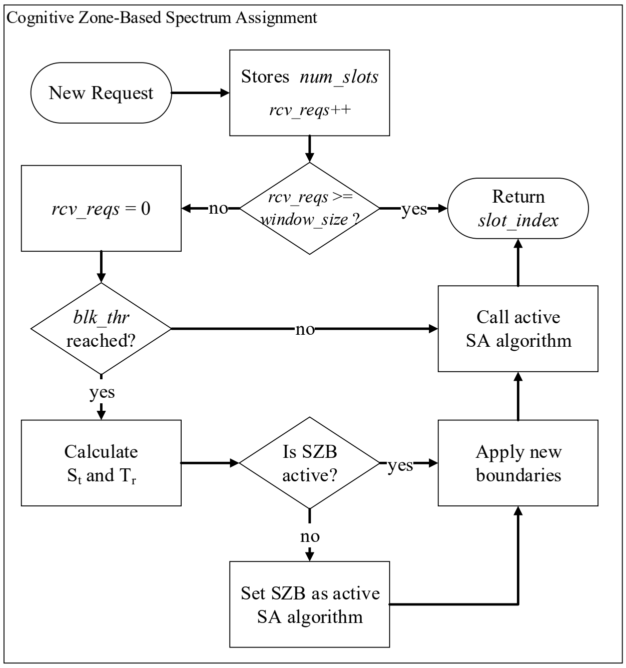


Fig. 2. Cognitive Zone-Based spectrum assignment algorithm.

If at least blk_thr requests were rejected, CZB reads the stored data of all $window\_size$ previous requisitions and estimates the ratio between the number of slots (num_slots) held. The estimation is done by accounting how many times each num_slots was requested; then normalizing by the lowest value, rounding the results to the nearest integer. The result of this step is a list of current network services (St) and their relative ratio (Tr). After the estimation of the traffic ratio, CZB verifies if SZB is the active SA algorithm, setting it as active if it is not. Next, SZB is called, passing St and Tr as input. The Static Zone-Based algorithm then uses the estimated traffic ratio and delimits the new boundaries of the zones, according to Equations (1) and (2). Finally, the active SA algorithm is called (now SZB) and the resulting slot index is returned as the result of the whole process.

It is important to notice that the bigger the receiving window size (*window_size*) is, the higher is the chance of estimating the traffic ratio correctly. However, it takes longer to the network to adapt the zones to the newly detected traffic pattern. There is an opportunity cost involved, a trade-off between precision and requests missed because of a wrong zone delimitation. In the next section, we present the simulations performed and the results obtained using the Cognitive Zone-Based algorithm.

IV. Simulation and Results

As Equations (1) and (2) show, both SZB and CZB, are dependent on the traffic transported by the network. Therefore, it is interesting to evaluate how the algorithm responds to different traffic patterns. The objectives of the proposed tests are to evaluate if CZB can detect the right traffic and adapt correctly to it, and also evaluate how SZB and CZB perform concerning fairness.

We propose two tests scenarios: test T1 uses a non-uniform traffic ratio between services, increasing the ratio of most demanding services (i.e., 400 Gbps and 1 Tbps), whereas test T2 utilizes a non-uniform traffic ratio between services increasing the proportion of less demanding services (i.e., 40 Gbps and 100 Gbps). Since in previous work [7] we already tested the SZB algorithm performance under uniform traffic ratio, we omit it in this paper.

All simulations were performed using the ElasticO++ framework [12], and the NSFNET topology, composed of 14 nodes and 21 bidirectional links [4]. A dynamic network operation scenario is simulated following the Erlang model with new requests arriving at λ Poisson rate and exponential holding time (with a normalized mean of $1/\mu = 1$). Network load is given by $\rho = \lambda/\mu = \lambda$ (Erlang). In each simulation run, $1x10^5$ requests are generated, and each chart point is represented by the average of 30 runs with different random seeds. Error bars represent the standard deviation.

Each new request is composed of a source, a destination, and a bitrate requirement. In all tests, four different service types are allowed in the network with bitrates of 40 Gbps, 100 Gbps, 400 Gbps, and 1 Tbps. Those bitrates are translated to the set of service types $St = \{3, 4, 7, 16\}$ (in slots) after applying an implementation of the DP-QPSK modulation format and considering a 10 GHz guard band, according to the Table 1 in [3]. Moreover, each test follows a distinct set of traffic ratio between services. Tests T1 and T2 utilize a non-uniform ratio of $Tr = \{1, 2, 3, 5\}$ and $Tr = \{5, 3, 2, 1\}$ respectively.

In each test, four Routing, Modulation, and Spectrum Assignment (RMSA) algorithms are compared. Each RMSA algorithm is composed of four parts: a routing algorithm, a modulation scheme, a spectrum management technique, and a spectrum assignment algorithm as described in [13]. Since the focus of this work is the spectrum management and assignment, and as an effort to reduce the number of variables, each RMSA algorithm tested shares the same routing algorithm and the modulation scheme, thus reducing this test to a SA (Spectrum Assignment) problem. The routing algorithm chosen is the Yen's K-Shortest Paths [14], using $K = 1$ for simplicity. Link lengths are also not considered in this test. Therefore, Yen's algorithm selects the shortest route by evaluating the number of hops. Finally, regarding the modulation scheme, it is assumed that DP-QPSK modulation can be assigned to all connections with no physical layer problems. The compared algorithms are:

- SS_FF: Spectrum Sharing First-Fit [15].
- SZB: Static Zone-Based.
- CZB27k and CZB45k: Cognitive Zone-Based with 27k and 45k sized receiving windows respectively. Both CZB27k and CZB45k use $blk\_thr = 100$.

Four metrics are used to evaluate algorithms performance in following tests: requests blocked rate (RBR), bitrate blocked rate (BBR), and two fairness metrics (RBR_{Sti} and RBR_{diff}). RBR is defined as $RBR = R_b/R_t$, where R_b represents the number of requests blocked at the end of the simulation and R_t is the total number of requisitions generated. Likewise, the BBR is given by $BBR = B_b/B_t$, where B_b is the total bitrate blocked, and B_t is the total bitrate requested. The first fairness metric is a comparison of the service requests blocked rates among all service types, and is defined as $RBR_{Sti} = R_{bSti}/R_t$, where R_{bSti} stands for the number of requests blocked of service type St_i and R_t is the total number of requisitions generated. The greater are the differences between the blocked rates the more unfair is the algorithm in the scenario analyzed. Finally, the second fairness metric reflects the difference between the maximum and minimum service requests blocked rates, obtained through: $RBR_{diff} = max(RBR_{Sti}) - min(RBR_{Sti})$.

A. Test T1 - Traffic Ratio (1:2:3:5)

The test T1 is set to use a non-uniform traffic ratio between service types, prioritizing the arrival of heavier demands. The traffic ratio used is $Tr = \{1, 2, 3, 5\}$. Using Tr values with $B_{max} = 336$ and $St = \{3, 4, 7, 16\}$, Equation (1) gives $C_{max} = 3$. The value $B_{max} = 336$ was chosen to prevent non-integer C_{max} values, that would imply in spectrum wasted by SZB and consequently by CZB, making this comparison less fair since SS_FF would have extra resources.

T1 results are presented in Figure 3 and are organized in the following manner: (a) and (b) show the request blocked rates (RBR) and bitrate blocked rates (BBR) respectively. The request blocked ratios (RBR_{Sti}) for each service type are shown in Figure 3 (c) SS_FF, (d) CZB27k, and (e) SZB; whereas (f) shows the difference between the maximum and minimum service requests blocked rates (RBR_{diff}).

In Figure 3 (a), the SS_FF algorithm presents the best performance concerning RBR, followed by CZB45k and CZB27k, and at last by SZB algorithm. Those results are expected since Dedicated Partition algorithms tend to block more due to the restrictive zone allocation policy. This extra blocking happens in situations where one zone is entirely occupied due to a burst of requisitions, while other zones may still have free resources. As SZB zone assignment is restrictive, requests can be blocked even when there are available resources in the network. It is interesting to see that before 125 Erlang, neither the CZB algorithms nor SS_FF experience requests blocked. In fact,

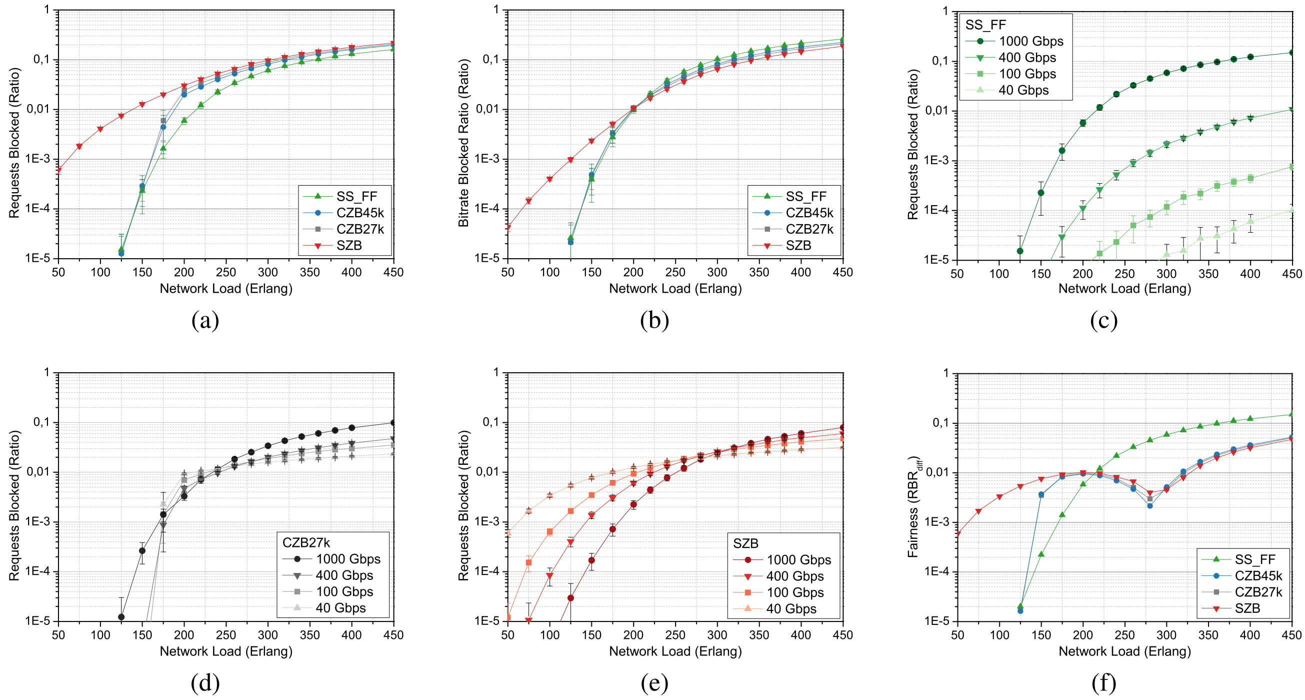


Fig. 3. Test T1 - traffic ratio (1:2:3:5) results: (a) Requests blocked ratio (RBR). (b) Bitrate blocked ratio (BBR). Requests blocked ratio distinguish per Service Type (RBR_{Sti}): (c) Spectrum Sharing First-Fit (SS_FF); (d) Cognitive Zone-Based (CZB27k). (e) Static Zone-Based (SZB); (f) Fairness comparison between the four tested algorithms (RBR_{diff}).

this is due to SS_FF being chosen as the auxiliary algorithm during CZB initialization phase. Since not enough requests were blocked (less then blk_thr), the SZB algorithm was not activated (Figure 2). For network loads of 125 Erlang and higher, the CZB algorithms achieve results between SS_FF and SZB, tending to the SZB results.

Similar behavior is observed in the BBR results (b). The SZB algorithm performs worst than SS_FF under light loads but starts performing better after ≈220 Erlang. We believe two reasons justify this behavior: the heavier traffic pattern and the fairness. As the strongest point of the SZB is to prevent unfairness, it enables a higher number of more demanding services to be accepted at the expense of less demanding services, thus reducing the total bitrate blocked. Once more, CZB results range between SZB and SS_FF curves. It should be noted that CZB improves SZB results under lower loads.

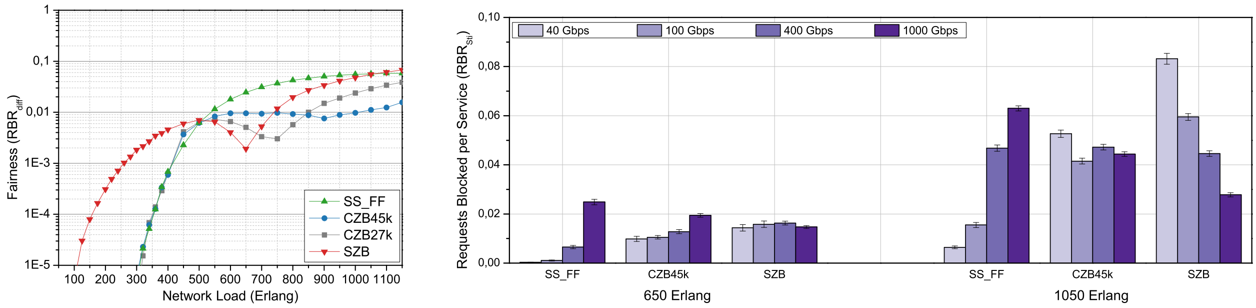
Regarding fairness, Figure 3 (c) presents the results of the Spectrum Sharing First Fit (SS_FF) algorithm. As SS_FF does not apply any spectrum management method, the higher is the bitrate requirement of the requisition, the higher is the probability of it being blocked. Comparing the SS_FF results with the results of CZB27k (d) and SZB (e), it is clear how the curves are more distant, thus indicating increased levels of unfairness. The differences between the maximum and minimum services blocked ratios (RBR_{diff}) are plotted in (f). It can be seen that for loads smaller than 125 Erlang, both CZB algorithms and SS_FF obtain same fairness levels. Between 125 and 200 Erlang, it is possible to see the CZB transition between SS_FF and SZB. In this same range, the SS_FF algorithm obtains the best results. We believe this happens due to SS_FF overall lower RBR at this load (≈ 0.6% of blocked requests). Above ≈220 Erlang (≈ 1.2% of blocked requests), the other algorithms start to outperform the SS_FF in this fairness metric. It is also noticeable that between 220 and 300 Erlang, both CZB algorithms achieve better results than SZB and SS_FF, up to 10 times better fairness under 260 Erlang (≈ 3.4% of blocking ratio) when compared to SS_FF.

Finally, it is interesting to notice that the obtained results for CZB45k are more similar to the SS_FF results than the CZB27k. That is explained by the receiving window size of the algorithms. Since CZB45k has a bigger receiving window size, it takes longer to switch from the auxiliary algorithm (SS_FF) to SZB. Moreover, it is intriguing to think CZB as a combination of SS_FF and SZB, or, in a broader sense, as a combination of the auxiliary algorithm and SZB. This combination is especially impactful depending on the ratio between the total number of requests of the simulation and the receiving window.

B. *Test T2 - Traffic Ratio (5:3:2:1)*

In Test T2 we simulate a scenario with a non-uniform traffic ratio between service types, prioritizing the arrival of lighter demands, i.e., $Tr = \{5, 3, 2, 1\}$. We use $B_{max} = 342$ to obtain an integer value for C_{max} ($C_{max} = 6$). Since the smallest services are the most abundant in the network, it is expected to SP_FF algorithm obtain better fairness results when comparing to the previous test. We omitted some charts since the results follow a similar behavior from the observed on test T1.

The fairness metric RBR_{diff} is shown in Figure 4 (a). It is interesting to note that since SS_FF is more suited to the Tr



(a) (b)

Fig. 4. Test T2 - traffic ratio (5:3:2:1) results: (a) Fairness comparison between the four tested algorithms (RBR_{diff}). (b) Requests blocked ratio distinguish per Service Type (RBR_{Sti}) under 650 Erlang and 1050 Erlang load.

used in this test, and since CZB is a combination of SS_FF and SZB, from ≈750 Erlang, both CZB27k and CZB45k start to outperform SZB in fairness. Figure 4 (b) shows two points of interest of (a): the 650 Erlang load in which the SZB has its local minimum value, and the 1050 Erlang load where SS_FF obtains a better result then SZB.

Two points in Figure 4 are worth a mention. First, in (b) the ascending trend observed in the SS_FF algorithm under 1050 Erlang is counterbalanced by the descending trend of the SZB algorithm, culminating in the fairer result obtained by CZB45k. This observation reinforces our conclusion that CZB is a combination of those algorithms. Second, even though the SS_FF result in (a) matches the SZB result under higher loads, a more in-depth analysis reveals the differences among the services blocked ratio are more evenly distributed in SZB algorithm than in SS_FF, Figure 4 (b) 1050 Erlang. However, this result compels us to investigate the fairness in non-uniform situations further and consider novel ways to establish the partitions other than following the traffic ratio linearly.

V. Conclusion

In this work, we present the Cognitive Zone-Based (CZB) spectrum assignment algorithm. Our algorithm is capable of observing the network traffic and acquiring information regarding the network services, thus using it to calibrate the division of the spectrum into partitions. To achieve such a partitioning, the CZB algorithm uses an upgraded version of the Static Zone-Based spectrum assignment algorithm [7]. Our results show that CZB algorithm can indeed achieve its objective, and even improve the fairness under certain conditions. The fairness results are presented in Section IV, and as Figure 3 (f) shows, between 220 and 300 Erlang, CZB algorithms obtain the best results, achieving up to 10 times better fairness under 260 Erlang load (≈ 3.4% of blocking ratio) when compared to the Spectrum Sharing First-Fit algorithm (SS_FF). Those results are confirmed in test T2 (Figure 4) in which CZB algorithms also achieves the best fairness results under higher loads (after 700 Erlang load).

Acknowledgment

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References

[1] C. V. N. Index, "Forecast and methodology, 2016–2021," *Technical Report, Cisco, Tech. Rep.*, 2017. [Online]. Available: "https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.pdf"

[2] R. Wang, S. Bidkar, R. Nejabati, and D. Simeonidou, "Load-aware nonlinearity estimation for efficient resource allocation in elastic optical networks," in *International Conference on Optical Networking Design and Modeling (ONDM)*, 2017, pp. 1–6.

[3] O. Gerstel, M. Jinno, A. Lord, and S. B. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Communications Magazine*, vol. 50, no. 2, pp. s12–s20, 2012.

[4] R. Wang and B. Mukherjee, "Provisioning in elastic optical networks with non-disruptive defragmentation," in *International Conference on Optical Networking Design and Modeling (ONDM)*, 2013, pp. 223–228.

[5] S. Talebi, F. Alam, I. Katib, M. Khamis, R. Salama, and G. N. Rouskas, "Spectrum management techniques for elastic optical networks: A survey," *Optical Switching and Networking (OSN)*, vol. 13, pp. 34–48, 2014.

[6] R. Wang and B. Mukherjee, "Spectrum management in heterogeneous bandwidth optical networks," *Optical Switching and Networking (OSN)*, vol. 11, pp. 83–91, 2014.

[7] R. S. Tessinari, B. Puype, D. Colle, and A. S. Garcia, "Zone based spectrum assignment in elastic optical networks: A fairness approach," in *Opto-Electronics and Communications Conference (OECC)*, 2015, pp. 1–3.

[8] N. Hara and T. Takahashi, "A study on dynamic spectrum assignment for fairness in elastic optical path networks," in *International Conference on Signal Processing and Communication Systems (ICSPCS)*, 2014, pp. 1–7.

[9] R. A. Scaraficci and N. L. Da Fonseca, "Alternative routing and zone-based spectrum assignment algorithm for flexgrid optical networks," in *IEEE International Conference on Communications (ICC)*, 2014, pp. 3295–3300.

[10] J.-L. Izquierdo-Zaragoza, P. Pavon-Marino, and M.-V. Bueno-Delgado, "Distance-adaptive online rsa algorithms for heterogeneous flex-grid networks," in *International Conference on Optical Network Design and Modeling (ONDM)*, 2014, pp. 204–209.

[11] R. W. Thomas, D. H. Friend, L. A. DaSilva, and A. B. MacKenzie, "Cognitive networks," in *Cognitive radio, software defined radio, and adaptive wireless systems*, 2007, pp. 17–41.

[12] R. S. Tessinari, B. Puype, D. Colle, and A. S. Garcia, "ElasticO++: An elastic optical network simulation framework for OMNeT++," *Optical Switching and Networking (OSN)*, vol. 22, pp. 95–104, 2016.

[13] R. S. Tessinari, D. Colle, and A. S. Garcia, "A defragmentation-ready simulation framework for elastic optical networks," *Journal of Communication and Information Systems (JCIS)*, vol. 32, no. 1, 2017.

[14] J. Y. Yen, "Finding the k shortest loopless paths in a network," *Management Science*, vol. 17, no. 11, pp. 712–716, 1971.

[15] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, and A. Hirano, "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network," *IEEE Communications Magazine*, vol. 48, no. 8, pp. 138–145, 2010.