A Wireless Link-Up Augmentation Design for Disaster-Resilient Optical Networks

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Introduction

Today marks 5th anniversary of Japan earthquake and tsunami (Friday March 11, 2011)

- Disaster-resiliency measures for optical network infrastructure are crucial.
  - Deployment of extra resources in the form of redundancies
  - Allocate additional backup optical links for alternate paths

- Both primary and backup optical links can be vulnerable to the same disaster.
  - Also spatially inefficient and costly

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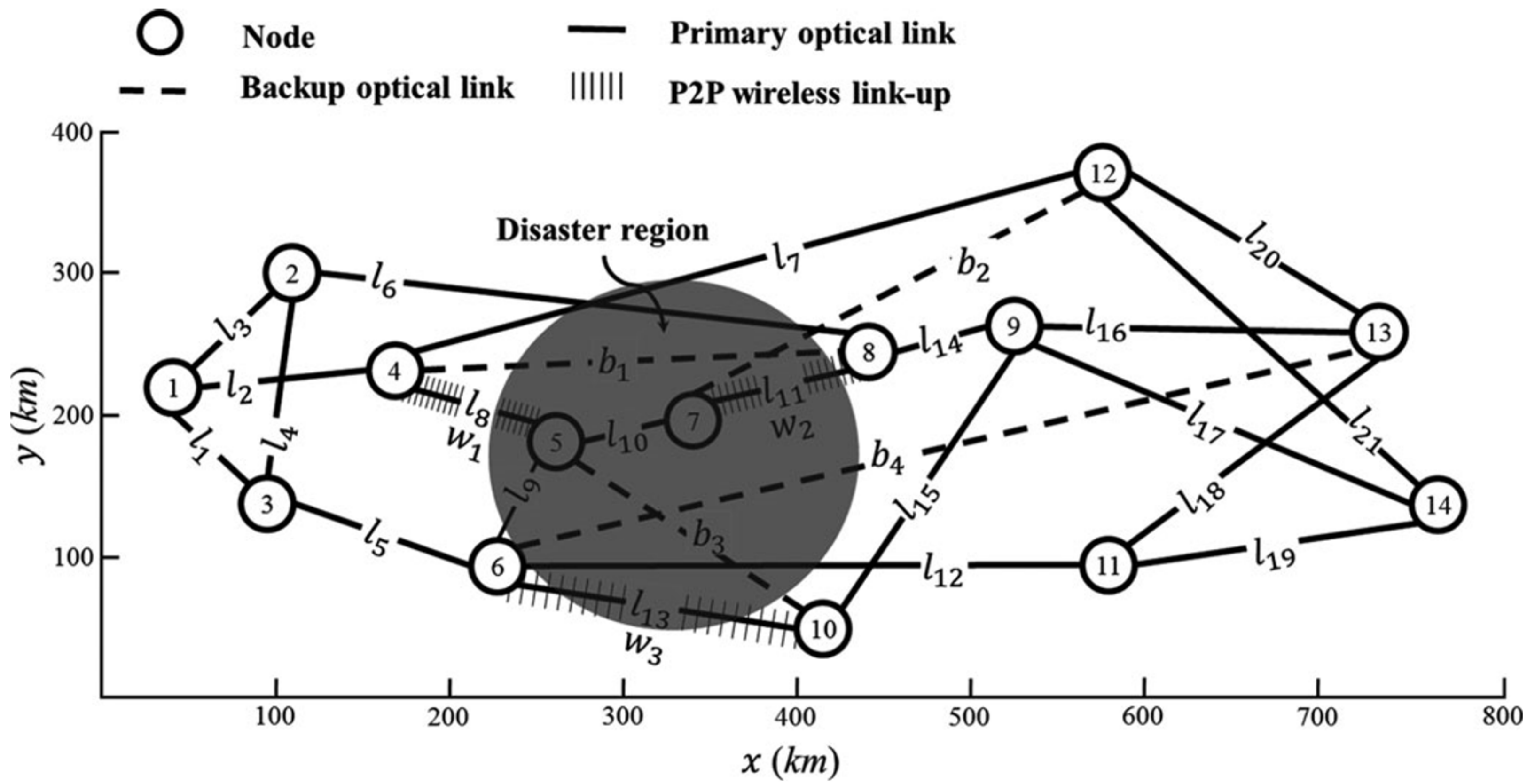
P2P Wireless technology

- Recent development in point-to-point (P2P) wireless technology has greatly enhanced the capacity, reliability, reachability, and connection stability.
  - Medium diversification can potentially overcome the limited performance of wired infrastructure.

- Optical fiber links are vulnerable to earthquakes and landslides but remains intact during events such as jamming or weather conditions, whereas it is the other way around for a wireless connection.

- By employing novel techniques such as channel aggregation, dual polarization transmission and adaptive modulation, a P2P wireless connection can provide up to 10 Gb/s data rate with an availability of 99.999% for a communication range well beyond 100 km.



Node
Primary optical link
Backup optical link
P2P wireless link-up
Disaster region
y (km)
x (km)
400
300
200
100
100
200
300
400
500
600
700
800

Link Augmentation

- A wireless augmentation *wl* of a primary optical link *l* can be realized as a single long-range P2P connection or as a relay of shorter range wireless antennas between the end nodes of link *l.*

- During the primary optical network configuration phase, a subset of its links can be selected to be augmented with additional backup P2P wireless connections, referred to as wireless link-ups.

- The traffic of disrupted primary optical links can then be rerouted via these wireless connections in the event of a random disaster failures. The amount of traffic granted protection is decided depending on the available capacity of corresponding wireless link-ups. Hence, the network can be designed to provide differentiated services under normal and disaster conditions.

Network Disaster-Resiliency Metrics

- Different metrics are considered to measure disaster-resiliency of a network infrastructure, such as network connectivity and service functions such as packet loss and average delay.
  - However, these metrics may not provide an accurate assessment for some particular kinds of network vulnerabilities, especially when considering the high probability of network segmentation.

- **ONA** (overall network availability) may be of more significance to network operators with respect to disaster failures as it measures the probability that a network can be found in its operating state at a random time in the future.

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Availability

Steady-state availability of a network component

$$A_q = \frac{\mathrm{MTTF}_q}{\mathrm{MTTF}_q + \mathrm{MTTR}_q} \quad ($$

$$A(l|f) = \begin{cases} (1 - P(l,f))\, A_l, & \text{if } l \text{ intersects } f \text{ and } l \notin \mathbf{W} \\ A_l, & \text{otherwise.} \end{cases} \quad ($$

Al - If a link *l* is augmented with a wireless link-up, the connectivity between its two end nodes is maintained with an availability *Al.*

A(l|f) - post-disaster availability of a link *l* under the impact of a disaster failure *f*.

W - set of links selected for wireless link-up augmentation.

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Upper bound

- Evaluation of ONA is an NP-hard problem, hence an upper bound is adopted.

$$\mathrm{ONA}(\mathbf{T}|f) = 1 - \sum_{i=1}^{\mathrm{N}} \left(\prod_{l_{k,i} \in E_i} \left(1 - A\left(l_{k,i}|f\right)\right) \prod_{j=1}^{i-1} \left(1 - \frac{\prod_{l_{k,j} \in E_j} \left(1 - A\left(l_{k,j}|f\right)\right)}{\left(1 - A\left(l_{i,j}|f\right)\right)} \right) \right)$$

- Evaluating random failures over entire network domain is numerically infeasible.
  - Hence adopt a grid-partition method for approximation.

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Problem Formulation

- Given a network topology **T(N,L)**, where **N** is a set of nodes and **L** is a set of primary optical links, and a random disaster region failure *f* (modeled as a circular cut of radius *r* with a deterministic failure probability), find a subset **W** of **L** whose augmentation with wireless link-ups maximizes the post-disaster **ONA** of the network for a given budget constraint.

$$\mathbf{W}^* = \arg \max_{\mathbf{W} \in \Psi} \sum_{p \in \mathbf{P}} \frac{\mathrm{ONA}\left(\mathbf{T}\left(\mathbf{N}, \mathbf{L} \cup \tilde{\mathbf{W}}\right) | f(p, r)\right)}{\mathrm{P}}$$

Subject to:

$$\mathbf{W} \subset \mathbf{L}$$

$$C_{\mathrm{W}} \leq C_0.$$

- Budget constraint: the augmentation cost *CW* of a design **W** needs to be within the cost budget *C0.*
  - *C0* = $\alpha \cdot$*Cmax*,
  - *Cmax* - cost of augmenting every primary optical link with two wireless antennas such that *Cmax* = 2L
  - α - augmentation ratio.

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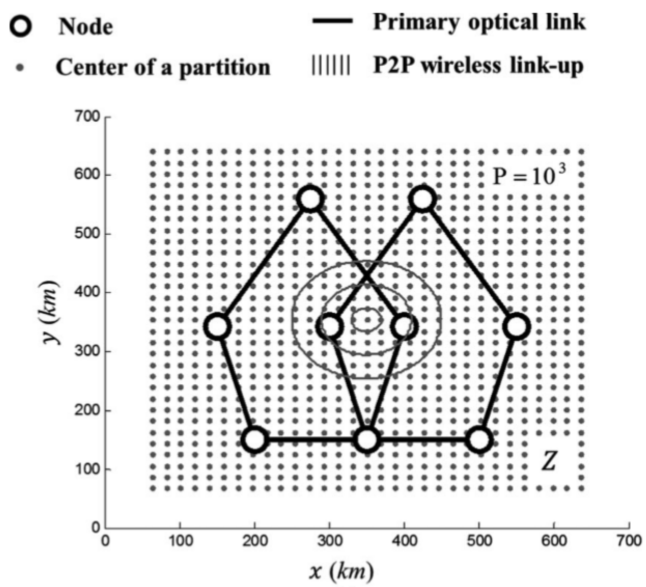
Wireless link-up augmentation design of a 9N10L sample topology using exhaustive enumeration algorithm (ExS)



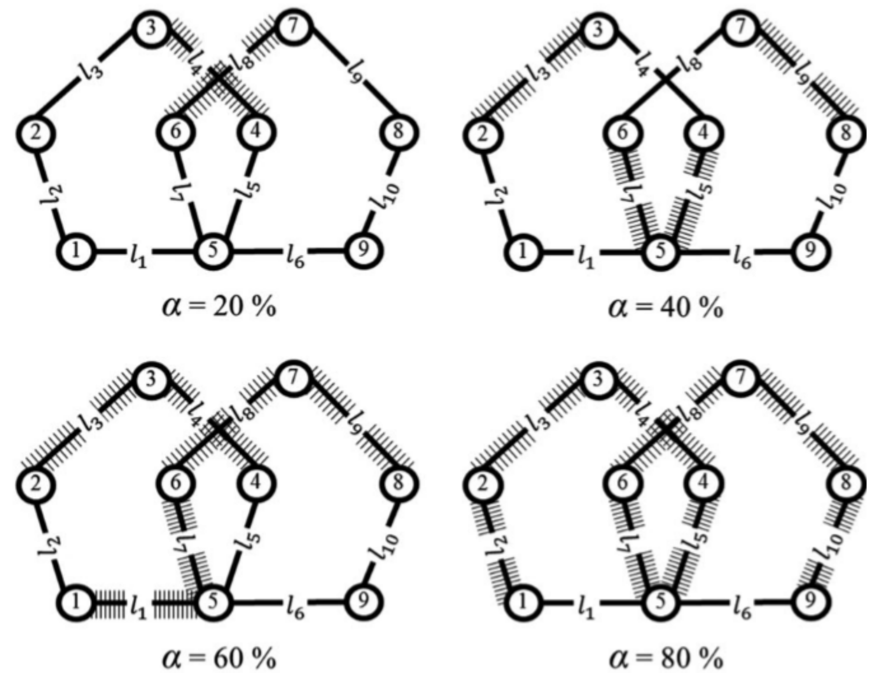


TABLE II
OPTIMAL AND WORST POST-DISASTER ONA WITH RESPECT TO DIFFERENT AUGMENTATION RATIOS α AND RADII r FOR THE WIRELESS LINK-UP AUGMENTATION DESIGN OF A 9N10L TOPOLOGY

α	ONA					
	r = 20 km		r = 60 km		r = 100 km	
	Optimal	Worst	Optimal	Worst	Optimal	Worst
0%	95.5272%		68.2566%		26.7214%	
20%	97.5514%	96.7378%	83.3820%	77.7259%	60.8627%	42.7198%
40%	99.5730%	97.7532%	96.7824%	84.7867%	91.1831%	60.6598%
60%	99.9854%	98.3685%	99.9473%	88.6596%	99.8946%	69.9848%
80%	99.9957%	99.3839%	99.9850%	96.1356%	99.9690%	89.4521%
100%	99.9992%					

Heuristic

- Finding the optimal wireless link-up augmentation design by means of exhaustive enumeration is limited to small scale networks as the search space grows exponentially.
- Heuristic procedure can be utilized to produce a suboptimal solution.

Ranking-Based Heuristics

- A related method to provide transportation networks with the desired protection from disaster failures proposes adopting the betweenness centrality (BC) measure.

- Link prioritization betweenness centrality (BC) measure, which represents how often a link lies along the shortest path between all possible node pairs in the network, for ranking the links in the order of their protection.

- Although the BC ranking may be suitable for the case of isolated random failures, it ignores factors such as the availability and length of each link, radius of the region failure, and network topological structure.
  - Typically, the longer the optical link, the more failures it may intersect a failure region and thus the higher its probability of failure will be. Conversely, protecting the shortest link first (SLF) may be favorable since it has higher availability. However, the network topological structure is not reflected in any of these criteria.

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Link vulnerability

- Link vulnerability is a measure of the amount of degradation on the ONA of a given network by failure regions intersecting that link.

- The vulnerability *vl* of a link *l*

$$v_l = (1 - \mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \backslash l))) \frac{1}{\mathrm{P}} \sum_{p \in \mathbf{P}} P(l, f(p, r)).$$

Unavailability of the network as a result of disconnecting link *l*

probability that link l intersects a random region failure f

- The link vulnerability measure thus can provide a more accurate decision of which link to be selected first for wireless link-up augmentation.

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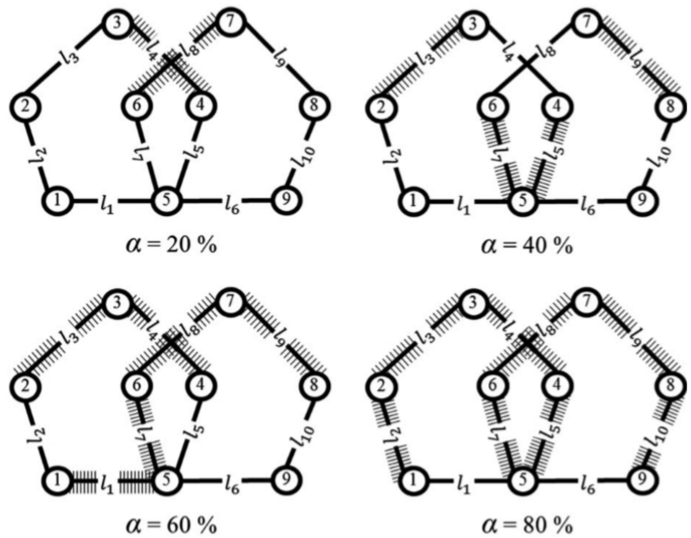
Sample topology is evaluated according to *vl*



- It can be noted that an optimal design for α = 20% elects the two most vulnerable links, *l4* and *l8*, to be augmented with wireless link-ups. At the same time, the selected links connect four different nodes, which is the maximum number of nodes that can be connected using two links.
- When the augmentation ratio is increased to α = 40%, an optimal design gives preference to enhancing node connectivity over link vulnerability by selecting links *l5* and *l7*, although links *l4* and *l8* have higher vulnerability.
- Similarly for α = 60%, *l1* is selected for augmentation instead of the higher vulnerability links *l2*, *l5,* or *l10* so that more nodes are connected. At α = 80%, a spanning tree is constructed from the most vulnerable links.

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The Most-Vulnerable Spanning-Tree (MVST) Algorithm

- Despite its simplicity, the approach of ranking the links and augmenting them one at a time may not result in selecting a subset of links of an efficient design, even when the link vulnerability measure is used.

- This is because the ONA depends on the network topological structure, and can be altered when links are disconnected by a disaster failure or by the links selected for augmentation with wireless link-ups.

- An optimal budget-constrained wireless augmentation design, such that it maximizes post-disaster ONA, must connect as many nodes as possible using the most vulnerable links whenever possible.

MVST Algorithm

Algorithm 1: Most-Vulnerable Spanning-Tree (MVST)

Given: $\mathbf{N}, \mathbf{L}, \mathbf{T}, \mathbf{Q}, r, \mathrm{P}, \alpha$;

► **Initialization**

1: Find the vector $\mathbf{l}$ of lengths of each link $l \in \mathbf{L}$ based on node coordinates $\mathbf{Q}$ and $\mathbf{T}$;
2: Evaluate the availability A_l of each link $l \in \mathbf{L}$;
3: Let the total augmentation cost $C_{\max} = 2\mathrm{L}$;
4: Calculate the cost budget $C_0 = \alpha \cdot C_{\max}$;
5: Define the network-plane Z based on $\mathbf{Q}$ and r ;
6: Divide Z into P equal-size partitions and find the coordinates of each partition center point $p \in \mathbf{P}$;
7: Let sets $\mathbf{I}, \mathbf{M}, \mathbf{W} = \varnothing$;

Initialization step of Algorithm 1.

The availability *Al* of each link is calculated based on its corresponding length.

Define the complete augmentation cost *Cmax*, calculate cost budget *C0* with respect to α.

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▶ **Building of Initial Design**

Let an integer variable $k = 0$;
for each link $l \in \mathbf{L}$ **do**
  Restore k;
  for each point $p \in \mathbf{P}$ **do**
    if link l intersects region failure $f(p,r)$ **then**
      Let $P(l, f(p,r)) = 1$;
    else
      Let $P(l, f(p,r)) = 0$;
    end if
    Let $k = k + P(l, f(p,r))$;
  end for
  Let $\mathrm{I}_l = k$;
  Evaluate $\mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \setminus l))$ using Eq. (6);
  Evaluate the vulnerability of link l such that

$$v_l = \left(1 - \mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \setminus l))\right) \frac{\mathrm{I}_l}{\mathrm{P}};$$

  Let link weight $w_l = -log(v_l)$;
end for
Find the most-vulnerable spanning-tree $\mathbf{M}$ using Prim's least-weight spanning-tree algorithm;
Let an initial design $\mathbf{W} = \mathbf{M}$;
Let $C_{\mathbf{W}} = 2|\mathbf{W}|$;

MVST **M** - a spanning tree constructed from the most vulnerable links is a suitable initial design to begin with.

To build **M**, Step A of algorithm starts by evaluating the vulnerability of each link. **M** can be found as the minimum weight spanning tree by using any of the existing approaches such as Prim's algorithm.

Weight of each link *l*, $wl = -\log(vl)$. **M** is the initial wireless link-up augmentation design W and its cost *CW* is calculated.

► **Modifying Initial Design**

while $C_{\mathbf{W}} > C_0$ **do**
  for each link $l \in \mathbf{W}$ **do**
    Evaluate $\mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \cup \mathbf{W} \setminus l))$ using Eq. (6);
    Re-evaluate the vulnerability of link l such that
    $$v_l = (1 - \mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \cup \mathbf{W} \setminus l)))\frac{\mathrm{I}_l}{\mathrm{P}};$$
  end for
  Delete the link with minimum v_l from $\mathbf{W}$;
end while
Let the set of remaining links $\mathbf{R} = \mathbf{L} \setminus \mathbf{W}$;
for each link $l \in \mathbf{R}$ **do**
  if $C_{\mathbf{W}} + C_l > C_0$ **do**
    Let $\mathbf{R} = \mathbf{R} \setminus l$;
  end if
end for
while $C_{\mathbf{W}} < C_0$ and $\mathbf{R} \neq \varnothing$ **do**
  for each link $l \in \mathbf{R}$ **do**
    Evaluate $\mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \cup \mathbf{W} \cup l))$ using Eq. (6);
    Re-evaluate the vulnerability of link l such that
    $$v_l = (1 - \mathrm{ONA}(\mathbf{T}(\mathbf{N}, \mathbf{L} \cup \mathbf{W} \cup l)))\frac{\mathrm{I}_l}{\mathrm{P}};$$
  end for
  Add the link with maximum v_l to $\mathbf{W}$;
  Let $\mathbf{R} = \mathbf{R} \setminus l$;
end while

Return: $\mathbf{W}$;

To meet the cost budget *C0*, Step B modifies the initial design **W**. For the case when *CW* surpasses *C0*, algorithm finds and deletes the least vulnerable link from W until *C0* is satisfied.

The vulnerability of each link *l* in **W** must be re-evaluated such that the ONA is calculated after augmenting each link in design **W** except for the link *l*.

When *CW* is below *C0*, the most vulnerable link among the remaining links is added to **W** after confirming that none of the links would have a cost that violates *C0* when added to **W**.

Results

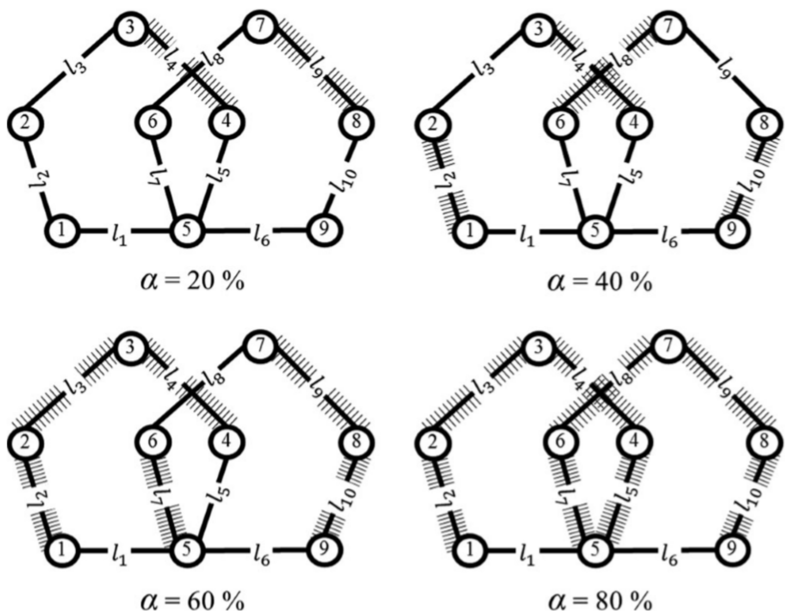

TABLE III
OPTIMALITY OF MVST HEURISTIC ALGORITHM FOR THE WIRELESS LINK-UP AUGMENTATION DESIGN OF A 9N10L TOPOLOGY

α	ONA					
	r = 20 km	Ω	r = 60 km	Ω	r = 100 km	Ω
20%	97.5514%	100%	82.8783%	91.09%	58.1385%	84.98%
40%	99.5707%	99.87%	96.7824%	100%	90.8534%	98.92%
60%	99.9854%	100%	99.9460%	99.99%	99.8903%	99.99%
80%	99.9957%	100%	99.9850%	100%	99.9690%	100%

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100%	99.9992%					

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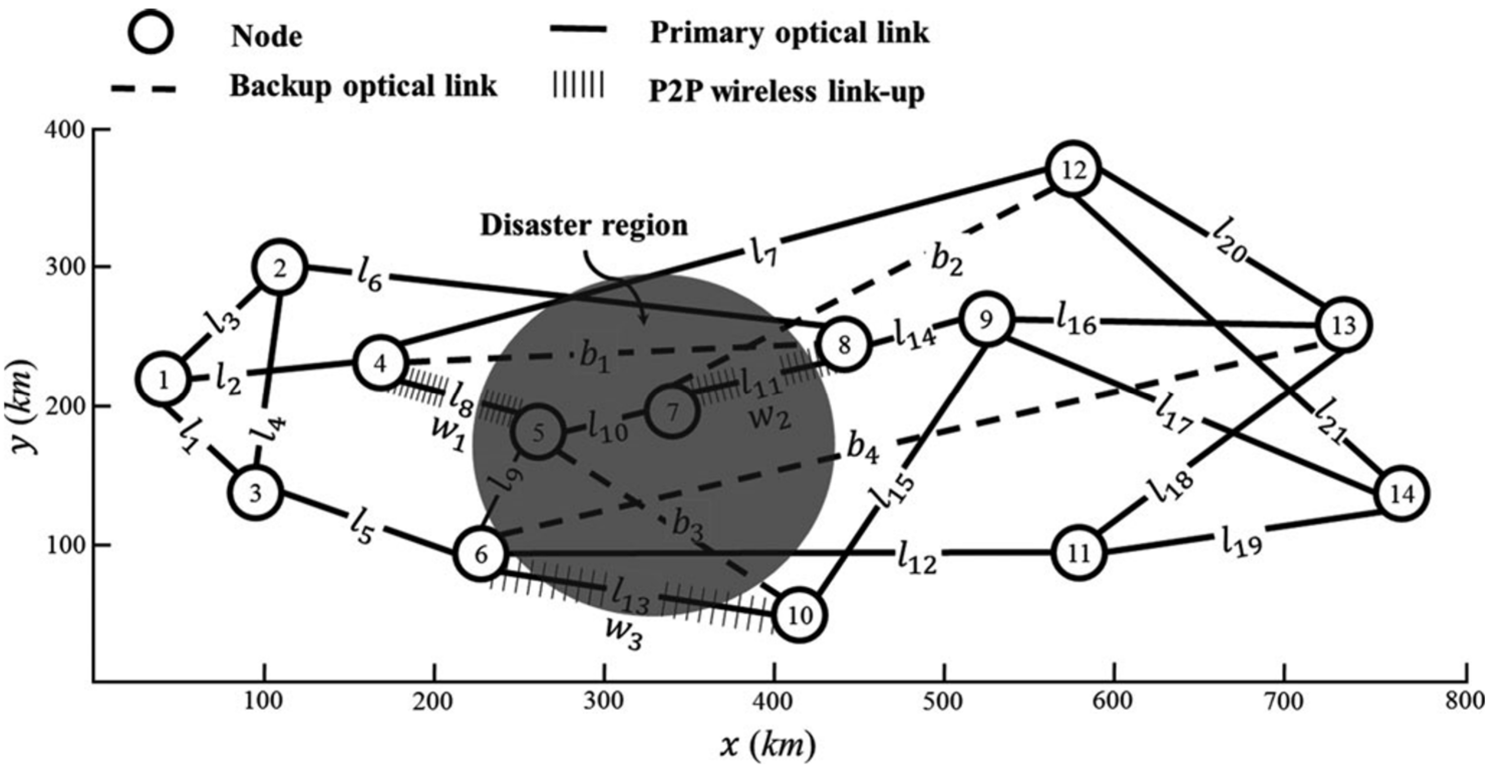
Simulation topology



For realistic network settings, link availabilities are generated based on their corresponding lengths, and we consider the values of CC = 300,which indicates the average cable length suffering from one cable-cut a year, and MTTR = 12h.

Due to the infeasibility of obtaining an optimal design solution for a large-scale network such as NSFNET, the performance of the MVST-based algorithm is evaluated in comparison to the simple ranking based heuristics.

Betweenness centrality (BC)
Longest link first (LLF)
Shortest link first (SLF)
Most vulnerable link first (MVLF)

Longest spanning tree (LST)
Shortest spanning tree (SST)

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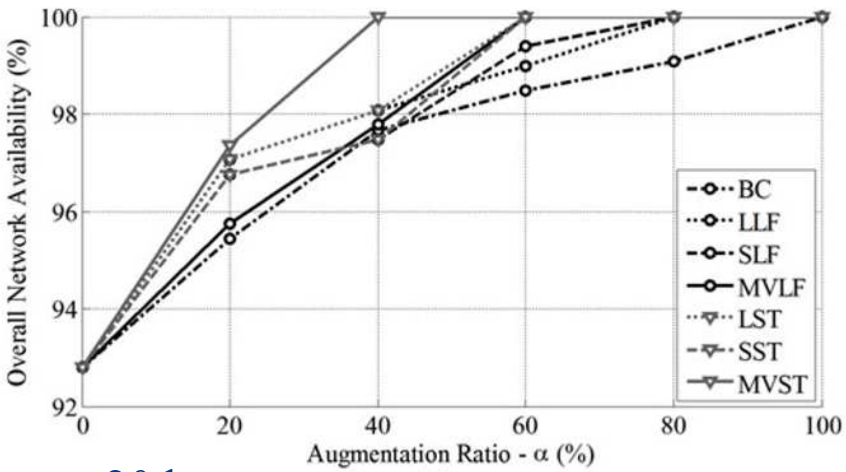
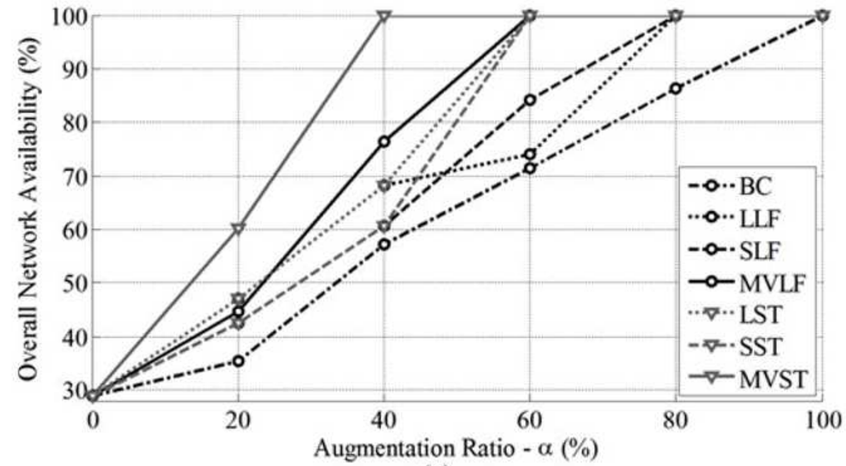


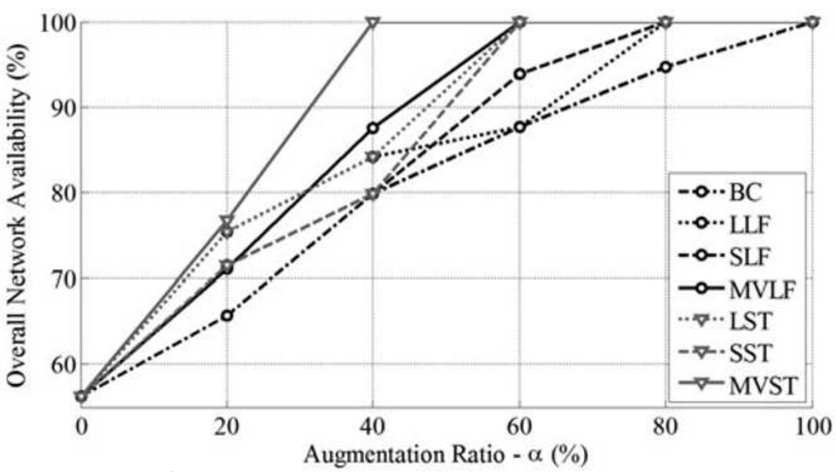
r = 20 km

(a)



r = 100 km

(c)



r = 60 km

(b)

Betweenness centrality (BC)
Longest link first (LLF)
Shortest link first (SLF)
Most vulnerable link first (MVLF)
Longest spanning tree (LST)
Shortest spanning tree (SST)

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Result

- BC ranking heuristic shows the worst performance regardless of how much we increase the augmentation ratio or reduce the radius of disaster failure, as these variables are not reflected in the BC measure.
- The link length based ranking heuristics, LLF and SLF, provide an improvement of the ONA, but not as much as that achieved by the MVLF ranking algorithm.
- We also can observe the steady performance of MVLF in comparison to the fluctuations of LLF and SLF with respect to the augmentation ratio α.
- MVST algorithm achieves more than 90% of the original ONA after augmenting only 40% of the links in the network topology, whereas this is not achievable by the MVLF, LST and SST algorithms until α = 60%, by the LLF and SLF algorithms until α = 80%, and by BC until reaching full augmentation

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Conclusion

- Designed a system model for utilizing the capability of P2P wireless link-ups in maintaining the operability of the network when a disaster failure impacts its primary optical topology.
- Formulated the optimization problem of finding the subset of links in an optical network topology whose wireless link-up augmentation maximizes post-disaster ONA for a given budget constraint.
- Presented a link vulnerability measure based on which a greedy-based heuristic algorithm is proposed to find a suboptimal solution in a polynomial time.
- The algorithm constructs the MVST as an initial wireless link-up augmentation design, which is modified by the addition or deletion of links in view of their vulnerabilities to satisfy a given cost budget.