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Routing and Spectrum Assignment for Constant Bit Rate Connections in Spectrum Sliced Elastic Optical Path Networks

***Abstract**. In this paper a heuristic algorithm for finding an optical path in elastic optical path networks is proposed. The proposed algorithm for connection requests finds a spectrum required from an aggregated spectrum of the path belonging to a set of shortest paths measured by the number of links. It has been shown that the proposed algorithm rejects definitely fewer connection requests than the well-known algorithms solving the same problem.*

***Streszczenie.** W pracy zaproponowano heurystyczny algorytm wyboru ścieżek w elastycznych sieciach optycznych. Zaproponowany algorytm zajmuje dla napływającego żądania wymagane pasmo w zagregowanym widmie ścieżki, należącej do zbioru najkrótszych ścieżek mierzonych liczbą łączy. W pracy wykazano, że algorytm ten odrzuca mniejszą liczbę żądań niż znane algorytmy minimalizujące rzeczywistą długość ścieżki. (**Kierowanie i przypisanie widma dla połączeń o stałej szybkości transmisji w elastycznych sieciach optycznych**).*

Keywords: Routing and Spectrum Assignment (RSA) problem, optical path, OFDM modulation.
Słowa kluczowe: problem rutingu i przypisania widma, ścieżka optyczna, modulacja OFDM.

Introduction

The dynamic growth in demand for a bandwidth in the network due to an increase in IP traffic customers and increasing dissemination of high-rate applications that require high bandwidth, such as Video on Demand, high definition TV and cloud computing, require cost-effective and scalable networking infrastructure. Traditional WDM networks provide transport possibilities with large capacities. However, the rigid grid frequency, proposed by the International Telecommunication Union (ITU) leads to inefficient use of spectrum in these networks, provided that the volume of traffic of the connections is not enough to fill the entire capacity of wavelengths. To eliminate these disadvantages of WDM network, a spectrum-sliced elastic optical path network (SLICE) has been proposed. Orthogonal frequency modulation (OFDM) used in SLICE networks allows service connections with arbitrarily high data rate by dividing the transmitted data into several low data rate sub-carriers. Due to a different way of allocating bandwidth in both networks, the classic Routing and Wavelength Assignment (RWA) problem specified for WDM networks can not be directly applied to the SLICE network. Routing and Spectrum Assignment (RSA) problem formulated for the SLICE network beyond the optimization objective function must ensure the spectrum continuity constraint and non-overlapping spectrum constraint for adjacent connections on the network links. In addition, this problem can be considered on the assumption that the set of connections is known in advance (static problem) or the stream of connection requests and the duration of these connections are random (dynamic problem). The difference is that in the first case to solve the RSA problem more accurate off-line algorithms are used, whereas in the second case, polynomial on-line algorithms are required with low computational complexity.

In [1] the complete RSA problem which takes into account the relationship between traffic bit-rates and a signal spectrum has been formulated. Stream of connection requests and the duration of these connections in this problem are random (connections are not known in advance) and transmission rate of the connections is constant. The key to solving the complete RSA problem is to solve the basic RSA problem, which for a fixed modulation level, optimizes the path length with the spectrum continuity constraint and the non-overlapping spectrum constraint for adjacent connections on the network links. To solve the basic RSA problem, several algorithms are used from heuristic algorithms to the exact algorithm. In [2] the static RSA problem has been formulated for a known set of demands in advance as an integer linear programming task. To solve this problem, a heuristic algorithm based on the collision metric has been proposed when ILP solution is not achievable. In [3] the static RSA problem with a set of connections known in advance has been formulated. The objective function minimizes the maximum utilized spectrum slot while maintaining non-overlapping spectrum for adjacent connection constraints. To solve this RSA problem several algorithms have been proposed from optimal and decomposition ILP algorithms to a sequential heuristic algorithm combined with appropriate ordering policies and simulated annealing meta-heuristic. In [4] the RSA problem of serving time-varying traffic has been considered in which a set of demands with the required number of slots is known in advance. To solve this problem a heuristic algorithm based on spectrum expansion/contraction schemes has been proposed.

In this paper an algorithm solving basic RSA problem in which the objective function minimizes the path length, while maintaining spectrum continuity constraints and non-overlapping spectrum constraints is proposed. The proposed algorithm determines a path with the required number of slots from a calculated off-line set of paths between each pair of nodes providing greater reduction in blocking probability of the connection requests than other well-known algorithms based on the path length minimization.

It should be noted that further studies of the RSA problem to determine the new RSA algorithms to minimize the blocking probability of the connection requests with small function of the computational complexity are required.

The remaining part of this paper is as follows: the second chapter contains a formulation of the optimization problem. In the third chapter a heuristic algorithm for solving this problem is proposed. The fourth chapter presents the results, while the fifth chapter contains a summary and conclusions.

Problem formulation

In [1] the complete RSA problem, in which the objective function includes minimizing the length of the path while the spectrum continuity constraints and non-overlapping spectrum for adjacent OFDM signal constraints play the role of constraints of the considered problem, is shown. This problem also takes into account the relationship between the bit rate of the connection and the signal spectrum. In order to solve this optimization problem an iterative algorithm where each iteration consists of three steps has been proposed. In the first one, for a fixed number of bits per baud, the required signal spectrum is determined. Then, for this spectrum, in step 2, the algorithm solves the basic RSA problem which includes minimizing the path length while maintaining the spectrum continuity constraints and non-overlapping spectrum constraints on the network links. In the third step, the path length obtained in step 2 is checked with the constraint of the path length depending on the number of bits per one baud (half-distance law). The algorithm starts by assigning the maximum number of bits per one baud in the first iteration. If there is no path with the required spectrum the request is rejected, otherwise, it is checked whether the found path satisfies the required constraint of the path length. If this condition is met the algorithm terminates, otherwise the number of bits per one baud is reduced and the algorithm goes to the next iteration.

The main step in this algorithm is step 2, where the basic RSA problem is solved. In [1], this problem has been formulated for the spectrum segment representation as integer linear programming task. Here, a similar RSA problem, considered in this paper, has been formulated for the spectrum slot representation, in which each slot represents an optical channel. The optical path is implemented by assigning the number of adjacent slots dependent on the required bandwidth and modulation format. Let the network be a graph $G(N, E)$, where N is the set of nodes, and E is the set of unidirectional links (arcs). D is the set of weights of arcs d_{ij}, such that the arc $(i,j)\in E$. Furthermore, let $F=\{f_1, f_2,..., f_{|F|}\}$ be the set of slots implemented on each link $(i,j)\in E$. R is the rate of symbol (in baud), while G (Hz) is the guard band between adjacent OFDM signals on the network links. The number of slots for a request depends on the required bandwidth and the modulation format. The incoming request is determined by a triple (s, d, C), where s and d are the source and destination node respectively, and C is the bit rate of the signal. The relationship between the bit rate C and the signal spectrum B in the case of OFDM modulation, assuming that each sub-carrier has the same format with m bits per symbol, can be defined as [1]:

(1) $$B=(\lceil C/2mR\rceil+1)R$$

where: $n=\lceil C/2mR\rceil$ is the number of sub-carriers that is equal to the number of required slots and R is the symbol rate (in baud).

It should be noted that in order to eliminate interference between the adjacent OFDM signals a guard band $G = 1$ slot must be used. Moreover, the spectrum of the link S_{ij} can be represented as the sum of L_{ij} sets of available slots, ie.

(2) $$S_{i,j}=\bigcup_{l=1}^{L_{ij}}(a^l_{ij},b^l_{ij})$$

where: a^l_{ij} and b^l_{ij} is the first and the last slot respectively of l-set.

In [1] a basic RSA problem is to find the shortest path P_{sd} between a pair of nodes s,d for incoming connection request with n slots while maintaining the spectrum continuity constraint and non-overlapping spectrum constraint for adjacent connections on the network links. Fulfillment of the spectrum continuity constraints involve finding a set of contiguous and available $n+G$ slots for connection requests in the aggregate spectrum of the path S_{sd} between a pair of nodes s,d. Aggregated spectrum of the path $S_{s,d}$ is defined as the intersection of spectrum of links S_{ij} belonging to the path P_{sd}, ie.

(3) $$S_{s,d}=\bigcap_{(i,j)\in P_{s,d}} S_{ij}$$

Before the formal definition of the optimization problem, variables used in this problem will be defined. Let x_{ij} be a binary variable equal to 1 if the connection is routed on link (i,j) and 0 otherwise, x^l_{ij} -binary variable equal to 1 if the connection is routed on link (i,j) and the spectrum for this connection equal to $n + G$ slots is allocated in the l-th set of available slots (a^l_{ij},b^l_{ij}) and 0, otherwise. Variables f_a and f_b are the first and the last slot respectively for the connection request, ie. $f_b-(f_a-1)=n+G$. Formulation of the basic RSA problem for spectrum slot representation of the network is presented below.

(4) $$Min \sum_{(i,j)\in E} x_{i,j}d_{ij}$$

Objective function (4) minimizes the length of path being selected. Path length is understood here as the transmission distance.

(5) $$\sum_j x_{i,j}\le 1 \quad \forall_{i\in N}$$

Constraint (5) ensures that the found path between the pair of nodes (s, d) does not contain cycles, which means that only one arc ($x_{ij}=1$) may output from given node i when this node belongs to the path and does not output any arc ($x_{ij}=0$), when node i does not belong to the path.

(6) $$\sum_i x_{i,j}-\sum_i x_{j,i}=\begin{cases}-1, & j=s\\ 1, & j=d\\ 0, & j\neq s,d\end{cases} \qquad \forall_{i\in N}$$

Equation (6) defines the flow balance.

(7) $$\sum_{l=1}^{L_{ij}} x^l_{i,j}=x_{ij} \qquad \forall_{i,j\in N}$$

Equation (7) ensures that only one set of available slots from L_{ij} sets is available on link (i, j) for the path being found.

(8) $$f_b-f_a+1=n+G$$

Equation (8) defines the realized spectrum by adjacent slots depending on the required number of $n+G$ slots for connection request (see Eq. (1)).

(9) $$\begin{cases} f_b-b^l_{i,j}\le |F|\left(2-x_{i,j}-x^l_{i,j}\right)\\ a^l_{ij}-f_a\le |F|\left(2-x_{i,j}-x^l_{i,j}\right)\end{cases} \quad \forall\, ij\in E, \forall k$$

In turn, the non-overlapping spectrum constraint of adjacent connections of the network links is provided by equation (9). When the path for connection request passes through link (i,j) and this path is implemented by l set of available slots (a^l_{ij},b^l_{ij}), i.e. $x_{i,j}=1$ and $x^l_{i,j}=1$, the system of inequalities (8) takes the form:. $a_{ij}^{l} \le f_a$, $f_b \le b_{ij}^{l}$. This means that the spectrum of the connection (from f_a to f_b) is included in the set l of available slots $(a_{i\,j}^{l}, b_{i\,j}^{l})$. For the remaining sets of available slots $(a_{i\,j}^{\bar{l}}, b_{i\,j}^{\bar{l}})$, $\bar{l} \in \{1, 2, ..., l-1, l+1, L_{i,j}\}$, through which the connection does not pass ($x_{i,j}$=1, $x_{i,j}^{l}$=0), the system of inequalities becomes: $f_b - b_{ij}^{\bar{l}} \le |F|$, $a_{i,j}^{\bar{l}} - f_a \le |F|$, which means that the spectrum of the connection (in slots) does not go beyond the scope of the spectrum of link *(i, j)*.

The formulated problem is the integer linear programming problem and can be solved by normal MILP algorithms. The solution of this problem for the connection request is the shortest path with the required number of $n+G$ slots, while maintaining constraints (5) - (9).

Solution of the basic RSA problem

In [1] to solve the basic RSA problem, which has been formulated for the spectrum segment representation, three different algorithms are proposed. The first of them, named as Spectrum - Constraint Path Vector Searching Algorithm (SPV), generates a path vector searching tree, which is similar to the trees generated by algorithms based on the branch and bound method. The root of the tree is the source node, which is at zero level. Next, the tree nodes, that represent paths from the initial node, are achieved along the arcs of the graph network, ensuring minimization of the actual path length, provided that the path does not include the loop and the aggregated spectrum enables the request. If these conditions are not fulfilled, subsequent successors of this node in the generated tree are not determined. The computational complexity of this algorithm is exponential and equal to $O(N) = q_m^{|N|-1}$, where q_m is the maximum out-degree of the graph. Due to the limited scalability of the algorithm it can only be used to verify the solutions obtained by other algorithms for networks with a small number of nodes. The second algorithm named as KSP (k Shortest Paths) uses the set-k of shortest paths sequenced ascending relative to the length for each pair of nodes. These paths are calculated *off-line* by well-known Yen's algorithm with computational complexity equal to $O(k|N|^3)$. For a connection request between the pair of nodes s, d, an aggregated spectrum is determined for each of k paths. The solution of this problem is the shortest path with the spectrum available for the connection. This algorithm with the computational complexity function equal to $O(k|N|)$ can provide approximate solutions only, on grounds of limited set of paths between each pair of nodes. The third algorithm named as Modified Shortest Path Algorithm (MSP) is a modification of the well-known Dijkstra's algorithm [5]. The modification is based on the introduction of the aggregated spectrum for links belonging to the considered path and check if a bandwidth for connection requests is available. After reaching the destination node by the algorithm the first free segment of the aggregate spectrum path is occupied for the connection request. The computational complexity of this algorithm is polynomial and equal to $O(|N|^2)$. In [6] (MSP2 algorithm) it is shown that a small reduction of the rejected connection requests can be achieved taking into account the narrowest segment of the path aggregate spectrum which allows a connection. However, the analysis of all segments of the aggregate spectrum at each node of the path is required.

It should be noted that the SPV, MSP [1] and MSP2 [6] algorithms are designed as one-step approaches [7], where in the two first of them the selection of available spectrum slots for the connection request is based on the first-fit scheme, while in MSP2 algorithm the selection of available slots for the connection request is based on the best-fit scheme. Algorithms using one-step approach find the path and available spectrum (contiguous slots) simultaneously. In turn, the KSP algorithm in [1] is a two-step approach. In these algorithms, RSA problem is divided into two sub-problems that are sequentially solved. In the first sub-problem the algorithm calculates k shortest paths taking into consideration the transmission distance or the length of the path measured by the number of links or utilization of spectrum slots of these paths, etc., while in the second sub-problem this algorithm searches for the available spectrum slots based on a selected scheme, e.g. first-fit [1],[8]. Several other ordering schemes are proposed in [3].

To solve the basic RSA problem a heuristic algorithm named as Sequence Paths algorithm (SP) is proposed in this paper. The general idea of this algorithm is as follows: for each pair of nodes a set of k shortest paths, measured by the number of links, is designated *off-line*. To calculate this set, an algorithm based on Latin multiplication [9] with computational complexity equal to $O(|N|^3)$, if the algorithm calculates the paths to obtain the Hamiltonian paths, is used. For connection requests between the pair of nodes s, d , an aggregated spectrum for the first path $S_{s,d}(1)$ is determined. Then, the spectrum of this path is searched starting from the available set of slots with the smallest index l until finding a set of at least $n + G$ available slots for a connection request. Let $\Phi(\mathrm{S}_{s,d}^{l}(i), n+G)$ be the logical function equals *true* if the l-th set of available slots $(a_{s\,d}^{l}(i), b_{s\,d}^{l}(i))$ of aggregated spectrum $\mathrm{S}_{s,d}^{l}(i)$ of i-th path between the pair of nodes s, d enables realization of $n+G$ slots and *false,* otherwise. In the absence of the $n+G$ available slots on i-th path, an aggregated spectrum of the next path is searched for. The connection request is rejected in the case of absence of at least $n+G$ adjacent slots in any of k paths. Below, an algorithm to solve the basic RSA problem is presented. Assuming that computational complexity for spectrum aggregation $\mathrm{S}_{s,d}(i)$ is equal to $O(|N|)$ the complexity function of the SP algorithm is $O(k|N|)$. It should be noted that SP algorithm is proposed as two-step approach. In the first step, k shortest paths measured by the number of links is calculated, while in the second step, these paths are searched sequentially from the shortest path to find a set of adjacent slots for the connection request in the aggregate spectrum of the path. The process of path searching using the $\Phi(\,)$ function starts with the set of available slots with the smallest index and continues until finding the set which allows admitting requested connection. Thus, the second step follows the first-fit scheme.

Input: Graph $G(N, E)$. The set of k paths for each pair of nodes s, d. The connection request between pair of node s,d with C units of bandwidth.

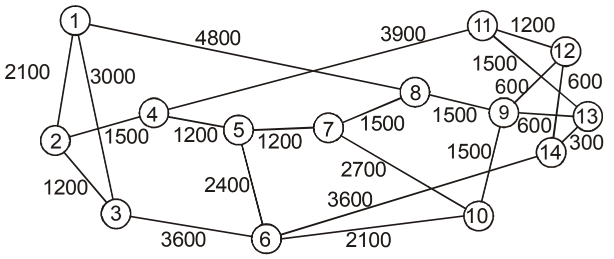
Output: The shortest path $P_{s,d}(i)$ with $n+G$ available spectrum slots.

SP Algorithm;

Based on Eq. (1) calculate required number of slots n for C units of bandwidth.
status←***false***; i←1;
while not(status) **and** (i <=k) **do**
  u←s;
  for each node $v \in P_{s,d}(i) \setminus s$ **do**
    $S_{s,v}(i) \leftarrow S_{s,u}(i) \cap S_{u,v}(i)$;
    {Spectrum aggregation of i-th path }
    u←v;
  end for
  if $\Phi(S^{l}_{s,d}(i), n+G)$ **then**
    Status← **true**
    j←i;
  end if
  i←i+1;
end while
If *status* **then**
  return $P_{s,d}(j)$
  $f_a \leftarrow a^{l}_{s\,d}(j);\ f_b \leftarrow f_a + n + G - 1;$
else Blocking
end if

Obtained results

a)



b)

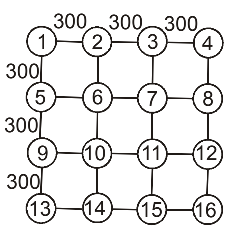


Fig. 1. Topological structure of the network [1]: a) the NSFNET b) the GRID.

Study of the proposed algorithm for the considered RSA problem was carried out for two different networks. The first, shown in figure 1a [1] contains 14 nodes connected by links and each of them carries *T* slots. The second network, as shown in figure 1.b [1] includes 16 nodes connected by links and each of them carries the *T*-slots too. The edges of the graphs in figure 1.a and 1.b represent a pair of oppositely directed links, while the numbers designate their length. Assuming that each node may be both an input and output node, 196 pairs of nodes can be distinguished in the first network and 256 pair of nodes in the second network. The study of the algorithm was based on the simulation using Monte Carlo method. In the simulation model it was assumed for simplicity, that the stream of connection requests for each pair of nodes *(s,d)* is the Poisson with parameter λ, while the duration of the connections is exponential with parameter μ = 1. The bandwidth of connection requests is uniformly distributed from 30 to 90 GBps, with the mean equal to $\overline{C}$ = 60 Gbps. Thus, the volume of traffic (in bps) between each pair of nodes is equal to $\rho\overline{C}$, where ρ is the volume of traffic in erl. Network simulation was carried out under dynamic conditions, i.e. the requests are set up and disconnected (short-lived connections). The results were recorded after obtaining a steady-state model. For each load of the network the simulation run was repeated 30 times. In addition, it was assumed that the symbol rate R = 2.5 Gbaud and the number of bits per boud is m = 2. The results were compared with those obtained by the MSP algorithm, which provides the lower probability of blocking then other algorithms presented in [1], with and exception of the SPV algorithm, that determines the exact solution. Figure 2 shows the blocking probability of the connection requests depending on the total traffic offered to the network (in Tb/s). From the figure it follows that the proposed SP algorithm rejects a similar number of connection requests, regardless of the number of paths in a wide range of network load. It should be noted, however, that the difference in the number of rejected connection requests for adjacent values decreases with increase in the number of paths. For example, for load equal to 68.7 Tbps the number of rejected connection requests for successive k = 3,4,5,7 are: 120.7, 98.6, 80.5 and 78.1 respectively. Furthermore, for the same load of the network the number of rejected connection requests for each k is much smaller than the number of rejected requests by the MSP algorithm. For example, for the same load equal to 68.7 Tbps MSP algorithm rejects 154 connection request, while the SP algorithm rejects average 94.5 connection requests, which means that rejects 38.6% fewer requests. For subsequent load of the network these numbers are 17.3%, 13.2%, 7.5% and 5.5% respectively.

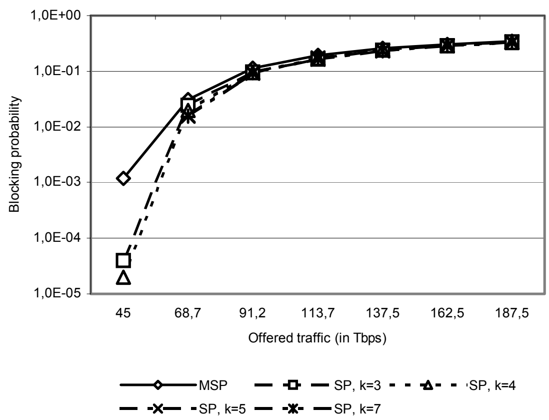


Fig. 2. Blocking probability of the connection requests depending on the traffic offered to the network (in Tb/s)

The reason for this is that the number of potential paths in SP algorithm was limited to k shortest paths, measured by the number of links. The above path length limit will increase the possibility of finding adjacent slots to satisfy spectrum continuity constraint for connection requests in aggregate spectrum of the path, while an increase in the number of nodes on the path makes it difficult to ensure the spectrum continuity constraint. MSP algorithm based on the classical Dijkstra algorithm [5], which is a greedy algorithm calculates the long path, occupying the spectrum, regardless of the future connection requests which will arrive.

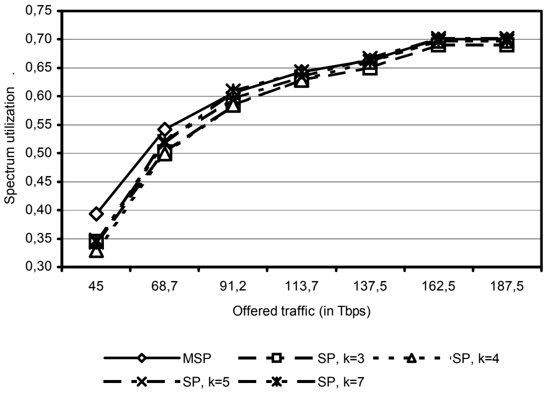


Fig. 3. Spectrum utilization ratio, depending on the traffic offered to the network (in Tb/s)

Figure 3 shows the spectrum utilization ratio, which is defined as a quotient of the occupied spectrum (number of occupied slots on the links) in the network to the total spectrum (the total number of slots on the links) in the network. The figure indicates that up to 91.2 Tbps this coefficient is lower for the proposed SP algorithm, regardless of the number of paths, than for the MSP algorithm. This is because a smaller the size of the spectrum is occupied on shorter paths for the connections.

Table 1. Number of rejected requests for network consisting of n=16 nodes.

Load (Tbps)	MSP	SP		
		k=2	k=3	K=4
60	464.4±54.8	374.9±25.6	274.0±31.8	237.5±27.4
90	1058.9±44.6	954.5±37.0	859.5±36.6	858.9±25.7

Table 2. Spectrum utilization ratio.

Load (Tbps)	MSP	SP		
		k=2	k=3	K=4
60	0.487±0.011	0.475±0.012	0.479±0.006	0.491±0.012
90	0.584±0.011	0.547±0.010	0.574±0.014	0.580±0.007

In turn, table 1 shows the number of rejected requests, while table 2 shows the spectrum utilization ratio depending on the load of the network whose structure is shown on figure 1.b. The results for the network in figure 1b are fully consistent with the results obtained for the network in figure 1a.

Summary and Conclusions

In this paper an algorithm for finding optical paths in the spectrum sliced elastic optical path networks is proposed. The considered basic RSA problem involves minimizing the length of the path while maintaining the spectrum continuity constraint and non-overlapping spectrum constraint between adjacent OFDM signals on the network links.

The obtained results show that the proposed SP algorithm, based on the sequence of the shortest paths, measured by the number of lines, provides much better solutions for a wide range of loads than the well-known MSP algorithm. An additional advantage of the proposed algorithm is computational complexity, which makes the algorithm scalable and possible to be used in an iterative algorithm to solve the complete RSA problem, even for large networks.

REFERENCES

[1] Wan X., Hua N., Zheng X., Dynamic Routing and Spectrum Assignment in Spectrum –Flexible Transparent Optical Networks, *Opt. Commun. Netw.*,4, (2012), No 8, 603-613
[2] Klinkowski M., Walkowiak K., Routing and Spectrum Assignment in Spectrum Sliced Optical Path Network. *IEEE Communications Letters,* 15 (2011), No 8, 884-886
[3] Christodoulopoulos K., Tomkos I., Varvarigos A.E., Routing and Spectrum Allocation in OFDM-based Optical Networks with Elastic Bandwidth Allocation. *Telecommunications Conference (GLOBECOM 2010)*, 2010 IEEE 6-10 Dec. 2010.
[4] Christodoulopoulos K., Varvarigos E., Routing and Spectrum Allocation Policies for Time Varying Traffic in Flexible Optical Networks. *Optical Network Design and Modeling (ONDM)*, 16th International Conference, 17-20 April 2012.
[5] Sysło M.M., Deo N, Kowalik J., Discrete Optimization Algorithms: With Pascal Programs Mineola, N.Y.: Dover Publications, (2006).
[6] Olszewski I., Algorithms of Routing and Spectrum Assignment in Spectrum Flexible Transparent Optical Networks, *Przegląd Elektrotechniczny,* ISSN 0033-2097, Nr 10/2013
[7] Zhang G., Leenheer M., Morea A., Mukherjee B. A survey on OFDM-based Elastic Core Optical Networking, *IEEE Communications Surveys & Tutorials*, 15 (2013) No 1, 65-87.
[8] Takagi T., Hasegawa H., Sato K., Sone Y., Kozicki B., Hirano A. and Jinno M., Dynamic Routing and Frequency Slot Assignment for Elastic Optical Path Networks that Adopt Distance Adaptive Modulation, *Proc. OFC/NFOFC* 2011, Paper Otu17
[9] Kaufmann A., Graphs, Dynamic Programming and Finite Games, *Academic Press*, (1967), 270-280.

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