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Research Article

Enhancing Optical Network Performance during Failures; Value Proposition from Dense Wavelength Division Multiplexing

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ABSTRACT

The advancement of optical networks as the backbone of modern telecommunications has been enhanced by their high data capacity, minimal latency, and adaptability. Fiber optic technology is essential for sending large volumes of data over extensive distances, serving applications include video streaming, cloud computing, and gaming on the internet. Ensuring network survivability, defined as the ability to endure disruptions from natural or physical disasters, is essential. Fiber cable cuts are a common type of network failure, requiring efficient traffic restoration methods to ensure service continuity. Restoration solutions, divided into facility repair and facility restoration, entail trade-offs between flexibility and capacity needs, affecting their efficiency. In this context, cross-layer analytics which integrates the physical layer and data link layer of optical network are vital for improving network resilience. Dense Wavelength Division Multiplexing (DWDM) is a crucial innovation in optical communication that provides substantial benefits in capacity, distance, and spectral efficiency, rendering it essential in the core networks of telecommunication systems. This study is proposed to examine fixed and variable backup path techniques to enhance signal redirection during connection breakdowns. A comparative examination with existing methods, such as Kruskal and Hamiltonian algorithms, illustrates the effectiveness of the proposed strategy. The results enhance restoration procedures in optical networks, responding to the increasing need for dependable and high-capacity telecommunications infrastructure. The study has taken in to account secondary data concerned with capital expenditure (CAPEX) and operational expenditure (OPEX), where in network operators can determine the most cost-effective solutions while maintaining optimal network performance. It was identified that the DWDM offers a compelling value proposition in terms of cost-efficiency, scalability, and long-term operational savings.

Keywords: Fixed backup Path, Variable Path links, working channel assignment, Spare capacity assignment.

1. Introduction: Networking and technology have become important parts of modern life that make many parts of daily life and global activities easier. Because communication systems can transmit messages consistently and rapidly across great distances, they facilitate information sharing, event planning, and staying in touch.

This has had a big effect on many areas, such as emergency response, public services, business processes, and communication between people. Since the internet continues to expand, more processing power, faster transmission rates, and more space are needed to handle the growing amount of data flow.

Networking, the process of linking multiple computer systems and devices for the exchange of resources and information, is essential for both businesses and individuals. It facilitates data and idea exchange, promotes collaborative work settings, and ensures rapid access to resources such as printers and servers. In a growing digital environment, a resilient networking infrastructure is essential for the continuous functioning of most sectors including finance, healthcare, education, and entertainment.

Optical networks are now the fundamental infrastructure of contemporary telecommunications because of their superior data capacity, little delay, and potential to expand. Fiber optic cables are utilized for the transmission of large quantities of data across extensive distances, rendering them indispensable in our contemporary society. Optical networks have the capability to carry data at high throughput and accommodate a wide variety of applications, such as video streaming, cloud computing, and internet-based gaming. In this situation, the ability of a network to remain functional and operational is of great importance. Survivability refers to the ability of a communication network to withstand and prevent any disruption or disturbance of service, namely caused by combat, fire, earthquakes, hazardous radiation, or other physical or natural disasters [1]. Among network failures, the most prevalent system failure is the cutting of fiber cables. When there is a failure, the process of traffic restoration involves redirecting individual calls to bypass the failing network. These restoration solutions are specifically designed to utilize the existing capacity in order to restore or maintain service in the event of a failure [2]. Restoration strategies can be categorized into two groups based on survivability criteria. Facility repair and facility restoration. There are tradeoffs between the level of flexibility and the amount of additional capacity needed for each category of techniques. In general, advanced approaches typically have lower capacity requirements but can slow down the restoration process [2,9]. The more basic strategies allocate capacity in advance for the purpose of restoration. Link failures are a frequent occurrence that can happen in any type of network, including wide area networks and data center networks.
In order to resolve the problems related to the survivability of optical network, it is necessary to comprehend the cross-layer analytics of the network. The areas requiring additional focus include the optical (physical) layer, network layer, and data link layer. Continuous monitoring of physical layer problems in real time is essential for ensuring optimal network performance. The network management system utilizes monitoring tools and algorithms to promptly identify and resolve issues as they arise. This strategy involves modulating classical pieces of information associated with different users on distinct wavelengths, each with a discrete frequency spectrum separate from the other user's channel. WDM networks[6] are constructed using many architectures, topologies, and components. The parameters of wide spectrum range, low noise, and high repetition rate have been identified as potential for WDM applications [7].
Dense Wavelength Division Multiplexing (DWDM) is a significant advancement in optical communication technology that meets the requirements for more capacity, longer distances, and enhanced spectrum efficiency in current network design. It is very suitable for long-distance communications without requiring signal regeneration. DWDM offers the benefit of delivering a large amount of data over a single optical fiber, while also allowing for the flexible allocation of bandwidth to various channels. These networks may be readily enhanced to meet growing data requirements. DWDM is frequently employed in the core networks of telecommunication companies and internet service providers [8]. It has become an essential technology in the worldwide telecommunication system.
This study employs fixed backup path algorithms and variable backup path algorithms to redirect the signal in the event of a connection failure. The suggested algorithm is evaluated against established methods such as Kruskal algorithm [16] and Hamiltonian algorithm [15], yielding favorable outcomes. The subsequent sections of the document are structured as follows: Section 2 addresses the relevant literature. Section 3 outlines the intended works. Section 4 establishes the experimental outcomes, while Section 5 conveys the conclusion.

2. Related Work

Tsong-Ho-Wu [10] proposed a topology design by selecting the most economical routing of the fibers for the ring and point to point systems. Here the survivable network topology is chosen such that it minimizes the overall cost, including installation, material, splicing and regenerator cost. Xu et al. [11] employed optical neural networks (ONN) to illustrate the effectiveness of wavelength division multiplexing (WDM) techniques. This technique can leverage the broadband capability of the optical networks. This paper highlights on recent

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advancements in WDM based ONNs, in the use of integrated microcombs for implementation. Further, the review highlights the limitations and challenges of ONNs.
Higashimori et al. [12] discussed about improving the physical topology from the point of view of spectral graph theory and those that are based on improving dependability, which is important for network operations. The comparison study shows that the suggested two-step degree-bounded reliability-optimization model, which improves reliability with the proper node degree constraints, creates a physical topology with significant amounts of wavelength capacity without degrading reliability.

Neeraj Mohan et al [13] reviewed various single link and multiple link failures and various network protection and network restoration techniques are analyzed. Verma et al. [14 explored using a wavelength division multiplexing passive optical network (WDM-PON) for a long reach. The capability of this method extends to various access networks, including mobile, local area and metro area networks. The system data rate can reach up to 20 gigabits per second (Gbps) with a maximum range of 80 kilometers(km). For larger data speeds (i.e., 5Gbps or 10 Gbps), the distance limit is also 80km with a power of 30dBm. It also states that a higher data rate of 40 Gbps per channel was reached at a range of 30 km. This suggests that a new, better WDM-PON design could allow for a maximum data rate of 80Gbps (10 x 8) to 320Gbps (40 x 8). International Telecommunication Union (ITU) guidelines say that the bit error rate (BER), quality factor (Q), and eye height must all be within acceptable ranges in order to meet the needs of 5G or 6G applications in the last mile in the future.

3. Proposed System

The proposed approach to design a network involves reducing the number of operational and spare channels that are needed to meet the demand from end to end and to reach a certain level of network survivability assurance. To make the design problem computationally feasible, two techniques are discussed. First being the variable back up path and second is fixed back up path.
The structure of an optical network is shown as a linked graph G (V, E), where V is the set of nodes and E is the set of bidirectional optical fibre links within the network. Every link 'e' in E possesses a finite quantity of wavelengths represented by W. A non-negative link cost C(e) is allocated to each link 'e' in the network, denoting the distance between the connected neighboring node pair. Our model incorporates the following assumptions.

Assumptions:

- There is no wavelength conversion capabilities in the network, and each fiber link can transmit an equal amount of wavelengths.
- All light paths that share at least one fiber link are assigned unique wavelengths
- Every node can serve as both a routing node and an access node.
- Every node has a fixed number of movable transceivers.
- All channels exhibit uniform bandwidth.

Definitions and Notations:

V : Set of nodes; E: Set of optical links; W: Set of wavelengths used
P_{mn} : The cost of power for a link connecting m, n
C_{Th} : Minimum average channel capacity at which a link can be considered as failure.
$W_t(E_i)$: Weight of the link E_i
$Wt(E_{i+1})$: Weight of the link E_{i+1}
L_{mn} : The binary variable is assigned a value of 1 if a connection exists between the pair (m, n); otherwise, it remains 0
$L_{m,n,w}$: The binary variable equals to 1, if a light path is established between the pair(m, n) using the wavelength w, else it remains 0
$C_{m,n,w}$: Channel capacity of a light path between a node pair(m, n) on a wavelength wϵW

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The proposed algorithm for survivable topology search involves adapting the algorithm to consider redundancy and fault tolerance. Equation (1a) minimizes the power cost of a link.

$$Min[\sum_{m;m\neq n} \sum_{n;m\neq n} lm,n * Pm,n] \quad (1a)$$

Constraint:

Following constraints need to be considered while finding the survivable topology.

$$\sum_{m;m\neq n} \mathrm{Lm,n} = 1 \quad (1b)$$

Where m ∈ V and j ∈{1…V}

Here we include minimum number of links to minimize the power cost.

$$[\frac{\sum_w Lm,n,w*Cm,n,w}{W}] \geq CTh \quad \text{for} \quad \forall m,n \in E; m \neq n, \& w \in W \quad (1c)$$

Equation (1c) ensures that the average channel capacity remains above the desired threshold capacity.

$W_t(E_i) < Wt(E_{i+1})$

$E_{i+1} \in {}^{E}/_{Ei}$

Ei ={E1, E2,…Ei} (1d)

Equation (1d) guarantees that the link with the lowest weight is chosen first, followed by links with higher weights.

3.1 Variable Path links

In the variable backup link algorithm, the design problem is divided into two sub problems to enhance computational feasibility. They are Initial spare capacity assignment and Minimum Spare capacity assignment

3.1.1 Initial spare capacity assignment: This method focusses on allocating the initial amount of spare channels needed to meet end-to-end network demands while considering the network topology, node count, and node placements. The number and strategic placements of nodes are determined based on network requirements (network cost, number of users, bandwidth demand etc). Once the topology and node locations are known, demand routing can be performed by establishing a shortest path tree for each node to all others. End-to-end demands originating or terminating at the root node are then routed along these shortest path trees.

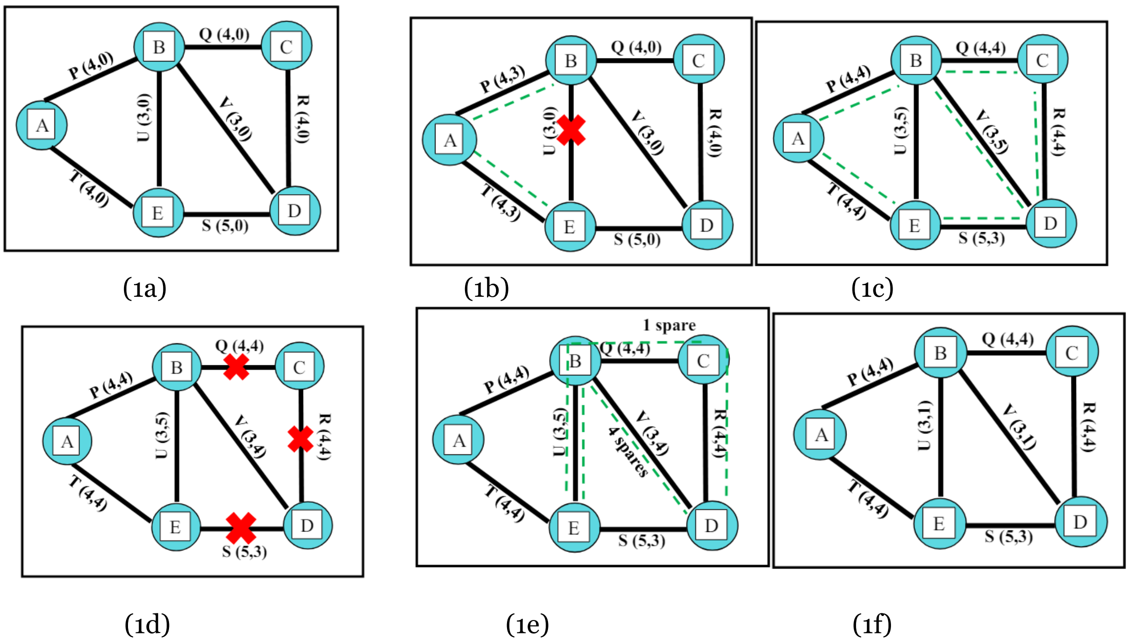

Figure 1: Spare capacity assignment algorithm. a) Initial condition b)Initial assignment for 1 link failure c)Result for initial assignment d)Delete 1 spare capacity path e)Find alternate route f) Final result

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Figure 1 shows an illustration of the working of proposed algorithm. A network having 5 nodes and 7 links with a total of 27 working channels is considered for discussion (Figure 1a). The connection 'L' has 'w' working channels and 's' spare channels, as shown by the notation L(w,s). The algorithm determines the shortest alternate path for every broken link during the first assignment phase. The link's spare capacity in the alternate path is updated to the required restored demand if its present spare capacity is less than the required restored channel. If the current spare capacity is sufficient to restore the necessary demands, then it remains the same. In the example network, spare capacity assignment for link U are displayed in Figure 1b. It shows that P- T is the alternate path selected for connection U. Thus, connections P and T get an additional 3 channels of spare capacity. The first spare capacity assignment is displayed in Figure 1c, which is obtained after repeating the previously mentioned process. The working capacity to spare capacity ratio in Figure 1c is 29/27. For every single link failure scenario, this spare to working ratio shows the fastest restoration plan and the highest spare capacity needed to restore 100% of the demand.

3.1.2 Minimum Spare capacity assignment: The process of allocating spare capacity involves placing of minimum of spare capacity required to recover, in the event of a single or multiple link failure.
A predetermined proportion of demands (restoration ratio) is defined as

$$\text{Restoration ratio} = \frac{restored\ demands}{affected\ demands} \quad (2)$$

Note that assignment designed for line restoration is adequate for path restoration because restoration of paths for line restoration may also be restoration paths for path restoration.
Other restoration links may share the surplus capacity allocated to one repair link. In the second stage , we are finding and eliminating few more redundant spare capacity to improve the restoration ratio given in equation(2). Figure 1d displays the role of a spare channel V(3,4) having four original spare links. We discover that a spare channel on 'V' is needed as alternate link during failure of Q(4,4) or R(4,4) or S(5,3). Since the present spare capacity in 'V' cannot restore the affected working demand, (5 channels for 'S'), addition to first path, another alternate path is found by the algorithm. Figure 1e with dotted lines shows the two alternate paths for link S. The split of demands are among the paths V and Q-R. So the working demands for 'S' can be restored via a path of U-V with 4 spare demands and another path of U-Q-R with 1 spare demand. The same procedure is repeated until the desired restoration ratio is attained.
Spare capacity is typically assigned using a centralized method that takes into account global network considerations. A few practical factors to take into consideration are the integrity of spare channel, the hop limit factor and the modularity of transmission systems that carry both working and spare capacity. Table 1 outlines the Pseudo code of variable back up path.

Table1: Pseudo code for Variable backup path
Step 1: Plot the nodes and associated links Initialize Network as a graph Add nodes to the graph For each pair of connected nodes: Add link between nodes with initial capacity Step 2: Assign the capacity for each link For each link in the network: Assign capacity to the link Step 3: Consider the failure of one of the links For each link in the network: Temporarily remove any link from the graph Find the least-cost path between the nodes connected by the failed link Assign the capacity of the failed link as backup capacity to the links along this path Restore the removed link

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Step 4: Consider failure of each link to determine backup links
For each link in the network:
Temporarily remove the link from the graph
Find the least-cost path between the nodes connected by the failed link
Assign the capacity of the failed link as backup capacity to the links along this path
Restore the removed link

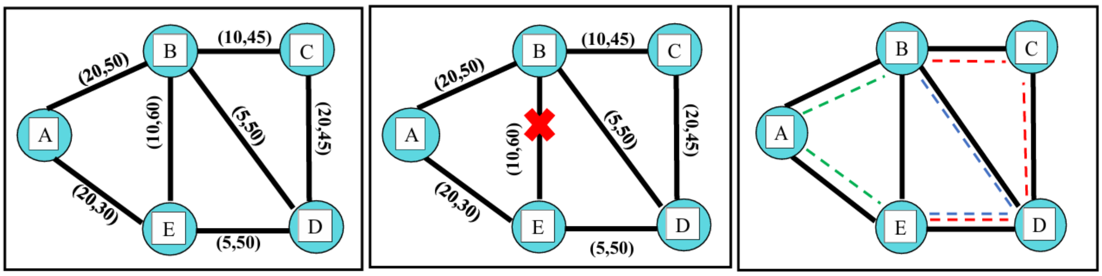
Step 5: Handle multiple backup links for a single link
For each link in the network:
If the link has more than one backup link:
Select the backup link with the least backup capacity value
Discard other backup links

3.2 Fixed back up path allocation:

This heuristic approach is used by the network to restore its working more quickly in the event of a link failure. During a single link failure, several backup shortest paths are calculated to help. The switch closest to the failing connection aids in packet forwarding using the collection of shortest pathways. The Djkstra algorithm is used to calculate the set of shortest paths, which minimises the memory overhead. Here the channels in the link are divided in the ratio 80%: 20%. 80% links are used for regular users and 20% links are reserved for high priority customers. Priority links are dedicated links only for special demands. During failure, based on available free channels, the high priority packets are transmitted first, and then regular packets. Figure 2 shows an illustration of the working of proposed algorithm. Let $C_T(A,B)$ represent the total capacity of the link between nodes A and B. To enforce uniformity across the network, we have assumed, total capacity of each path is 100 links . In figure(2a), the connection 'A-B' has 'D' as distance metric between the nodes and 'C_P' as current occupancy , as shown by the notation (D,C_P).The network demand condition is, $C_T(A, B)>C_P(A,B)$. In the event of a failure of the link B→E, as shown in figure (2b), the existing traffic flow $C_P(B,E)$ must be rerouted through alternative paths. The possible rerouting options are shown in figure (2c).

i)$C_P(B, E)\rightarrow C_P(B,A)+C_P(A,E)$
ii)$C_P(B, E)\rightarrow C_P(B,D)+C_P(D,E)$
iii)$C_P(B, E)\rightarrow C_P(B,C)+C_P(C,D)+C_P(D,E)$

For the computed minimum-distance path, we define the available capacity(L) for rerouting as:
$L=C_T-C_P$
The rerouting procedure involves the following steps:
Based on available free channels in the shortest path, the demands of the affected path are rerouted (B-D-E). The remaining traffic is rerouted via the next shortest available path (B-C-D-E) as shown in figure (2d). The process continues iteratively until the entire load of $C_P(B, E)$ is successfully rerouted.



(2a) (2b) (2c)

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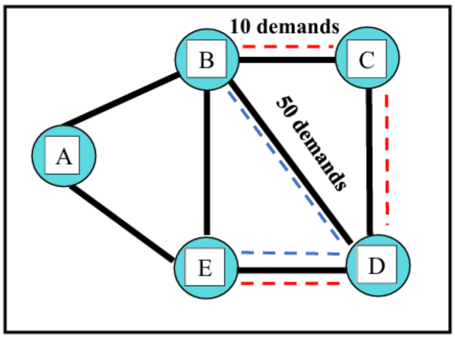

(2d)

Figure 2: Fixed link algorithm for back up link allocation. a) Initial condition. b) with B-E link failure c) Possible alternate routes. d) Redistribution of traffic via alternate paths.

This technique prevents additional link failure brought on by high bandwidth usage or congestion. Table 2 outlines the process of fixed back up path.

Table2: Pseudo code for Fixed backup path
Step 1: Plot the nodes along with the associated links Initialize Network Graph Add nodes to the graph For each pair of connected nodes: Add link between nodes with initial capacity Step 2: Assign the capacity for each link For each link in the network: Assign 80% of capacity as working capacity Assign 20% of capacity as backup capacity Step 3: Find the least-cost path for data transfer between source and destination Use least-cost path finding algorithm (Dijkstra's) Return path and cost Step 4: Consider single-link failure between source and destination For each link in the path from source to destination: Temporarily remove the link Calculate the least-cost path without the failed link Step 5: Reroute the data through the alternate path If alternate path found: Check if backup capacity along the path can accommodate the failed link's capacity If yes: Allocate backup capacity to reroute the data Else: Step 6: Handle excess data by finding additional paths Reroute excess data by finding the next least-cost path Repeat until all excess data is rerouted or no paths are available Restore the removed link

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4: Result and Discussion

4.1 Evaluation of Variable back up path algorithm:

4.1.1 Initial setup:

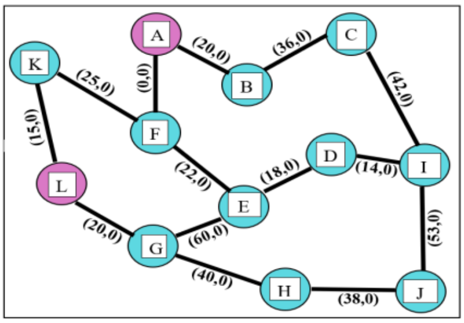

Figure 3(a): Initial Stage

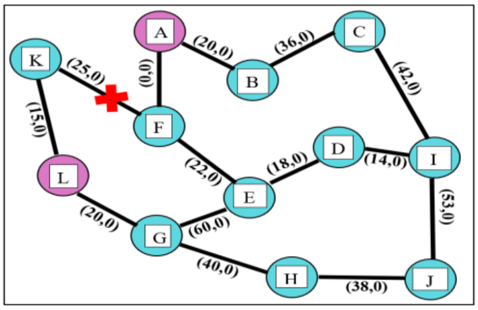

Figure 3(b): Condition of single link failure

We have utilized a network model consisting of 12 nodes and 14 links to simulate and analyze all of the aforementioned techniques. Figure 3(a) shows the initial stage with link assigned metric. The same network parameters were maintained in both methods. The performance metrics stated in Table 3 remains constant across all methods. The laser diode has a power cost of 1 decibel (dB), and the pin detector has a power cost of 0.5 dB. The necessary amplification of the EDFA is 0.07 decibels every 80 kilometers.

Table 3: Relative power cost required for network operation

Elements	Power costs in units	
	10Gbps	40Gbps
Electrical switching	18.4	25
Optical switching	9.2	18
Laser diode(Transmitter)	1	1.4
PIN detector(Receiver)	0.5	1
EDFA Amplification	0.07/80 km	0.3/80 km

Link capacity was the designated weight considered in this network. Initially considering node A is source and node L is destination, the link failure is observed between node F and K as shown in Figure 3(b). The shortest path from the source (A) to the destination (L) is initially determined. This path serves as the primary reference to determine necessary links for network connectivity.

Link Failure Simulation: Sequentially, individual links along the shortest path are intentionally disconnected to duplicate a failure. The network dynamically recalculates the next shortest path from source A to destination L in the event of a link failure. This guarantees the network's functionality by redirecting traffic through alternate routes.

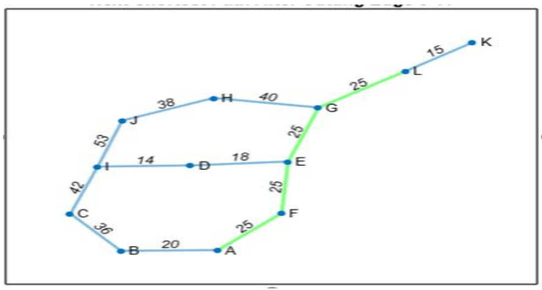

Figure 3(c)

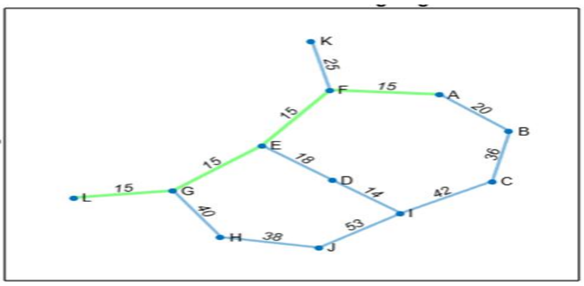

Figure 3(d)

Back up capacity calculation: Figure 3(c) shows the assignment of working capacity of link F→K(25) to the alternate path. Back up capacities of links A→F, F→E, E→G, & G→L are assigned as 25. Figure 3(d) gives

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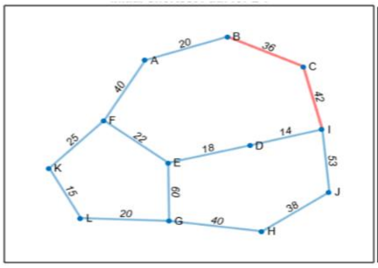
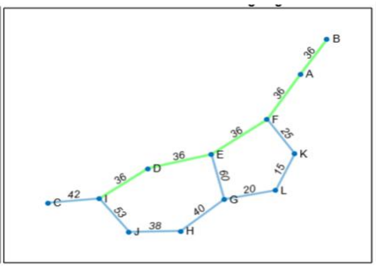
the similar calculation for the link failure G→H. Working capacity (15) is assigned for the back up path. This backup capacity guarantees that, in the event of a failure, adequate capacity is provided to manage traffic on an alternate route.

Iterative Failure and Backup Calculation:

This procedure of disconnecting each link and determining the associated backup capacity is reiterated for all links within the network. In situations where the route has multiple probable backup capacities from separate rerouting iterations, the least backup capacity value is employed. This guarantees that the network is equipped for worst-case scenarios and that each link provides the capacity to manage traffic during breakdowns. Figure 3(e) to Figure 3(j) are few examples of such iterations.


(3e)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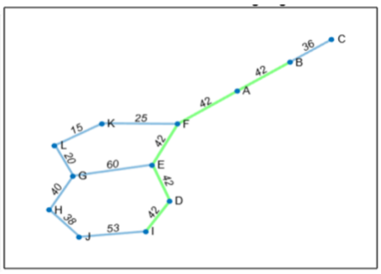
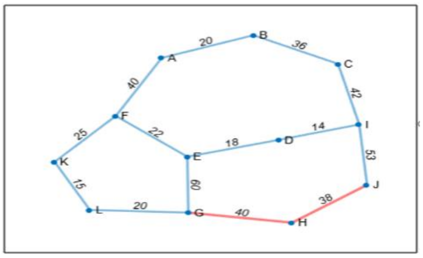
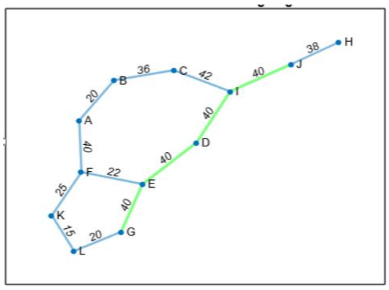

(3g)


(3h)


(3i)

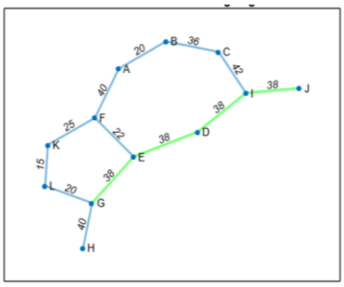

(3j)

Figure: (3e)-(3j): Backup capacity iterations

Final Backup Capacity:

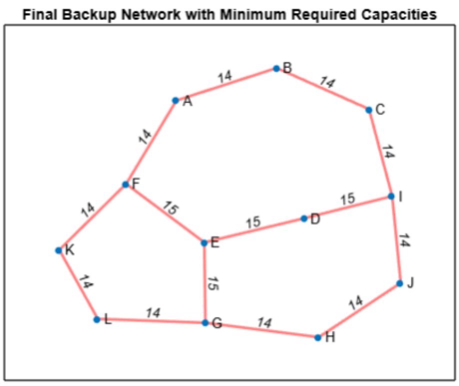


Figure (3k) : Network after the calculation of back up link capacities.

This iterative procedure determines the backup capacity for all network links. Each connection is allocated a capacity value that guarantees network resilience in the event of various link failures. Figure 3k gives the final back up link allocation for the given network. Here the ratio between working to spare capacity is 443/200.
We compared the time required for restoration of network with other previously obtained algorithms based on performance metrics. The dataset we have selected is sourced from [1] and is utilized for the purpose of

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comparing our approaches with other existing methods. Kruskal's algorithm [16] and Hamiltonian analysis [15] yield the results.

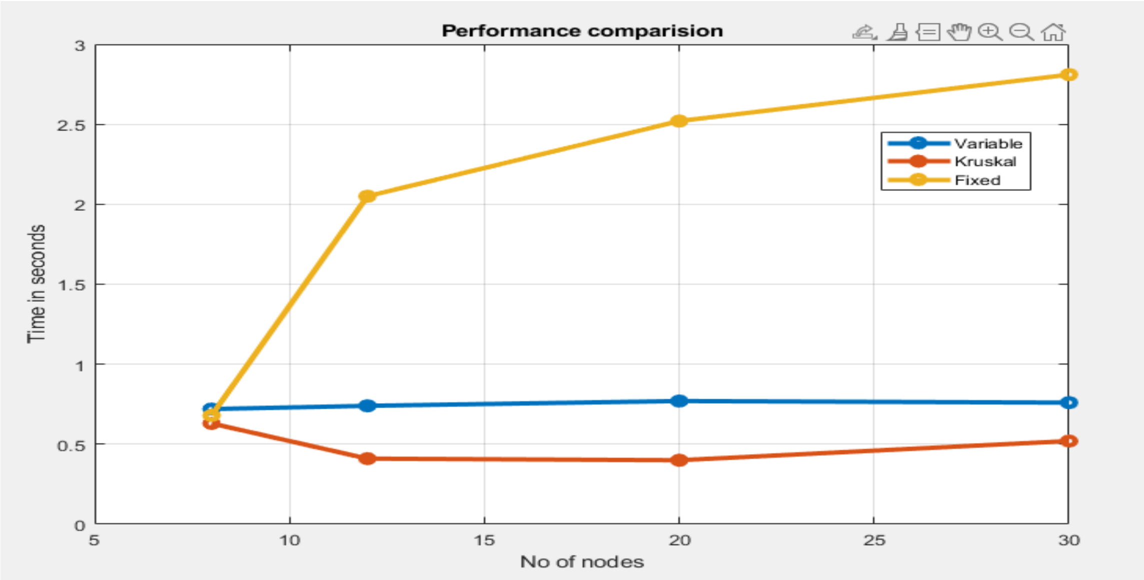

Figure 4: Comparison of the resilience time of proposed method with the existing method.

The graph in Figure 4 illustrates the performance comparison of three distinct algorithms or techniques namely Variable, Kruskal, and Fixed in terms of the time elapsed (in seconds) in relation to the number of nodes.

Evaluation of Kruskal's Algorithm:

Figure 5 shows the output of the Kruskal algorithm. It arranges all edges according to its rising edge weights, and the smallest edge is selected. The new edge in a spanning tree which produces cycle or loop is determined. It include the edge into minimum spanning tree (MST) if the cycle is not formed. From the performance graph it is observed that, the time taken is very consistent as the number of nodes increases from 5 to 30. Kruskal's algorithm's efficiency remains constant, with a time taken of around 0.4 seconds, regardless of the number of nodes, indicating no significant degradation in performance.

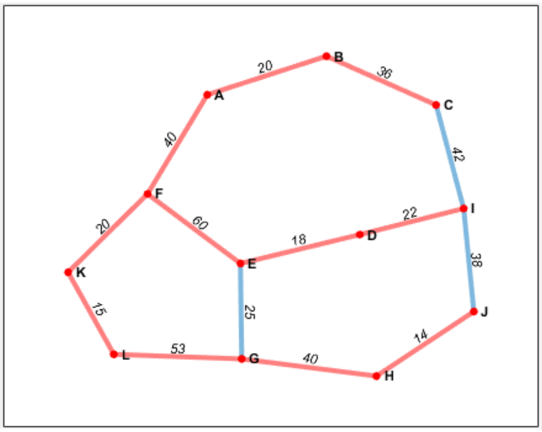

Figure 5: Kruskal output

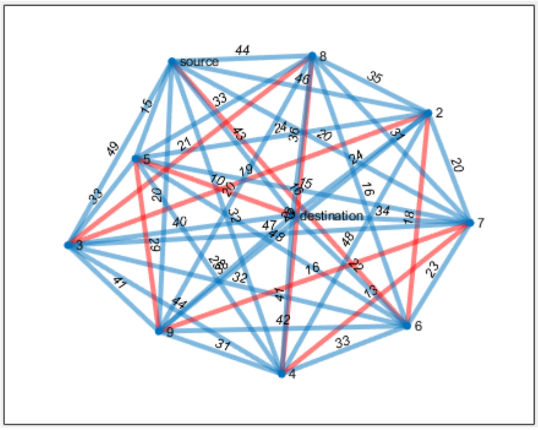

Figure 6: Hamiltonian output

Figure 6 represents the output of the Hamiltonian algorithm. It creates an empty path array and adds vertex 0 to it. Other vertices are then added, starting from the vertex 1. In order to identify an alternative path, the Hamiltonian algorithm makes use of mesh connections. Consequently, the duration of time needed is significantly longer (measured in minutes) than that required by other algorithms.

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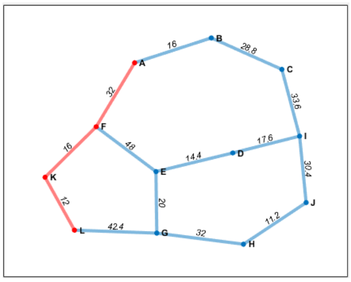
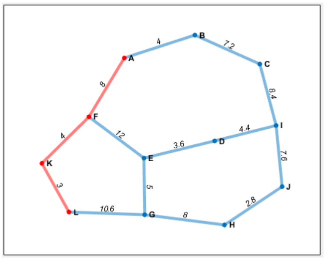
Research Article

Evaluation of Fixed back up path algorithm:

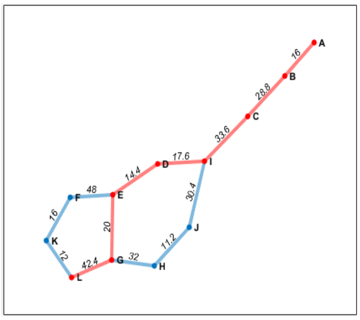
Fixed back up path calculations are shown in following figures. Figure 7a is the initial path considered and figure 7b & 7c represents the intermediate calculations for fixed path. Figure 7d shows the final rerouted path. Here, it is noted that rerouting occurs based on regular and priority allocations, with 80% of link allocations being calculated.



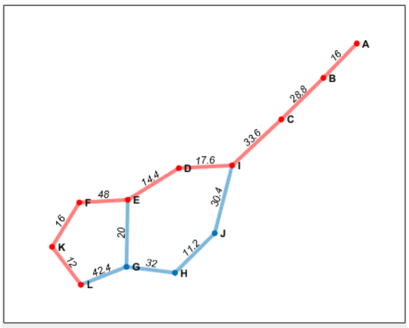
(7a)



(7b)



(7c)



(7d)

Figure 7: Iteration of fixed back up path allocation. a) Fixed path initial b), c) Fixed intermediate path d) Fixed path final

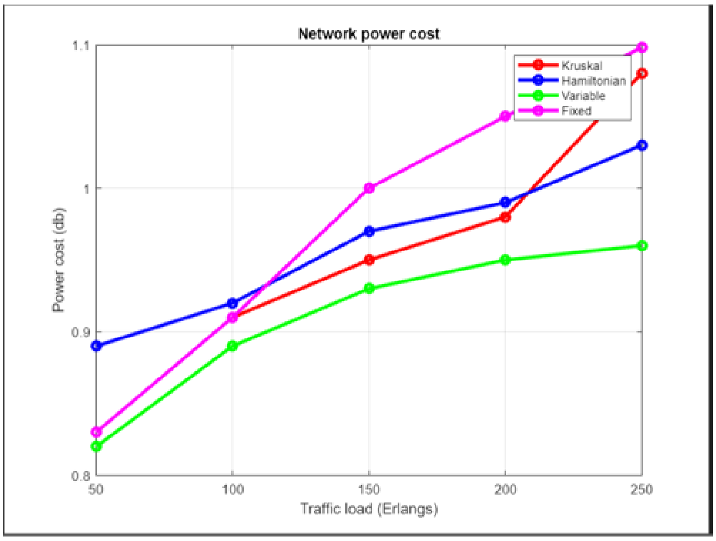


Figure 8: Comparison of utilized power in various algorithms

Figure 8 illustrates the correlation between network power cost (measured in decibels) and traffic load (measured in Erlangs) across all considered network design options. Variable Allocation is the optimal strategy in terms of power consumption, resulting in cheaper costs as traffic load grows.

The Fixed Allocation method incurs the highest power cost, which suggests that it is inefficient in managing heavier network demands.

Both the Kruskal and Hamiltonian algorithms exhibit equal performance, with Kruskal marginally surpassing Hamiltonian under lighter traffic conditions.

This graph can be used to emphasize the benefits of employing a variable allocation strategy for network design in situations when power efficiency is paramount. According to the data, as the amount of traffic increases, both the Kruskal and Hamiltonian approaches show similar performance, whereas the variable method consistently outperforms them.

Cost-Benefit Analysis of Optical Network Performance involving Dense Wavelength Division Multiplexing (DWDM)

The implementation of optimized spare link allocation techniques, specifically the Variable and Fixed Backup Path algorithms provides measurable performance improvements in optical network resilience and power efficiency. To measure these gains in terms of both capital expenditure (CAPEX) as well as operational expenditure (OPEX), a comparative cost-benefit analysis is conducted. Efficient resource management in optical networks is essential for addressing growing data demands while maintaining cost efficiency. Various strategies, including dynamic bandwidth allocation, power-aware mechanisms, and AI-driven optimizations, contribute to the effective utilization of network resources. A comprehensive cost-benefit analysis helps network operators make informed decisions regarding resource allocation, ensuring both economic and operational sustainability in modern optical communication infrastructures. With the increasing demand for high-speed data transmission, effective resource management strategies must balance cost, energy efficiency, and network resilience (Gomes et al., 2018). The rapid expansion of optical networks necessitates intelligent resource allocation to maximize efficiency. Various approaches, including dynamic bandwidth allocation (DBA), wavelength routing and assignment (WRA), and power-aware resource management, have been proposed to enhance performance (Sambo et al., 2019). Dynamic resource allocation enables networks to adapt to changing traffic patterns, reducing congestion and improving service quality. Moreover, energy-efficient resource management techniques help minimize power consumption without compromising network reliability (Zhani et al., 2013). Cost-benefit analysis (CBA) plays a fundamental role in assessing different resource management strategies in optical networks. By evaluating capital expenditure (CAPEX) and operational expenditure (OPEX), network operators can determine the most cost-effective solutions while maintaining optimal network performance (Srinivasan et al., 2021). For instance, deploying flexible-grid optical networks instead of fixed-grid systems can enhance spectrum utilization, thereby improving cost efficiency and scalability (Renaud et al., 2020). Network failures can lead to significant economic losses and service disruptions. Therefore, implementing robust protection and restoration mechanisms, such as dedicated and shared path protection, ensures network reliability (Ji et al., 2022). These mechanisms must be cost-efficient to justify their deployment, balancing redundancy and resource utilization (Cugini et al., 2017). Machine Learning (ML) and Artificial Intelligence (AI) based techniques are emerging as powerful tools for optimizing resource management in optical networks. These approaches facilitate predictive analytics, traffic forecasting, and autonomous network reconfiguration, significantly reducing OPEX while enhancing overall efficiency (Zhou et al., 2021). As highlighted in Dey et al. [2023], CAPEX and OPEX optimization is central to WDM network design, especially when scaling to metro or backbone infrastructures. The CAPEX for Variable Backup implementation is primarily influenced by cost of additional transceivers and monitoring systems, development of intelligent routing algorithms and initial network planning overheads. However, these are offset by lower ongoing energy consumption, enhanced failure recovery mechanisms, which reduce service-level agreement (SLA) violation penalties. Variable Path Algorithm requires more computation and a centralized controller for spare path optimization, but consistently shows reduced power usage and faster restoration times. Fixed Path Algorithm is simpler to implement but results in higher operational costs due to inefficient bandwidth.

Dense Wavelength Division Multiplexing (DWDM) significantly enhances optical network performance by multiplexing multiple wavelengths on a single fiber, thereby increasing bandwidth utilization and reducing the need for additional physical infrastructure. From both an economic and technical standpoint, DWDM offers a compelling value proposition in terms of cost-efficiency, scalability, and long-term operational savings (Verma et al., 2023). Patel et al. [2012] demonstrated that DWDM networks with optimized regenerator and grooming node placements showed OPEX savings of approximately 20–30% compared to traditional fixed-channel routing architectures. However DWDM systems involve higher initial investment in specialized equipment such as optical multiplexers, demultiplexers, tunable transceivers, and wavelength-specific monitoring tools which are offset by enhanced spectral efficiency, reduced latency and improved quality of service across multi-service transport (Gupta, Y.K. & Goel, A., 2023) networks. When deployed strategically within a cross-layer optimized network, DWDM can defer costly fiber trenching and node expansions, enable revenue growth via support for high-demand services (e.g., video streaming, cloud services, 5G transport) as well as deliver higher return on investment (ROI) over a 5 to 10 year lifecycle, especially when combined with dynamic path rerouting and power-aware restoration techniques (Pandya & Jashvantbhai, 2020).

5. Conclusion

The evaluation of the Variable Backup Path algorithm on a network model with 12 nodes and 14 links demonstrates its capability to ensure robust performance under dynamic failure conditions. The iterative failure simulation and backup capacity assignment process effectively recalibrates paths and allocates backup capacities to maintain uninterrupted traffic flow. For instance, in the event of a failure between nodes F and K, backup capacities of 25 units were assigned to alternate paths such as A→F, F→E, E→G, and G→L. Similarly, a failure on the G→H link resulted in a working capacity of 15 units being allocated to the backup path.
Across the entire network, the final backup capacity ratio between working and spare capacities was calculated to be 443/200, reflecting an efficient balance between operational and reserved resources. This ensures network resilience while minimizing excess resource allocation.
When compared with alternative methods, the Variable Backup Path algorithm significantly reduced restoration times. As discussed in result section and shown in Figure 4, the restoration time for 12 nodes was approximately 0.2 seconds, compared to 0.4 seconds for Kruskal's algorithm and several minutes for the Hamiltonian approach. This indicates superior adaptability and efficiency of the proposed method.
In terms of power cost, the Variable Allocation strategy demonstrated notable advantages. At a traffic load of 40 Gbps, the network's power cost was considerably lower—approximately 18 dB—compared to Fixed Backup Path methods, which incurred the highest power cost at over 25 dB. The Kruskal and Hamiltonian algorithms performed similarly, with costs slightly higher than Variable Allocation but much lower than the fixed method.
These results highlight the Variable Backup Path algorithm's capacity to optimize network resilience and resource usage, making it a highly effective solution for networks with 12 nodes and 14 links. Future work could scale this approach to larger, more complex networks while exploring further enhancements to minimize power consumption and restoration time under heavy traffic loads.

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8 Conflict of Interest

The authors affirm that they do not have competing interests.

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