Multi-Constraint Routing and Relay Scheduling Algorithms for Optical Networks*

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***Abstract*—The challenge of optimal optical signal transmission in optical fiber networks is crucial for enhancing the network's reliability, performance, and service quality. Traditional pathfinding methods, such as Dijkstra's algorithm, focus on finding the shortest path but fail to account for critical factors like optical signal loss and wavelength continuity. This paper proposes a novel algorithm that integrates traditional pathfinding methods with multi-constraint checks to effectively overcome these challenges. Inspired by the similarity between multi-constrained pathfinding in optical networks and vehicle charging path planning model, our approach aims to identify the optimal path in large-scale optical networks quickly. The simulation results demonstrate that our approach successfully addresses the complex requirements of optical signal routing and relay under multiple constraints, achieving promising outcomes.**

***Index Terms*—WDM Optical Network, Multi-Constraint Routing, Relay Scheduling Algorithms, Optical Signal-to-Noise Ratio, Vehicle Charging Path Planning Model**

I. INTRODUCTION

Optical network technology, a critical facet of modern network information systems, enables high-speed data transmission and communication across various industries [1]. The field of intelligent optical network technology has spurred extensive research into the nuances of optical network communications both domestically and internationally [2]. Key to the functionality of these networks are efficient routing and relay mechanisms, which ensure optimal signal transmission, maximize distance, and enhance resource utilization.

Routing in optical networks is a complex task that requires careful consideration of both path selection and wavelength assignment. The primary objective is to identify the optimal route and allocate appropriate wavelengths to facilitate uninterrupted signal transmission. Traditional routing methods typically employ pre-calculated, fixed paths, such as those determined by the shortest path algorithm or minimum hop count algorithms [3]. These methods, while effective for initial network configurations, often lack the flexibility to adapt to dynamic network conditions. Furthermore, they typically simplify the optical loss model, failing to accurately capture the intricate loss characteristics present in real-world networks.

Especially, the development of effective routing and relay scheduling algorithms for optical networks has garnered significant attention from researchers globally. Lai et al. [4] introduced a topology-pruning based fast routing (TPFR) scheme for fast routing in large satellite optical networks, focusing on topological construction to address routing complexities. While these studies aim to tackle the growing time complexity of traditional routing algorithms and address spectrum allocation issues [5] [6], they often neglect critical factors such as optical signal loss and wavelength continuity. In large-scale optical fiber networks, where signal loss is a significant concern, this oversight can lead to suboptimal performance and reliability.

By drawing inspiration from the "vehicle charging path planning model"(VCPPM), which involves optimizing paths for electric vehicles to ensure efficient charging and travel [7] [8], we propose a novel routing and relay algorithm for optical networks that accounts for multiple constraints. The key contributions of this paper are as follows:

- We remodel the optical network topology based on the vehicle path planning framework, mapping the complexities of optical signal transmission losses to this new model.
- We introduce an innovative path planning algorithms, named the candidate path iteration method, and validate

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its effectiveness through experimental simulations.
- We design a relay board activation algorithm that optimizes board allocation within the path planning framework, enhancing the overall efficiency of the routing and relay process.

II. MOTIVATION

The motivation for this research stems from the recognition of these limitations and the necessity to develop more sophisticated models that can handle the complex dynamics of optical signal transmission. Inspired by the conceptual parallels between ”large-scale optical network routing and relay scheduling” and ”vehicle charging path planning,” we propose a novel approach that models large-scale optical networks similarly to vehicle charging path scenarios. As depicted in Fig 1, the relay board in an optical network functions similarly to a charging station in a vehicle network. Both systems share key characteristics: just as a vehicle depletes its power during travel, an optical signal experiences gradual Optical Signal-to-Noise Ratio (OSNR) loss along its transmission path. In optical networks, recovery nodes act like charging stations, activating at the beginning of each sub-path to restore the optical signal by clearing accumulated OSNR loss, thereby initiating a new segment of transmission. Unlike the vehicle charging path planning problem, our approach also incorporates the critical constraint of wavelength continuity, which must be considered when constructing the optical network topology.

This study aims to fill the gap in existing research by addressing the overlooked aspects of optical signal loss and wavelength continuity in routing algorithms, thereby contributing to the advancement of more robust and reliable optical network technologies.

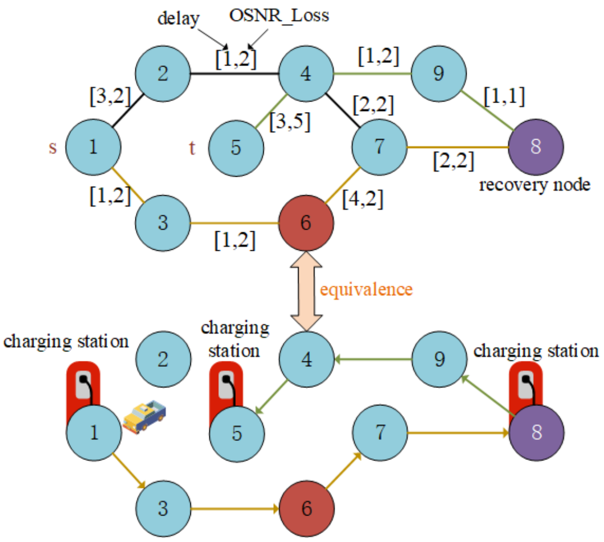


Fig. 1. The relay scheduling problem in optical network is similar to the vehicle pathfinding problem

III. PRELIMINARIES

A. Wavelength Continuity

Wavelength continuity, emphasized in this paper [9], is a critical constraint addressed in optical networks. Current WDM networks typically employ a fixed-size bandwidth allocation scheme [10], necessitating consistent allocation of optical wavelengths along end-to-end paths to maintain wavelength continuity.

In WDM networks, nodes are commonly equipped with wavelength converters (WCs) to manage wavelength continuity constraints [11]. WCs facilitate wavelength conversion when necessary, allowing signals to traverse the network without violating wavelength continuity. However, due to their costliness, WCs are sparingly deployed across network nodes, leading to strategic placement at critical points. During routing, algorithms prioritize paths that minimize the need for wavelength conversion, thereby optimizing resource utilization and minimizing operational costs.

Considering these factors, our routing algorithm design incorporates the wavelength continuity constraint to ensure efficient and cost-effective operation within WDM optical networks.

B. OSNR Loss

OSNR is a crucial parameter in optical communication systems, serving as a key indicator of signal quality and performance optimization [12]. OSNR loss refers to various impairments experienced by optical signals during network transmission, occurring on links or at relay nodes. Defined by the IEC standard, OSNR is expressed as the ratio of the peak signal power of a channel to the noise power added at the peak position. The OSNR calculation formula is given by:

$$OSNR = 10 \cdot \log\left(\frac{P_i}{N_i}\right) + 10 \cdot \log\left(\frac{B_m}{B_r}\right) \tag{1}$$

where $\boldsymbol{P_i}$ represents the optical signal power of the ith channel (in watts), $\boldsymbol{B_m}$ is the measured resolution bandwidth, $\boldsymbol{N_i}$ is the inserted noise power value measured with a measured resolution bandwidth $\boldsymbol{B_m}$, and $\boldsymbol{B_r}$ is the reference optical bandwidth, which is usually selected as 0.1nm [13]. The second term in the formula normalizes the OSNR value across different measurement instruments, ensuring comparability.

During optical signal transmission, optical losses impact signal quality and strength, which significantly constrain the scalability of optical networks. Especially, in applications like elastic optical networks, it is imperative to ensure that optical signal-to-noise ratio loss remains within acceptable limits before signals reach subsequent recovery nodes. Therefore, the algorithm design in this study considers optical signal-to-noise ratio loss as a critical constraint for optimizing optical signal routing.

IV. THE PROPOSED FRAMEWORK

A. Problem Description

Let us consider a typical scenario, in which an optical signal S carrying data needs to propagate through an optical network from a starting point A to a designated destination B as quickly as possible. The network is composed of regular optical signal switching nodes N_i where $i = 1, 2, \ldots, n$ represents the number of regular nodes and recovery nodes R_j where $j = 1, 2, \ldots, m$ represents the number of recovery nodes, which are equipped with relay boards capable of mitigating optical losses. Each recovery node R_j is typically situated at the beginning of a segment within the network. As the optical signal S traverses the network, it passes through several switching nodes and recovery nodes. The role of each recovery node R_j is crucial; if the OSNR loss in the preceding segment exceeds a recoverable threshold, the relay board at R_j is activated to restore the signal quality. This ensures that the signal can maintain the required OSNR loss levels across the network and reach the destination B without significant degradation. To ensure effective transmission, the optical signal's OSNR loss must remain within a recoverable range. In Fig 1, starting from node 1 to node 5, our purpose is to fully utilize the functionality of the recovery node, meaning the total OSNR loss for any sub-path must not exceed a threshold of 8. If the OSNR loss surpasses this threshold, the relay board must be activated to restore signal quality. Additionally, it is crucial to note that the propagation of optical signals across sub-paths utilizes a shared wavelength index resource, which serves as another constraint to consider in the routing process.

Inspired by the VCPPM, we can model the pathfinding problem in optical networks as follows. The network comprises V nodes, including D charging stations. W represents the size of the sliding window, and the constraint is that the vehicle's battery $E > 0$. The objective of the routing and relay scheduling algorithm is to determine the quickest route from the starting node (Start Node) to the destination node (End Node) that satisfies these constraints.

Let us define some notations as follows.

- P_i: The path from Start Node to End Node.
- $T(P_i)$: Time taken by the optical signal along path P_i.
- $OSNR_{\text{Loss}}(P_i)$: OSNR loss for path P_i.
- $\lambda(P_i)$: Wavelength index resource usage for path P_i.
- CS: Constraint set where $CS = \{C_1, C_2\}$.

There are two constraints:

- C_1: $OSNR_{\text{Loss}}(P_i) \leq 8$
- C_2: Wavelength continuity is maintained (i.e., $\lambda(P_i)$ meets network requirements).

Then, the objective is to minimize the transmission time while satisfying the constraints C_1 and C_2.

$$\begin{aligned} &\text{Minimize} \quad T(P_i) \\ &\text{subject to} \\ &\quad OSNR_{\text{Loss}}(P_i) \leq 8 \quad \forall P_i \in PS \\ &\quad \lambda(P_i) \text{ is consistent} \quad \forall P_i \in PS \\ &\quad C_1(P_i) = \text{true}, \quad C_2(P_i) = \text{true} \\ &\quad T(P_i) \leq T(P_j) \quad \forall P_i, P_j \in PS, \quad i \neq j \\ &\quad \text{and} \quad C_1(P_j) = \text{true}, \quad C_2(P_j) = \text{true} \end{aligned} \tag{2}$$

B. Basic Idea

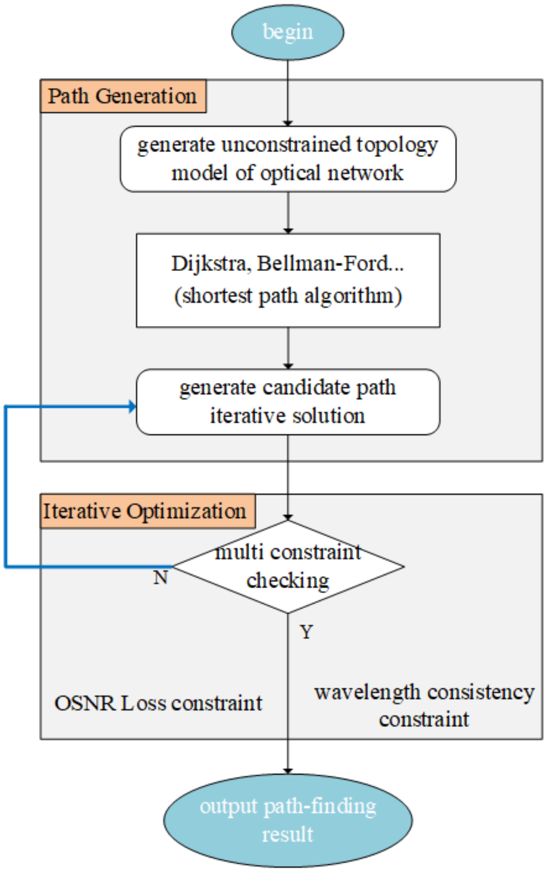


Fig. 2. The algorithm framework

The purpose of this paper is to seek a routing solution that can take into account wavelength consistency and optical loss constraints, so as to search for the minimum path from the starting end to the destination end that meets multiple constraints. In our opinion, a large-scale optical network multi-constraint pathfinding problem is decomposed into three parts: path generation (Part 1), constraint checking (Part 2), and iterative optimization process (Part 3). Part 1 is responsible for finding the shortest path based on the unconstrained topology modeling of the network, and part 2 is responsible for multi-constraint checking for the shortest path found. Once the path is generated and checked, the next step is an iterative optimization process (Part 3). Part 3 is responsible for path evaluation and selection, and re-iteration when the conditions are not met. The specific software framework is shown in the Fig 2.

It's evident that OSNR Loss increases with the number of nodes an optical signal traverses. We draw a parallel between the relationship of vehicle power consumption as it progresses along a path and the increase in OSNR Loss as an optical signal passes through multiple nodes, as shown in Fig. 3. Constraint 1, which requires maintaining acceptable OSNR levels, is akin to the need for a vehicle to reach a

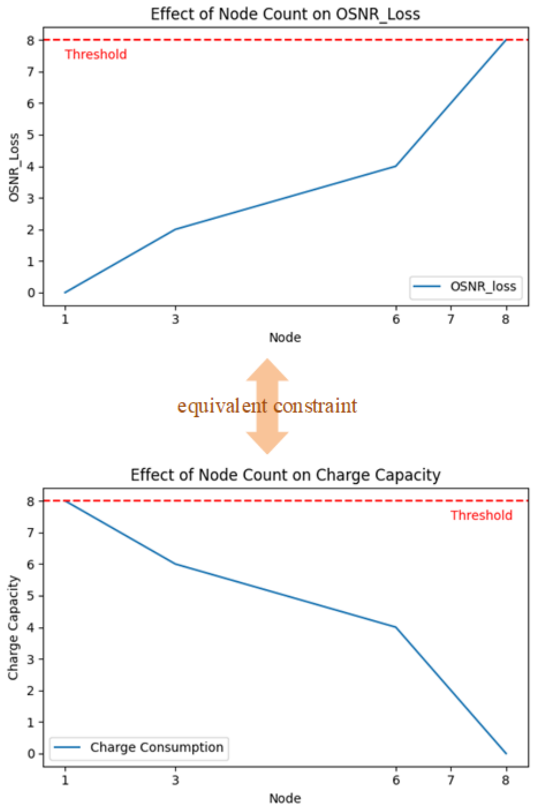


Fig. 3. The constraints of the pathfinding in optical networks and VCPPM are equivalent

charging station before its battery is depleted. This constraint is represented as C_1.

The wavelength continuity constraint is a fundamental concept in optical network routing, particularly in wavelength division multiplexing (WDM) networks. This constraint requires that the wavelength used from the ***Start Node*** to the ***End Node*** must remain consistent throughout the path. In other words, each sub-segment (or sub-path) along the entire route must utilize the same wavelength. If a particular wavelength is unavailable on any sub-segment of the path, that path cannot be selected.

Consider the following simple optical network:

$$\boldsymbol{Start\ Node \longrightarrow A \longrightarrow B \longrightarrow End\ Node}$$

The available wavelength resources for each link are as follows:

$$\text{Start Node} \rightarrow A : \{\lambda_1, \lambda_2, \lambda_3\}$$

$$A \rightarrow B : \{\lambda_2, \lambda_3\}$$

$$B \rightarrow \text{End Node} : \{\lambda_1, \lambda_2\}$$

To determine a valid path, we first record the wavelength resources available on each link. We then identify common wavelengths available across all sub-segments by calculating the intersection of these resources. For this example, the intersection of the available wavelengths is λ_2. Thus, λ_2 can be selected as the wavelength from the Start Node to the End Node, satisfying the wavelength continuity constraint.

V. IMPLEMENTATION CONSIDERATIONS

The general operational principle of the pathfinding scheme depicted in Fig 4 involves two distinct stages: offline calculation and online calculation. Upon the arrival of a service request (or when a link failure necessitates pathfinding anew), the expedient determination of the shortest viable path for the service is crucial to maintain service stability. This real-time pathfinding process is referred to as the online computing stage, which significantly influences the timeliness of service provisioning. To mitigate the computational burden associated with creating complex data structures or loading extensive datasets into memory during online computing, offline calculation is employed as a preemptive measure before actual service pathfinding requirements arise.

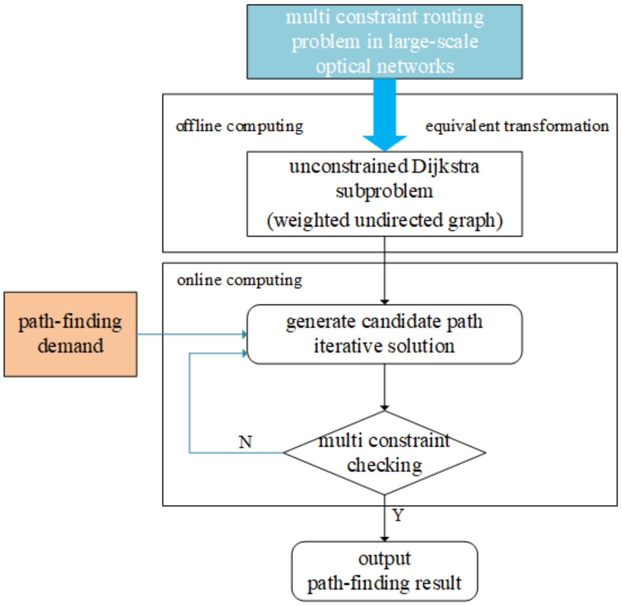


Fig. 4. Multi-constraint iterative pathfinding computing process for large scale optical networks.

1) Offline calculation stage: The primary objective of the offline computing phase is to prepare necessary data structures and computing resources for subsequent online computing. This phase aims to minimize IO operations and computational intensity during online computing by pre-building network topology, data indices, performing equivalence transformations, and other preprocessing tasks.

Unlike traditional pathfinding problems tackled by the Dijkstra algorithm, optical networks feature multiple optical links between nodes. Apart from transmission delays across links, signal degradation in terms of OSNR also occurs along the path. Nodes equipped with relay boards can mitigate OSNR loss, introducing constraints that render direct application of Dijkstra algorithm impractical without modifications or alternative algorithms.

To enable the use of the Dijkstra algorithm, constraints need temporary suspension. This involves transforming the original optical network into a weighted graph where edges represent only delay (weight), allowing straightforward application of Dijkstra's shortest path algorithm between nodes. Similarly, each node's OSNR loss is evaluated and compared with delay importance to establish an equivalent weighted undirected graph based on the original network, facilitating Dijkstra algorithm compatibility (although other shortest path algorithms could also be considered).

Certain optical constraints, such as wavelength index resource limitations on links, are universal across services. Links that cannot meet these wavelength resource constraints for services are preemptively removed from the network topology during the offline calculation phase. This proactive step reduces computational overhead during subsequent online calculations.

2) Online calculation stage: Based on the preprocessing performed during the offline stage, various optical constraints within the optical network are relaxed, transforming the problem into an unconstrained shortest path scenario. Here, the optical network is represented as a weighted undirected graph. Algorithms like Dijkstra's algorithm can efficiently solve the unconstrained shortest path problem, generating a set of potential paths between nodes. These paths are then filtered based on the specific constraints of the original problem.

The original problem imposes two main constraints on path planning in optical networks:

- Constraint 1: Wavelength continuity. Optical signals on each sub-path must utilize a common set of wavelength index resources, ensuring that the intersection of available wavelengths across multiple links on the sub-path is non-empty.
- Constraint 2: OSNR Loss. The cumulative OSNR Loss along each sub-path should not exceed a specified threshold of 8.

The optimization process involves iteratively generating candidate paths and performing multi-constraint checks. Upon finding a path that meets the optimization criteria, the service repair is initiated, and the routing results are promptly returned. If no suitable path is found within the timeout threshold, or if no better path is discovered after iterations, the service repair fails.

VI. PERFORMANCE EVALUATION

The experiment aims to evaluate the performance of the multi-constraint routing and relay scheduling algorithm in optical networks.

A. Simulation design

The simulation environment is configured to model a complex optical network topology consisting of various node types, including standard optical switching nodes and nodes equipped with relay boards (denoted as R-nodes). The simulated network topology is designed to mimic real-world optical networks, featuring interconnected nodes and links with defined capacities. There are 4096 nodes in the simulated network topology, with a fixed delay of 100 for each node. Each node type is strategically placed to simulate practical network scenarios, ensuring a diverse and representative environment.

We use a snapshot from the simulation to illustrate the path repair process, as shown in Fig. 5(a). In the figure, LinkID=22, corresponding to the source $\rightarrow$ target pair (10 $\rightarrow$ 38), is identified as a broken chain link, affecting a total of 35 businesses. The repair process involves:

- Marking LinkID=22 as unavailable due to the broken chain.
- Releasing the resources allocated to all 35 affected businesses with LinkID=22, resetting the wavelength index resource of the optical link they traverse to available.
- Sequentially finding new paths for each of the 35 businesses to ensure continuity of service.

B. Simulation Results

The repair outcomes in the simulation are detailed in Fig. 5(b). For clarity, only a portion of the network is illustrated, with some paths and labels overlapping. Node roles are identified by their prefixes in the figure:

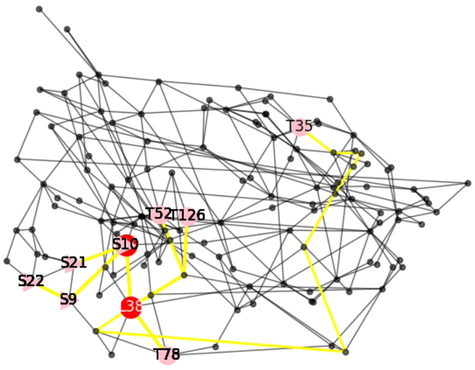
- Nodes starting with **L** indicate broken link nodes.
- Nodes starting with **S** represent service source nodes.
- Nodes starting with **T** denote service target nodes.
- Nodes starting with **R** signify nodes where a relay board is enabled.

As shown in Fig. 5(a), the link from S10 to L38 is faulty prior to repair, and the paths of related services impacted by this faulty link are depicted as yellow dotted lines. In Fig. 5(b), the repaired service paths are displayed in green. Nodes labeled with "R" indicate where the trunk board is enabled.

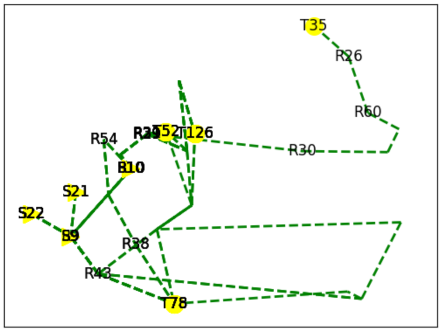
Fig 6 illustrates the relationship between service repair time, service success rate, and total service count. From the first subgraph, it can be seen that there is no strong correlation between service repair time and service success rate. However, when the service success rate is 100%, the service repair time of the vast majority of simulation instances is below 0.02. The second subgraph clearly shows that the service repair time is approximately proportional to the total service count. As the total service count increases, the service repair time also becomes longer. Fig 7 shows the service repair time under different link damage scenarios, where different links affect different nodes, resulting in significant differences in service repair time.

VII. CONCLUSION

This paper presents a novel and efficient solution for routing and relay scheduling problem in optical networks. It integrates



(a) Before repair



(b) After repair

Fig. 5. Successful repair of all 35 services affected by DamagedLink 22 (10 → 38)

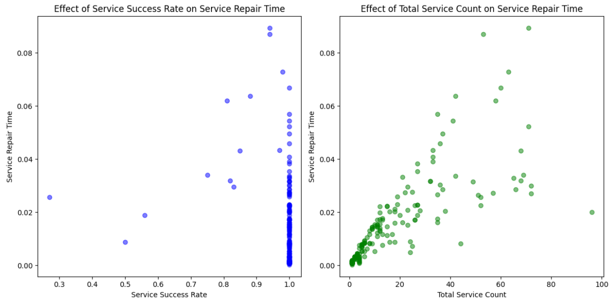


Fig. 6. The relationship between service repair time, total service count, and service success rate

traditional shortest path methods with multi-constraint evaluations to address issues of optical loss and wavelength continuity. Inspired by the vehicle charging path planning model, we design an iterative approach to significantly improves pathfinding speed, ensuring efficient and reliable network performance. The results demonstrate that the service repair time is approximately proportional to the total service count, which validates the algorithm's effectiveness. Future work will focus on optimizing the algorithm for parallel computing environments, promising further reductions in pathfinding time and enhanced network efficiency.

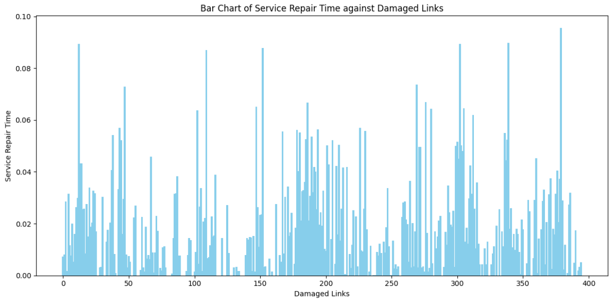


Fig. 7. Service repair time for different link damage scenarios

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