Dynamic Routing and Spectrum Assignment for Varying Traffic in Flexible Optical Networks

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Abstract. The problem of service time-varying traffic in flexible transparent optical networks, assuming that the incoming connections and their duration are not known in advance, is considered in this work. Time-varying traffic requires dynamic spectrum allocation for connections implemented in the network. In the considered problem, a path with the required spectrum around the reference frequency is determined for each incoming connection by the routing algorithm. In order to take into account the dynamic spectrum allocation for the connections in the network, two spectrum expansion/contraction schemes have been applied on the basis of which the average blocking probability for the incoming request additional slot was determined.

1 Introduction

A spectrum-sliced elastic optical path network (SLICE) has been proposed as an efficient solution for flexible bandwidth allocation in optical networks. The applied optical orthogonal frequency -division multiplexing (OFDM) supports the transport of the multi-granularity Internet traffic, however, it requires a grid-flexible (sliced or mini-grid) or fully gridles network. In SLICE, the spectra of OFDM signals are flexible and sliced into any continuous spectrum slots transferring traffic with any speed transmission. Similarly to Routing and Wavelength Assignment Problem in DWDM networks, Routing and Spectrum Assignment Problem (RSA) also appears in the SLICE networks. In [1] the dynamic problem of RSA, which takes into account the relationship between the spectrum bandwidth, modulation format and traffic bitrates, has been formulated. The objective function includes minimizing the path length, and spectrum continuity constraints and non-overlapping spectrum assignment constraints which play the role of constraints in the formulated optimisation problem. To solve this problem, two different algorithms based on the segment representation of the spectrum, which naturally support both mini-grid and fully gridless networks, have been proposed. Whereas, in [2] a dynamic routing algorithm with adaptive modulation in distance SLICE networks has been proposed. In [3] the RSA problem has been formulated as an integer linear programming task and a heuristic algorithm for solving this problem has been proposed, if the ILP solution is not

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achievable. In [4] a k-path Signaling-based RSA scheme has been proposed and simulation results show that in Flexible Bandwidth Optical Networks it performs better than other RSA schemes. In turn, in [5] the problem of planning an optical network based on OFDM, where connections are protected by the spectrum non-overlap rule, has been formulated. To solve this problem there have been proposed several algorithms including optimal and decomposition ILP algorithms and a sequential heuristic algorithm combined with appropriate ordering policies and simulated annealing meta-heuristic.

In [6] the problem of serving time-varying traffic in a spectrum flexible optical network is considered, where the spectrum allocated on the connections changes dynamically with time so as to follow the required source transmission rate. For a description of these spectrum changes, two spectrum expansion/contraction schemes have been proposed, basing on which, a model determining the probability of the network has been developed. It should be emphasized that in the considered problem the number of connections with the number of slots required for each of them is known in advance and the connections are only set up (long-lived connections).

In this paper, the RSA problem has been formulated, in which a stream of request connection is random with random duration of these connections (short-lived connections) and the number of slots in the connections varies dynamically in order to follow the source transmission rate. Furthermore, an algorithm solving this problem has been proposed.

It should be noted that further searching of algorithms solving the dynamic RSA problem, where connections come randomly with random duration, is necessary.

The remaining part of this paper is as follows: the first part contains a formulation of the optimization problem, the second part contains the proposed algorithm solving the formulated RSA problem, assuming that connections with the required number of slots are not known in advance. The third part presents the obtained results, and the fourth one contains a summary and conclusions.

2 Formulation of the Considered Problem

Let $G(N, L)$ be the network, where N is a set of nodes, and L is a set of unidirectional lines l, such that $l \in L$. The spectrum of each link l is divided into T slots (numbered from 0 to $T-1$) with a granularity equal to 12.5 or 6.25 GHz. R is the symbol rate (in baud), and G (Hz) is a guard band between adjacent connections. Furthermore, let the current request be for C units of bandwidth [in b/s] between a pair of nodes: $s, d \in N$. The relationship between the bit rate of signal C and the spectrum of signal B in case of OFDM modulation can be described as follows [1]:

$$B = (\lceil C/2mR \rceil + 1)\, R \tag{1}$$

where m is the number of bits per one symbol, and R is the symbol rate (in baud) for each of the subcarriers. The above relationship was obtained assuming that all the subcarriers have the same signal format: PDM and the AMF. The

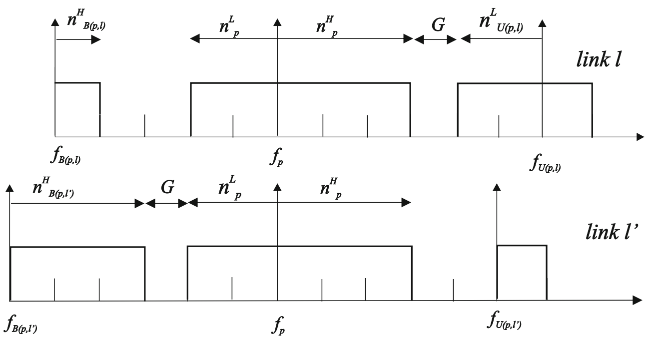

Fig. 1. Using the spectrum of slots by connection p and the adjacent connections on links l and l' at the same time

required path p between the pair of nodes (i, j) with the required number of slots $n_p = n^L_p + n^H_p$ around the reference frequency f_p for random incoming request of the connection is determined by the RSA algorithm. Duration of the connection is also random. It should be noted that in order to satisfy the spectrum continuity constraint, the same slots must be assigned for connection p on all links l, $l \in p$. Moreover, for dynamic RSA problem, the required number of slots of the connection varies in time so as to follow changes source transmission rate while maintaining non-overlapping spectrum assignment constraint, which means that two or more connections can not use the same slots on any link at the same time. Fig. 1 [6] shows the spectrum slots utilization on two links l and l', belonging to the path p. Let $B(p, l)$ and $U(p, l)$ denotes the bottom and upper spectrum-adjacent connectins on link $l \in p$. Whereas, let $f_{B(p,l)}$ and $n^H_{B(p,l)}$ be the reference frequency and the number of upper slots of the spectrum (above the reference frequency) for bottom adjacent connection to connection p on link l. In turn, let $f_{U(p,l)}$ and $n^H_{B(p,l)}$ be the reference frequency, and the number of lower slots of the spectrum (below the reference frequency) for upper adjacent connection to connection p on link l. G is a guard band between the adjacent connections on link l. In case of traffic fluctuations in time, the volume of spectrum for connection p can be increased by additional slots reservation or reduced by releasing some slots. The range of variability of the number of slots n^L_p and n^H_p around the reference frequency f_p, while maintaining the non-overlapping spectrum assignment constraint, can be determined as follows [6]:

$$0 \leq n^L_p \leq f_p - \max_{l \in p} \left(f_{B(p,l)} + n^H_{B(p,l)} \right) - G \tag{2}$$

$$0 \leq n^H_p \leq \min_{l \in p} \left(f_{U(p,l)} - n^L_{U(p,l)} \right) - f_p - G \tag{3}$$

To determine the impact of the traffic dynamic changes on the network blocking probability in [6], there have been proposed two spectrum allocation (Expansion/Contraction) schemes, on link l belonging to connection p. In the first scheme, named as *Constant spectrum allocation (CSA) scheme*, the slots for connection p can be used from reference frequency f_p to reference frequency $f_{U(p,l)}$ of adjacent connection p on link l. Therefore, the range of slots variation n_p^H used in this scheme can be described as:

$$0 \le n_p^H \le N_p^H \tag{4}$$

$$\text{where } N_p^H = \min_{l \in p} \left(f_{U(p,l)} \right) - f_p - G \tag{4a}$$

Thus, in this scheme, no slots can be shared between the adjacent connections on the links of the network. If the request of additional slot appears for connection p and the number of slots n_p^H in this time is equal to N_p^H, then this request will be blocked. Thus, this scheme can only be used for comparative purposes. In the second scheme, named as *Dynamic High Expansion-Low Contraction (DHL) scheme*, slots for connection p can be used both below and above the reference frequency f_p. If the transmission rate for connection p increases, additional slots on link l are occupied, first above frequency f_p increasing n_p^H up to the slots used in a given time by the upper adjacent connection, i.e.:

$$0 \le n_p^H \le N_p^H \tag{5}$$

$$\text{where } N_p^H = \min_{l \in p} \left(f_{U(p,l)} - n_{U(p,l)}^L \right) - f_p - G \tag{5a}$$

In the absence of free slots, the requested slots for connection p are occupied below frequency f_p increasing ^L_p up to the slots used in a given time by the bottom adjacent connection, i.e.:

$$0 \le n_p^L \le N_p^L \tag{6}$$

$$\text{where } N_p^L = f_p - \max_{l \in p} \left(f_{B(p,l)} - n_{B(p,l)}^H \right) - G \tag{6a}$$

In the absence of free slots the request will be blocked.

After determining the schemes of using the free slots, the considered problem in this paper can be defined as the problem of RSA, in which the stream of arrival connections is random with random duration of these connections and the required number of slots in the connections is dynamic - varying in time, so as to follow the required source transmission rate.

The solution to this problem involves determining an algorithm that for every request incoming to the network would determine the path and the reference frequency, together with the required number of slots, taking into account the possibility of slots sharing, so as to minimize the average blocking probability.

In [6] to find a solution for the dynamic (time-varying) RSA problem, in which the set of connections with a designated number of slots for each of them is known in advance, the heuristic algorithm is proposed. Assuming that the transmission system supports T slots on each link (fiber) and knowing the volume of traffic for each connection, the dynamic (time-varying) RSA problem is transformed into a static RSA problem. Then, the static RSA problem is solved by a heuristic algorithm based on Simulated Annealing [7]. After solving the static RSA problem (resulting in the path p is obtained with the reference frequency fp for each connections), the blocking probability is determined using the presented schemes spectrum expansion/contraction in case of changes (increase/decrease) in the source transmission rate on the connections. Then, for the same set of connections and a number of slots for each of them, next iteration is performed. The algorithm terminates after K acceptable solutions. A solution that provides the minimum blocking probability of the network from the set of K solutions is the final solution.

It should be emphasized that the designation of the solution that minimizes the blocking probability is based on repetition of the algorithm for the known in advance set of connections with the required number slots for each of them.

In this paper the analysis of the network using both spectrum allocation schemes and taking into account the intensity of the arrival of requests for additional slots in the existing connections has been carried out. The general idea of the analysis of the network is as follows: the connection requests with C units of bandwidth (in bit/s) uniformly distributed from $C_{\min}$ to $C_{\max}$ arrive to the network consisting of n nodes. A stream of requests between each pair of nodes is the Poissonian, with intensity λ (for simplicity the same for each pair of nodes), and the connection duration has an exponential distribution with the mean equal to $1/\mu = 1$. Therefore, the average traffic (in bps) between each pair of nodes is equal to $\rho\bar{c}$, where $\rho = \lambda/\mu$ is the traffic in Erl. Implementation of C units of bandwidth for the incoming request requires the signal spectrum, defined by formula (1). After taking into account the grid with granularity equal to 6.25 or 12.5 GHz, the required number of slots for a given connection can be determined. Then, to solve the formulated RSA problem, algorithm 2 in [8], which is a modification of the MSP algorithm (Modified Shortest Path Algorithm) [1] is used. The algorithm in [1] has been proposed to solve the static RSA problem where the stream of requests is Poissonian and the connection duration has an exponential distribution. In [1,8], a spectrum segmented representation which fully supports the coarse mesh WDM network, a mini-grid networks (slot-based) and ideal fully gridless networks, have been used. The algorithm used in this paper designates path p and reference frequency f_p together with the required number of slots for each incoming request between the pair of nodes (i, j). It should be noted that the designated slots must satisfy the spectrum continuity constraint and the non-overlapping spectrum assignment constraint. Moreover, guard band G (in slots) is allocated between adjacent connections to eliminate interference. After allocating a specified number of connections (where each of them requires the number of slots based on (1)), the network given state is obtained. The set of feasible states of the network is determined by the occupied slots on the links by the connections and is described by (2) and (3). For a given state of the network, an analysis of the network is made according to the assumption that the required number of slots for the connections dynamically vary in time so as to follow the source transmission rate.

3 The Solution of the Considered Problems Taking into Account the Slots Allocation Schemes

The network dynamic operation is achieved by associating Poissonian stream of requests of additional slots with intensity λ_p with each connection p, in a given state of the network. The duration of the slots is exponentially distributed with the mean equal to $1/\mu_p = 1$. In order to simplify, it was assumed that the arrival intensity of the additional slots for all the connections in a given state of the network is the same and equal to λ_p. The defined problem is solved for both shown slots allocation schemes.

3.1 Solving the Problem for Constant Spectrum Allocation (CSA) Scheme

In the constant spectrum allocation scheme the slots are occupied for connection p above the reference frequency f_p of the interval defined by (4). Thus, the incoming request allocation of additional slots for this connection encounters $N_p^H - n_p^H$ of free slots. Rejection of this request will appear, when $n_p^H = N_p^H$. Thus, the blocking probability for the incoming request on the path p can be determined as first Erlang function: $b_p = E_{1,N_p^H - n_p^H}(a_p)$, where $a_p = \lambda_p/\mu_p$. Knowing the connections in a given state of the network and the blocking probability of requests for additional slots for each of the connection it is possible to determine the average probability in the network.

3.2 Solving the Problem of Dynamic High Expansion-Low Contraction (DHL) Scheme

On the other hand, in case of DHL schema, the required slots for connection p are occupied both above and below the reference frequency f_p. Above frequency f_p, additional slots are occupied from the range $\left(n_p^H - N_p^H\right)$, where N_p^H is defined by equation (5a). In order to simplify the analytical model it was assumed that all connections in the network, except the connection on path p, occupy the slots above the reference frequency. Thus, the blocking probability for the incoming request additional slot from $N_p^H - n_p^H$ free slots above the frequency f_p, where $N_p^H = \min\limits_{l \in p}\left(f_{U(p,l)}\right) - f_p - G$ can be described as $b_p^H = E_{1,N_p^H - n_p^H}(a_p)$, where $a_p = \lambda_p/\mu_p$. If the request is blocked, it will be directed to the free slots below frequency f_p. In this case, however, according to the assumption adopted above, for all links of connections p, $l \in p$, the slots lying below f_p will be affected by slots of the bottom adjacent connections. Therefore, each link $l \in p$ should be considered separately, which is a further simplification. The blocking probability request of the free slot for connection p on link $l \in p$ below f_p can be defined as

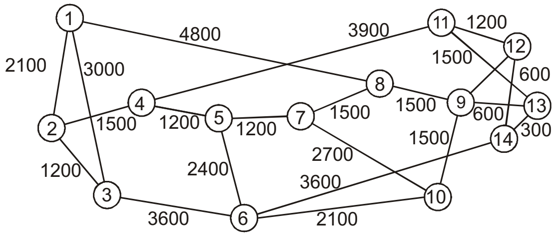

Fig. 2. Topological structure of the network, NSFNET [1]

$b^L_{p,l} = E_{1,N^L_{p,l}-n^L_{p,l}}\left(a_p(1+b^H_p)\right)$, where $N^L_{p,l} = f_p - \left(f_{B(p,l)} + n^H_{B(p,l)}\right) - G$. Thus, the average probability of the blocking request additional slots on the path p can be determined as $b_p = b^H_p \left[1 - \prod_{l \in p}\left(1 - b^L_{p,l}\right)\right]$. Knowing the connections for some state of the network and the probability of blocking request for additional slot for each of them the average probability of blocking request for additional slots in the network can be determined.

4 Obtained Results

Verification of the considered models was performed for the network, whose topological structure is shown in Fig. 2 [1]. It consists of 14 nodes connected by links and each of them includes T slots. Each edge in this graph is a pair of unidirectional links. In this work it is assumed that each node may be an input and output node. Thus, 196 pairs of nodes in the network can be distinguished. The lengths of the links are shown on the edges of the graph. The network simulation was carried out basing on Monte Carlo method. It was assumed that the stream of connection requests between each pair of nodes (s, d) is Poissonian with intensity $\lambda = 2$. The duration of the connections is exponentially distributed with mean $1/\mu = 1$. Bandwidth of the connections is uniformly distributed from 50 Gbps to 200 Gbps with mean equal to $=$ 125 Gbps. The intensity of the requests for additional slots for each connection p is a parameter and the duration of these slots is exponentially distributed with mean $1/mu_p = 1$. Simulation of the network was performed under dynamic conditions, it means that the connections are set up and released (short-lived connections). Then, for the state of the network, which also depends on the number of the connections, a simulation of the dynamic changes of the spectrum (in slots) is performed for all connections. Registration of the rejected requests additional slots is performed after obtaining the system steady state. It should be noted that both the analytical and simulation models take into account the adopted spectrum allocation schemes and these models are carried out for the same state of the network. For the input data, the obtained results are averaged on the basis of 30 simulation (30 states of the network for the same data input). Furthermore, it was assumed that OFDM

Table 1. The blocking probability depending on the intensity of arriving requests

$\sum \lambda_p$	$\lambda = 2, \mu = 1, m = 2$, $\bar{C}$ = 125 Gbps, R=1 Gbaud, G=1, T=300			
	CSA		DHL	
	Analytical model	Simulation	Analytical model	Simulation
3.8E+01	0.5379±0.02238	0.3568±0.01997	0.2630±0.01560	0.3372±0.02540
7.5E+01	0.5404±0.01304	0.3811±0.01589	0.2684±0.01660	0.3356±0.01495
1.5E+02	0.5630±0.01354	0.3918±0.01795	0.2860±0.01448	0.3446±0.02107
2.2E+02	0.5824±0.01261	0.4187±0.01759	0.3177±0.01918	0.3779±0.02159
2.9E+02	0.5878±0.01760	0.4262±0.02566	0.3391±0.02006	0.3895±0.01474
3.6E+02	0.5958±0.01075	0.4644±0.01903	0.3743±0.01318	0.4204±0.01800
4.6E+02	0.6080±0.02063	0.4717±0.02230	0.3765±0.02386	0.4233±0.02469
4.9E+02	0.6194±0.01372	0.4803±0.01826	0.3887±0.01652	0.4280±0.01705
5.2E+02	0.6299±0.01146	0.4985±0.01353	0.4157±0.02158	0.4604±0.01967
6.3E+02	0.6490±0.01297	0.5235±0.02429	0.4312±0.01714	0.4752±0.01972
7.3E+02	0.6564±0.00920	0.5335±0.01288	0.4407±0.01507	0.4789±0.01728

Table 2. The blocking probability depending on the number of slots provided by a transmission system on each link

T	$\Lambda = 2, \mu = 1, m = 2$, $\bar{C}$ = 125 Gbps, R=1 Gbaud, G=1, $\sum \lambda_p$=3.6E+02			
	CSA		DHL	
	Analytical model	Simulation	Analytical model	Simulation
300	0.5958±0.01075	0.4644±0.01903	0.3743±0.01318	0.4204±0.01800
320	0.6007±0.02428	0.4420±0.02336	0.3555±0.02736	0.4190±0.02586
340	0.5887±0.01504	0.4495±0.01026	0.3571±0.00991	0.4180±0.01928
360	0.6077±0.01431	0.4580±0.01948	0.3732±0.01443	0.4214±0.01699
380	0.6058±0.02169	0.4564±0.03022	0.3730±0.02544	0.4270±0.02927
400	0.5896±0.01417	0.4422±0.01931	0.3614±0.01481	0.4249±0.01158

systems have the same symbol rate equal to $R = 1$ Gbaud, and the guard band is equal to $G = 1$ slot. Table 1 shows the average blocking probability of additional slot request depending on the intensity of the arrival of additional slots requests for the connections in the network with a fixed number of slots $T = 300$ realized by a transmission system on each link. The obtained results prove that the probability of blocking additional slot request using the CSA scheme is the upper bound for the results obtained using DHL scheme for the whole considered range of λ_p. This results from the fact that in case of DHL scheme slots are shared by the adjacent connection as opposed to the CSA. Moreover, the blocking probability of additional slot request is surprisingly large compared to the results in [6]. It should be emphasized that these two RSA problems are completely different. In the considered dynamic RSA problem in [6], the set of connections with the required number of slots is known in advance, while in the dynamic RSA problem considered in this work, the stream of incoming requests to the network is Poissonian and the connections are not known in advance.

In turn, Table 2 shows the blocking probability of additional slots request depending on the number of slots implemented by the transmission system on each link of the network. As can be seen, even with a large increase in the number of slots (over 30%), implemented on the links of the network, the blocking probability of requests is practically unchanged. This is caused by the applied algorithm proposed in [1] and revised in [8] for solving the static RSA problem, in which a stream of requests is Poissonian and duration of the connections is exponentially distributed (the number o connections is not known in advance). The algorithm is based on the classical Dijkstra algorithm [9], which is an avid algorithm, which means that in every step it makes a selection of locally optimal decision, regardless of the situation in the next step. Therefore, to solve the defined problem in this work we should go in the direction of heuristic algorithm with prediction, which during determining the path p for incoming request could predict the ability to dynamically change the number of the required slots (taking into account the sharing of slots) minimizing the blocking probability of additional slots.

The thesis accepted at the beginning of this paper confirms that it is necessary to search for algorithms for solving dynamic RSA problem, in which a stream of connections and service time are not known in advance. Furthermore, the connections implemented for the assumed input data require from 3 to 9 slots. Thus, the realization of the request for additional slot increases the amount of traffic (in slots) from 11% to 33% for the connection. Therefore, for a given state of the network, in which the specified number of connections chosen by avid algorithm are realized the request of additional slots is rejected with quite a high probability.

5 Conclusions

The paper presents a dynamic time-variable RSA problem, in which a stream of requests and duration of the connections are random (connections are not known in advance). To solve this problem, two schemes of slots allocation on the connections have been used in order to follow the required source transmission rate. The first one does not take into account the possibility of sharing slots between adjacent connections on links of the network and it is presented for comparative purposes only. The second scheme enables sharing slots between adjacent connections taking into account the spectrum continuity constraints and the spectrum non-overlap constraints. To solve the formulated problem in this paper we transform this problem into a static problem of RSA, in which a stream of requests and connections duration are random. Then, after obtaining a given state of the network, requests for additional slots for connections are generated taking into account slots allocation schemes. To solve the static RSA problem the algorithm based on Dijkstra algorithm, which is an avid algorithm, has been used. Moreover, to make a comparison of analytical and simulation models (for each considered slot allocation scheme), these models were used for the same network state. The obtained results prove that the blocking probability of additional slots requests obtained on the basis of DHL scheme, for both the analytical and the simulation model, are upper bounded by results obtained on the basis of the CSA schema. This shows that in case of DHL scheme, there is spectrum (in slots) sharing for both the analytical and the simulation model. Large values of the blocking probability result from the algorithm used to solve the static RSA problem. Simultaneously, these results indicate the direction of further studies to determine the heuristic algorithms with prediction, solving the dynamic RSA problem, in which the incoming request and the call duration are random (not known in advance).

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