# On Survivable Routing of Mesh Topologies in IP-over-WDM Networks

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# Outline

- Introduction
- Problem Formulation
- SMART Algorithm
- SMART Application
- Simulation
- Conclusion

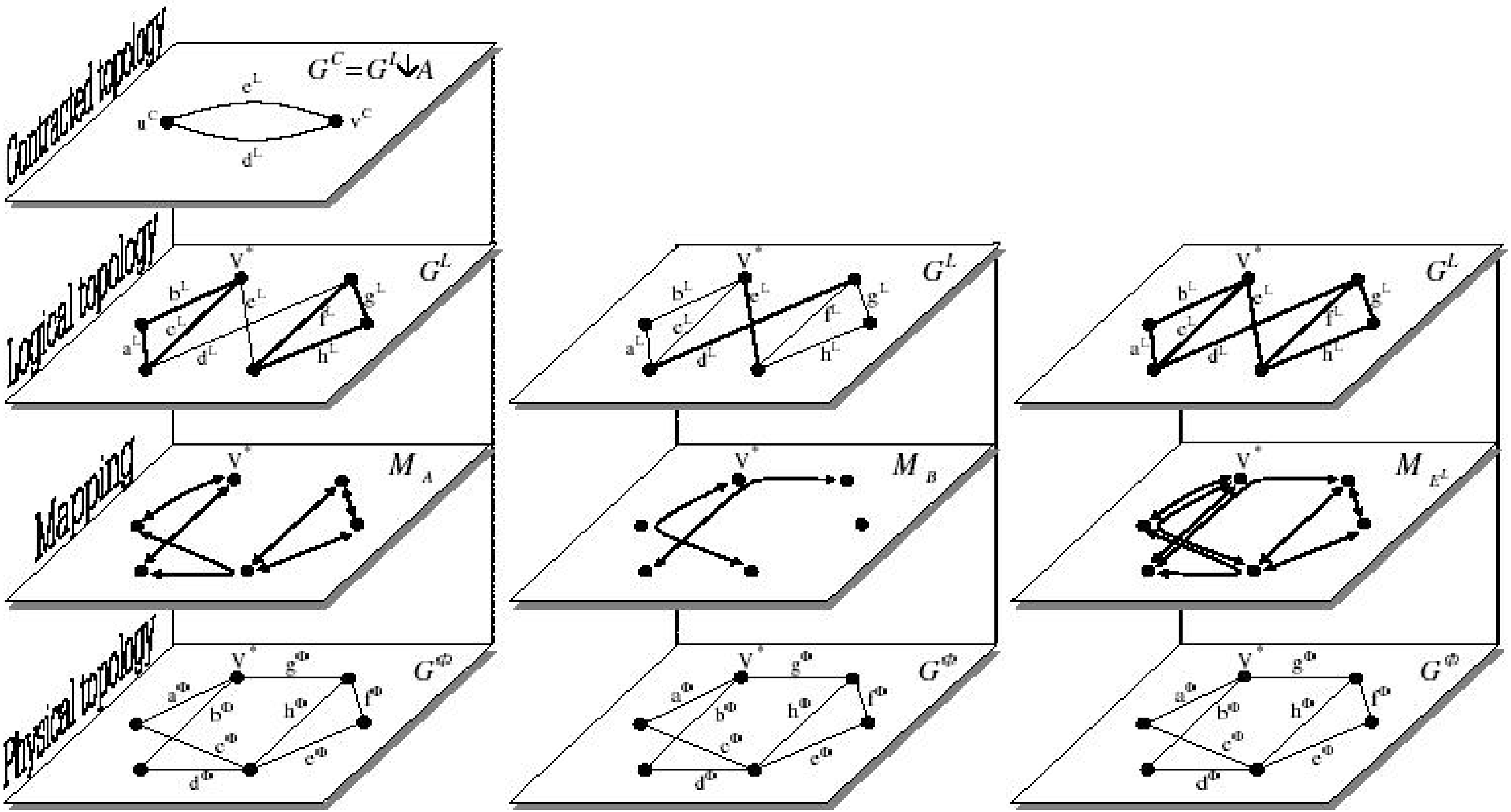
# Introduction

- IP over WDM network
  - Protection and restoration mechanisms can be provided at IP layer or WDM layer
  - IP layer survivability mechanisms can handle failures that occurs at both layers
  - Each logical (IP) link is mapped on the physical (WDM) topology as a lightpath
- In this paper
  - Only IP restoration is considered
  - The existence of a link/node survivable mapping for general mesh topologies at both layers are studied
  - SMART– an efficient and scalable algorithm that searches for a survivable mapping is proposed

# Notation

- $\phi$ corresponds to the *physical* topology
- $L$ corresponds to the *logical* topology
- C corresponds to the *contracted* topology
- *a, b, c, d, e, …* are used to denote edges/links
- *u, v, w, …* are used to denote vertices/nodes
- $p$ is used to denote a path, $p_{v,u}$: a path from $v$ to $u$
- $G^\phi = (V, E^\phi)$, $G^L = (V, E^L)$ physical and logical
- $P^\phi$ be a set of all possible physical path, $A \subset E^L$, a mapping $M_A$ is a function $M_A: A \rightarrow P^\phi$

# Mapping Examples

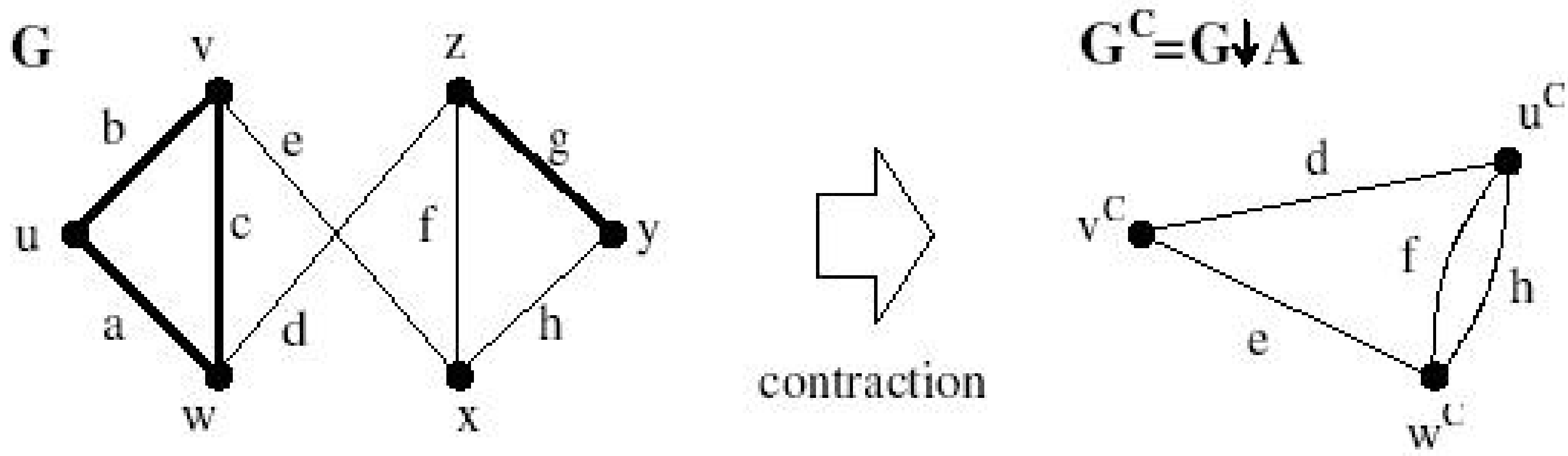



a) Mapping of the set
$A=\{a^L, b^L, c^L, f^L, g^L, h^L\}$

b) Mapping of the set
$B=\{d^L, e^L\}$

c) Full mapping
$E^L = A \cup B = \{a^L, b^L, c^L, d^L, e^L, f^L, g^L, h^L\}$

# Contraction and Origin



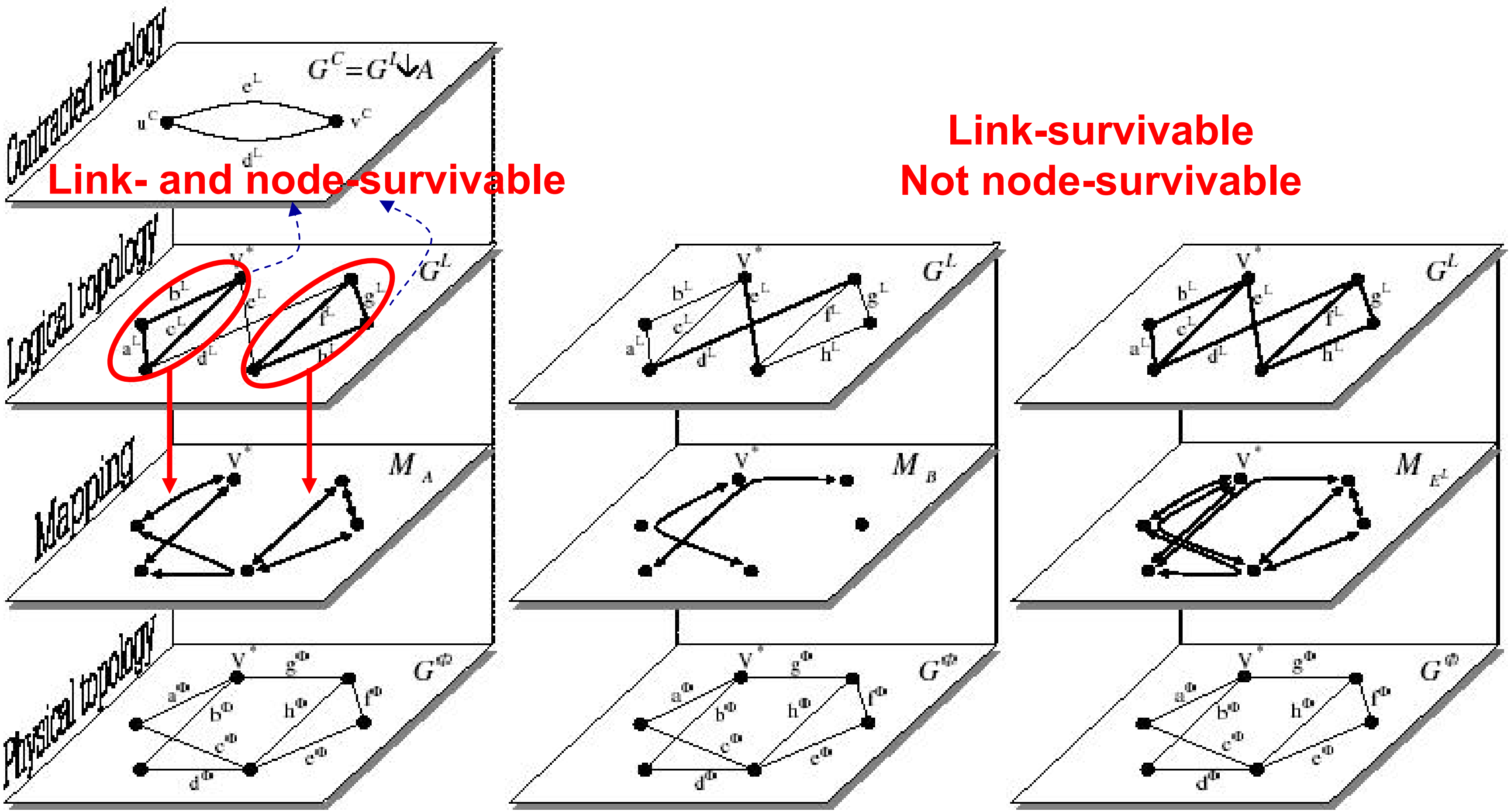

$A=\{a,b,c,g\}$

$$\begin{aligned}
\mathit{Origin}(\mathrm{e}) &= \mathrm{e} \\
\mathit{Origin}(\mathrm{v}^C) &= (\{\mathrm{u,v,w}\}, \{\mathrm{a,b,c}\}) \\
\mathit{Origin}(\mathrm{u}^C) &= (\{\mathrm{y,z}\}, \mathrm{g}) \\
\mathit{Origin}(\mathrm{w}^C) &= \mathrm{x} \\
\mathit{Origin}((\{\mathrm{u}^C,\mathrm{w}^C\}, \{\mathrm{f,h}\})) &= (\{\mathrm{x,y,z}\}, \{\mathrm{f,g,h}\})
\end{aligned}$$

# Survivability

- Let $G^L = (V, E^L)$, $A \subset E^L$, $G^C = (V^C, E^C) = G^L \downarrow A$ , take any connected subgraph $G^C_{sub} = (V^C_{sub}, B)$, let $M_B$ be a mapping of the logical link set $B$
  - $[G^C_{sub}, M_B]$ is *link-survivable* if the failure of any single physical link $e^\phi$ does not disconnect $G^C_{sub}$
  - $[G^C_{sub}, M_B]$ is *node-survivable* if the failure of any single node $v^* \in V$ does not disconnect the graph $G^C_{sub} \setminus \{v^C \in G^C_{sub} : Origin(v^C) = v^*\}$
  - Examples

# Examples of Survivability




a) Mapping of the set $A=\{a^L, b^L, c^L, f^L, g^L, h^L\}$

b) Mapping of the set $B=\{d^L, e^L\}$

c) Full mapping $E^L=A \cup B=\{a^L, b^L, c^L, d^L, e^L, f^L, g^L, h^L\}$

# Piecewise Survivability

- Let $M_A$ be a mapping of a set $A \subset E^L$ on the physical topology
  - $[G^L, M_A]$ is piecewise link/node-survivable if for every vertex $v^C$ of the contracted logical topology $G^L \downarrow A$ , the pair $[Origin(v^C), M_A]$ is link/node-survivable
  - Example: in Fig. 1a, the pair $[G^L, M_A]$ is piecewise link- and node-survivable

# Expansion of Survivability

- Theorem 1:
  - Let $M_A$ be a mapping of a set of logical edges $A \subset E^L$ on the physical topology $G^\phi$, such that the pair $[G^L, M_A]$ is piecewise link/node-survivable
  - Let $G^C = G^L \downarrow A$, take any subgraph of $G^C$, call it $G^C_{sub} = (V^C_{sub}, B)$
  - Let $M_B$ be a mapping of the set $B$

  ⇨ If the pair $[G^C_{sub}, M_B]$ is link/node-survivable then the pair $[\mathrm{Origin}(G^C_{sub}), M_A \cup M_B]$ is also link/node-survivable

# Existence of a Survivable Mapping

- Theorem 2:
  - Let $M_A$ be a mapping of a set of logical edges $A \subset E^L$, such that the pair $[G^L, M_A]$ is piecewise link/node-survivable

  ⇨ A link/node survivable mapping $M^{surv}_{E^L}$ of a set $G^L$ on $G^\phi$ exists if and only if
  There exists a mapping $M^{surv}_{E^L \backslash A}$ of the set of logical links $E^L \backslash A$ on $G^\phi$, such that the pair $[G^L \downarrow A, M^{surv}_{E^L \backslash A}]$ is link/node-survivable

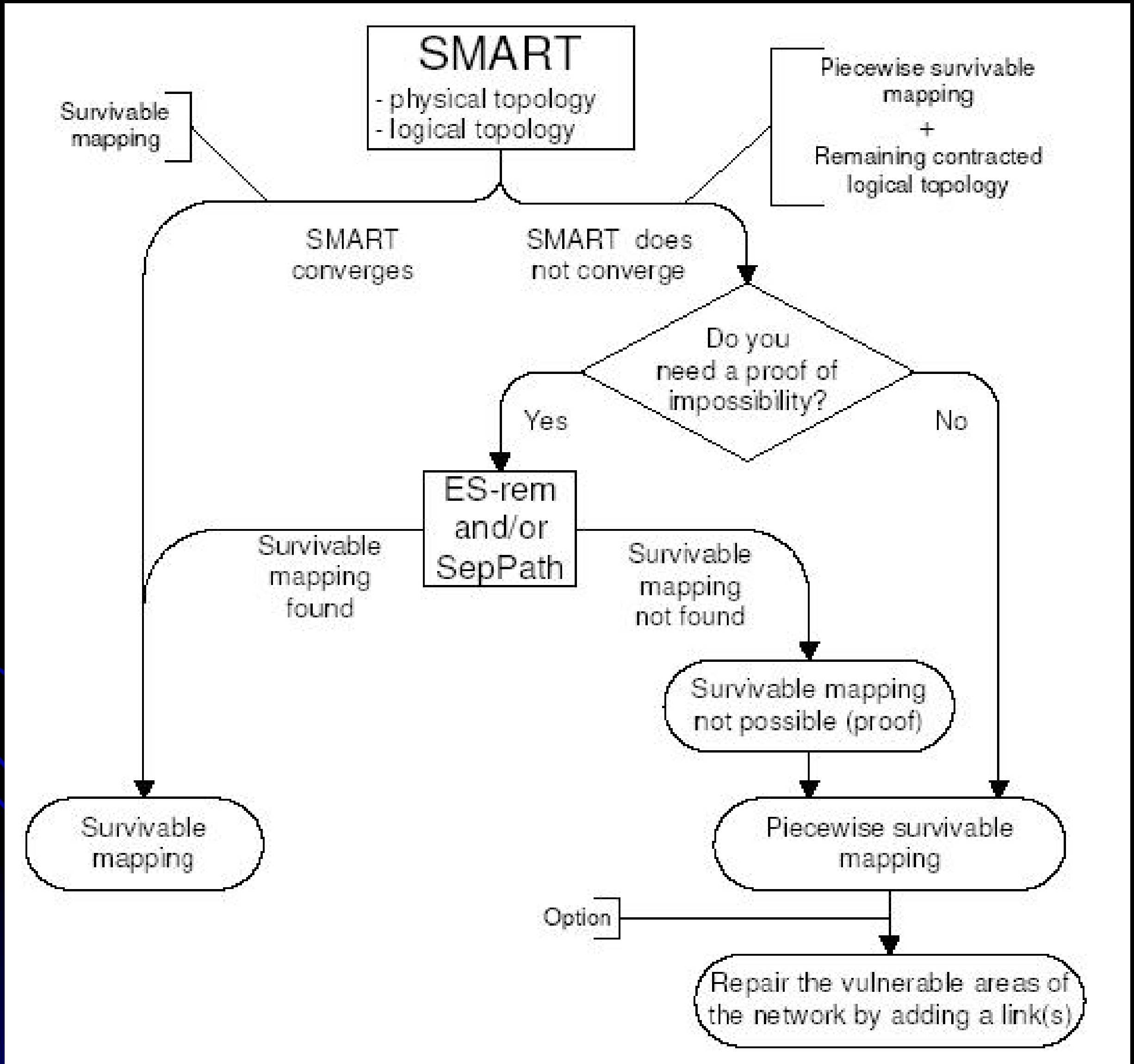
# SMART Algorithm (1/2)
## (Survivable Mapping Algorithm by Ring Trimming)

| | |
|---|---|
| *Step 1* | Start from the full logical topology $G^C = G^L$, and an empty mapping $M_A = \emptyset, A = \emptyset$; |
| *Step 2* | Take some subgraph $G^C_{sub} = (V^C_{sub}, B)$ of $G^C$ and find a mapping $M_B$, such that the pair $[G^C_{sub}, M_B]$ is link/node-survivable. IF no such pair is found, THEN RETURN $M_A$ AND $G^C = G^L \downarrow A$, END. |
| *Step 3* | Update the mapping by merging $M_A$ and $M_B$, i.e., $M_A := M_A \cup M_B$; |
| *Step 4* | Contract $G^C$ on $B$, i.e., $G^C := G^C \downarrow B$; |
| *Step 5* | IF $G^C$ is a single node, THEN RETURN $M_A$, END. |
| *Step 6* | GOTO Step 2 |

# SMART Algorithm (2/2)

- SMART converges if the contracted topology $G^C$ converges to a single node
- SMART does not converge if SMART terminates before $G^C$ converges to a single node, and the *remaining contracted logical topology* $G^C = G^L \downarrow A$ *is* piecewise link/node survivable

# Application of SMART



# Formal Verification of Existence of Survivable Mapping

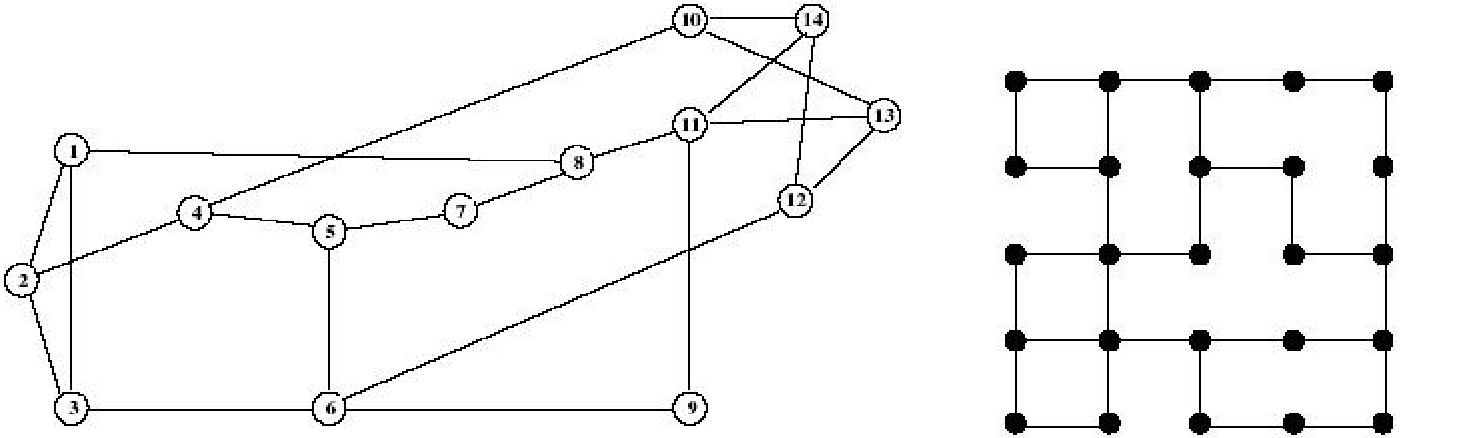
- Two methods to verify the existence of a link/node-survivable mapping for $G^L \downarrow A$
  - Exhaustive Search (ES-rem)
  - Separated Path check (*SepPath*)
    - If $G^L \downarrow A$ contains a path $p^C$ such that all nodes on $p^C$, but the first and the last ones, are of degree 2, then all the logical links in $p^C$ must be mapped edge-disjointly to enable link-survivability
    - Failure of an exhaustive search for an edge-disjoint mapping of $p^C$ will prove impossibility

# Modifying Topology to enable Mapping

- After SMART, the remaining contracted logical topology $G^L \downarrow A$ and the piecewise-survivable mapping $M_A$ are returned
  - Choose at random two nodes $u^C$, $v^C$ in $G^L \downarrow A$ and pick any two nodes $u$, $v$ in $G^L$, such that $u \in Origin(u^C)$ and $v \in Origin(v^C)$
  - Connect u and v with an additional logical/physical link
  - If this link already exists, repeat the procedure

# Simulation

- Physical topologies



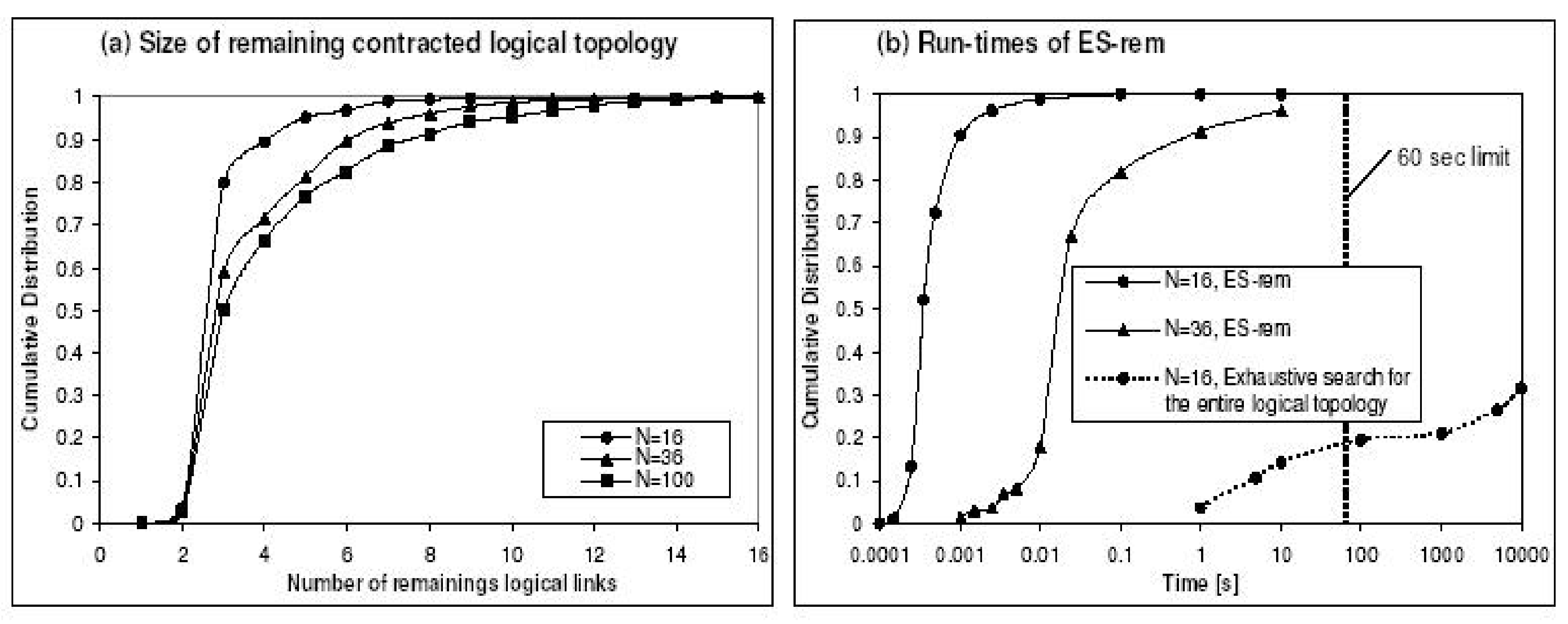

a) NSFNET b) *f*-lattice (2-node-connected)

**A fraction *f* of edges is deleted**

- Logical topologies: 2-node-connected random graphs of various average vertex degree

# Simulation Results

- For each number of nodes
  - Generate a number of physical/logical topology pairs
  - Keep first 1000 for which SMART does not converge



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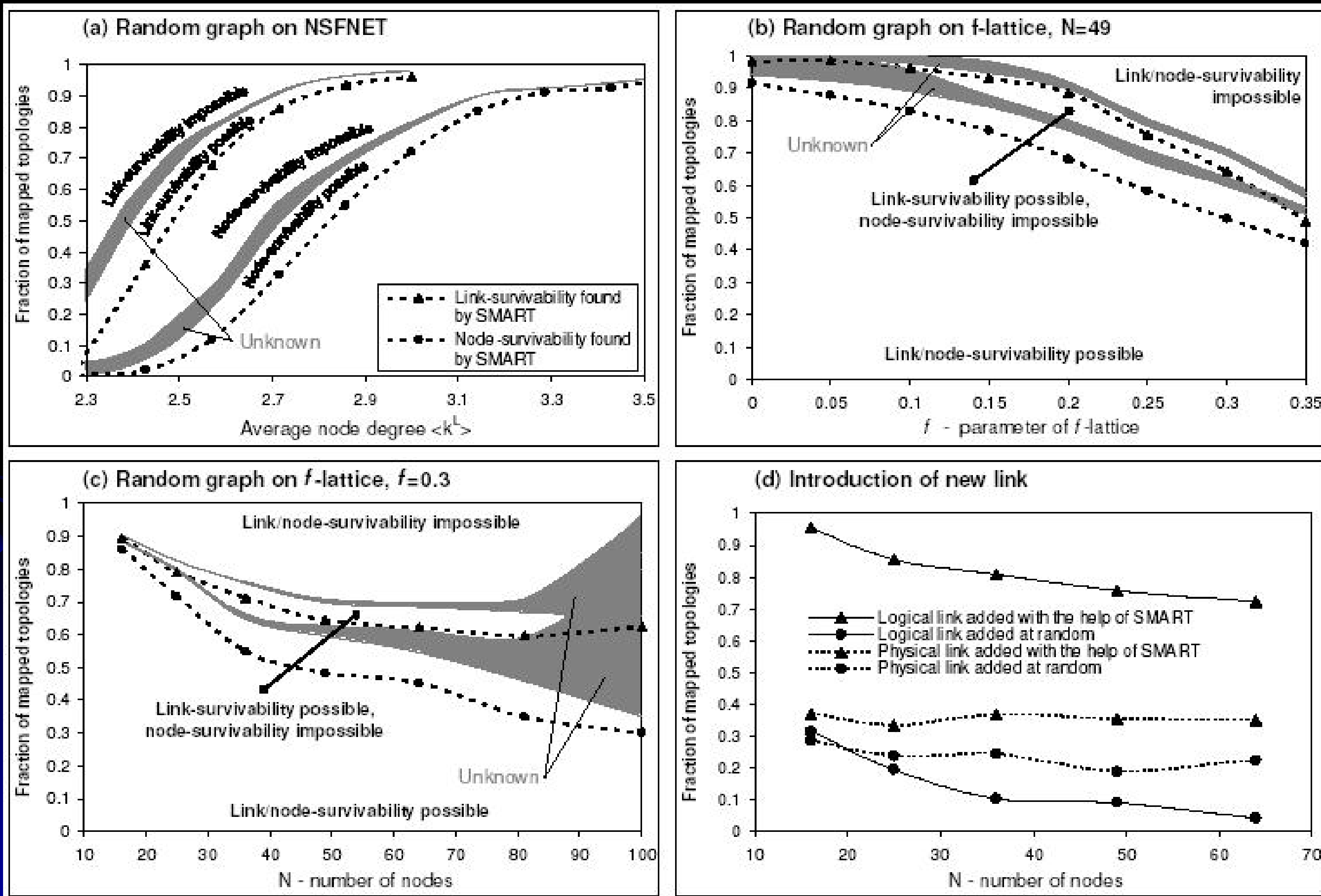

# Conclusion

- Piecewise survivable mapping enables
  - Verification of the existence of a survivable mapping
  - Tracing vulnerable areas in a network and pointing where new links should be added
  - Combination of SMART algorithm and formal analysis of the survivability problem – giving a powerful tool to designing, diagnosing and upgrading the topologies in IP over WDM networks
- Future work
  - Address the capacity-constrained-version problem
  - Consider the case of multiple failures