# Viable Model for Diversified Path Restoration in WDM Networks

Jovan Stosic[1] and Boris Spasenovski[2]

*Abstract* – **In this paper we deal with planning and optimization of survivable WDM networks. We investigate routing and planning of working and spare capacity for Wavelength Path and Virtual Wavelength Path networks. Models for recommendation of $k$ diversified paths and diversified path restoration for WDM networks are presented. The results show the dependency of spare capacity cost from number of $k$ recommended paths and used restoration strategy.**

*Keywords* – **WDM networks, optimization, network planning and modeling, diversified path restoration**

## I. Introduction

Most appropriate way for providing multiplexing in current optical transport networks is by WDM (Wavelength Division Multiplexing) technologies. The topic of this paper is planning and optimization of survivable WDM networks. Therefore, routing and planning of working and spare capacity are investigated. In order to determine the influence of different network parameters to the total cost of the survivable network, we've developed a tool called IOE (Integrated Object Environment) for object network modeling. Using this environment one can design the network graphical model, introduce all necessary network parameters, control the optimization process, and analyze the obtained results. Mathematical models for routing and wavelength assignment (RWA) of working and spare capacity are developed.

| s | d | a | b | deltaM | p | Fpm |
|---|---|---|---|---|---|---|
| 1 | 6 | 2 | 3 | 1 | 2 | 12 |
| 1 | 6 | 1 | 2 | 1 | 2 | 12 |
| 1 | 6 | 3 | 6 | 1 | 2 | 12 |
| 1 | 6 | 5 | 6 | 1 | 3 | 8 |
| 1 | 6 | 4 | 5 | 1 | 3 | 8 |
| 1 | 6 | 1 | 4 | 1 | 3 | 8 |
| 1 | 8 | 1 | 7 | 1 | 2 | 10 |
| 1 | 8 | 7 | 8 | 1 | 2 | 10 |

Fig. 1. Clip from the table representing links in working paths

In Section II, we present models for recommendation of $k$ diversified paths and diversified path restoration in Section III. The models are written in MPL (Mathematical Programming Language) and solved by CPLEX 7.1 MIP (Mixed Integer Programming) solver.

[1]Jovan Stosic is with Macedonian Telecommunications, MTcom, Orce Nikolov BB, 1000, Skopje, Macedonia, E-mail: jstosic@mt.net.mk

[2]Boris Spasenovski is with Faculty of Electrical Engineering, University "Ss. Cyril and Methodious", Karpos 2, 1000, Skopje, Macedonia, E-mail: boriss@etf.ukim.edu.mk

Two types of WDM networks are considered: WP (Wavelength Path) and VWP (Virtual Wavelength Path) with diversified path restoration (PRd) strategy in case of single link failure. This strategy is compared with link restoration (LR) and path restoration (PR). Results of this comparison, dependency of spare capacity cost from number of recommended $k$-MSP (Most Suitable Paths) and used restoration strategy are presented in Section IV.

## II. Model for Recommendation of $K$ Diversified Paths for Rerouting

This model is combination of $k$ shortest paths and min-max flow network problems, a kind of approach that gives two basic benefits. Firstly, it is solved with classical ILP techniques, and secondly, it is aware of links' capacities and residual network capacity that could be used for rerouting. In this model it is not important to observe the interrupted link and search for $k$-MSP for restoration. Actually in the model the interrupted link is not mentioned at all. The crucial information is the disrupted path, regardless the fact we investigate the restoration in case of one link failure. This is due to the demand for diversification. The model should recommend $k$-MSP not having link in common with working path, regardless of which link of the working path is in failure. This is realized with diversity constraint (Eq. 7). Part from an important table for VWP model is given on Fig. 1, where routing of working paths is shown. It is obvious that traffic demand of 1-6 ($sd$) pair amounting 20 units is transported over two routes (1-2-3-6 and 1-4-5-6). Index $p$ is identifying the working paths of $sd$ pair. For example, for 1-6 traffic pair $p = 2$ represents path 1-2-3-6, and $p = 3$ represents working path 1-4-5-6. For every sd pair and for each path between this nodes the model search for $k$-MSP for restoration that don't have link in common with working path. In the model we use the following decision variables that have to be adapted by means of optimization technique:

$UL_{p,k}^{m,j}$ : binary variable with value 1 if restoration route $k$ which carries part from the traffic flow of $m$-th $sd$ pair which has been passing through $p$-th working route in failure, is passing through link $j$, otherwise 0;

$PATHS_{p,k}^{m}$ : binary variable with value 1 if route $k$ is used for rerouting of $p$-th working route in failure, otherwise 0;

$FMAX$ : integer variable representing the flow of most loaded link in the network;

$HD_k^{m.p}$ : integer variable that represents the number of hops in $k$-th restoration route for $p$-th working route from $m$-th $s, d$ traffic pair. It is used in the sorting algorithm.

following parameters given from the graphical model or derived from output of previous mathematical model (i.e. model for routing and assignment of working capacities):

$d_m$ : traffic demand of $m$-th $s, d$ pair;

$\Lambda_j$ : number of wavelengths per optical fiber;

$IR_p^{m.j}$ : 1 if $p$-th working route of $m$-th $s, d$ pair passes through link $j$, otherwise 0[3];

$MF_j$ : maximal number of optical fibers per direction (total number of fibers in the cable is twice as large);

$F_j$ : flow of the working traffic through link $j$[3];

$F_p^m$ : flow of $m$-th $s, d$ pair that have been passing through $p$-th working route in failure[3];

$MaxP$ : number of different working routes per $s, d$ pair (we take the value of traffic pair that has largest number of working routes);

and following indices:

$j = \{a, b\}$ : index that represents the link $j$ $(j : 1...L)$ with adjacent nodes: $a, b$ $(a : 1...N, b : 1...N)$;

$m = \{s, d\}$ : index denoting $s, d$ pair of nodes with traffic demand equal to $d_m$ $(m : 1..M)$;

$n$ : an index that denotes the node in observed network topology $(n : 1...N)$;

$k$ : index denoting the different restoration routes;

$p$ : index denoting the different routes used for routing of working traffic.

Objective is to minimize the flow of maximally loaded link:

$$MIN \qquad FMAX \tag{1}$$

Decision variables are bounded by number of constraints which define the dependence between these variables and the given input parameters.

1) With this constraint we bound a variable that represents the flow of most loaded link.

$$FMAX \geq \sum_{m=1}^{M} \sum_{k=1}^{F_p^m} \sum_{p=1}^{MaxP} UL_{p,k}^{m,j}, \qquad \forall j. \tag{2}$$

2) The constraint given with (3) is for flow conservation. The amount of flow that enters a given node has to leave it. It should be noticed that upper bound for the number of $k$-MSP is given by the flow of $p$-th working path.

$$\sum_{\substack{b=1\\a\neq d}}^{N} UL_{p,k}^{s,d,a,b} - \sum_{\substack{b=1\\a\neq s}}^{N} UL_{p,k}^{s,d,a,b} = \begin{cases} PATH_p^{m,k} & \text{if} \quad s = a \\ -PATH_p^{m,k} & \text{if} \quad d = a \\ 0 & \text{otherwise} \end{cases}$$
$$\forall s, d, a; \qquad \forall k = 1, 2, ..., F_p^m. \tag{3}$$

[3]It is obtained as output from previously solved model for RWA of working capacity.

3) This constraint is concerning the capacity of the links and compared to the models for RWA of working traffic in the RHS (Right Hand Side) of the statement the flow allocated to the working traffic is taken in account. The number of restoration routes that pass through a given link $j$ should not be greater than the number of free wavelengths.

$$\sum_{m=1}^{M} \sum_{k=1}^{F_p^m} \sum_{p=1}^{MaxP} UL_{p,k}^{m,j} \leq MF_j \Lambda_j - F_j, \qquad \forall j. \tag{4}$$

4) For the $p$-th working path in failure the model would recommend as many $k$-MSP for rerouting as is the value of the flaw[4] for this path $(F_p^m)$.

$$\sum_{k=1}^{F_p^m} PATH_p^{m,k} = F_p^m \qquad \forall m, \forall p. \tag{5}$$

5) The constraint for symmetry in rerouting is imposed for each $p$ working path. In other words, for $p$-th working path of $sd$ traffic pair and for $p$-th working path for $ds$ traffic pair, the $k$ restoration routes should be symmetrical i.e. pass the same links but in opposite direction.

$$UL_{p,k}^{s,d,a,b} = UL_{p,k}^{d,s,b,a}$$
$$\forall s, d, a, b, p, \quad \forall k = 1, 2, ..., F_p^m. \tag{6}$$

6) This constraint is essential for the PRd models. It states that any used link in $k$-th restoration route should not be the same with any link passed by $p$-th working path.

$$UL_{p,k}^{m,j} + IR_p^{m,j} \leq 1$$
$$\forall m,\ \forall j;\ \forall k = 1, 2, ..., F_p^m;\ \forall p = 1, 2, ..., MaxP. \tag{7}$$

7) The following two constraints prevents occurrence of cycles (paths that return to the previously traversed nodes) in the $k$ recommended routes. The constraint (8) excludes the possibility for an originating node of one link to become a destination node of the restoration route, as well the possibility a termination node of one link to become a source node of the restoration route. Second constraint (9) precludes the route from using the links with same adjacent nodes but opposite directions.

$$\sum_{b=1}^{N} \sum_{k=1}^{F_p^m} UL_{p,k}^{s,d,a=d,b} + \sum_{a=1}^{N} \sum_{k=1}^{F_p^m} UL_{p,k}^{s,d,a,b=s} = 0;\ \forall s, d, p \tag{8}$$

$$UL_{p,k}^{s,d,b,a} + UL_{p,k}^{s,d,a,b} \leq 1$$
$$\forall s, d, a, b;\ \forall k = 1, 2, ..., D_x^m;\ \forall p = 1, 2, ..., MaxP. \tag{9}$$

8) The constraint (10) actually is not a constraint but only an auxiliary statement for definition of the $HD$ (Hop Distance) variable, which represent the number of hops traversed by $k$-th restoration route. It is used in an algorithm for sorting of proposed $k$-MSP by ascending number of hops.

$$HD_k^{m,p} = \sum_{j=1}^{L} UL_{p,k}^{m,j}$$
$$\forall m,\ \forall k = 1, 2, ..., F_p^m;\ \forall p = 1, 2, ..., MaxP. \tag{10}$$

[4]Unit for measurement of the flow is a wavelength.

9) Last but not least constraint is to impose integer values for some variables.

$$\begin{aligned} & UL_{p,k}^{m,j},\ PATHS_p^{m,k} \in \{0,1\}, \\ & \forall j = 1,2,...,L;\ \forall m = 1,2,...,M;\ \forall k \\ & FMAX,\ HD_k^{m,p} \in Z^+ \end{aligned} \quad (11)$$

From $UL_{p,k}^{m,j}$ variable by means of database programming we generate table containing links in failure. The link in failure is represented by two dimensional index $x = \{e, f\}$. Namely, in the PR and PRd models the paths to be restored are identified by the link in failure $(x)$ and by the order number $(m)$ they have occupied in that link. In Fig. 2 parts of two tables are shown: a) recommendation of $k$-MSP for PRd model and b) recommendation of $k$-MSP for PR model. Considering that working path 3-4 is routed through 3-8-4 the recommended diversified k-MSP should not pass through links 3-8 and 8-4. This condition (Fig. 2a) is fulfilled in the case of model for recommendation of diversified routes and not fulfilled for model with non-diversified routes (Fig. 2b). In second case this is confirmed by the fact that link 8-4 is used in the $k = 2$ and $k = 4$ recommended restoration routes.

a)

| s | d | a | b | k | dm | p | m | e | f | HD |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 4 | 2 | 1 | 1 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 1 | 4 | 1 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 3 | 2 | 1 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 2 | 7 | 2 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 7 | 4 | 2 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 3 | 2 | 2 | 6 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 3 | 6 | 3 | 3 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 5 | 4 | 3 | 3 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 6 | 5 | 3 | 3 | 1 | 1 | 3 | 8 | 3 |
| 3 | 4 | 8 | 5 | 4 | 3 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 6 | 8 | 4 | 3 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 3 | 6 | 4 | 3 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 5 | 4 | 4 | 3 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 3 | 2 | 5 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 8 | 7 | 5 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 2 | 8 | 5 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 7 | 4 | 5 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 3 | 6 | 6 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 8 | 7 | 6 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 6 | 8 | 6 | 1 | 1 | 1 | 3 | 8 | 4 |
| 3 | 4 | 7 | 4 | 6 | 1 | 1 | 1 | 3 | 8 | 4 |

b)

| s | d | a | b | k | dm | m | e | f |
|---|---|---|---|---|---|---|---|---|
| 3 | 4 | 6 | 5 | 1 | 9 | 1 | 3 | 8 |
| 3 | 4 | 3 | 6 | 1 | 9 | 1 | 3 | 8 |
| 3 | 4 | 5 | 4 | 1 | 9 | 1 | 3 | 8 |
| 3 | 4 | 3 | 6 | 2 | 2 | 1 | 3 | 8 |
| 3 | 4 | 6 | 8 | 2 | 2 | 1 | 3 | 8 |
| 3 | 4 | 8 | 4 | 2 | 2 | 1 | 3 | 8 |
| 3 | 4 | 3 | 2 | 3 | 4 | 1 | 3 | 8 |
| 3 | 4 | 2 | 7 | 3 | 4 | 1 | 3 | 8 |
| 3 | 4 | 7 | 4 | 3 | 4 | 1 | 3 | 8 |
| 3 | 4 | 8 | 4 | 4 | 1 | 1 | 3 | 8 |
| 3 | 4 | 2 | 8 | 4 | 1 | 1 | 3 | 8 |
| 3 | 4 | 3 | 2 | 4 | 1 | 1 | 3 | 8 |
| 3 | 4 | 2 | 1 | 5 | 4 | 1 | 3 | 8 |
| 3 | 4 | 1 | 4 | 5 | 4 | 1 | 3 | 8 |
| 3 | 4 | 3 | 2 | 5 | 4 | 1 | 3 | 8 |

Fig. 2. Recommendation of k-MSP for PRd and PR models: a) diversified routing; b) non-diversified routing

## III. Model for Diversified Path Restoration

Chosen paths by the models for recommendation of $k$-MSP for rerouting are feasible but not optimal. Optimization task is done by the model for diversified path restoration (PRd) which uses recommended paths as input parameters. Actually we use well known "non-diversified" PR model as presented in [2], i.e. [1]. The objective of optimization is to minimize the total cost of network resources used for spare capacity assignment, with requirement of 100% survivability in case of single link failure. For VWP models it is presented by following objective function:

$$MIN \sum_{j=1}^{L} (\beta_j SF_j + \gamma_j SC_j) + \sum_{n=1}^{N} \sum_{i=1}^{I} C_i \delta_i^n \quad (12)$$

while for WP network:

$$MIN \sum_{j=1}^{L} \left( \beta_j SF_j + \gamma_j \sum_{\lambda=1}^{\Lambda} SC_\lambda^j \right) + \sum_{n=1}^{N} \sum_{i=1}^{I} C_i \delta_i^n \quad (13)$$

where: $SF_j$ is variable that represents the number of spare optical fibers in link $j$; $SC_j$ is variable that represents the number of spare optical channels in link $j$; $SC_\lambda^j$ is variable that represents the number of spare optical channels on wavelength $\lambda$ in link $j$; $\delta_i^n$ is variable denoting the type $i$ of the node $n$; $\beta_j, \gamma_j$ are parameters denoting the cost of the link ($\beta$ is cost related to a fiber and $\gamma$ to a channel); $C_i$ cost of using the node of type $i$.

The constraints bounding the variables are based on the constraints presented in [2] and are thoroughly elaborated in [1]. One crucial constraint that is important for understanding the model for VWP is:

$$SC_j \geq \sum_m \sum_p \delta_{m,p}^{j,x} F_p^{x,m} \quad \forall j,\ \forall x, j \neq x \quad (14)$$

and for WP network:

$$SC_{j,\lambda} \geq \sum_m \sum_p \delta_{m,p}^{j,x} F_{p,\lambda}^{x,m} \quad \forall j,\ \forall x,\ \forall \lambda, j \neq x \quad (15)$$

where: $F_p^{x,m}$ is variable representing the flow of $p$-th restoration route for $m$-th working path which has been passing through $x$-th interrupted link; $F_{p,\lambda}^{x,m}$ is variable denoting the flow of $p$-th restoration route for $m$-th path on wavelength $\lambda$ which has been passing through $x$-th interrupted link; $\delta_{m,p}^{j,x}$ is binary parameter with value 1 if the $p$-th restoration route for $m$-th path passing through $x$-th interrupted link is using link $j$, otherwise 0; $m$ is index denoting the working path with traffic demand $d_m^x$ which has been passing through $x$-th interrupted link. It doesn't contain information for $s, d$ traffic pair but enumerates paths that have been passing through $x$-th interrupted link; $x$ is index denoting the interrupted link.

In PR and PRd models it is possible to reuse the capacity that is released by working path in failure. In this case the LHS of the constraints (14) and (15) should be augmented by this capacity.

| s | d | a | b | Fxmp | m | p | e | f |
|---|---|---|---|---|---|---|---|---|
| 3 | 4 | 2 | 1 | 9 | 1 | 1 | 3 | 8 |
| 3 | 4 | 1 | 4 | 9 | 1 | 1 | 3 | 8 |
| 3 | 4 | 3 | 2 | 9 | 1 | 1 | 3 | 8 |
| 3 | 4 | 7 | 4 | 5 | 1 | 2 | 3 | 8 |
| 3 | 4 | 2 | 7 | 5 | 1 | 2 | 3 | 8 |
| 3 | 4 | 3 | 2 | 5 | 1 | 2 | 3 | 8 |
| 3 | 4 | 3 | 6 | 6 | 1 | 3 | 3 | 8 |
| 3 | 4 | 5 | 4 | 6 | 1 | 3 | 3 | 8 |
| 3 | 4 | 6 | 5 | 6 | 1 | 3 | 3 | 8 |

Fig. 3. Part of the path rerouting table

On Fig. 3 it is shown that traffic demand of path 3-4 in case of failure of link 3-8 would be rerouted over three restoration routes (3-2-1-4, 3-2-7-4, 3-6-5-4). These three routes are chosen from the six recommended routes (Fig. 2) in order to minimize the total cost of spare capacity.

## IV. Results

Fig. 4 depicts the studied network. We have chosen an arbitrary physical topology and arbitrary traffic matrix. By means

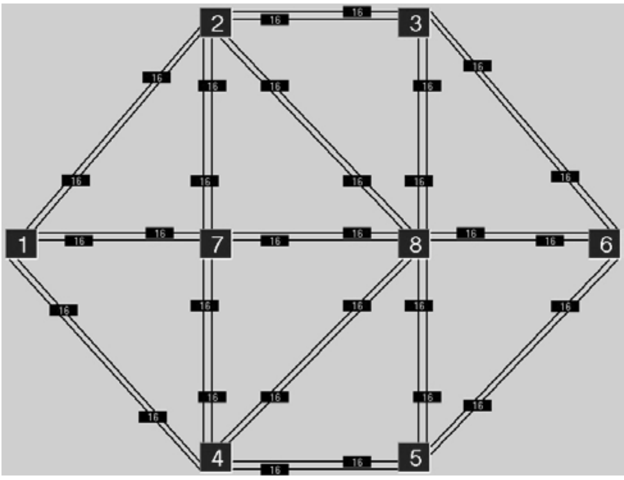


Fig. 4. Topology of the observed network

of IOE other physical topologies and traffic matrices could be easily constructed.

Dependency of the cost of spare capacity from the number of recommended $k$-MSP for rerouting is shown on Fig. 6. The costs are in arbitrary currency. On same figure, beside PRd and PR models results for LR are given. For WP PRd and PR models two cases are considered: case where optical transmitters and receivers are tunable, and the restoration route on another wavelength can be used (WPa), and case where transmitter wavelength is fixed and the restoration route must be found on the same wavelength (WPb). It is found that by increasing of the considered $k$-MSP for rerouting, the cost of spare capacities could be up to 20% decreased. Increasing of $k$ above 3 gives very small reduction of costs (less then 10%); however more computational effort is required. By imposing the integer constraints (Eq. 11) CPLEX solver automatically uses MIP strategies for solving the problems. Used algorithm is branch and cut (B&C). Sometimes, for WPa models getting an optimal integer solution takes more time, therefore the B&C algorithm has to be stopped on $n$-th feasible integer solution. However for considered network B&C algorithm had found an optimal solu-

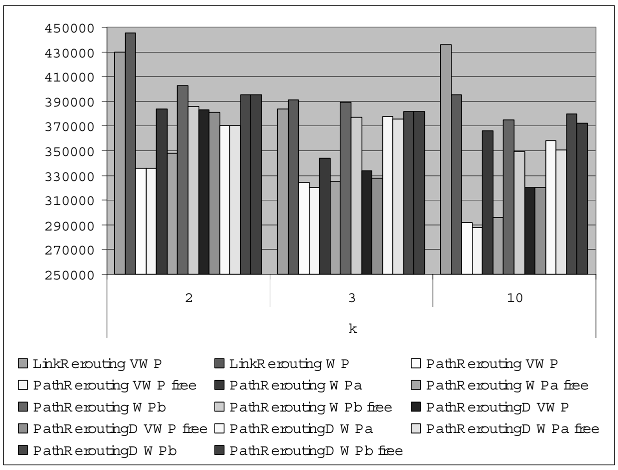


Fig. 5. Network cost dependency from $k$-MSP

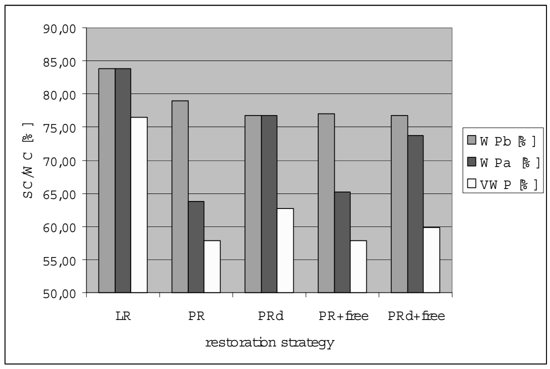


Fig. 6. Network cost dependency from restoration strategy

tions in reasonable time period (not larger then 30 min on Pentium III with 128 MB RAM). We obtained these results with default CPLEX settings except we applied a rounding heuristic on every 5th node.

We stress again that obtained results strongly depend from network meshing degree and traffic matrix. Greater benefit could be gained from using higher value for $k$-MSP in networks with larger meshing degree and larger traffic demands. From Fig. 5 it is obvious that the difference in cost of spare capacity between PR and PRd is negligible (also see Fig. 6). The difference is smaller for lower number of $k$-MSP. The fact that diversified path restoration starts the restoration in case of any link failure affecting the specific path, in authors' opinion is great advantage for implementation in the network management by using the current transport networks' control plane standards. Therefore we think investing in a bit more expensive spare capacity for diversified path restoration is worth of having easier implementation.

On Fig. 6 the dependency of the cost of the network from the used restoration strategy is shown. The results are expressed as ratio between spare and working optical channels. From aspect of largest requirement of spare capacity link restoration is most expensive. PR and PRd strategies are cheaper. In PR and PRd strategies by using of released capacity of the disrupted paths extra saving of capacity could be gained (PR+free, PRd+free). Moreover large difference between PRd VWP and WPa models is determined (much larger compared to PR) i.e. using of wavelength converters in PRd models could be justified. One more reason for using of PRd VWP models instead PRd WPa models is latter's long computation time.

## V. Conclusions

In this paper routing and planning of working and spare capacity in WDM networks are investigated with specific approach for diversified path restoration. This strategy was compared with link restoration and path restoration. The model for diversified path restoration is presented as model that gives results similar to path restoration technique, and is most practical for implementation in present transport networks. Although it might give even greater benefit in networks with larger line system, the use of wavelength converters in diversified path restoration networks is justified.

## References

[1] Jovan Stosic, “Modeling, planning and optimization of survivable WDM networks” – Masters thesis, Faculty of Electrical Engineering, University “Ss. Cyril and Methodious”, Skopje, Macedonia, November 2002.

[2] Bart Van Caenegem, Wim Van Parys, Filip De Turck, and Piet M. Demeester, “Dimensioning of Survivable WDM Networks”, *IEEE Journal on Selected Areas In Communications*, vol. 16, No.7, September 1998.

[3] Biswanath Mukherjee, “Optical Communication Network,” McGraw-Hill, 1997.