A Novel Genetic Approach to Provide Differentiated Levels of Service Resilience in IP-MPLS/WDM Networks

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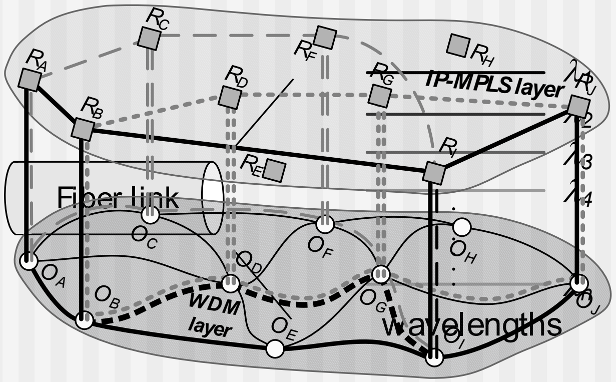
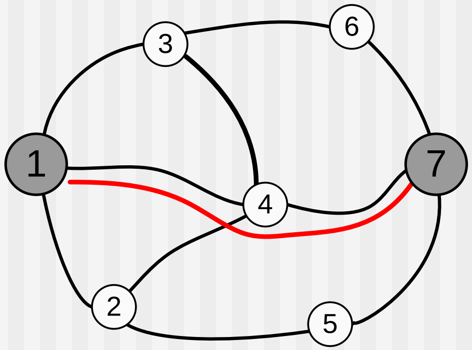
The Agenda

- Survivability Issues in Multilayer Networks
- The Need for Differentiated Protection
- Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks
- Modeling Results
- Concluding Remarks

Survivability Issues in Multilayer Networks

- IP-MPLS/WDM network survivability
- WDM (Wavelength Division Multiplexing):
  - each link consists of a set of channels (i.e. wavelengths)
  - each channel is capable of transmitting the data independently at a speed of a few Gbps
  - data transmission is performed by means of connections

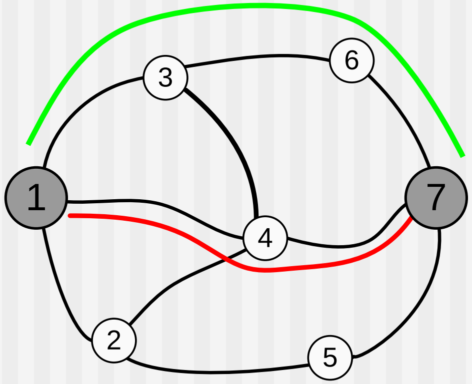




- Any failure may lead to severe data and revenue loses

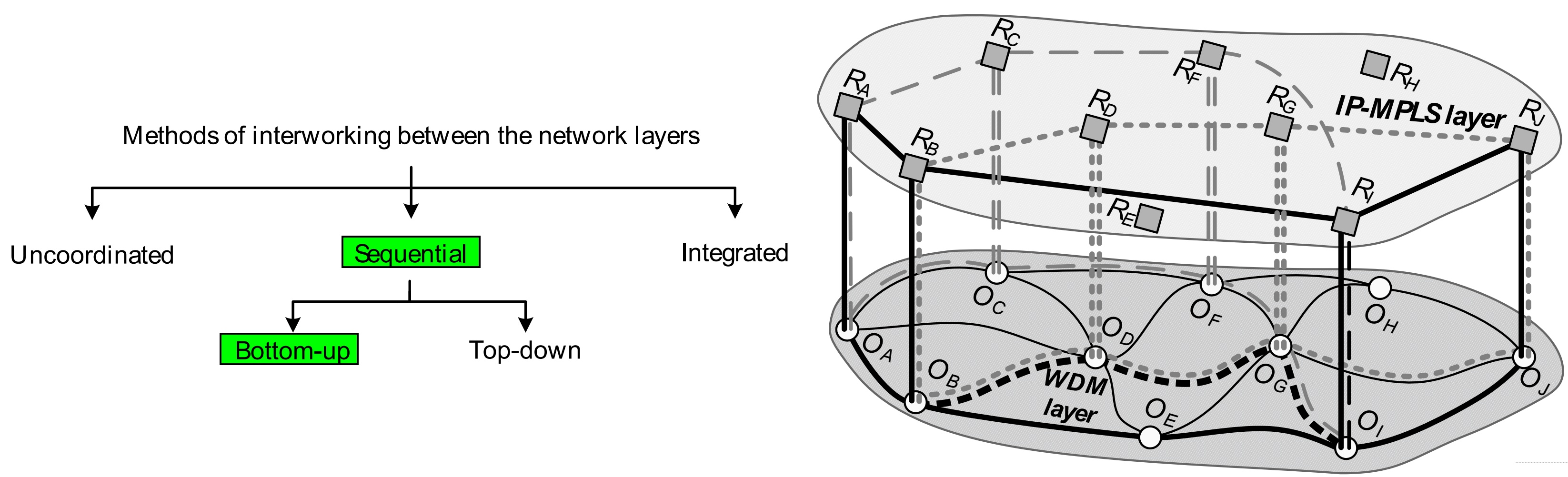
Survivability Issues in Multilayer Networks

- survivability: the capability to deliver services in the presence of failures
- utilization of backup paths to provide protection for working paths
- path, segment, link protection against a **node**/link **failure**



Survivability Issues in Multilayer Networks

- in a multilayer network each network layer may have its own recovery scheme
- it is often necessary to make these schemes cooperate with each other



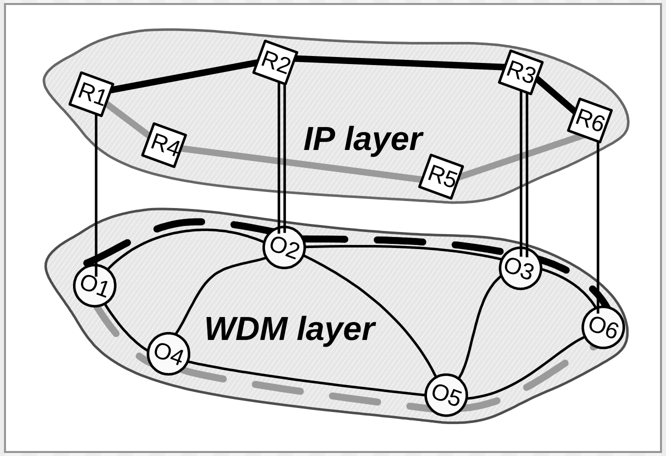
The Need for Differentiated Protection

- provisioning the differentiated levels of survivability is necessary in order to respond to heterogeneous demands of end-users
- Client-imposed factors include:
  - the willingness to pay for service (low-priced best-effort services or high quality of service, e.g. for the real-time data transmission)
  - the availability requirements, which may be application-dependent (high tolerance of service unavailability: e.g. e-mail service, file transfer; 100% restorability requirement: military, medical applications)

Providing only one level of service recovery is highly uneconomical, since most of the service is overprovisioned

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

- we consider a survivable IP-MPLS-over-OTN-WDM network protected against a single node failure
- demands for IP-MPLS flows are given



- *M* service classes are assumed, numbered from 0 to *M*-1.
- class 0 represents the demands for which all the service recovery actions must be performed as fast as possible (i.e**. in WDM layer** only).
- for other (lower priority) classes, the restoration time values may increase (i.e. recovery actions may also take place in the IP-MPLS layer)
- the respective optimization problem is **NP-Complete**

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

ILP Formulation of the Problem

objective

It is to find the paths transporting the required IP-MPLS flows from sources to destinations, protecting them against a single node failure with the scope of backup path protection comprising two consecutive links of working paths in both the IP-MPLS and the WDM layer, and minimizing the linear cost:

$$\varphi(x) = \sum_{r=1}^{|V_R|}\sum_{l=1}^{\Lambda}\sum_{k=1}^{|A|}\sum_{\epsilon=1}^{|\vartheta|}\left(\xi_k \rho_r^{k,l} + \hat{\xi}_k \psi_{r,\epsilon}^{k,l} + \hat{\hat{\xi}}_k \varsigma_r^{k,l}\right) \quad (6.1)$$

constraints:

a) on the number of allowed transmitters and receivers at each IP-MPLS layer node:

$$\sum_{\substack{r\in\{r:v_r\equiv(n,j,o)\in V_R;\\ j=1,2,\dots,N;\\ o=1,2,\dots,O;\, j\neq n\}}} \varpi_r \le TR_n \quad (6.2)$$

$$\sum_{\substack{r\in\{r:v_r\equiv(i,n,o)\in V_R;\\ i=1,2,\dots,N;\\ o=1,2,\dots,O;\, i\neq n\}}} \varpi_r \le RV_n \quad (6.3)$$

where: $v_r = (i, n, o)$ = virtual arc incident into a node n; $v_r = (n, j, o)$ = virtual arc incident out of a node n; $n = 1, 2, \dots, |N|$

b) flow conservation constraints of the primary LSPs in the IP-MPLS layer:

$$\sum_{\substack{r\in\{r:v_r\equiv(n,j,o)\in V_R;\\ j=1,2,\dots,N;\\ o=1,2,\dots,O;\, j\neq n\}}} \omega_r^t - \sum_{\substack{r\in\{r:v_r\equiv(i,n,o)\in V_R;\\ i=1,2,\dots,N;\\ o=1,2,\dots,O;\, i\neq n\}}} \omega_r^t = \begin{cases} 1 & if \quad n = p_t \\ -1 & if \quad n = q_t \\ 0 & \text{otherwise} \end{cases} \quad (6.4)$$

where: $v_r = (i, n, o)$ = o-th virtual arc incident into node n; $v_r = (n, j, o)$ is a virtual arc incident out of node n; $t = 1, 2, \dots, |D_{IP}|$; $n = 1, 2, \dots, |N|$;

c) flow conservation constraints of the backup LSPs protecting a given transit node $n(\vartheta_\epsilon)$ in the IP-MPLS layer:

$$\sum_{\substack{r\in\{r:v_r\equiv(n,j,o)\in V_R;\\ j=1,2,\dots,N;\\ o=1,2,\dots,O;\, j\neq n\}}} \upsilon_r^{t,\epsilon} - \sum_{\substack{r\in\{r:v_r\equiv(i,n,o)\in V_R;\\ i=1,2,\dots,N;\\ o=1,2,\dots,O;\, i\neq n\}}} \upsilon_r^{t,\epsilon} = \begin{cases} \left\lfloor \dfrac{\omega_p^t+\omega_q^t}{2} \right\rfloor & if \quad n = src(\vartheta_\epsilon),\ v_p = (src(\vartheta_\epsilon), n(\vartheta_\epsilon)),\ v_q = (n(\vartheta_\epsilon), dst(\vartheta_\epsilon)) \\ -\left\lfloor \dfrac{\omega_p^t+\omega_q^t}{2} \right\rfloor & if \quad n = dst(\vartheta_\epsilon),\ v_p = (src(\vartheta_\epsilon), n(\vartheta_\epsilon)),\ v_q = (n(\vartheta_\epsilon), dst(\vartheta_\epsilon)) \\ 0 & \text{otherwise} \end{cases} \quad (6.5)$$

where: $v_r = (i, n, o)$ = o-th virtual arc incident into a node n; $v_r = (n, j, o)$ is a virtual arc incident out of a node n; $\epsilon = 1, 2, \dots, |\vartheta|$; $t = 1, 2, \dots, |D_{IP}|$; $n = 1, 2, \dots, |N|$;

d) constraints to ensure that every backup LSP is node-disjoint with a given part of each working LSP it protects:

$$\sum_{\substack{r\in\{r:v_r\equiv(n,j,o)\in V_R;\\ j=1,2,\dots,N;\\ o=1,2,\dots,O;\, j\neq n\}}} (\omega_r^t + \upsilon_r^{t,\epsilon}) \le 1 \quad (6.6)$$

$$\sum_{\substack{r\in\{r:v_r\equiv(i,n,o)\in V_R;\\ i=1,2,\dots,N;\\ o=1,2,\dots,O;\, i\neq n\}}} (\omega_r^t + \upsilon_r^{t,\epsilon}) \le 1 \quad (6.7)$$

where: $n = n(\vartheta_\epsilon)$; $t = 1, 2, \dots, |D_{IP}|$; $\epsilon = 1, 2, \dots, |\vartheta|$;

e) constraint on the maximum amount of flow to be served by a single virtual IP arc:

$$\sum_{t=1}^{|D_{IP}|}\left(\omega_r^t \cdot f(\mu_t)\right) + \sum_{t=1}^{|D_{IP}|}\sum_{\epsilon=1}^{|\vartheta|}\left(\upsilon_r^{t,\epsilon} \cdot f(\mu_t)\right) \le \varpi_r \cdot f \quad (6.8)$$

$r = 1, 2, \dots, |V_R|$

f) flow conservation constraints in the physical topology for each working lightpath of a virtual arc v_r:

$$\sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(n,j)\in A;\\ j=1,2,\dots,N;\, j\neq n\}}} \rho_r^{k,l} - \sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(i,n)\in A;\\ i=1,2,\dots,N;\, i\neq n\}}} \rho_r^{k,l} = \begin{cases} \varpi_r & if \quad n = s_r \\ -\varpi_r & if \quad n = t_r \\ 0 & \text{otherwise} \end{cases} \quad (6.9)$$

where: $a_k = (i, n)$ = arc incident into a node n; $a_k = (n, j)$ = arc incident out of a node n; $r = 1, 2, \dots, |V_R|$; $n = 1, 2, \dots, |N|$

g) flow conservation constraints in the physical topology for each backup lightpath of a virtual arc v_r:

$$\sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(n,j)\in A;\\ j=1,2,\dots,N;\, j\neq n\}}} \psi_{r,\epsilon}^{k,l} - \sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(i,n)\in A;\\ i=1,2,\dots,N;\, i\neq n\}}} \psi_{r,\epsilon}^{k,l} = \begin{cases} \left\lfloor \dfrac{\sum_l \rho_p^{k,l} + \sum_l \rho_q^{k,l}}{2} \right\rfloor & if \quad n = src(\vartheta_\epsilon),\ a_p = (src(\vartheta_\epsilon), n(\vartheta_\epsilon)),\ a_q = (n(\vartheta_\epsilon), dst(\vartheta_\epsilon)) \\ -\left\lfloor \dfrac{\sum_l \rho_p^{k,l} + \sum_l \rho_q^{k,l}}{2} \right\rfloor & if \quad n = dst(\vartheta_\epsilon),\ a_p = (src(\vartheta_\epsilon), n(\vartheta_\epsilon)),\ a_q = (n(\vartheta_\epsilon), dst(\vartheta_\epsilon)) \\ 0 & \text{otherwise} \end{cases} \quad (6.10)$$

where: $a_k = (i, n)$ = arc incident into a node n; $a_k = (n, j)$ = arc incident out of a node n; $\epsilon = 1, 2, \dots, |\vartheta|$; $r = 1, 2, \dots, |V_R|$; $n = 1, 2, \dots, |N|$

h) flow conservation constraints in the physical topology for the unprotected backup LSP:

$$\sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(n,j)\in A;\\ j=1,2,\dots,N;\, j\neq n\}}} \varsigma_r^{k,l} - \sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(i,n)\in A;\\ i=1,2,\dots,N;\, i\neq n\}}} \varsigma_r^{k,l} = \begin{cases} \upsilon_r^{t,\epsilon} & if \quad n = s_r \\ -\upsilon_r^{t,\epsilon} & if \quad n = t_r \\ 0 & \text{otherwise} \end{cases} \quad (6.11)$$

where: $a_k = (i, n)$ = arc incident into a node n; $a_k = (n, j)$ = arc incident out of a node n; $r = 1, 2, \dots, |V_R|$; $n = 1, 2, \dots, |N|$; $\epsilon = 1, 2, \dots, |\vartheta|$; $t = 1, 2, \dots, |D_{IP}|$

i) constraints to ensure that every backup lightpath is node-disjoint with its working lightpath:

$$\sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(n,j)\in A;\\ j=1,2,\dots,N;\, j\neq n\}}} (\rho_r^{k,l} + \psi_{r,\epsilon}^{k,l}) \le 1 \quad (6.12)$$

$$\sum_{l=1}^{\Lambda}\sum_{\substack{k\in\{k:a_k\equiv(i,n)\in A;\\ i=1,2,\dots,N;\, i\neq n\}}} (\rho_r^{k,l} + \psi_{r,\epsilon}^{k,l}) \le 1 \quad (6.13)$$

where: $r = 1, 2, \dots, |V_R|$; $n = n(\vartheta_\epsilon)$; $\epsilon = 1, 2, \dots, |\vartheta|$

j) constraints on finite capacity of physical arcs:

$$\sum_{l=1}^{\Lambda}\sum_{r=1}^{|V_R|}\rho_r^{k,l} + \sum_{l=1}^{\Lambda}\sum_{r=1}^{|V_R|}\sum_{\epsilon=1}^{|\vartheta|}\left(\varsigma_r^{k,l} + \psi_{r,\epsilon}^{k,l}\right) \le \Lambda \quad (6.14)$$

where: $k = 1, 2, \dots, |A|$

k) constraints on the allowed relations between values of variables:

$$\rho_r^{k,l} \le \Upsilon_k \quad (6.15)$$

$$\rho_r^{k,l} \le \varpi_r \quad (6.16)$$

$$\psi_{r,\epsilon}^{k,l} \le \Upsilon_k \quad (6.17)$$

$$\psi_{r,\epsilon}^{k,l} \le \varpi_r \quad (6.18)$$

$$\varsigma_r^{k,l} \le \Upsilon_k \quad (6.19)$$

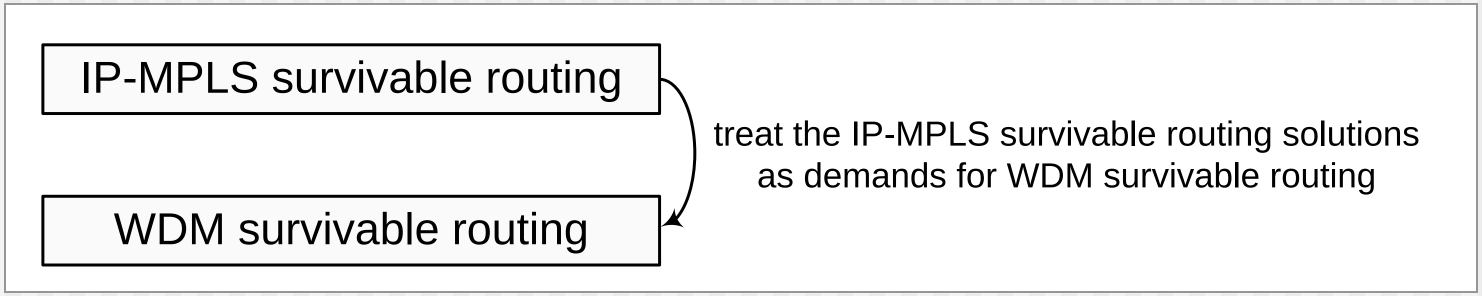
$$\varsigma_r^{k,l} \le \varpi_r \quad (6.20)$$

where: $k = 1, 2, \dots, |A|$; $l = 1, 2, \dots, \Lambda$; $r = 1, 2, \dots, |V_R|$; $\epsilon = 1, 2, \dots, |\vartheta|$;

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

We divide the IP/WDM survivable routing problem into two subproblems:

1) survivable IP-MPLS routing
   - determining the IP virtual topology
   - finding the survivable routing of IP layer demands
2) survivable WDM routing
   - lightpath routing
   - wavelength assignment



Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

SUBPROBLEM 1 - IP-MPLS Survivable Routing

The number of active LSP links depends on the service class *m* and is determined as:

$$r_m = \left\lceil \frac{l_c - 1}{M - 1} \times m + 1 \right\rceil$$

where: l_c is the number of links of the end-to-end shortest path between the given pair of source *s* and destination *d* nodes in the WDM layer,

m is the class of a demand,

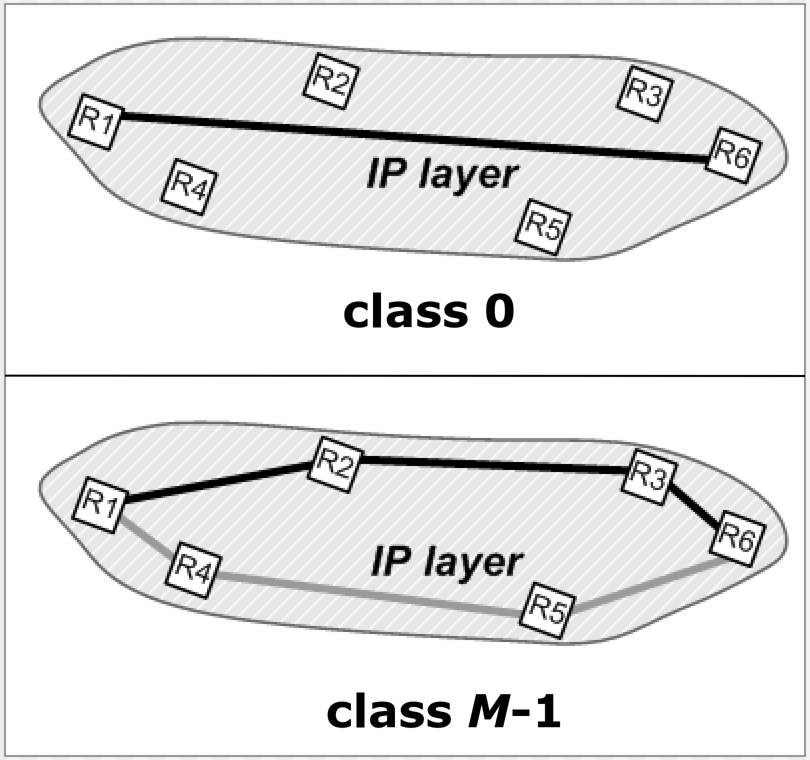
M is the number of service classes

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

SUBPROBLEM 1 - IP-MPLS Survivable Routing

$$r_m = \left\lceil \frac{l_c - 1}{M - 1} \times m + 1 \right\rceil$$

- any working LSP for the **class *m* = 0** is realized by a direct IP-MPLS link implying that **no IP-MPLS recovery actions will take place**
- for **class *m* = *M*-1** each working LSP link will be mapped onto a single-link WDM lightpath, **implying frequent recovery actions at the IP-MPLS layer**.



Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

SUBPROBLEM 2 - Survivable WDM Routing

- the IP demands are groupped into service classes on IP-MPLS links and mapped onto the protected lightpaths
- The scope of WDM protection depends on the service class number *m*
- For that purpose the number of backup lightpaths protecting the given working lightpath is determined as:

$$b_m = \left\lceil -\frac{l_c - 1}{M - 1} \times m + l_c - 1 \right\rceil$$

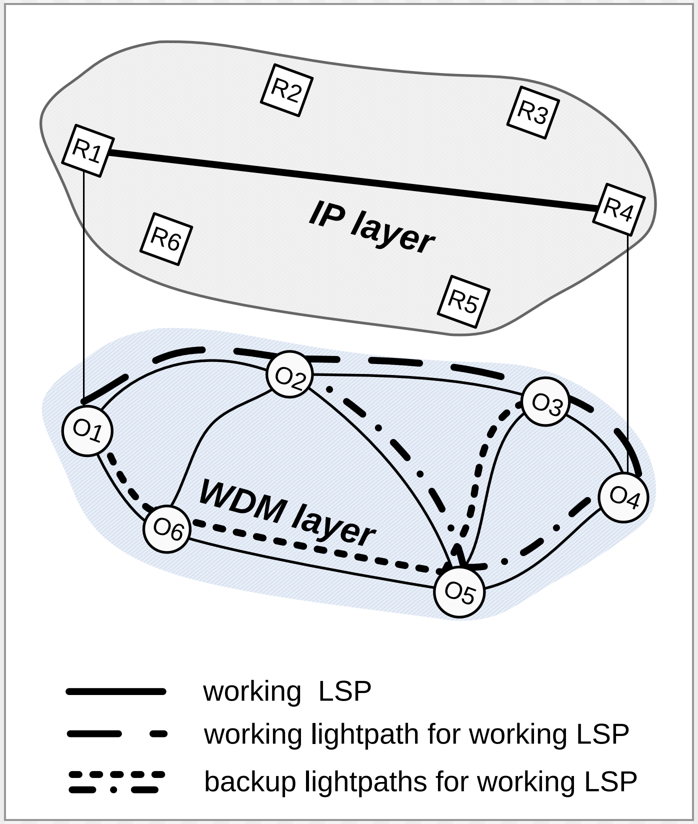
Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

SUBPROBLEM 2 - Survivable WDM Routing

$$b_m = \left\lceil -\frac{l_c - 1}{M - 1} \times m + l_c - 1 \right\rceil$$

For the highest **class *m* = 0**:

- each two adjacent WDM links of the working lightpath are protected by a backup lightpath providing **fast service recovery**
- No recovery actions are performed at the IP-MPLS layer



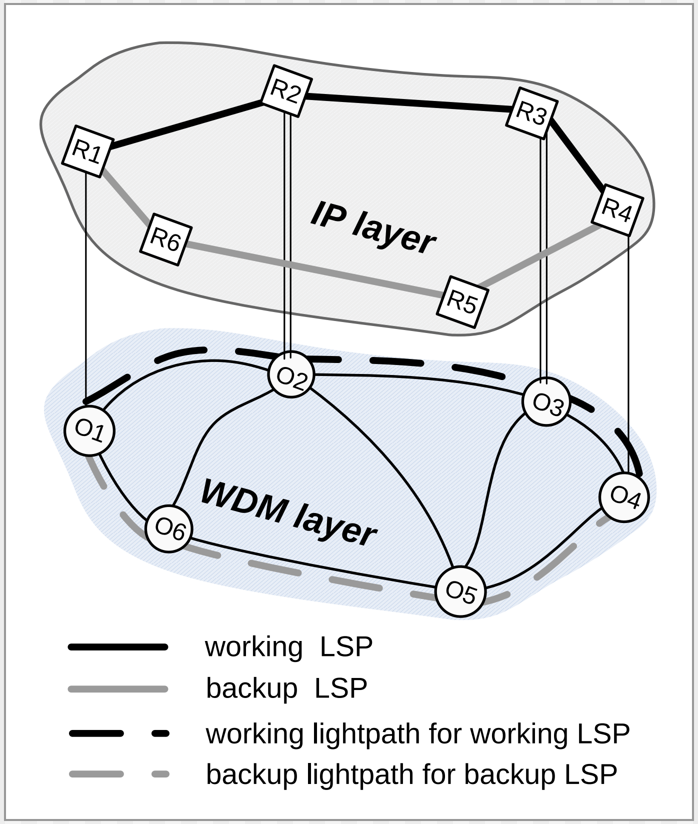
Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

SUBPROBLEM 2 - Survivable WDM Routing

$$b_m = \left\lceil -\frac{l_c - 1}{M - 1} \times m + l_c - 1 \right\rceil$$

For the lowest **class *m* = *M*-1**:

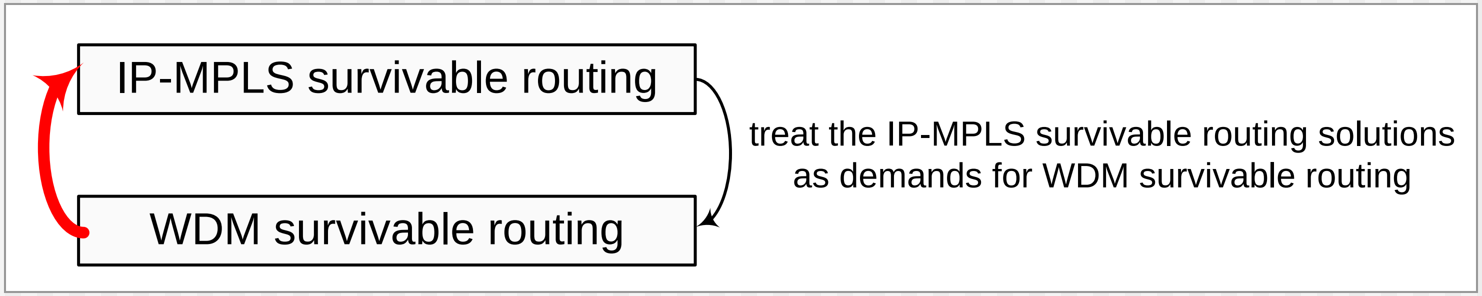
- there is no backup lightpath
- all the recovery actions must be performed at the IP-MPLS layer



Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

Genetic Approach

- finding the solution to the survivable IP-MPLS routing problem in each network layer separately certainly leads to suboptimal solutions

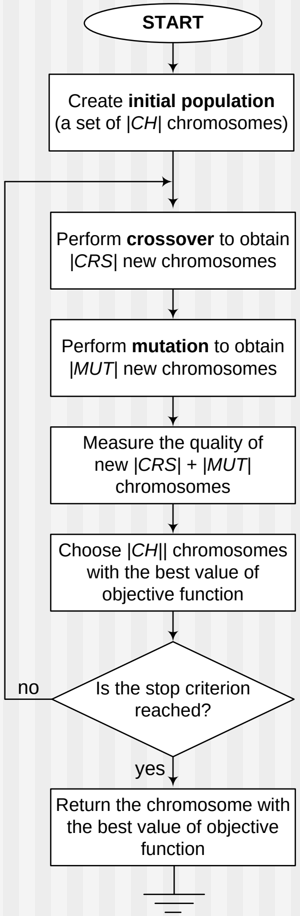


- the use the metaheuristic approach based on genetic programming to improve the quality of results by solving the problem iteratively

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

Genetic Approach

- initial **population** of |*CH*| **chromosomes**
- obtaining new (|*CRS*| and |*MUT*|) chromosomes in a **crossover** and **mutation** operations
- crossover: two chromosomes, randomly chosen from the current population, are used to produce a new pair of chromosomes
- mutation: makes changes within an individual chromosome, randomly chosen from the population chromosomes
- selection of best |*CH*| chromosomes out of |*CH*| + |*CRS*| + |*MUT*| as a next population



Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

Genetic Approach

- **chromosome**: formed by a matrix Ξ of costs ξ_h of arcs $a_h = (i, j)$ used when finding the working and backup LSPs

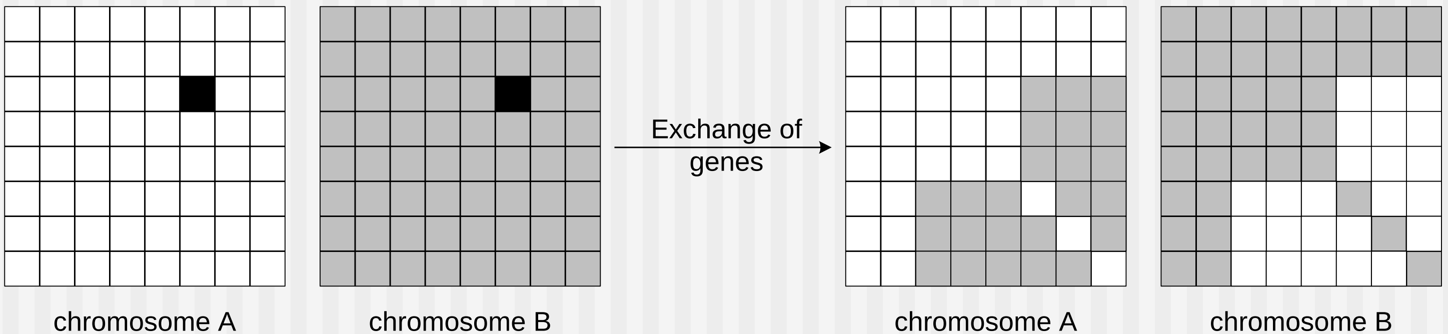
  The quality of a chromosome was measured in terms of the total link capacity utilization ratio by finding the solution to the respective IP-MPLS/WDM survivable routing problem

- **initial population** of $|CH|$ chromosomes was formed by $|CH|$ matrices Ξ of arc costs ξ_h, each matrix obtained by introducing the random modifications to the matrix Ξ of the reference costs ξ_h of WDM arcs a_h

Proposed Approach to Provide Differentiated Levels of Survivability in IP-MPLS/WDM Networks

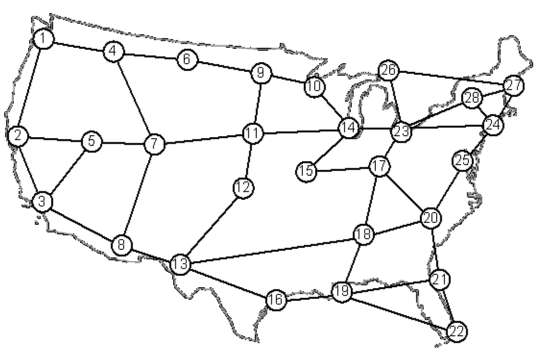
Genetic Approach

- **mutation**: a randomly chosen gene $ge_1 = (i, j)$ of a given randomly chosen chromosome, being the respective cost of a given arc $a_h = (i, j)$, was set a random value from the set $(0, \xi^{MAX})$, where ξ^{MAX} was the length of the longest arc in the WDM layer
- **crossover** was performed on a pair of randomly chosen chromosomes ch_A and ch_B assumed the exchange of parts of the symmetric matrix Ξ of arc costs

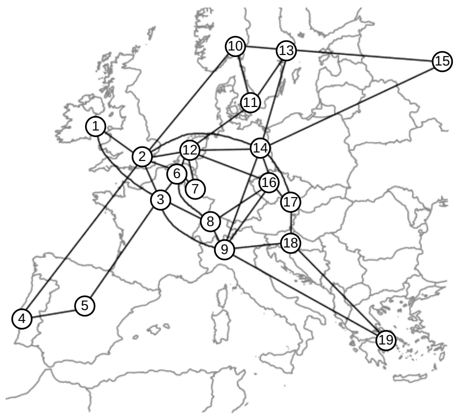


Modeling Assumptions

- modeling was performed for the U.S. Long-Distance Network, and European COST 239 Network, NSF Network and Italian Network
- simulations were to measure:
  - the link capacity utilization ratio
  - the number of broken connections restored at the IP and WDM layers
  - the values of connection restoration time



U.S. Long-Distance Network



European COST 239 Network

Modeling Assumptions

- modeling was performed for the U.S. Long-Distance Network, and European COST 239 Network, NSF Network and Italian Network
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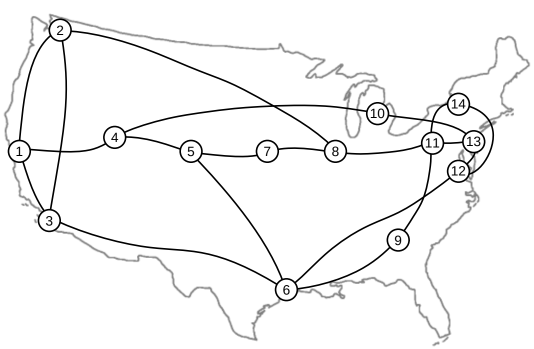
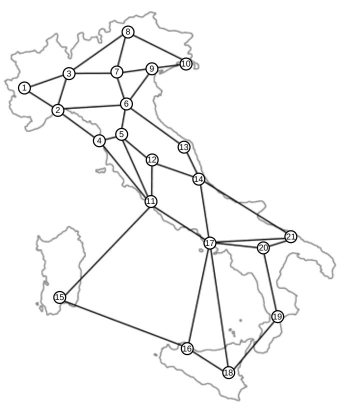


NSF Network



Italian Network

Modeling Assumptions

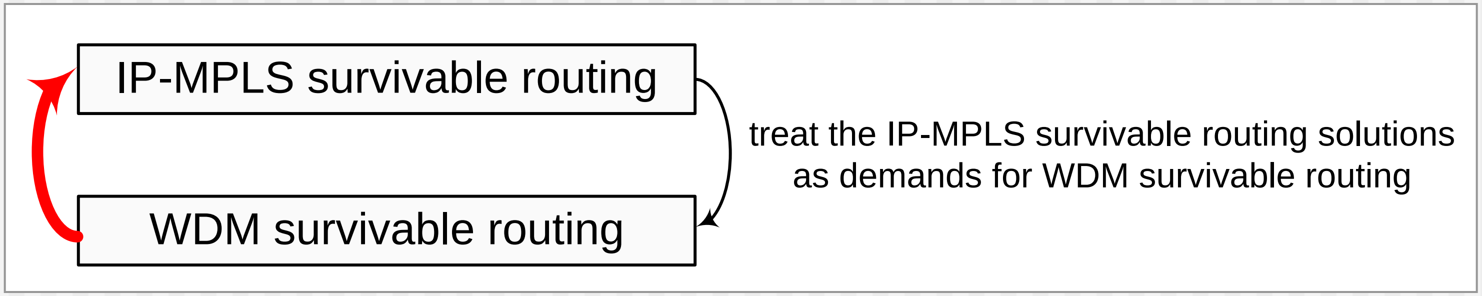
- all the WDM layer links were assumed to have 32 channels
- channel capacity unit was considered to be the same for all the network links
- optical nodes were assumed to have a full wavelength conversion capability
- the IP link propagation delay to be equal to the aggregate delay of the respective WDM lightpath realizing this IP link
- the size of a demand set consisting od 25% and 100% of randomly chosen network node pairs

Modeling Assumptions

- demands from M = 5 service classes with protection against a single node failure,
- the demanded capacity equal to 1/8 of the WDM channel capacity,
- provisioning 100% of the requested bandwidth after a network element failure,
- a demand to assure unsplittable flows in both IP and WDM layer,
- the distance metrics
- Using the Dijkstra’s shortest path algorithm to find the the unprotected lightpaths for the backup LSP links
- The Bhandari’s algorithm of finding k-node disjoint paths (here k = 2) in all other cases
- the three-way handshake protocol of service restoration in WDM layer (the exchange of LINK FAIL, SETUP and CONFIRM messages)

Modeling Assumptions

- number of generated populations set to *ic* = 1000



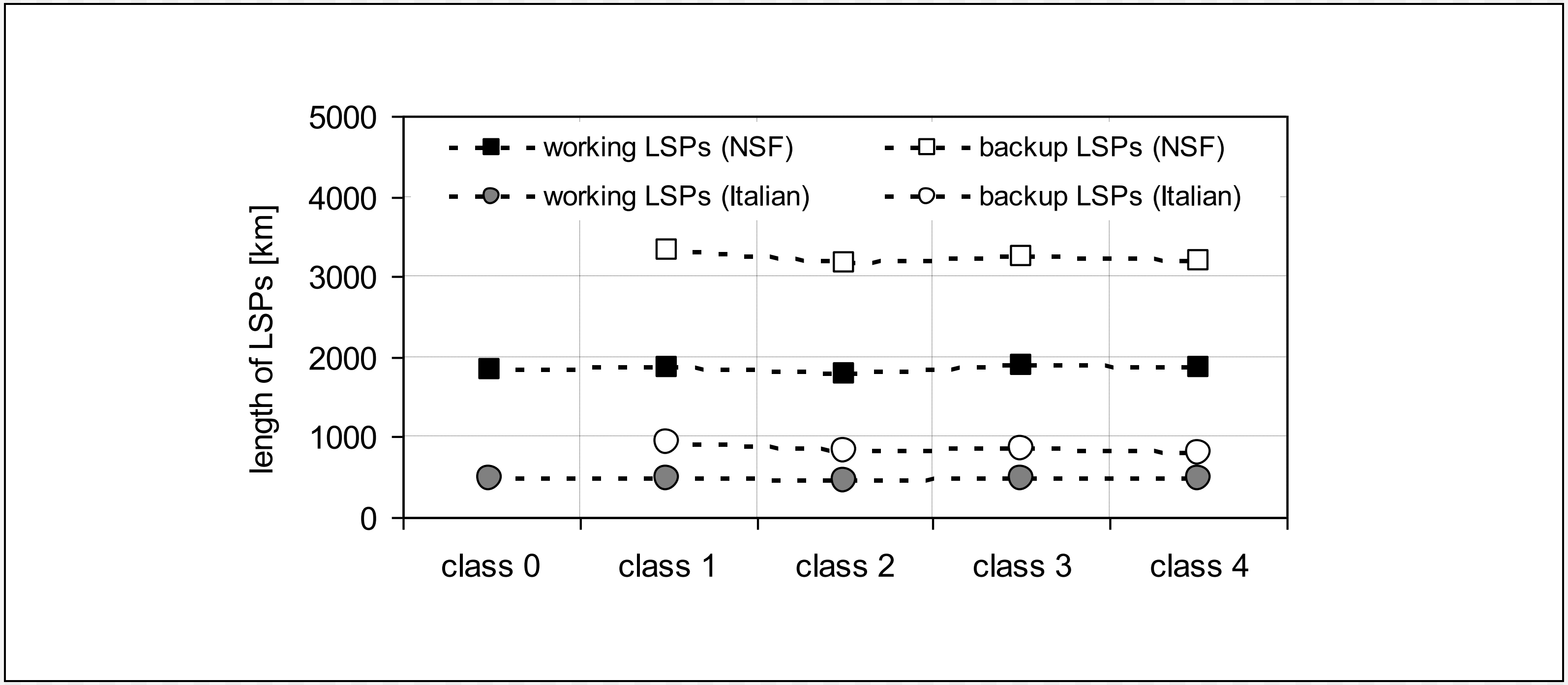
- the size each population equal to |*CH*| = 20 chromosomes
- number of chromosomes achieved during the crossover and mutation operations in each iteration:

  |*CRS*| = 10 and |*MUT*| = 10, accordingly
- percentage of chromosome genes changed during the mutation operation: 10%
- type of mutation: random value insertion

Modeling Results

IP-MPLS Layer

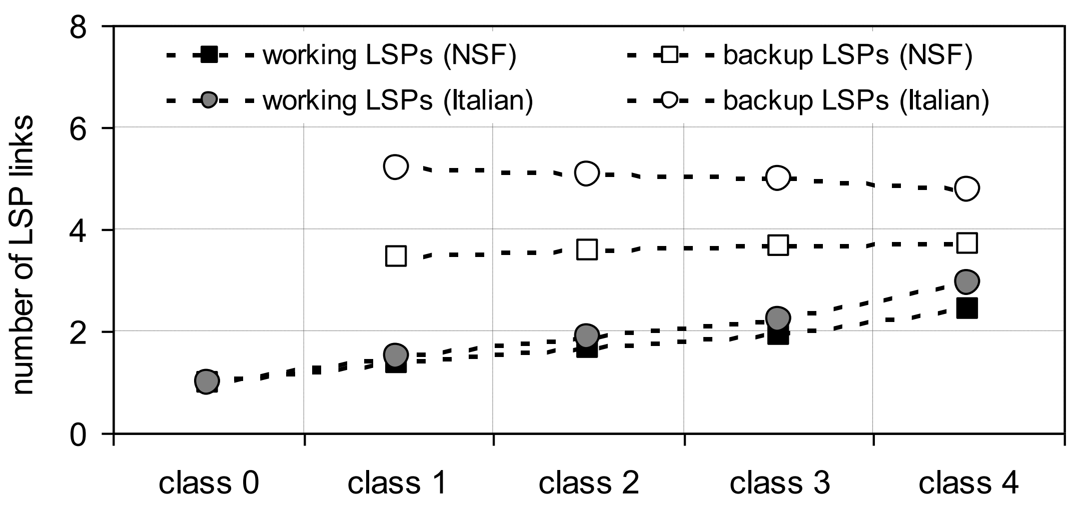
AVERAGE LENGTH OF LSPs



Modeling Results

IP-MPLS Layer

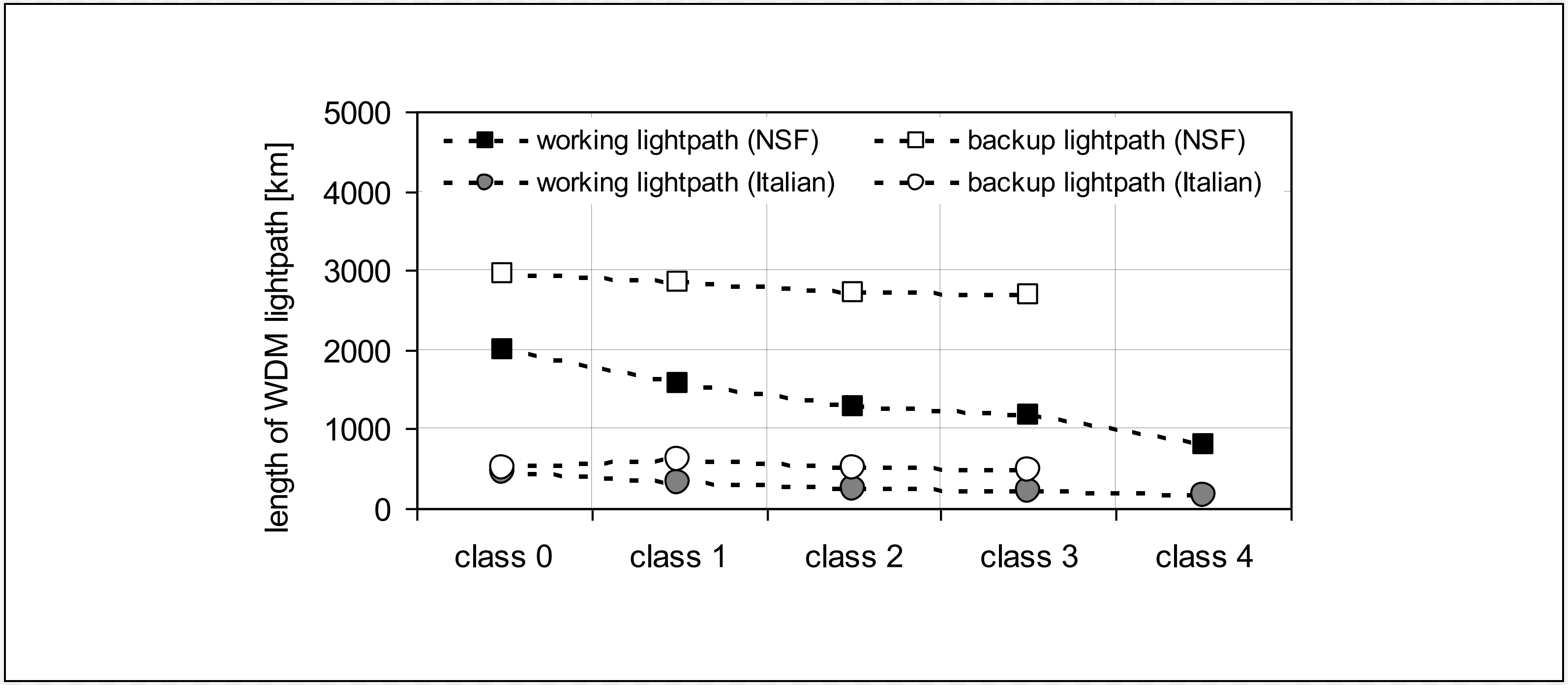
AVERAGE NUMBER OF LSP LINKS



Modeling Results

WDM Layer

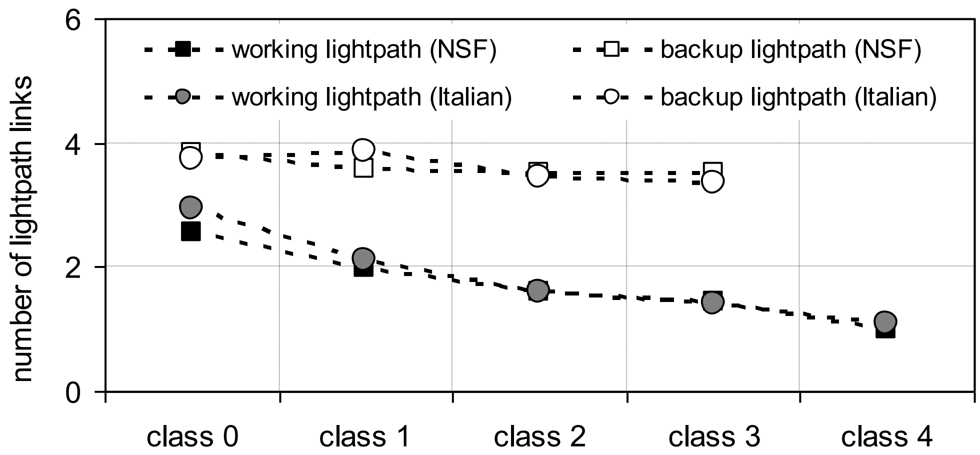
AVERAGE LENGTH OF A LIGHTPATH



Modeling Results

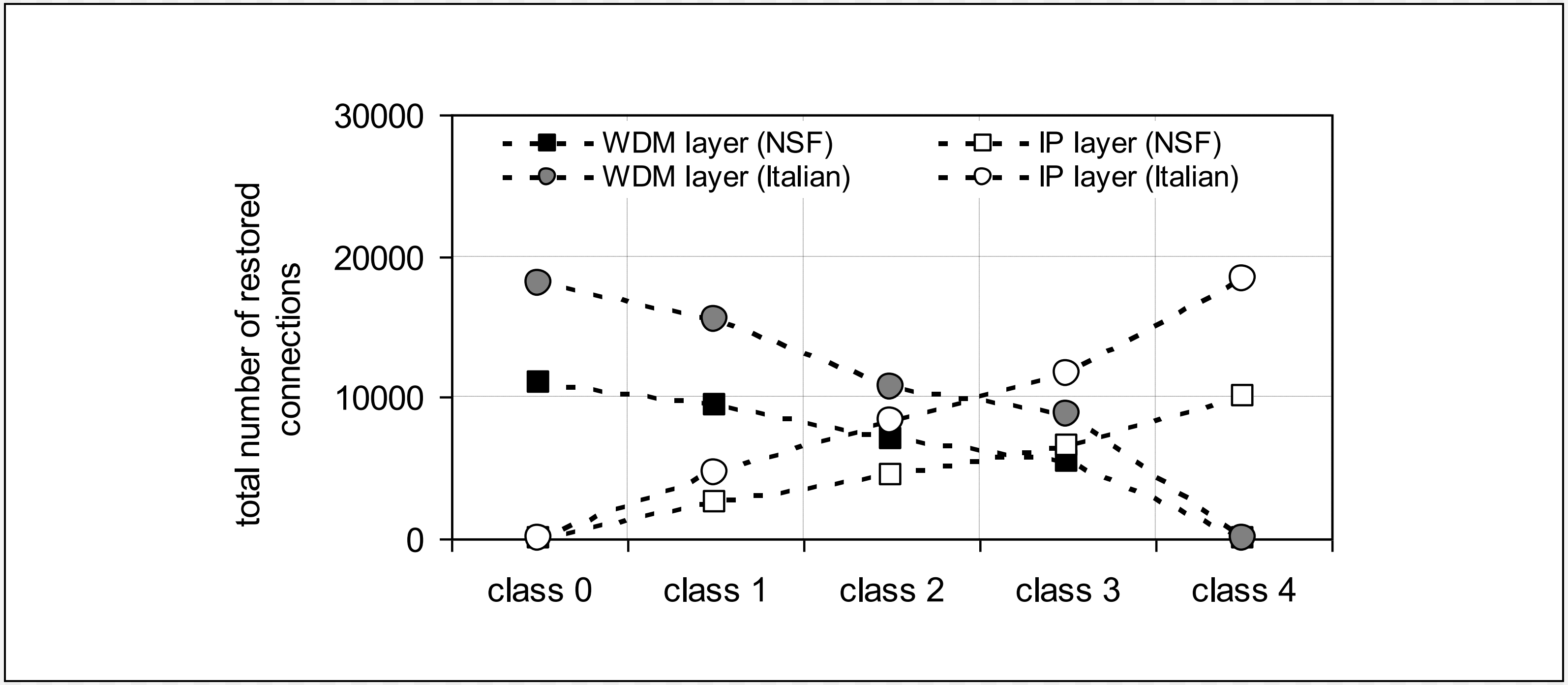
WDM Layer

AVERAGE NUMBER OF LIGHTPATH LINKS



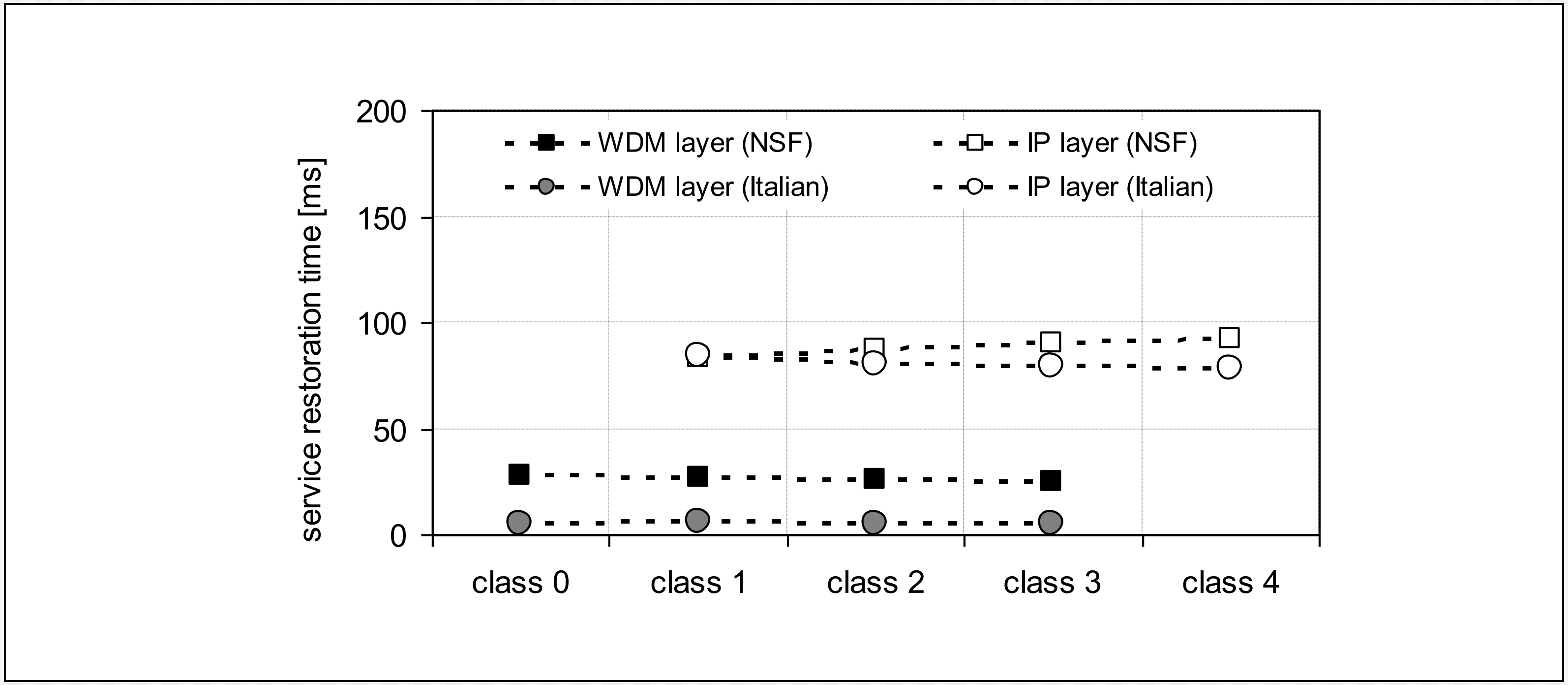
Modeling Results

TOTAL NUMBER OF RESTORED CONNECTIONS



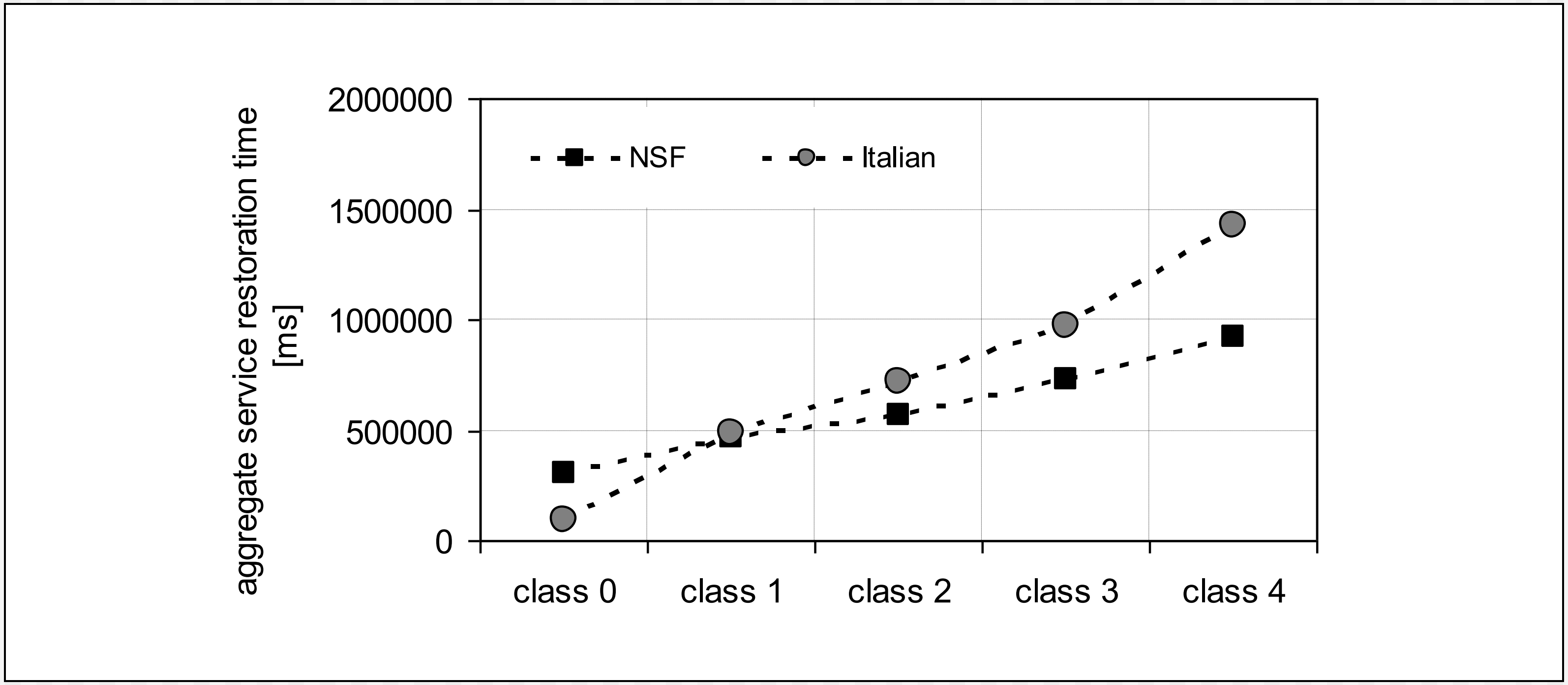
Modeling Results

VALUES OF CONNECTION RESTORATION TIME



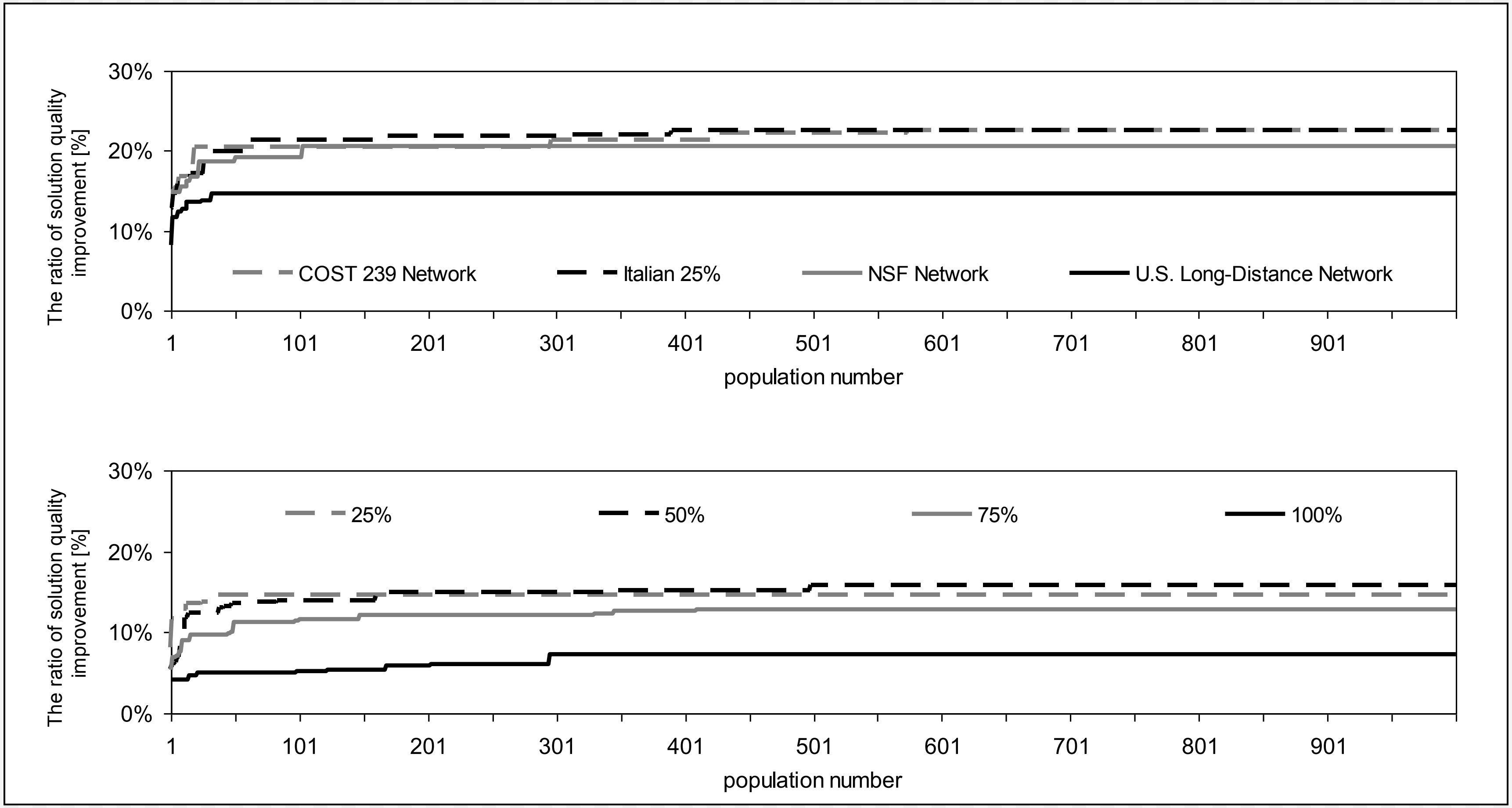
Modeling Results

AGGREGATE VALUES OF CONNECTION RESTORATION TIME



Modeling Results

RATIO OF SOLUTION QUALITY IMPROVEMENT



Concluding Remarks

- we introduced the novel class-based algorithm of survivable routing in IP-MPLS/WDM networks providing differentiated levels of service survivability
- this differentiation was defined in terms of the values of service recovery time and the frequency of performing the time-consuming recovery actions in the IP-MPLS layer
- the original problem of survivable routing in IP-MPLS/WDM network was divided into two subproblems, one for each network layer
- the metaheuristic approach based on genetic programming was proposed to improve the quality of results by solving the problem iteratively
- the advantage of up to 22.55% was achieved, compared to the case of solving the two subproblems in each network layer exactly once

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