EEN115 - RMSA Project Final Report

Group 6
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Abstract

This report presents our approach to solving the Routing, Modulation, and Spectrum Assignment (RMSA) problem with the objective of minimizing the maximum Shannon entropy in the optical network. Shannon entropy is a key metric for evaluating spectrum fragmentation, and reducing its maximum value can lead to improved spectral efficiency. Our developed heuristic algorithm is compared against the benchmarking algorithm Fixed Shortest Path + First Fit SA, evaluating performance based on entropy levels, spectrum utilization, and network load distribution. The results demonstrate the trade-offs and effectiveness of our approach.

1 Introduction

The Routing, Modulation, and Spectrum Assignment (RMSA) problem is a critical issue in optical network design, affecting resource efficiency and network fragmentation. In this project, our goal is to minimize the maximum Shannon entropy to achieve a more structured and predictable spectrum allocation. Reducing entropy helps in preventing excessive fragmentation, leading to better spectral efficiency and reducing blocking probability.

2 Problem Definition

2.1 Inputs

There are two inputs to this project assignment, which are state below:

- **Network infrastructure:** The physical network infrastructure consists of nodes and links, with each link having a finite capacity that can be divided into frequency slots of fixed or varying sizes. A flex-grid or elastic optical network (EON), which is the focus of this project, divides the spectrum into smaller frequency slot units (FSUs).
- **Traffic demands:** Each request is characterized by a source and one or multiple destinations, as well as the requested traffic volume.

2.2 Objectives

The RMSA process is typically aimed at minimizing the network resource usage. Our objective is to minimize the maximum Shannon entropy [1] in the network, which is calculated as:

$$H = -\sum_{i} p_i \log_2 p_i \tag{1}$$

where p_i represents the proportion of spectrum slots occupied in different sections of the network. High Shannon entropy indicates high fragmentation, making future spectrum allocation inefficient.

2.3 Constraints

- Spectrum continuity: A connection must use the same set of spectral slots on all physical links included in its path.
- Spectrum contiguity: The slots that are assigned to a connection must be adjacent.
- Spectrum clash: No two lightpaths that share any common link can use the same spectrum.

3 Developed Approach

3.1 Routing Strategy

3.1.1 Fixed Shortest Path

The benchmark algorithm adopts a fixed shortest path approach, which directly selects the shortest available path.

3.1.2 K-Shortest Paths with Least Loaded Selection

The developed algorithm applies K-shortest paths with least-loaded selection to minimize maximum Shannon entropy. With $K = 5$, the algorithm returns five shortest paths and selects the one with the lowest average occupied FSU per link.
This strategy helps reduce maximum Shannon entropy by:

1. **Balancing Load to Avoid Hotspot Links**
   Frequently used links tend to generate spectral fragments. Least-loaded selection distributes traffic more evenly, reducing entropy peaks.
2. **Minimizing Fragmentation Spread**
   To meet spectrum continuity constraints, some assignments may create fragments on other links. Choosing cleaner paths helps prevent this, effectively lowering maximum Shannon entropy.

3.2 Modulation Constraint

3.2.1 Routing Considerations

When selecting the least-loaded path, modulation constraints must be incorporated. Specifically, the algorithm prioritizes paths that allow for higher-order modulation formats to avoid excessive spectrum usage. Using longer paths often forces the system to switch to lower-order modulation, increasing the number of required FSUs, which exacerbates fragmentation.
Avoiding long paths allows the use of higher modulation formats, which in turn enables a higher line rate. A higher line rate reduces the bandwidth demand per request, leading to fewer FSUs being required. Consequently, the lower FSU usage helps minimize spectral fragmentation.

3.2.2 FSU Calculation

The modulation format directly impacts the required number of FSUs. The calculation follows:

$$\eta = \frac{R}{B} \tag{2}$$

$$N_{\text{req}} = \frac{D}{\eta} / W_{\text{slot}} \tag{3}$$

- η represents the **spectrum efficiency**, which measures how efficiently the available bandwidth is used. It is determined by the chosen modulation.
- R represents the **line rate** (Gbps), which refers to the data transmission rate.
- B represents the **bandwidth** (GHz), which refers to the allocated frequency range for transmission.
- D represents the **demand**, which is the required data transmission rate.
- W_{slot} represents the bandwidth of each slot, it is 12.5 GHz in this project.

By considering both routing and modulation constraints, the algorithm ensures an optimized balance between spectral efficiency and fragmentation minimization.

3.3 Spectrum Assignment Strategy

3.3.1 First Fit

The First Fit strategy assigns spectrum by selecting the first available contiguous block of FSUs that satisfies the demand, which is used in benchmark algorithm.

3.3.2 Best Fit

The Best Fit strategy is implemented in developed algorithm. It selects the smallest available FSU block that meets the required bandwidth demand. This approach aims to minimize spectral fragmentation by efficiently utilizing the available spectrum.
Best fit minimize the maximum Shannon entropy by:

1. **Prioritizing the Smallest Available Block**
   Ensures that larger free spectrum blocks remain unused, which is particularly important for high-demand traffic that requires continuous FSUs.
2. **Even Distribution of Spectrum Usage**
   Compared to First Fit, Best Fit helps to preserve lower-index FSUs and promotes more uniform utilization of the entire spectrum, preventing early depletion of specific frequency regions.

4 Performance Analysis

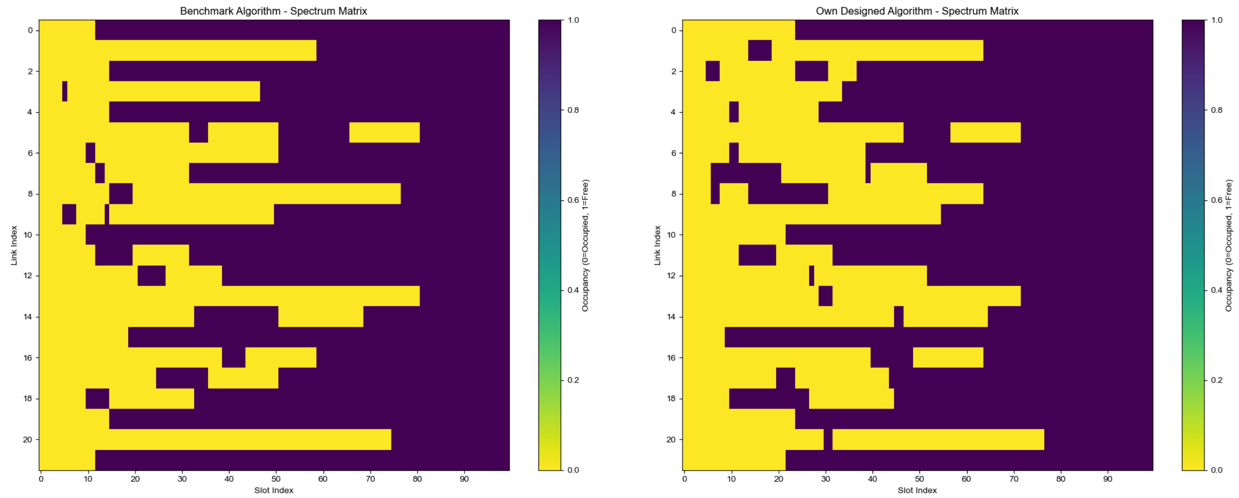
This section presents a comparative analysis of our developed RMSA algorithm against the benchmark approach and examines the impact of different constraints and protection mechanisms.

4.1 Analysis for Questions 1 and 2: Algorithm Performance Comparison

To evaluate our algorithm, we compare its performance against the benchmark which is Fixed Shortest Path + First Fit Spectrum Assignment on different parameters.

4.1.1 Spectrum Fragmentation Metrics

According to Figure 1, The own designed algorithm has less fragmentation compared to the benchmark algorithm. In the benchmark algorithm, there are many small, scattered free spectrum slots (yellow areas), which create fragmentation and reduce the efficiency of future spectrum allocation. In contrast, the designed algorithm results in larger, more continuous free blocks, making it easier to accommodate new traffic and improving spectral efficiency. This shows that the designed algorithm effectively reduces fragmentation by compacting spectrum usage.



(a) Benchmark Algorithm

(b) Own Designed Algorithm

Figure 1: Spectrum Matrix Comparison between Benchmark and Own Designed

4.1.2 FSU Usage

Highest used FSU on any link The highest FSU index is lower when the entropy goes down. This indicates that spectral resources are used more compactly, with fewer spectral fragments. The reason is that the *Best Fit* strategy helps fill the existing spectral gaps, making usage more continuous and therefore reducing the highest FSU index.

Total number of used FSUs As the entropy decreases, the total number of used FSUs increases slightly (within about 5%). This happens because the *k-shortest with least-loaded* approach does not always choose the shortest path. Hence, even with modulation-aware protection, the number of traversed links may increase, requiring additional guard bands (typically 1 FSU each). Thus, the total FSU usage goes up, but only by a small margin.

Table 1: Germany-7 Network - Benchmarking vs Designed Algorithm (Ascending)

Traffic Matrix	Algorithm Used	Highest FSU Used	Total FSUs	Resource Increase	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
G7-matrix-1	Benchmarking	16	168	2.4%	0.2266	92.0%	0.0060
	K-shortest	14	172		0.1180		0.0056
G7-matrix-2	Benchmarking	44	426	4.7%	0.4486	15.8%	0.0077
	K-shortest	44	446		0.3875		0.0070
G7-matrix-3	Benchmarking	80	848	4.7%	0.6005	13.7%	0.0071
	K-shortest	76	888		0.5283		0.0083
G7-matrix-4	Benchmarking	128	1392	7.9%	0.7192	-12.8%	0.0074
	K-shortest	112	1502		0.8250		0.0078
G7-matrix-5	Benchmarking	188	2073	3.2%	1.2121	8.7%	0.0063
	K-shortest	140	2139		1.1136		0.0068

Table 2: Italian-10 Network - Benchmarking vs Designed Algorithm (Ascending)

Traffic Matrix	Algorithm Used	Highest FSU Used	Total FSUs	Resource Increase	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
IT10-matrix-1	Benchmarking	27	248	7.3%	0.3861	20.1%	0.0079
	K-shortest	21	266		0.3214		0.0100
IT10-matrix-2	Benchmarking	53	686	5.4%	0.6111	9.5%	0.0135
	K-shortest	46	723		0.5581		0.0163
IT10-matrix-3	Benchmarking	110	1266	3.9%	1.2870	35.5%	0.0167
	K-shortest	92	1315		0.9500		0.0164
IT10-matrix-4	Benchmarking	163	2069	2.6%	1.4926	40.6%	0.0181
	K-shortest	122	2122		1.0614		0.0183
IT10-matrix-5	Benchmarking	247	3047	3.0%	1.7990	21.0%	0.0192
	K-shortest	187	3137		1.4873		0.0207

Table 3: Germany-7 Network - Benchmarking vs Designed Algorithm (Descending)

Traffic Matrix	Algorithm Used	Highest FSU Used	Total FSUs	Resource Increase	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
G7-matrix-1	Benchmarking	18	168	2.4%	0.1650	0%	0.0056
	K-shortest	13	172		0.1650		0.0063
G7-matrix-2	Benchmarking	38	426	4.9%	0.4144	-10.9%	0.0068
	K-shortest	33	447		0.4595		0.0083
G7-matrix-3	Benchmarking	80	848	0%	0.6116	6.1%	0.0077
	K-shortest	66	848		0.5766		0.0071
G7-matrix-4	Benchmarking	120	1392	1.7%	0.9287	6.0%	0.0085
	K-shortest	108	1416		0.8758		0.0076
G7-matrix-5	Benchmarking	194	2073	4.6%	1.0189	1.1%	0.0083
	K-shortest	182	2169		1.0078		0.0085

Table 4: Italian-10 Network - Benchmarking vs Designed Algorithm (Descending)

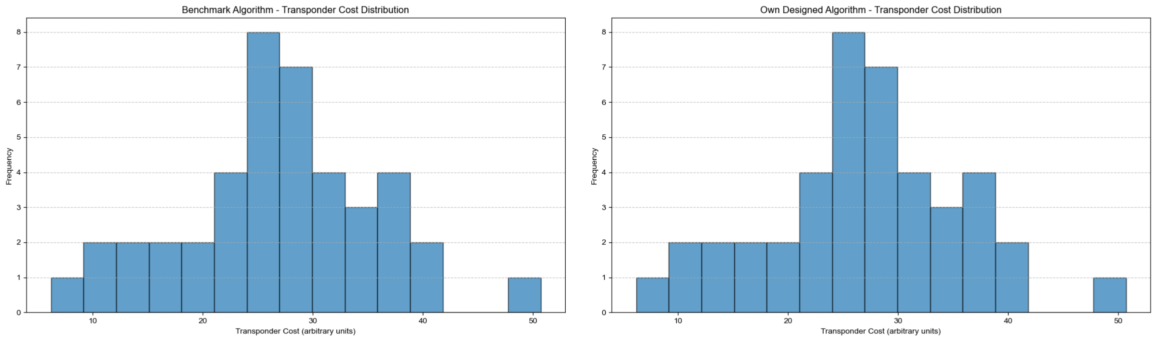
Traffic Matrix	Algorithm Used	Highest FSU Used	Total FSUs	Resource Increase	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
IT10-matrix-1	Benchmarking	25	248	6.0%	0.4278	45.9%	0.0092
	K-shortest	17	263		0.2932		0.0093
IT10-matrix-2	Benchmarking	50	686	6.0%	0.6783	23.5%	0.0149
	K-shortest	44	727		0.5492		0.0149
IT10-matrix-3	Benchmarking	105	1266	4.8%	1.2823	56.3%	0.0144
	K-shortest	86	1327		0.8204		0.0182
IT10-matrix-4	Benchmarking	158	2069	0.0%	1.4448	1.7%	0.0159
	K-shortest	152	2069		1.4203		0.0158
IT10-matrix-5	Benchmarking	231	3047	0.0%	1.8592	-8.9%	0.0176
	K-shortest	230	3047		2.0421		0.0186

4.1.3 Distribution of Transponder Cost

The transponder cost [2] is calculated as:

$$\text{Total Cost} = C_m \times \left(\frac{\text{Demand}}{10}\right).$$

Both the designed and benchmark algorithms yield the same transponder cost distribution, because under modulation constraints, the same demand typically ends up using the same modulation format. Consequently, they share the same basic cost C_m, indicating no direct causal relationship between fragmentation levels and transponder cost.



(a) Benchmark Algorithm

(b) Own Designed Algorithm

Figure 2: Transponder Cost Distribution Comparison between Benchmark and Own Designed

4.1.4 Link Usage Distribution

From the figure 3, the "benchmark" (blue bars) shows many links whose usage ratio is either very low (e.g., 0.01) or relatively high (e.g., 0.05). Meanwhile, the "designed" algorithm (orange bars) more often concentrates link usage in a moderate range (e.g., 0.02–0.03). In other words, the benchmark method results in some links being barely used while others are heavily occupied, whereas the designed method balances the usage more evenly across links. This more uniform distribution of spectral resources helps reduce fragmentation.

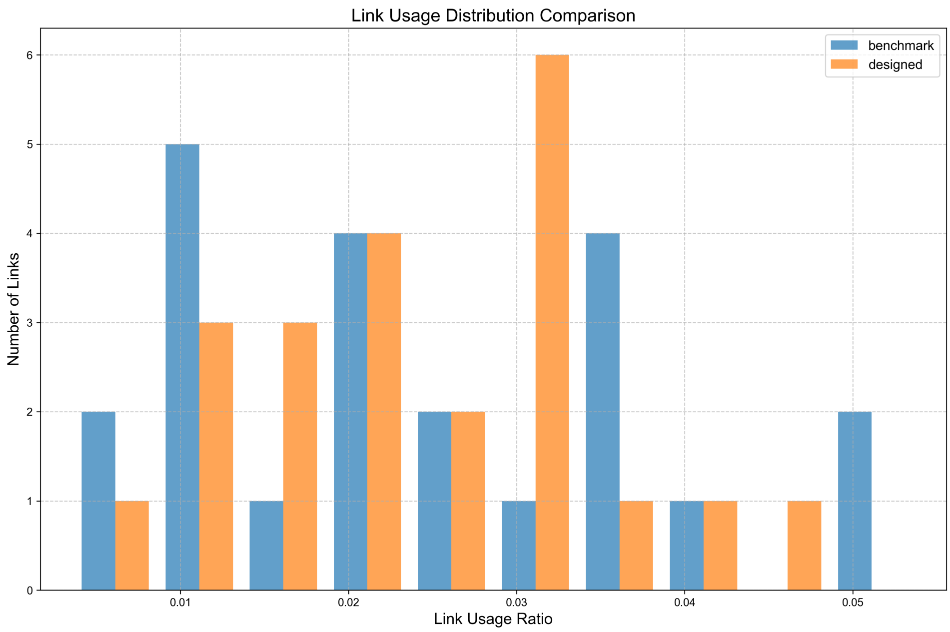


Figure 3: Link Usage Distribution Comparison between Benchmark and Own Designed

4.1.5 Path Length Distribution

According to Figure 4, compared to the benchmark (blue bars), the designed algorithm (orange bars) uses longer paths for some demands. This is because the *k-shortest with least-loaded* approach may avoid links that are heavily occupied or prone to fragmentation, and therefore sometimes resorts to "detours" in order to find less congested links.

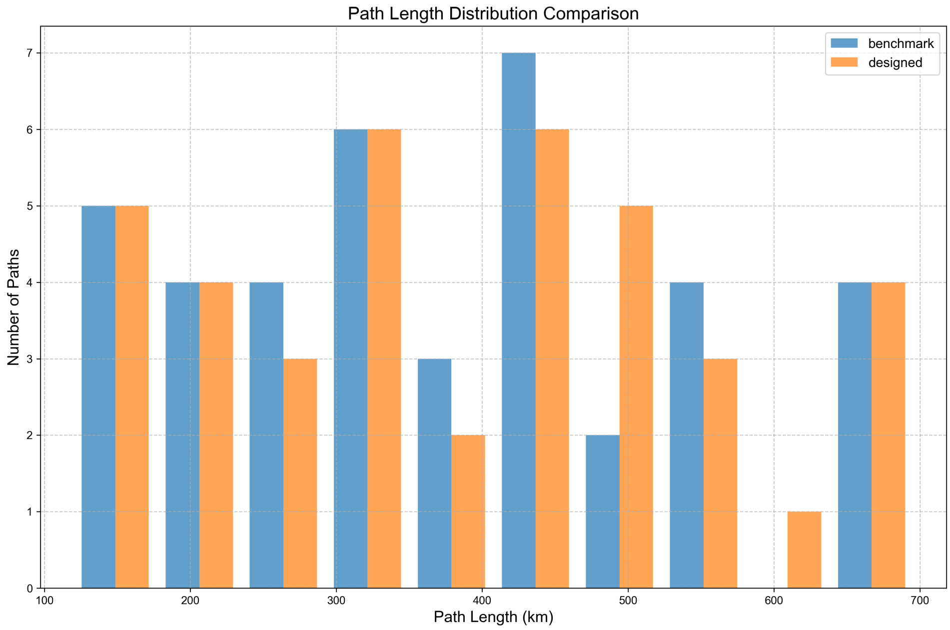


Figure 4: Path Length Distribution Comparison between Benchmark and Own Designed

4.2 Analysis for Question 3: Impact of Spectrum Continuity and Contiguity Constraints

When removing the spectrum continuity constraint and spectrum contiguity constraint, the following impacts on optical network performance can be observed:

4.2.1 Effects of Removing the Spectrum Continuity Constraint

The spectrum continuity constraint mandates that a connection must use the same spectrum slots along its entire path. When this constraint is removed, several performance changes are observed:

Firstly, there is a reduction in the highest used FSU, as spectrum assignment can now be optimized per link rather than across the entire path. This flexibility leads to a decrease in total FSU usage, improving overall spectral efficiency. Additionally, it results in a more balanced link load distribution, reducing congestion on highly utilized links by allowing connections to take advantage of different spectral slots at different segments.

Another key impact is a decrease in spectrum fragmentation, as measured by lower Shannon entropy and utilization entropy values. Without this constraint, the spectrum can be allocated in a more structured manner across multiple connections. However, the trade-off comes in the form of increased implementation costs, as the network must now deploy wavelength converters at various nodes to handle spectrum transitions, leading to higher equipment and operational complexity.

4.2.2 Effects of Removing the Spectrum Contiguity Constraint

The spectrum contiguity constraint requires that spectrum slots assigned to a connection must be adjacent. Eliminating this constraint introduces additional flexibility, resulting in higher spectrum utilization, as fragmented spectrum slots can now be utilized even if they are not adjacent.

As a result, there is a potential reduction in total FSU usage, since previously unusable non-contiguous spectrum blocks can now be allocated. However, while physical fragmentation still exists, its service impact is somewhat mitigated. Despite these advantages, removing this constraint introduces new challenges. Transponder costs increase, as multiple narrower bandwidth transponders may be required instead of a single wide-band transponder. Moreover, signal processing complexity rises, as handling non-contiguous spectrum allocations requires more sophisticated modulation and demodulation techniques.

4.2.3 Effects of Removing Both Constraints Simultaneously

When both constraints are removed together, maximum spectrum flexibility is achieved. This leads to optimal spectrum utilization, drastically reducing both the highest used FSU and total FSU usage. Additionally, link loads are more balanced, as connections can adapt their spectrum allocation dynamically across different network segments. The blocking rate decreases significantly, as more spectrum options become available for assignment.
However, this maximum flexibility comes at a cost. The equipment and control plane complexity increase substantially, requiring advanced wavelength converters at multiple nodes and a highly sophisticated control plane to manage fragmented spectrum assignments. Furthermore, energy consumption rises, as additional resources are needed for wavelength conversion and handling non-contiguous allocations.

4.2.4 Summary

While removing these constraints enhances network performance by reducing fragmentation and improving spectral efficiency, it introduces substantial challenges in terms of implementation complexity, equipment costs, and energy consumption. In practical network deployments, these factors must be balanced against network design objectives, available budget, and operational feasibility.

4.3 Analysis for Questions 4 and 5: Impact of 1+1 and Shared Path Protection

To assess the impact of 1+1 dedicated [3] path protection and shared path protection, we extend our algorithm to incorporate these mechanisms and compare them against the original implementation.

4.3.1 Comparison of 1+1 Dedicated vs. Shared Protection

The 1+1 dedicated protection reserves a fully redundant backup path for each connection, ensuring maximum reliability at the cost of increased resource usage. In contrast, shared protection allows multiple connections to share backup resources, optimizing overall spectrum utilization while still providing resilience.
The following tables and plots summarize the performance results for the Germany-7 and Italian-10 network topologies under different traffic matrices.

Table 5: Germany-7 Network - 1+1 Dedicated vs Shared Protection (Ascending)

Traffic Matrix	Protection Type	Highest FSU Used	Total FSUs	Resource Reduction	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
G7-matrix-1	1+1 Dedicated	51	583	42.4%	0.5837	47.3%	0.0172
	Shared	25	336		0.3077		0.0118
G7-matrix-2	1+1 Dedicated	130	1735	62.9%	1.3457	60.2%	0.0282
	Shared	50	643		0.5358		0.0187
G7-matrix-3	1+1 Dedicated	220	3326	67.1%	1.4488	59.4%	0.0331
	Shared	87	1093		0.5879		0.0184
G7-matrix-4	1+1 Dedicated	319	4849	65.5%	1.4562	23.0%	0.0291
	Shared	129	1671		1.1209		0.0184
G7-matrix-5	1+1 Dedicated	317	5835	59.3%	1.4322	-16.2%	0.0248
	Shared	186	2373		1.6643		0.0194

Table 6: Italian-10 Network - 1+1 Dedicated vs Shared Protection (Ascending)

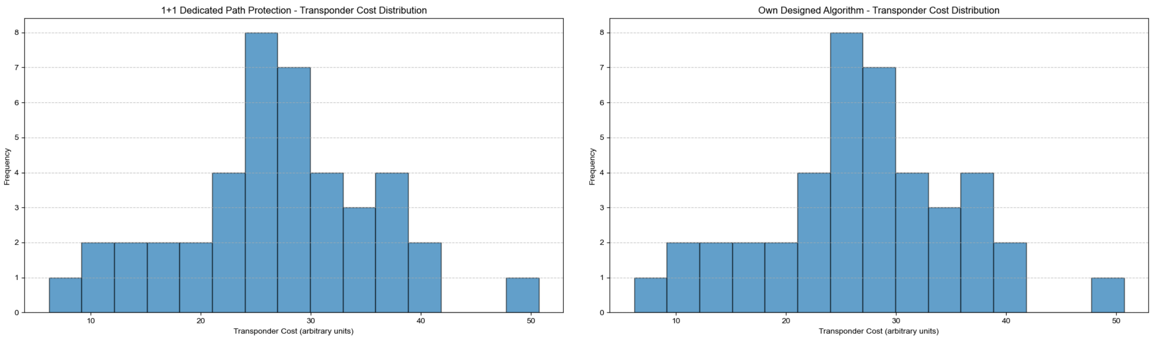
Traffic Matrix	Protection Type	Highest FSU Used	Total FSUs	Resource Reduction	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
IT10-matrix-1	1+1 Dedicated	60	844	30.7%	0.7480	30.0%	0.0283
	Shared	36	585		0.5235		0.0212
IT10-matrix-2	1+1 Dedicated	131	2307	51.5%	1.3714	36.1%	0.0512
	Shared	75	1120		0.8758		0.0306
IT10-matrix-3	1+1 Dedicated	257	4531	60.5%	1.9061	39.4%	0.0597
	Shared	117	1788		1.1551		0.0349
IT10-matrix-4	1+1 Dedicated	318	6760	62.0%	1.9935	9.0%	0.0653
	Shared	147	2571		1.8147		0.0356
IT10-matrix-5	1+1 Dedicated	319	7443	50.3%	1.7270	-62.3%	0.0598
	Shared	217	3703		2.8029		0.0445

Table 7: Germany-7 Network - 1+1 Dedicated vs Shared Protection (Descending)

Traffic Matrix	Protection Type	Highest FSU Used	Total FSUs	Resource Reduction	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
G7-matrix-1	1+1 Dedicated	44	634	49.2%	0.5251	47.7%	0.0188
	Shared	22	322		0.2745		0.0104
G7-matrix-2	1+1 Dedicated	116	1687	60.3%	1.1976	50.1%	0.0291
	Shared	45	669		0.5978		0.0154
G7-matrix-3	1+1 Dedicated	233	3117	63.6%	1.7022	30.6%	0.0264
	Shared	78	1135		1.1817		0.0199
G7-matrix-4	1+1 Dedicated	319	5145	66.8%	1.8998	22.8%	0.0294
	Shared	129	1707		1.4661		0.0192
G7-matrix-5	1+1 Dedicated	317	5589	57.0%	1.3009	31.1%	0.0167
	Shared	197	2406		1.8887		0.0215

Table 8: Italy-10 Network - 1+1 Dedicated vs Shared Protection (Descending)

Traffic Matrix	Protection Type	Highest FSU Used	Total FSUs	Resource Reduction	Max Shannon Entropy	Entropy Improvement	Utilization Entropy
IT10-matrix-1	1+1 Dedicated Shared	44 34	786 542	31.0%	0.5636 0.5162	9.4%	0.0261 0.0184
IT10-matrix-2	1+1 Dedicated Shared	112 67	2252 1104	50.9%	1.3188 0.8295	37.1%	0.0449 0.0293
IT10-matrix-3	1+1 Dedicated Shared	223 110	4571 1806	60.5%	2.1128 1.2537	40.7%	0.0627 0.0341
IT10-matrix-4	1+1 Dedicated Shared	319 152	6867 2631	61.7%	1.8702 1.8547	27.7%	0.0577 0.0359
IT10-matrix-5	1+1 Dedicated Shared	318 232	7543 3597	52.3%	1.4627 2.0894	30.0%	0.0425 0.0340



(a) 1+1 Dedicated

(b) Shared Protection

Figure 5: Transponder Cost Distribution Comparison between Dedicated and Shared Protection

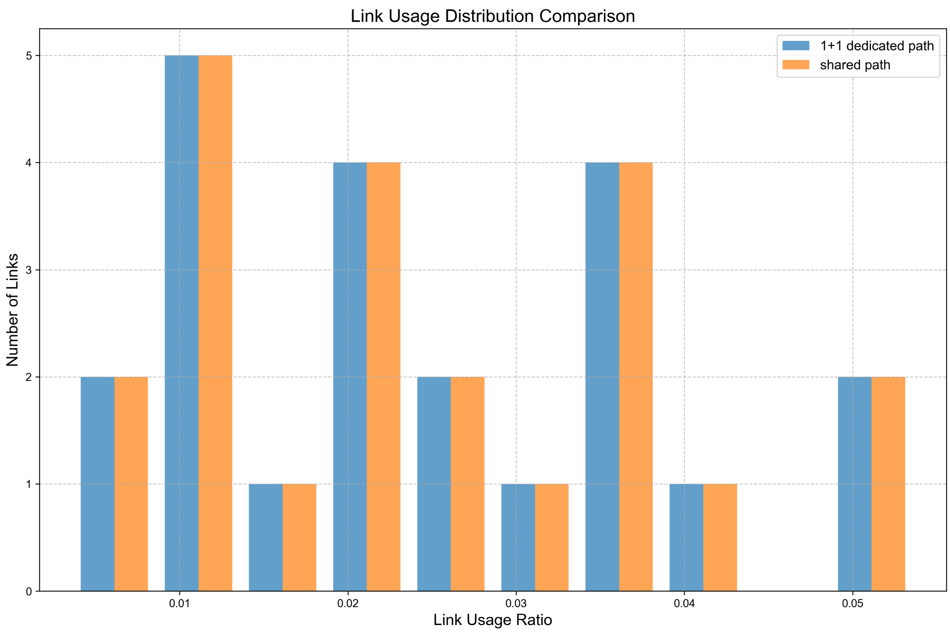


Figure 6: Link Usage Distribution Comparison between Dedicated and Shared Protection

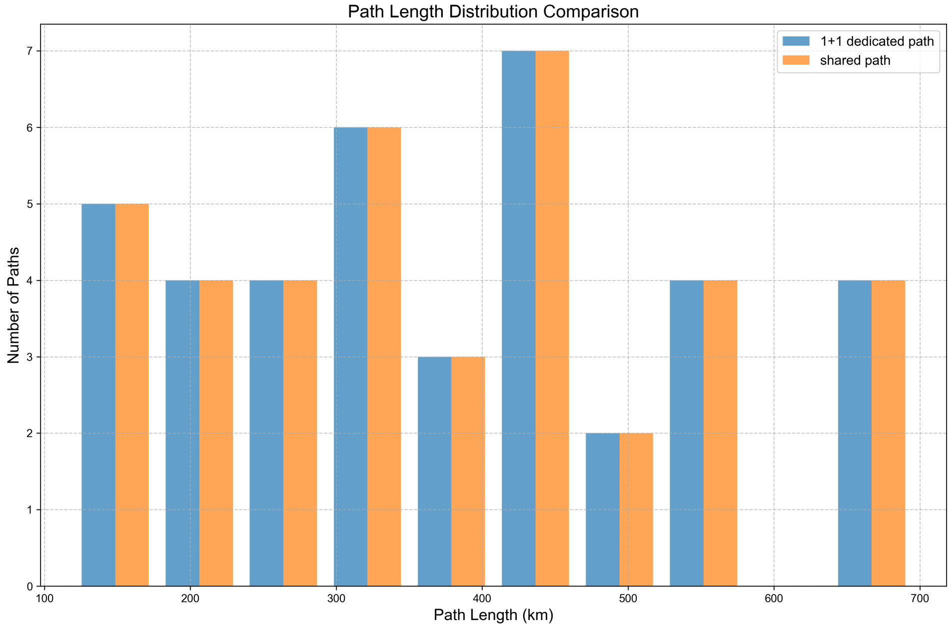


Figure 7: Path Length Distribution Comparison between Dedicated and Shared Protection

4.3.2 Discussion and Analysis

From the results, we observe that shared protection significantly reduces resource consumption compared to 1+1 dedicated protection. Topology complexity also influences resource consumption. The Germany-7 network exhibits a higher potential for resource sharing, with an average 60% reduction in FSUs, compared to 51% in the Italian-10 network. This suggests that topologies with fewer nodes and more shared paths can leverage the benefits of shared protection more effectively than networks with more complex connectivity.

Shannon entropy and utilization entropy measure the fragmentation level of the link spectrum. Analyzing Shannon entropy, we observe that in most cases, shared protection results in lower Shannon entropy values, indicating less fragmentation. However, in high-load scenarios (G7-matrix-5 and IT10-matrix-5), shared protection exhibits higher Shannon entropy, suggesting that under extremely heavy loads, fragmentation increases due to the dynamic nature of resource-sharing.

By examining the highest FSU indices from individual reports, we find that shared protection consistently requires lower maximum FSU indices than dedicated protection. This allows for more efficient spectrum usage, meaning that shared protection can support the same traffic demands using a smaller overall spectrum window.

Link usage and path length distribution for both cases are the same, since we use the same algorithm for path selection and spectrum assignment.

Although shared protection significantly improves resource efficiency, it comes with trade-offs in network resilience. While it minimizes total FSU usage and enhances spectrum utilization, its fault tolerance is lower than that of 1+1 dedicated protection. In scenarios where network reliability is the top priority, dedicated protection remains the preferred choice despite its higher spectrum requirements.

These findings highlight an inherent trade-off between network resource efficiency and fault tolerance. The selection of a protection strategy should be tailored to the network's operational constraints and reliability requirements. Shared protection is most effective under moderate traffic loads, but under extreme congestion, its fragmentation impact must be carefully managed.

5 Conclusion

- Our heuristic algorithm effectively minimizes maximum Shannon entropy, reducing spectrum fragmentation.
- The performance comparison shows a significant reduction in entropy while maintaining a reasonable total spectrum usage.
- Future improvements could involve integrating adaptive routing strategies, taking sorting traffic demand in descending order into consideration based on our own algorithm and objective.

A Annex 1: Statement of Contributions

- **Jingcheng Wang:** Optimized parameters and structure of the designed algorithm, tested benchmarking and designed algorithm, evaluated performance parameters of spectrum fragmentation metrics, participated in the writing of reports.
- **Tianqi Zhao:** Tested the performance of different routing and spectrum assignment strategies. Participated in the design of dedicated and shared protection. Contributed to the final report with teammates.
- **Mengyuan Zhou:** Developed our own RMSA algorithm, tested the performance of benchmark, our own algorithm, 1+1 dedicated and shared path protection, implemented the visualization of performance parameters of interest. Participated in completing the final report.
- **Weirui Zhao:** Implemented topology processing and traffic matrix management, developed First Fit spectrum assignment strategy, researched, implemented Shannon entropy and utilization entropy calculation, analyzed performance metrics based on referenced papers and team discussions.
- **Tingting Zhao:** Tested 1+1 dedicated and shared path protection using our RMSA algorithm, evaluated performance across different topologies and traffic matrices, contributed to writing the final project report with corresponding parts.

B Annex 2: Reflection on Group Work

- Strengths: Effective and enjoyable discussions, regular meetings ensuring steady progress, strong algorithmic improvements through collaboration and idea-sharing. Working in a group allowed team members to exchange insights, refine problem-solving approaches, and improve both technical and communication skills.
- Challenges: Understanding the project problem setup and modeling, developing an RMSA algorithm that outperformed the benchmark (as the benchmark initially performed better), and debugging data type issues. These challenges required extensive troubleshooting, discussions, and iterations, which helped in strengthening analytical thinking and debugging skills.
- Improvements for future: Collaborating in a group improved our ability to divide tasks efficiently and leverage each member's expertise. If we were to start again, we would allocate more time for initial problem formulation and benchmarking analysis to accelerate algorithm development. Additionally, exploring machine learning-based methods for RMSA could be a future direction to enhance optimization performance.

References

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[3] Z. Xu et al., “1+ 1 dedicated optical-layer protection strategy for filterless optical networks,” IEEE Commun. Lett., vol. 18, no. 1, pp. 98–101, Jan. 2014.