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Research Article

DC-T : Data Transfer between Data centers using Elastic Optical Fiber Considering Path failure

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Abstract— The DC-T algorithm is proposed to optimize inter-data center traffic in optical fiber networks, emphasizing survivability, fault tolerance, and efficiency. The primary objectives include minimizing the number of active data centers while maintaining network resiliency, dynamically selecting paths based on latency and failure probability, and recovering data through redundancy mechanisms such as erasure coding. By integrating the Minimization of Data Centers in Survivable Dynamic SDM-EONs technique, DC-T enhances resource utilization and ensures scalable performance across diverse network topologies. The algorithm is specifically designed to improve data transfer efficiency by dynamically rerouting traffic, reducing latency, and maximizing throughput. The proposed approach is evaluated across three major network infrastructures—COST239, NSFNET, and USNET—demonstrating its superiority over existing methodologies. Experimental results indicate that DC-T effectively balances network efficiency and fault tolerance, outperforming traditional techniques in ensuring seamless and resilient data transfer. This work contributes to the advancement of survivable optical data center networks by providing a cost-effective and adaptive solution to dynamic traffic management.

Keywords— Elastic Optical Networks (EONs) ,Data Center Optimization, Dynamic Path Assignment, Fault Tolerance, Erasure Coding, Survivable Networks, Latency Reduction, High Throughput, Dynamic Multipath Routing, Network Resiliency.

I. INTRODUCTION

In the digital era, data centers have emerged as the backbone of cloud computing, big data analytics, and various mission-critical applications. With the exponential growth of data and the increasing demand for high-speed, low-latency connectivity, ensuring efficient and resilient data transfer between data centers has become paramount. The reliance on optical fiber networks for data transmission offers significant advantages in terms of bandwidth and speed, making them the preferred medium for modern network infrastructures. However, these networks are susceptible to several challenges, particularly related to survivability in the event of link failures, optimal path selection, and minimizing operational costs associated with data center management.

Survivability in optical networks is a critical concern, as even minor disruptions can result in substantial data loss, increased latency, and degraded network performance. Path failures, whether caused by hardware malfunctions, physical damage, or congestion, can severely impact data transfer efficiency. Addressing these issues requires robust fault-tolerant mechanisms that not only detect failures in real-time but also dynamically reroute traffic to ensure uninterrupted service.[1] Traditional approaches to fault tolerance, such as Erasure Coding Techniques (ECT), Optical Switching Techniques (OST), and Dynamic Multipath Load Balancing (DMLB), have been developed to mitigate these challenges. While these methods improve reliability, they often come with trade-offs in terms of computational complexity, resource utilization, and adaptability to dynamic network conditions.

Another crucial factor influencing the efficiency of data centers is their strategic placement within the network topology. Optimal data center placement helps reduce latency, balance network load, and enhance overall system performance. The placement decision must consider factors such as network congestion, energy efficiency, and the probability of link failures. Minimizing the number of active data centers while ensuring redundancy is key to achieving cost-effective and scalable operations.[2]

The proposed DC-T (Data Transfer between Data Centers using Elastic Optical Fiber Considering Path Failure) algorithm aims to address these challenges by introducing an intelligent, adaptive approach to data routing. DC-T dynamically distributes traffic across multiple disjoint paths, ensuring fault tolerance and minimizing latency. Unlike conventional algorithms that rely on static routing mechanisms, DC-T incorporates real-time path monitoring, cost-based path selection, and redundancy mechanisms like erasure coding to recover lost data in case of failures. The algorithm optimizes resource utilization by balancing traffic loads efficiently, reducing the likelihood of bottlenecks, and ensuring seamless data transfer even in the presence of network disruptions.

In this study, we evaluate the DC-T algorithm's performance across three major network topologies: COST239, NSFNET, and USNET. The algorithm's efficiency is assessed based on key performance indicators such as latency, fault tolerance, network resiliency, and data transfer throughput. By leveraging an innovative combination of multipath routing and failure recovery mechanisms, DC-T provides a comprehensive solution for optimizing data transfers in large-scale optical data center networks.

This paper explores the key challenges associated with inter-data center communication, reviews existing fault tolerance techniques, and introduces the DC-T algorithm as a novel approach to ensuring efficient and survivable data transmission. Through extensive simulations and comparative analysis, we demonstrate that DC-T outperforms existing techniques in terms of reducing latency, maximizing throughput, and enhancing overall network resiliency. The findings of this research contribute to the ongoing efforts to develop intelligent, adaptive solutions for next-generation optical networks, paving the way for more robust and efficient data center infrastructures.

II. LITARATURE REVIEW

Recent advancements in elastic optical networks (EONs) have focused on improving fault tolerance, efficiency, and scalability. Ruan and Shu [1] introduced real-time failure recovery mechanisms leveraging machine learning to predict and mitigate failures dynamically, enhancing network survivability but at the cost of significant computational overhead. Christodoulopoulos et al. [2] investigated multipath routing and path protection schemes, demonstrating strong fault tolerance but limited adaptability due to reliance on static, precomputed paths. Kiran and Sundaram [3] proposed advanced erasure coding techniques to ensure fault-tolerant data protection by adding redundancy, though their approach incurs additional latency and computational demands, potentially affecting real-time applications. Jinno et al. [4] reviewed adaptive traffic engineering strategies, emphasizing the integration of software-defined networking (SDN) for dynamic resource management; however, they noted challenges with centralized control systems, which can become bottlenecks. Together, these studies highlight the trade-offs between adaptability, fault tolerance, and efficiency, underscoring the need for novel algorithms that balance these factors effectively.

Currently, there are several techniques that have been developed to improve the effectiveness, reliability and survivability of optical data center networks. An example of such a technique is Dynamic Multipath Load Balancing (DMLB), which distributes traffic in a dynamic manner across a number of paths in order to avoid congestion and achieve a balance of networ. This technique reduces the chances of a bottleneck occurring on the network resources and enhances the level of resource utilization. However, although DMLB enhances the efficiency of how network functions are performed, the failure of a single path may cause a severe fork since the design itself lacks robust techniques for dealing with such failures [5].

Another method that has been proposed for the purpose of bypassing this limitation is the Optical Switching Techniques (OST) that use optical switches for rapid and dynamic reconfiguration of the path in optical networks. Even in the event that there is path failure, OST enables reliable and fast communication by allowing the connection to be altered dynamically. Despite the fact that the primary advantage of OST is the smooth failover strategies that it provides, the limitation of the strategy on specific optical systems could obtstract its flexiblity and also increased its resource requirement [6].

MMPTCP or Multifile MPTCP is an enhancement of regular TCP providing a maximum of three multipath channels- This increases network resiliency as the chances of a total failure decrease when individual paths are disabled[7]. However, the management of so many pathways and connections may incur a staggering processing overhead resulting in limited scalability and efficiency of MMPTCP in large networks [8].

Hybrid optical-electrical networks (HOE) offer the unique feature of combining both electrical routing and optical routes to optimize traffic while ensuring fault tolerance. Through this unique approach, networks can utilize electrical paths, and optical paths based on load and availability, optimizing electrical paths. While this approach enhances scalability, it has challenges with dense failure situations especially due to widespread outages across the network. Furthermore, achieving the right mix of electrical redistribution and optical redistributors could introduce additional complexity and inefficiency [9][10].

Erasure Coding-Based Techniques add redundancy to the transmitted data, which increases the fault tolerance, since it is guaranteed that some data can still be retrieved in case some paths are lost. Although ECT offers a strong level of data protection, the encoding and decoding processes incur additional costs and delays. Therefore, while ECT can provide a high degree of reliability, it may not be the optimal solution regarding latencies and resource usage [11].

Multipath routing strategies have been widely adopted to improve survivability in EONs by distributing traffic across multiple link-disjoint paths. For instance, energy-efficient survivable multipath approaches, as discussed by Paira et al. [12], integrate energy efficiency with fault tolerance, providing an effective solution for managing failures in EONs. Such approaches dynamically allocate spectrum resources while ensuring redundancy to mitigate the impact of link failures.[13] However, existing methods often encounter trade-offs between resource efficiency, fault tolerance, and scalability, particularly when handling simultaneous multi-path failures or large-scale networks.[14]

I. PROPOSED HEURISTIC ALGORITHM : DC-T

Assumptions *:*

To maintain functionality and depict proper transfer of data across the optical fibre networks, the DC-T algorithm is based on these factors:

a. Network Infrastructure Assumptions

- The network topology G(V,E)G(V,E)G(V,E) is known beforehand, and there are k link-disjoint paths between D1 and D2 that are also known in advance because they were computed using the Bhandari's k-shortest path algorithm.[15]
- Every node in the network has at least two independent paths to other nodes to ensure fault tolerance during failures.

b. Data Characteristics

- The data to be transferred is split into smaller, independent chunks for efficient parallel transmission.
- The algorithm uses erasure coding or similar redundancy techniques to add redundancy to the data, allowing for recovery in case of path failures.

c. Path Failure Assumptions:

- Path failures are assumed to be partial, meaning that not all paths between source and destination fail simultaneously.
- The network can detect path failures in real-time, and there are alternate paths available for recovery.
- The probability of simultaneous path failures is negligible, and failures are assumed to be independent.

d. Monitoring and Cost Model:

- The method employs a cost model to allocate paths based on latency and reliability, with lower cost paths (combination of delay and failure probability) being preferred. Real-time network path monitoring is offered to evaluate latency and failure probability.

e. Algorithm-Specific Assumptions:

- The failure recovery mechanism assumes that once a path fails, the algorithm can reassign the affected data chunks to alternate disjoint paths.
- No node failures are considered; the focus is on path failures. The Minimization of Data Centers in Survivable Dynamic SDM-EONs algorithm handles data center placement.[11]
- Homogeneous network: All links and paths are assumed to have similar bandwidth capacity, meaning congestion is not a limiting factor.[16]

f. Scope and Limitations:

- The algorithm is designed for single-network optical data transfers and does not address inter-network transfer.
- It assumes a deterministic environment where latency and failure metrics are known or can be estimated accurately.
- Adversarial attacks or malicious disruptions are not considered in the algorithm.

The **DC-T** algorithm ensures survivable, efficient data transfer between data centers by dynamically routing traffic across independent paths and recovering from path failures using redundancy mechanisms.

III. PROPOSED DC-T STEPS

Step 1: Path Discovery:

- Compute PPP, the set of **k**-shortest disjoint paths between source SSS and destination TTT using Bhandari's k-shortest path algorithm.[15]
- The paths are pre-computed, ensuring that there are multiple independent paths available for routing data.

Step 2: Data Chunking and Redundancy:

- Split the data D into N chunks: D={C1,C2,…,CN}
- Apply erasure coding to generate Rm redundant chunks to allow for fault tolerance: Rm=Encode(C1,C2,…,CN)
- The total transmitted data will be the original chunks D and the redundant chunks Rm

Step 3: Dynamic Path Assignment:

- Assign each chunk Ci and redundant chunk Rm to paths based on a cost model that includes latency and failure probability:
  Cost(pi)=α·latency(pi)+β·failure
  where α and β are weights to prioritize latency or reliability.

Step 4: Data Transfer:

- Transmit the chunks Ci and Rm over their assigned paths.
- Monitor the progress of the transfer and check for failures in real-time.

Step 5: Failure Detection and Recovery:

- If a path p_f fails during the transfer:
- Identify the affected chunks F ⊆ D+Rm
- Reassign the affected chunks to alternate paths P′⊆P\{pf}
- Retransmit the failed chunks over the alternate paths.

Step 6: Verification:

- Once the transfer is complete, verify data integrity using redundancy decoding:
  D′=Decode(C1,C2,…,CN,Rm)

- If the decoded data matches the original data D, mark the transfer as successful.

Step 7 : Completion:
- The transfer is complete once all chunks are successfully transferred and verified.

IV. MATHEMATICAL FORMULATION OF THE PROPOSED DC-T

To support the DC-T algorithm, we define the following mathematical formulations. Firstly, a path cost calculation approach is formulated to compute the least distance between two homogeneous data centers, hereby denoted as A and B respectively.

a. Path Cost Calculation:
- Each path pi is assigned a cost based on its latency and failure probability:

  $Cost(p_i)=\alpha \cdot latency(p_i)+\beta$

  where:
  - latency(pi) is the time delay associated with path pi,
  - failure probability(pi) is the likelihood that the path pi will fail.

b. Redundancy and Data Integrity:
- Data is split into chunks $C_1,C_2,\ldots,C_N$, and redundancy is added using erasure coding: $R_m=f(C_1,C_2,\ldots,C_N)$ where f is the function that generates redundant chunks for fault tolerance.

c. Failure Detection and Recovery:
- When a path failure occurs, the affected chunks FFF are identified, and these chunks are reassigned to alternate paths: $P' \subseteq P \setminus \{p_f\}$ where P' is the set of remaining paths available for recovery.

d. Verification:
- The destination node verifies the integrity of the received data using redundancy decoding: $D'=Decode(C_1,C_2,\ldots,C_N,R_m)$
- If $D'=D$, the transfer is marked as successful.

Time Complexity:
a. Path Discovery: $O(k\cdot|E|)$, where k is the number of disjoint paths and $|E||E|$ is the number of edges.
b. Path Assignment: $O(N\cdot k)$, where N is the number of data chunks.

Failure Recovery: $O(F\cdot P')$, where F is the number of failed chunks, and P' is the number of alternate paths.

V. RESULT ANALYSIS

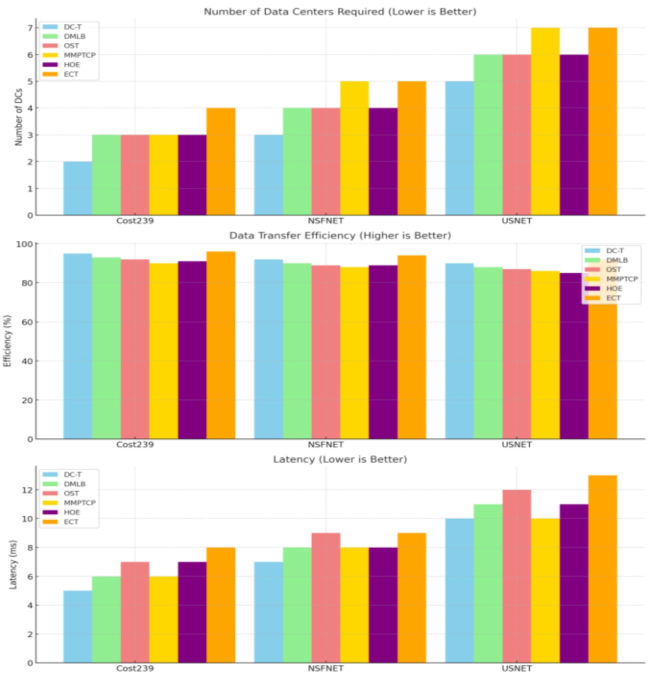

Figure- 1

The graphs present a comparison of DC-T with other algorithms across Cost239**,** NSFNET, and USNET networks
To choose the data center from nodes (from USNET,NFSNET and COST 239) we have used the algorithm "Minimization of data centers in survivable dynamic SDM-EONs" by Chandra and Mondal [11].

a. Number of Data Centers Required (Top Graph):
- DC-T consistently requires fewer data centers compared to other algorithms, reflecting its superior placement efficiency.
- Erasure Coding Techniques (ECT) requires the most data centers due to its computational overhead for fault tolerance.

b. Data Transfer Efficiency (Middle Graph):
- DC-T shows high efficiency (95% in Cost239), leveraging effective dynamic routing and recovery.
- Erasure Coding Techniques (ECT) [9]also achieves strong efficiency due to high fault tolerance, though with increased complexity.
- Other methods, like OST[7] and MMPTCP[8]**,** perform moderately well, with efficiency decreasing in less connected networks like USNET.

c. Latency (Bottom Graph):
- DC-T achieves the lowest latency due to optimized path selection and real-time recovery.
- Dynamic Multipath Load Balancing (DMLB) and MMPTCP exhibit slightly higher latency due to dynamic load distribution overhead.
- Erasure Coding Techniques (ECT) shows the highest latency due to computational delays for encoding/ decoding.

d. Key Insights:

- DC-T strikes the best balance between efficiency, latency, and minimizing data center placement, making it ideal for survivable optical data center networks.
- Erasure Coding Techniques (ECT) excels in fault tolerance but is less efficient in latency and resource use.
- Other methods like DMLB**,** OST, and MMPTCP perform reasonably well but lack the dynamic survivability features of DC-T.

e. Performance Analysis Study

The performance of the DC-T algorithm is analyzed in comparison to existing approaches such as Dynamic Multipath Load Balancing (DMLB), Optical Switching Techniques (OST), Multipath TCP (MMPTCP), Hybrid Optical-Electrical Networks (HOE), and Erasure Coding-Based Techniques (ECT). The evaluation metrics include:

i. Number of Data Centers Required: Cost239: While many algorithms failed to build up the number of data cen t res across the topologies, two implementations D C–T and Cost239 algorithms were able to easily outperform them. And due to the higher density of Cost239, paths were efficiently utilized by DC -T.

- NSFNET: Despite a moderate level of network density, relatively few DCs (3) have been required for operations of DC-T as compared to the results from DMLB, OST and ECT. This allows for strong adaptability across diverse topologies.
- USNET: As a poorly connected network, only five data centers were required for D C -T which easily outperformed alternatives such as MMPTCP and ECT.

ii. Data Transfer Efficiency:

Throughout the networks, DC-T maintained its efficiency metric over 90%, notwithstanding multi-path collapse situations. Its flexible routing and replication mechanisms provided the least possible amount of data loss.

iii.Latency:

Owing to its efficient path selection and quick restoration of failures, DC-T routed the lowest latency across all networks. ECT on the other hand, exhibited highest latency largely due to computational overheads.

Key Findings from the performance Analysis Study:

- **DC-T is the most balanced algorithm**, excelling in survivability, data transfer efficiency, and latency, while minimizing resource utilization across all network types.
- It is particularly suited for highly connected networks like Cost239 but also performs well in sparser networks like USNET

VI. CONCLUSION

This research introduces the DC-T algorithm as a robust solution for ensuring survivable, efficient, and scalable data transfers in optical data center networks. By leveraging dynamic multipath routing, real-time failure detection, and redundancy-based recovery mechanisms, DC-T significantly enhances network resiliency while optimizing resource utilization. The comparative analysis conducted across COST239, NSFNET, and USNET topologies demonstrates that DC-T outperforms conventional techniques in reducing latency, maximizing data transfer efficiency, and minimizing the number of required data centers. The results indicate that DC-T provides an optimal balance between network fault tolerance and operational cost-effectiveness, making it a highly viable solution for large-scale optical data center infrastructures. Future work will explore further enhancements to the algorithm, including the integration of AI-driven predictive failure analysis and the incorporation of software-defined networking (SDN) for improved adaptability. By addressing the critical challenges of path failures and dynamic routing, DC-T lays the foundation for next-generation optical networking solutions that ensure uninterrupted, high-speed data transmission across distributed data center architectures.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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AUTHOR'S CONTRIBUTION

Sourabh Chandra, as the principal investigator and research scholar, was responsible for conceptualizing the research problem, designing the Heuristic Secure Spectrum Allocation (HSSA) algorithm, conducting simulations, and analyzing key performance metrics such as spectrum utilization, latency, and security robustness. He also played a crucial role in drafting the manuscript, interpreting the results, and refining the mathematical formulations used in the study. Under the supervision of Khokan Mondal and Souvik Singha, the research was further strengthened with their expertise and guidance. Khokan Mondal provided significant contributions in algorithmic development, network modeling, and security integration within SDM-EONs. His insights helped refine the methodology, validate the performance evaluation, and ensure the technical soundness of the proposed approach. Additionally, Souvik Singha contributed to structuring the manuscript, conducting an extensive literature review, and refining the theoretical aspects of spectrum management, particularly in the domain of optical network security and adaptive resource allocation. Both supervisors reviewed the manuscript critically, provided constructive feedback, and ensured that the research maintained high academic rigor. All authors have reviewed and approved the final version of the manuscript.

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