Logical Topology Survivability in IP-over-WDM Networks: Survivable Lightpath Routing for Maximum Logical Topology Capacity and Minimum Spare Capacity Requirements

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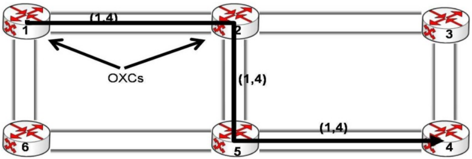
IP-over-WDM Network

- Two-layer network
  - IP (logical) network
  - WDM (physical) network
- Concept of *lightpath*

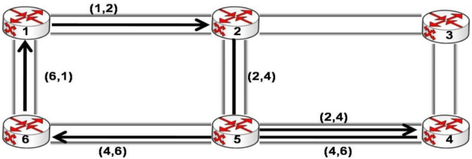
(a) A logical link (IP link)



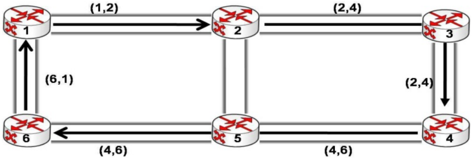
(b) A lightpath corresponding to the logical link (1,4) in physical topology.

Survivability in IP-over-WDM Networks

(a) Logical topology.

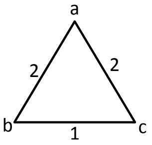


(b) An unsurvivable mapping.

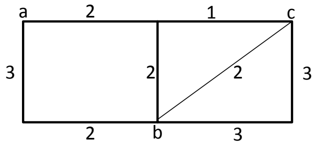


(c) A survivable mapping.

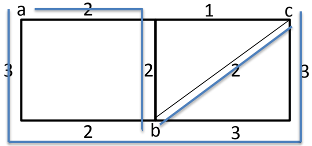
Capacitated IP-over-WDM Networks



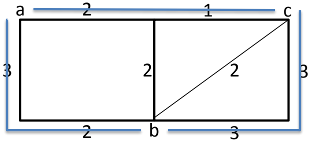
(a) Logical topology



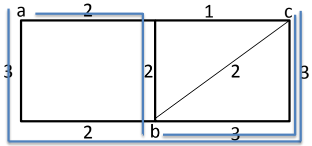
(b) Physical topology



(c) Survivable and all demands are satisfied



(d) Survivable and (a,c) demand is not satisfied



(e) Not survivable but all demands are satisfied

Pioneer Works

- Modiano and Narula-Tam, "Survivable routing of logical topologies in WDM networks", INFOCOM 2001
  - Propose ILP formulation to solve the survivable routing problem
  - Required to enumerate *ALL CUTSETS* in the topology
- Kurant and Thiran, "Survivable mapping algorithm by ring trimming (SMART) for large IP-over-WDM networks", BroadNets, 2004
  - Propose structural approach based on piecewise survivability and heuristics
- Thulasiraman et al., "Circuits/Cutsets duality and a unified algorithms framework for survivable logical topology design in IP-over-WDM optical networks", INFOCOM 2009
  - Study and extend the structural approach using circuits/duality
  - Propose CITCUIT-SMART, CUTSET-SMART, and INCIDENCE-SMART algorithms

Definitions

Definition

Weakly survivable routing: a lightpath routing that guarantees the logical topology remains connected after a single physical link failure

Definition

Strongly survivable routing: a weakly survivable routing that guarantees all logical demands are satisfied

Definition

Spare capacity: additional capacity added to physical links to satisfy logical demands

Problem Description

Problem 1:

- Given a capacitated IP-over-WDM network with demands on logical links
- Find a weakly survivable routing for the logical topology with different optimization criteria
  - Maximize total logical demand satisfied
  - Maximize demand satisfaction on one logical link
- Rerouting after a physical link failure to achieve maximum demand satisfaction

Problem Description

Problem 2:

- Given a capacitated IP-over-WDM network with demands on logical links
- Find a strongly survivable routing for the logical topology which requires minimum spare capacity

Weakly Survivable Routing – MILP Approach

Two-stage approach

- First stage:
  - Weakly survivable routing
  - Maximize demand satisfaction
- Second stage:
  - Minimize maximum unsatisfied demand through rerouting

Weakly Survivable Routing – MILP Approach

Variables used in MILP formulation

Variable	Description	Info.
y_{ij}^{st}	binary variable indicates whether the logical link $(s,t) \in E_L$ is routed through the physical link $(i,j) \in E_P$. If yes, $y_{ij}^{st} = 1$, otherwise, $y_{ij}^{st} = 0$.	first stage for Problem 1.
f_{ij}^{st}	flow on physical link (i,j) due to lightpath (s,t)	first stage for Problem 1.
r_{st}^{ij}	fractional variable for connectivity constraints.	first stage for Problem 1.
ρ_{st}	the capacity for the logical link (s,t), where ρ_{st} is the smallest capacity of links in the lightpath.	first stage for Problem 1.
θ	variable for max single logical link capacity.	first stage for Problem 1.
c_{ij}	capacity on the physical link (i,j).	given.
d_{st}	demand for the logical link (s,t).	given.
u_{ij}	link utilization request on the physical link (i,j)	given.
λ_{ij}^{st}	maximal flow for logical link (s,t) after a physical link failure and re-routing	second stage for Problem 1.
$x_{k\ell ij}^{st}$	rerouted flow on (k,ℓ) which can be maintained after the physical link (i,j) failure and re-routing.	second stage for Problem 1.
$z_{k\ell ij}^{st}$	binary variable indicates whether (s,t) re-route through (k,ℓ) after (i,j) failure.	second stage for Problem 1.
η_{ij}	amount of spare capacity required on the physical link (i,j) to satisfy strong survivability	second stage of Problem 2.
M	a large positive number	Problem 1.

Weakly Survivable Routing – MILP Approach (First Stage)

- Lightpath constraint:

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = 1, \qquad \text{if } s = i, (s,t) \in E_L \tag{1}$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = -1, \qquad \text{if } t = i, (s,t) \in E_L \tag{2}$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = 0, \qquad \text{otherwise}, (s,t) \in E_L \tag{3}$$

$$y_{ij}^{st} + y_{ji}^{st} \leq 1, \qquad (i,j) \in E_P, (s,t) \in E_L \tag{4}$$

selects a lightpath for each logical link

Weakly Survivable Routing – MILP Approach (First Stage)

- Flow equivalent constraint:

$$f_{k\ell}^{st} + M(y_{k\ell}^{st} - 1) \leq f_{pq}^{st} + M(1 - y_{pq}^{st}), \tag{5}$$
$$(s,t) \in E_L, (k,\ell), (p,q) \in E_P, (k,\ell) \neq (p,q)$$

  guarantees that the flow on each selected lightpath is the same for every physical link in the lightpath

Weakly Survivable Routing – MILP Approach (First Stage)

- Flow conservation constraint:

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = \rho_{st}, \qquad \text{if } s = i, (s,t) \in E_L \tag{6}$$

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = -\rho_{st}, \qquad \text{if } t = i, (s,t) \in E_L \tag{7}$$

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = 0, \qquad \text{otherwise}, (s,t) \in E_L \tag{8}$$

$$\rho_{st} \le d_{st}, \qquad (s,t) \in E_L \tag{9}$$

  requires the flow on each selected lightpath to be less than or equal to the logical demand

- Bounded flow constraint:

$$(f_{ij}^{st} + f_{ji}^{st}) \le M y_{ij}^{st}, \qquad (i,j) \in E_P, (s,t) \in E_L \tag{10}$$

  assures that each physical link carries flow only if the lightpath(s) route through the physical link

Weakly Survivable Routing – MILP Approach (First Stage)

- Capacity constraint:

$$\sum_{(s,t)\in E_L} (f_{ij}^{st} + f_{ji}^{st}) \leq c_{ij}, \qquad (i,j) \in E_P \tag{11}$$

  guarantees that the flow on a physical link will not exceed the capacity of the physical link
- Congestion constraint (optional):

$$\sum_{(s,t)\in E_L} (y_{ij}^{st} + y_{ji}^{st}) \leq u_{ij}, \qquad (i,j) \in E_P, \tag{12}$$

Weakly Survivable Routing – MILP Approach (First Stage)

- Idea: if there exists a logical spanning tree after any physical link failure, the routing is survivable (based upon Q. Deng et al., “Survivable IP over WDM: a mathematical programming problem formulation,” Allerton Conference on Communication, Control and Computing, 2002)
- For each physical link (i, j), the set of logical links (s, t) for which $r_{st}^{ij} \neq 0$ must form a spanning tree in the logical topology this guarantees that unfailed logical links form a connected graph
- Survivability constraint:

$$\sum_{(s,t)\in E_L} r_{st}^{ij} - \sum_{(t,s)\in E_L} r_{ts}^{ij} = -1, \qquad \text{if} \quad s = v_1, (i,j) \in E_P, \tag{13}$$

$$\sum_{(s,t)\in E_L} r_{st}^{ij} - \sum_{(t,s)\in E_L} r_{ts}^{ij} = \frac{1}{|V_L| - 1}, \qquad \text{otherwise}, (i,j) \in E_P, \tag{14}$$

$$0 \leq r_{st}^{ij} \leq 1 - (y_{ij}^{st} + y_{ji}^{st}), \qquad (i,j) \in E_P, (s,t) \in E_L, \tag{15}$$

$$0 \leq r_{ts}^{ij} \leq 1 - (y_{ij}^{st} + y_{ji}^{st}), \qquad (i,j) \in E_P, (s,t) \in E_L \tag{16}$$

- Benefit: do not need to enumerate all cutsets

Weakly Survivable Routing – MILP Approach (First Stage)

- Objective: maximize total logical link demands:

$$\max \sum_{(s,t)\in E_L} \rho_{st} \tag{17}$$

$$s.t. \text{ Constraint (1)–(11), (13)–(16),}$$

$$y_{ij}^{st} \in \{0,1\}, r_{ij}^{st} \geq 0, f_{ij}^{st} \geq 0, \rho_{st} \geq 0 \quad (i,j) \in E_P, (s,t) \in E_L \tag{18}$$

- Objective: maximize the minimum demand satisfaction on a single logical link:

$$\max \theta$$

$$\text{s.t.} \quad \theta \leq \rho_{st} \tag{19}$$

Weakly Survivable Routing – MILP Approach (Second Stage)

- R_{ij}: a set of logical links which is disconnected due to the failure of physical link (i, j)
- Re-routing constraint: For all $(i, j) \in E_P$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = 1, \qquad \text{if } s = k, (s,t) \in R_{ij} \quad (20)$$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = -1, \qquad \text{if } t = k, (s,t) \in R_{ij} \quad (21)$$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = 0, \qquad \text{otherwise}, (s,t) \in R_{ij} \quad (22)$$

finds alternative lightpath for disrupted logical link (s, t)

Weakly Survivable Routing – MILP Approach (Second Stage)

- Residual capacity constraint: For all $(i, j) \in E_P$

$$\sum_{(s,t)\in R_{ij}} (x^{st}_{k\ell ij} + x^{st}_{\ell kij}) \leq c_{k\ell} - \sum_{(u,v)\in E_L\setminus R_{ij}} \rho^{*}_{uv} y^{uv*}_{k\ell}, (k,\ell) \in E_P \setminus \{(i,j)\} \quad (23)$$

$$x^{st}_{k\ell ij} \leq Mz^{st}_{k\ell ij},\ (s,t) \in R_{ij}, \qquad (k,\ell) \in E_P \setminus \{(i,j)\} \quad (24)$$

$$\lambda^{st}_{ij} \geq x^{st}_{k\ell ij}, \quad (s,t) \in R_{ij}, \qquad (k,\ell) \in E_P \setminus \{(i,j)\} \quad (25)$$

$$\lambda^{st}_{ij} \leq x^{st}_{k\ell ij} + M(1 - z^{st}_{k\ell ij}), \qquad (s,t) \in R_{ij}, (k,\ell) \in E_P \setminus \{(i,j)\} \quad (26)$$

assures that each physical link on alternative lightpath for disrupted logical link carry flow up to its capacity

Weakly Survivable Routing – MILP Approach (Second Stage)

- Flow equivalence constraint:

$$x_{k\ell ij}^{st} + M(z_{k\ell ij}^{st} - 1) \leq x_{pqij}^{st} + M(1 - z_{pqij}^{st}), \tag{27}$$
$$(s,t) \in R_{ij}, (k,\ell), (p,q) \in E_P \setminus \{(i,j)\}$$

  guarantees that the flow on physical links of alternative lightpath will be equivalent

Weakly Survivable Routing – MILP Approach (Second Stage)

- Objective: maximum demand satisfaction

$$\max \sum_{(s,t)\in E_L} \sum_{(i,j)\in E_P} \lambda_{ij}^{st} \tag{28}$$

$$\begin{aligned} s.t.\ & \text{Constraints (20) to (27),} \\ & z_{k\ell ij}^{st} \in \{0,1\}, \lambda_{ij}^{st}, x_{k\ell ij}^{st} \geq 0, \\ & (i,j) \in E_P, (s,t) \in E_L, (k,\ell) \in E_P \setminus \{(i,j)\} \end{aligned} \tag{29}$$

Strongly Survivable Routing – MILP Approach

- First stage
  - Weakly survivable routing

$$\max \sum_{(s,t)\in E_L} \rho_{st} \tag{30}$$

$$s.t. \text{ Constraint (1)–(10), (12)–(15)}$$

- Second stage
  - Minimize spare capacity required to satisfy all demands after failure

$$\min \sum_{(i,j)\in E_P} \eta_{ij} \tag{31}$$

$s.t.$ Constraints (19) to (21), (23) to (26),

$$\sum_{(s,t)\in R_{ij}} d_{st}(z^{st}_{k\ell ij} + z^{st}_{\ell kij}) \leq c_{k\ell} - \sum_{(s,t)\in E_L\setminus R_{ij}} \rho^*_{st} y^{st*}_{k\ell} + \eta_{k\ell}, \tag{22$'$}$$

$$(i,j) \in E_P, (k,\ell) \in E_P \setminus (i,j)$$

Weakly Survivable Heuristics – First Stage

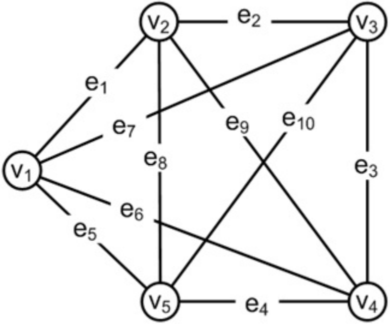
Assumption: all demands can be satisfied by physical link capacity
INCIDENCE-SMART+Augmentation

- Identify datum node $\triangle$ (logical node with the highest degree)
- If there exists a logical node v with degree ≥ 2
  - Find edge-disjoint lightpaths for any two adjacent edges of v
  - Remove v and all adjacent edges of v
- If there exists a logical node v with degree = 1 (logical edge (u, v))
  - Augment (u, v) with a parallel edge $(u^{'}, v^{'})$
  - Find edge-disjoint lightpaths for (u, v) and $(u^{'}, v^{'})$
  - Remove (u, v)
- If there exists a logical node v with degree = 0 (individual node)
  - Add two parallel edges connecting $(v, \triangle)$
  - Find two edge-disjoint lightpaths for $(v, \triangle)$
  - Remove v

INCIDENCE-SMART: An Example

$$
\begin{array}{c@{\,}c}
 & \begin{array}{cccccccccc} e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & e_7 & e_8 & e_9 & e_{10} \end{array} \\
\begin{array}{c} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{array} &
\begin{bmatrix}
1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1
\end{bmatrix}
\end{array}
$$

(a)



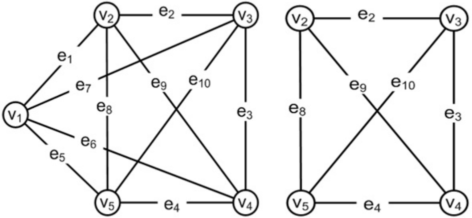
(b) Logical topology G_L, v_4 is the datum vertex.

INCIDENCE-SMART: An Example

- $INC(v_1), INC(v_2), INC(v_3), INC(v_5)$ is an INC-sequence of length $k = 4$
- Iteration 1:
  - Pick v_1, Degree $v_1 \geq 2$ in the current graph. Map at most two edges incident on $v_1(\{e_1, e_5\})$ into disjoint lightpaths
  - Delete $\{e_1, e_5, e_6, e_7\}$ from the graph

$$
\begin{array}{c}
\begin{array}{cccccccccc} e_1 & e_5 & e_6 & e_7 & e_2 & e_8 & e_9 & e_3 & e_{10} & e_4 \end{array} \\
\begin{array}{c} v_1 \\ v_2 \\ v_3 \\ v_5 \end{array}
\left[\begin{array}{cccc|ccc|cc|c}
1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1
\end{array}\right]
\end{array}
$$

(a)



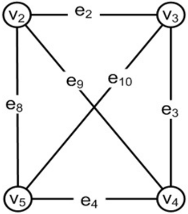
(b) (c)

INCIDENCE-SMART: An Example

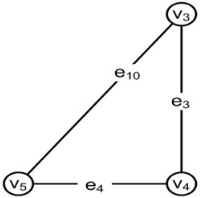
- Iteration 2:
  - Pick v_2, Degree $v_2 \geq 2$ in the current graph. Map at most two edges incident on v_2 $\{e_2, e_8\}$ into disjoint lightpaths
  - Delete $\{e_2, e_8, e_9\}$ from the graph

$$
\begin{array}{c} \\ v_1 \\ v_2 \\ v_3 \\ v_5 \end{array}
\begin{array}{c}
\begin{array}{cccccccccc} e_1 & e_5 & e_6 & e_7 & e_2 & e_8 & e_9 & e_3 & e_{10} & e_4 \end{array} \\
\left[\begin{array}{cccc|ccc|cc|c}
1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1
\end{array}\right]
\end{array}
$$

(a)



(b)

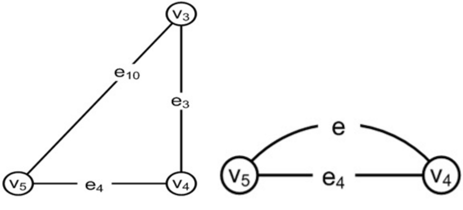


(c)

INCIDENCE-SMART: An Example

- Iteration 3:
  - Pick v_3, Degree $v_3 = 2$ in the current graph. Map the two edges incident on v_3 $\{e_3, e_{10}\}$ into disjoint lightpaths
  - Delete $\{e_3, e_{10}\}$ from the graph
- Iteration 4:
  - Pick v_5, Degree $v_5 = 1$ in the current graph
  - Provide a protection edge e
  - Map e and e_4 into disjoint lightpaths
  - Delete $\{e, e_4\}$ from the graph

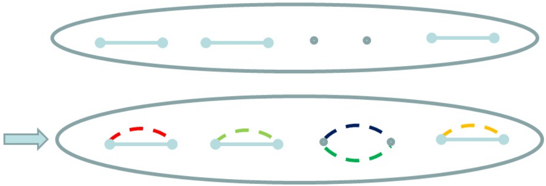
$$
\begin{array}{c}
 \\ v_1 \\ v_2 \\ v_3 \\ v_5
\end{array}
\begin{array}{c}
\begin{array}{cccccccccc} e_1 & e_5 & e_6 & e_7 & e_2 & e_8 & e_9 & e_3 & e_{10} & e_4 \end{array} \\
\left[\begin{array}{cccc|ccc|cc|c}
1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1
\end{array}\right]
\end{array}
$$



(a) (b) (c)

Solution in General Case

- K. Thulasiraman, Muhammad Javed, Tachun Lin, Guoliang (Larry) Xue, “Logical topology augmentation for guaranteed survivability under multiple failures in IP-over-WDM optical networks”, IEEE ANTS, 2009
- K. Thulasiraman, Tachun Lin, Muhammad Javed, Guoliang (Larry) Xue, “Logical topology augmentation for guaranteed survivability under multiple failures in IP-over-WDM optical networks”, Optical Switching and Networking, 2010



Weakly Survivable Heuristics – Second Stage

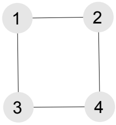
- For each physical link (i, j)
  - Find out a set of logical links R_{ij} which will be disconnected if (i, j) fails
  - Calculate the residual capacity on each physical link after (i, j) fails
  - For each logical link in R_{ij}
    - Find an alternative lightpath which avoids (i, j) and has maximal residual capacity along the path
    - Calculate the demand which can be satisfied with the alternative lightpath
    - Subtract the satisfied demands from the specified demands

Strongly Survivable Heuristics – Second Stage

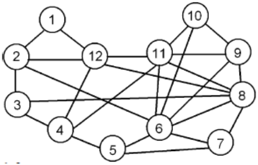
- For each physical link (i, j)
  - Find out a set of logical links R_{ij} which will be disconnected if (i, j) fails
  - Calculate the residual capacity on each physical link after (i, j) fails
  - For each logical link in R_{ij}
    - Find an alternative lightpath which avoids (i, j) and has maximal residual capacity along the path
    - Calculate the (extra) capacity required to satisfy with the alternative lightpath
  - Calculate the total extra capacity to be added to physical links to satisfy all logical demands after any single physical link failure

Simulation Results

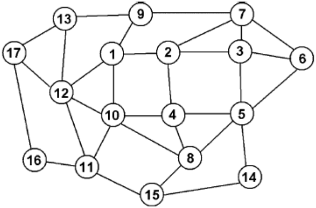
Tested physical topologies



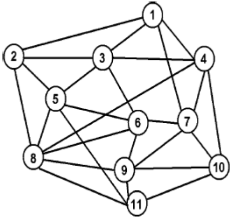
(a) SMALL



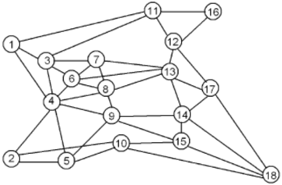
(b) G3



(c) G6



(d) EURO 1



(e) EURO 2

Simulation Results

Table 1: Comparison of MILP and heuristic results on demand satisfaction after failure (weakly survivable)

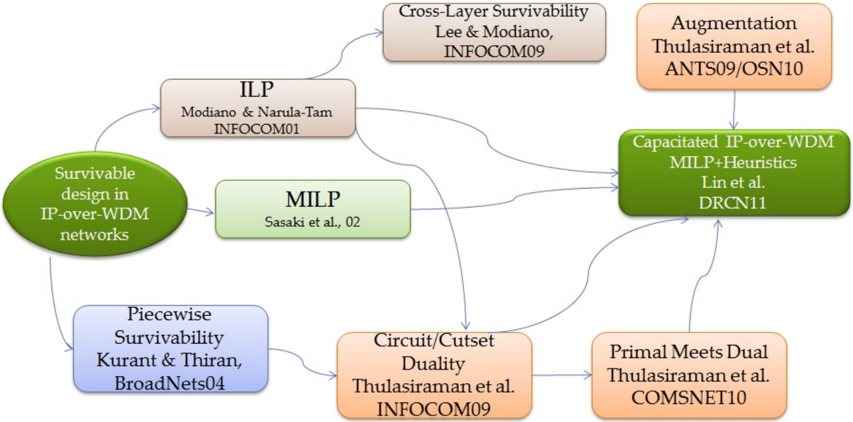
	SMALL	G3	G6	EURO 1	EURO 2	RAND
MILP	0/28	38/38	69/71	17/17	45/47	361/387
Ratio	0%	100%	97%	100%	96%	93%
Heuristic	0/28	32/36	44/62	10/17	41/47	317/372
Ratio	0%	89%	71%	59%	87%	85%

Table 2: Comparison of MILP and heuristic results on minimum spare capacity (strongly survivable)

	SMALL	G3	G6	EURO 1	EURO 2	RAND
MILP	26	3	17	10	6	2
Heuristic	26	3	21	12	6	18

State of the Art

Where we are



Conclusions

- Introduce the weakly and strongly survivable concept in capacitated IP-over-WDM networks
- Provide MILP formulation and heuristics for weakly and strongly survivable problem in capacitated IP-over-WDM networks
- Future works
    - Load-balancing on logical demand satisfaction
    - Augmentation in logical network to guarantee survivability in MILP formulation
    - Survivable routing for multiple failure scenario