EEN115 Project Introduction to Communication Networks

Routing, Modulation Format and Spectrum Assignment (RMSA)

Project Group 8

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Abstract

The project is focused on the problem of the design and dimensioning of optical communication network infrastructure. The choice of routing method in network design plays an important role of preventing network congestions and failures. Different approaches to RMSA, an analysis of the trade offs to the different performance parameters of interest such as spectrum usage and transponder costs is at the heart of this project. The general results were that the network could be optimised according to objectives and this resulted in interesting key differences when comparing entropies and different distributions.

1 Introduction

In Elastic Optical Networks (EONs), the way different service demands are supported in the network is ruled by the Routing, Modulation and Spectrum Assignment (RMSA) algorithm that decides how the spectrum resources of the optical network are assigned to each service demand. In a dynamic Elastic Optical Networks, which demand requests arrive randomly one at a time and the accepted demands last in the network for a random time duration. So, one important goal of the RMSA algorithm is the efficient use of the spectrum resources to increase the acceptance probability of future demand requests. On the other hand, multiple failure events are becoming a concern to network operators in that events are becoming more frequent in time. To minimize the failures in the network, different RMSA methods can be followed for different problems.

The project is focused on two objectives:

1. Optimise total spectrum usage: A portion of the electromagnetic spectrum is assigned to each lightpath at the physical optical layer. The ratio of total bandwidth used in the spectrum to the total bandwidth in the spectrum helps us find the spectrum usage.

2. Minimise transponder cost: After achieving an effective use of the spectrum, the solution is adapted to minimise the transponder cost. The selection of the modulation format plays an important role in order to better optimize the network respect to cost.

1.1 Related Work

Yu et al. [3] proposed an algorithm computes K-shortest paths between each pair of source-destination nodes, where K=3 for 5-node network, and sorts the requests and assigns the first available portion of spectrum that satisfies the demand.

Zhao et al. [4] also presented a similar algorithm that calculates k-shortest paths, sorts the requests and, for each path they chooses modulation format and set of available FSUs, computes the cost of each link in the path, assigning the one with the lowest cost.

Goscien et al. [5] proposed an algorithm that sorts requests in decreasing order then calculates k-shortest paths and allocates to each demand that minimizes the cost. They optimized their solutions by either changing the path or the modulation format.

In 2000, Zang et al. [6] proposed methods to assign wavelengths to lightpaths in the literature. They compared ten different heuristics and found out that most-used outperforms other wavelength assignment methods, however first-fit is advantageous in terms of the required computations.

To improve the resiliency of optical networks, dedicated path protection is proposed in 2010, by Takagi at al [7].

Ref	Year	Author	Methods	Objective
[3]	2014	Yu at al.	k-shortest path + first fit	Minimize spectrum utilization
[4]	2015	Zhao at al.	k-shortest path + modulation + spectrum allocation	Minimize the cost
[5]	2015	Goscien at al.	k-shortest path + tabu search	Minimize the cost
[6]	2000	Zang at al.	first fit + most used	Comparison of wavelength assignment approaches
[7]	2010	T. Takagi et al.	dedicated path protection	Improved resiliency

Table 1: Previous Works

1.2 Routing Algorithm

Monitoring network load is important so that we can ensure that the network is running smoothly and that no one is being blocked from getting online. The routing strategy also affects how much traffic is carried on the network. Fixed-path routing is a simple routing strategy in which one path is calculated for each source/destination pair, and that path is used for every connection request between those two nodes. If any link along that path reaches its capacity, then accepting further requests between the source and the destination is not possible.
The shortest-path algorithms that are the subject to this this project make the assumption that each connection has a cost metric that is additive.

1.2.1 Fixed Shortest Path

A shortest-path method determines the route from source to destination that minimizes the total cost measure under certain assumptions. It is possible to locate alternate paths that are very near the shortest path in most realistic networks, making the latency increase tolerable.

Fixed-path routing is quite limited and can result in inadequate performance by not taking into account such alternatives.

1.2.2 Dijkstra's Algorithm

The Dijkstra algorithm is the most well-known shortest-path algorithm. The algorithm keeps track of the shortest path between a source and the destination node. Dijkstra is categorized as a greedy algorithm since it selects the best option without considering the outcome at a later time. It is guaranteed to identify the best answer, which is the shortest route from source to destination, unlike many greedy algorithms.

1.3 Fixed Alternate Shortest Path

Network congestion may result from choosing the shortest path for each connection request between a certain source and destination. Having different alternate paths available for each source/destination combination is usually helpful.

1.3.1 K-Shortest Path Algorithm

Yen's Shortest Path algorithm computes a number of shortest paths between two nodes. The algorithm is often referred to as Yen's K-Shortest Path algorithm, where K is the number of shortest paths to compute. The algorithm supports weighted graphs with positive relationship weights.

1.4 Modulation Type

The selection of the modulation format plays an important role in network design in order to better optimize the network with respect to the given objectives. If it is chosen a more spectrally efficient modulation format, the amount of spectrum used can be reduced, while the signal bit-rate is maintained. Similarly, if the cost needs to be minimized, then a different network has to be designed to choose the modulation format accordingly.

1.5 Spectrum Assignment

Traditional optical networks only allows to carry a certain amount of spectrum. However, variable amount of spectrum can be allocated in EON's. Selecting that amount of spectrum that will be assigned to the lightpath is called the spectrum assignment.

The following constraints are hold when assigning spectrum to individual connections:

1. Spectrum continuity: There is no spectrum conversion in a transparent network, so the same spectrum slots need to be allocated on all links in the path. As a results, free frequency slot units might become not usable when the same slots are being used in most of the adjacent links.

That is also referred as horizontal fragmentation.
2. Spectrum contiguity: The spectrum slots allocated to a connection need to be adjacent in the spectrum. That causes fragmentation within the spectrum the spectrum of the single fiber. This is referred as vertical fragmentation.
3. Spectrum clash: A spectrum slot on a link can only be used for one connection at a time.
4. Guardband: To enable the network to function on a single channel without impacting other channels, a guardband is required between the optical channels. A typical guardband is usually one slot of bandwidth, which is also the case for this project. The guardbands represents lost bandwidth and result with a higher spectrum usage.

1.5.1 First Fit

This method keeps track of the occupied and empty frequency slots. Then, it searches for a set of adjacent frequency slots that satisfies the traffic demand. After sorting them in ascending index order, the first set of frequency slots that are available is allocated. First-fit is advantegous in many cases. It does not require comprehensive knowledge of the network and storage to maintain the network states. Therefore, the complexity is relatively small. Because of these reasons, first-fit is preferred in practice. [2]

1.5.2 Least Used

Least used method is an alternative way for first-fit method. It is more adaptive however it requires more computation. The wavelengths that are assigned to lightpaths are counted and the one that is used the least gets the lowest index.

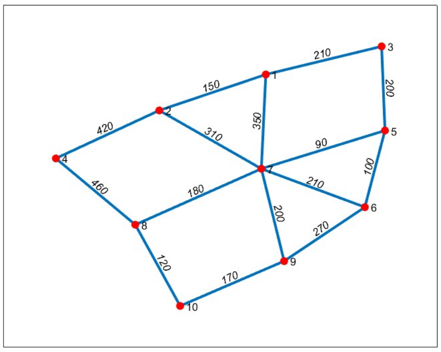
2 Problem definition

The problem is to solve the RMSA problem for two different objectives. First should the problem be solved to minimise the total spectrum usage over all the links in the network (Objective A). Thereafter the proposed algorithm should be adapted in such a way that the second objective is met. This objective is minimising the total transponder cost (Objective B).

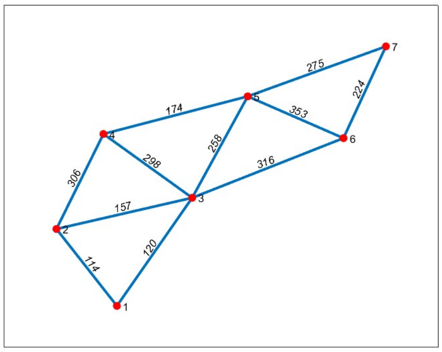
The proposed way of solving the task is to use a K-shortest paths routing algorihm and combine this with a method of modulation level selection and spectrum assignment. The spectrum assignment will be tested with a modified first fit algorithm. The first fit algorithm will be modified to prioritise paths with either objective A or objective B in mind.
For benchmarking purposes, a seperate RMSA algorithm is developed using fixed shortest path routing and a least used spectrum assignment. This will give qualitative measurements for a comparison between both the objective A and objective B.

A further study into the effects of network protection will help understand how the algorithms work with higher demand and stress. 1+1 dedicated path protection is implemented to further study differences between objective A, B and benchmarking.

Two different topologies will be tested, one for the large German infrastructure and one for the Italian one. The two topologies of interest can be seen in Fig. 1. In the figure all the links go both directions with the same length. Each topology comes with 5 different demand matrices that determine the load of the network. The matrices are labeled 1-5 where the matrix 1 has the lowest load and matrix 5 has the highest. Results are mainly reported on the Italian topology but interesting differences between the two topologies will be brought up for the German one.



(a) Italian Topology



(b) German Topology

Figure 1: Given Network Topologies

3 Methodology

Further follows the general methodology used to achieve results.
Routing is implemented in two steps. The goal was to implement Yen's algorithm to find K-shortest paths. Yen's algorithm however relies also on a fixed shortest path algorithm which also then had to be implemented. First the Dijkstra algorithm was developed as the primary alternative for the fixed shortest path routing, this also became the go to algorithm for the benchmarking where we wanted fixed shortest path. After the Dijkstra algorithm was written the Yen algorithm followed to find K-1 deviations of the shortest path. The weight metric used in the algorithms was the number of hops. It was believed that we minimise total spectrum usage in an easy way if we minimise the number of traversed links. Therefore Yen's algorithm was run with unitary weights on each link and each path length in km was calculated afterwards.

When it came to spectrum assignment the first fit algorithm was developed. After the standard algorithm was developed, it was modified according to our specification. It was modified in such a way so that for each demand we first checked every possible path to determine how many spectrum slot on the network every path would generate and also how much the transponder cost would be. Then after checking every possible K-paths we could sort these paths in a order of priority depending on if we wanted to achieve objective A or objective B. The first fit could then assign the demand according to the priority list. A simple least used spectrum assignment was then also developed as a part of the benchmarking.

The 1+1 path protection could then be implemented after routing and spectrum assignment was solved. For the path protection we first ran the RMSA as developed and then for each assigned demand we removed the designated path from the topology and calculated K-shortest paths again to pick K new paths from source to sink that does not have any overlapping links with first assigned path. This procedure was repeated for all demands and then we ran the spectrum assignment again on the already half filled spectrum matrix that the RMSA outputed the first round. In this way we have two non overlapping paths assigned for each demand and have created a 1+1 dedicated path protection that can be tested and analysed.

4 Results

Further follows results for the different tests using the different RMSA solutions. The general metrics for comparison between the objectives and the benchmark can be seen in Table 2, where the results are for tests with the Italian topology and the demand matrix 4. For total spectrum usage which we have as a percentage on how filled the spectrum is we see that objective A is clearly the best performing with objective B and benchmark far behind. This could be considered a success in the RMSA for objective A.

Metric	Objective A	Objective B	Benchmark
Total spectrum usage	0.2095	0.2835	0.2382
Number of used FSUs	2011	2722	2287
Highest used FSU	142	197	197
Average Utilisation Entropy (UE)	0.0162	0.0159	0.0320
Average Shannon Entropy (SE)	0.9877	1.2200	1.9189
Total cost	669.2	528.8	695

Table 2: Metrics with the Italian topology and demand matrix 4.

Interesting to note in Table 2 is that the average UE and SE both become slightly worse for objective A in comparison to the objective B. We want a low UE and a high SE. A likely explanation for this phenomena is because we constantly choose modulation to minimise the number of FSUs each block of FSUs on a link becomes smaller, as seen from the SE, but if we allow more FSUs such as in the objective B case the blocks for each demand becomes longer and the total usage on a given link becomes less sporadic, seen by UE.

The cost however is the lowest in objective B which once again can be considered a success for this objective. Objective B also have better SE than objective B and better UE than the benchmark. This indicates that for objective B we use the spectrum less sporadically. Taking a look at the link usage distribution in Fig. 2 we see that the benchmark uses the links more evenly than the objective B, the variance of the benchmark is around 0.0146 while objective B and A is around 0.0198 and 0.0084 respectively. This is possibly a result of the benchmark only using the fixed shortest path while the other two use K-shortest paths. The more evenly distributed link usage in objective B can also explain the higher SE, when each link is evenly filled it would be easier to fit demands evenly and tightly. The index of the link in Fig. 2 was an internal way of organising links where each index is its own link, if curious the full list can be found in Appendix A1.

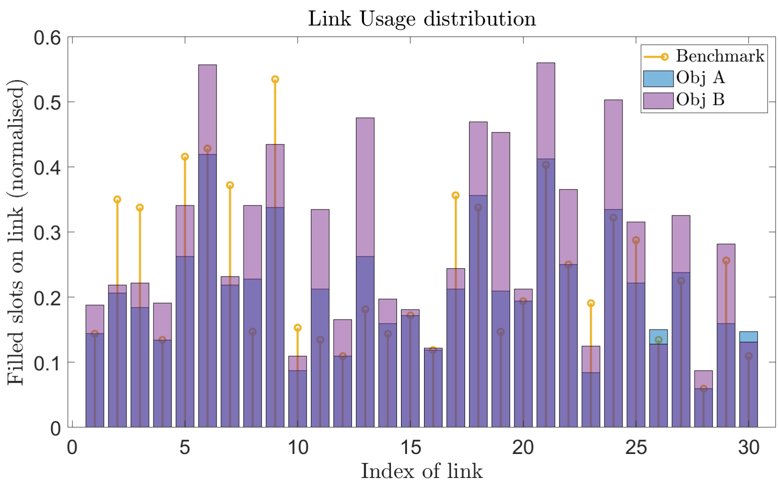


Figure 2: Link Usage Distribution

A path length distribution can be seen in Fig. 3. Objective A and B are in this case very similar and only differ in some places. The benchmark however takes somewhat longer paths, once again probably because of the fixed shortest path. The shortest path in this case was with unitary weights so some paths became a little longer.

A visualisation of cost distribution is found in Fig.4. Objective A has a high peak around 8 while objective B has a has a much flatter distribution with a lower mean which clearly explains the much lower total cost of objective B compared to objective A. We can therefore state that a trade off is made between effective use of spectrum, an efficient use of the spectrum that fit more users and demand will result in a more expensive system while the cost can be lowered if we do not need to support the highest demand in traffic.

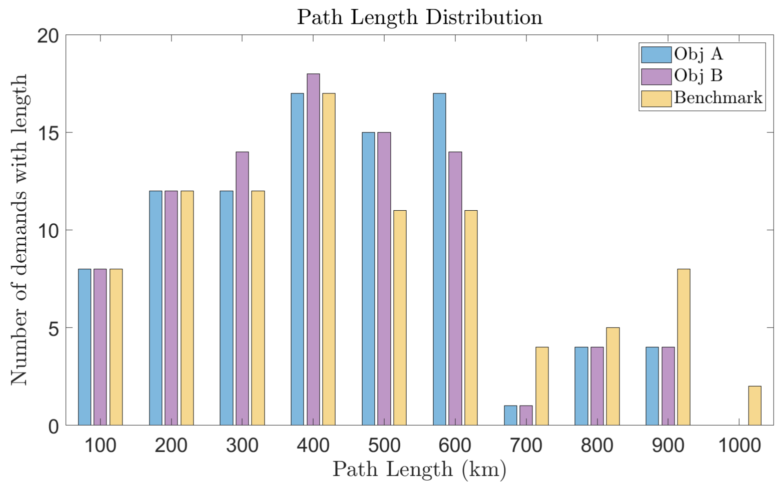


Figure 3: Path Length Distribution

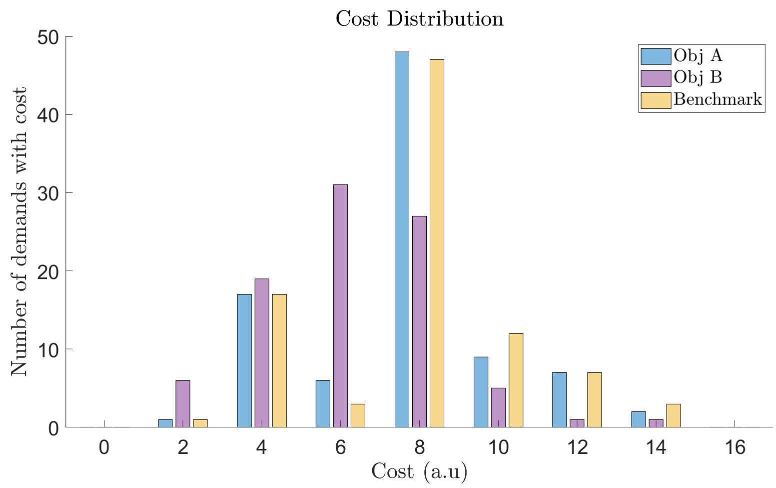


Figure 4: Cost Distribution

4.1 Difference between matrices and topologies and demand order

Thus far the results have been shown for a single demand matrix on the Italian topology. The conclusions from these results hold for all of the matrices but some interesting findings is worth sharing separately. One interesting trend that can be seen for a couple of metrics in Fig. 5 is that for lower demand all objectives and benchmarks converged. So for low demand all the RMSA algorithms had very similar performance. This is easily explained by the low demand of rate, for the rates in matrix 1 they were of the order 100-400 Gbps. With this range of demands the algorithms will choose similar modulation which result in similar metrics, the spectrum will also fill up slower and therefore the algorithms will most likely always assign spectrum on the first path in the priority list, resulting in similar performance.

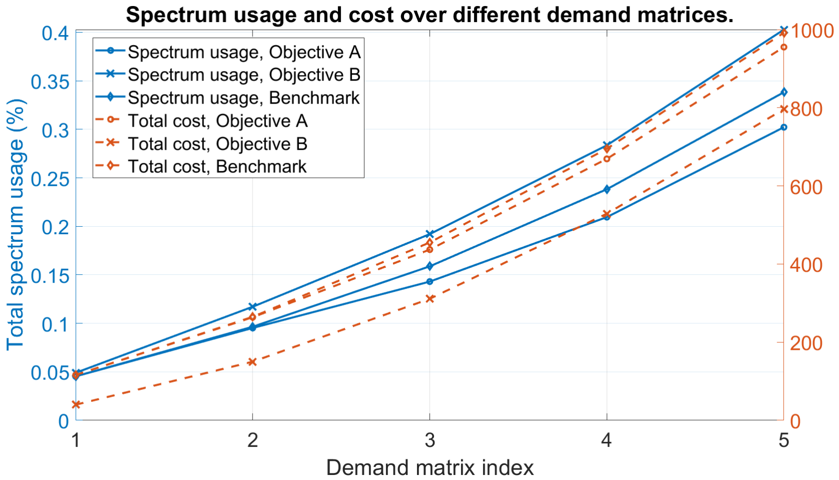


Figure 5: Spectrum usage and total cost over different demand matrices on the Italian topology.

Different metrics were analysed when comparing the impact of using descending or ascending order on the demand matrices, most times the results were the same. One of these tests was the index of the highest FSU on a link and the average, plotted over demand matrix index, can be found in Fig.6. The only noteworthy difference is with the benchmark where for the lower demand ascending and descending order differed before they converged for higher demand matrices. Concluded is that the ascending or descending order did not effect performance in the any significant way as expected, instead the results stayed relatively constant over the two methods.

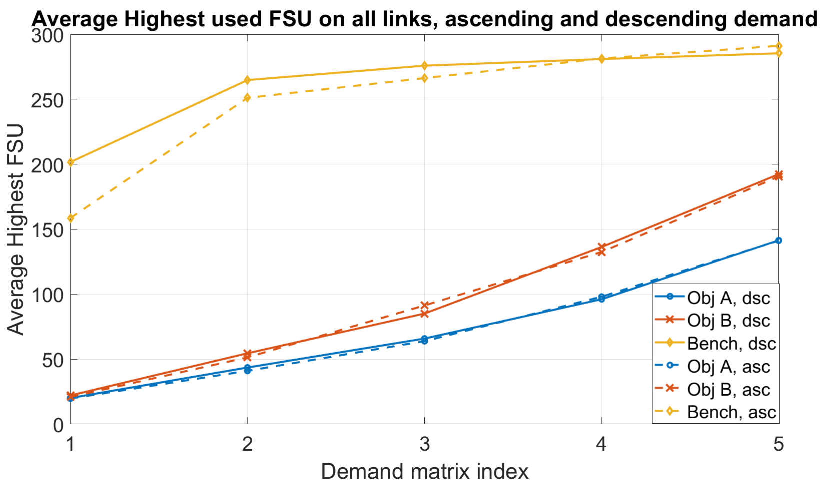


Figure 6: The average highest FSU index over all the link, for the Italian topology.

4.2 Differences between topologies

In general for the german topology all RMSA algorithms behaved similarly from the link usage distribution in Fig. 7 we see that the objective B still uses more spectrum but objective A and the benchmark are equal in their spectrum and link usage. The utilisation entropy between objective A and the benchmark is however different which can be seen in Table. 3 where the UE is much lower for Objective A than the benchmark. So the algorithms fill the spectrum differently even though the fill the same number of slots. The smaller differences in the German topology is believed to be because of the topology in general being smaller and that it have fewer links, resulting in less diversity in paths. The average path length for the German topology is around 365 while for the Italian one it is 432. This would result in more frequent usage of higher order modulation for the German topology and likely lead to similarities between the assignment methods.

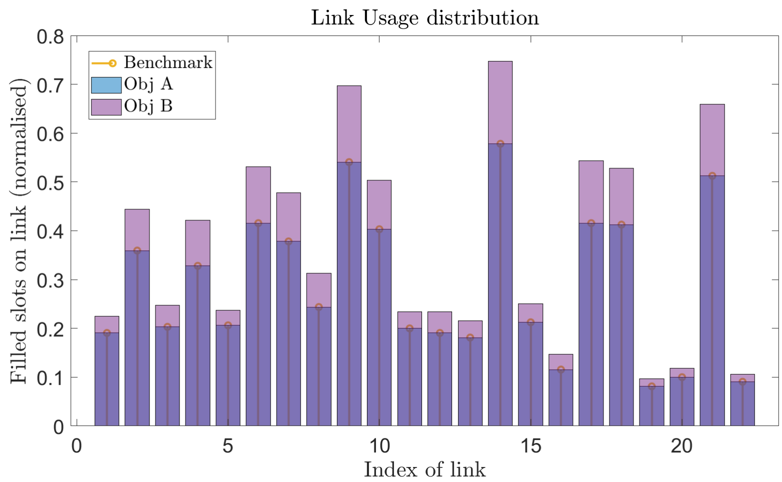


Figure 7: Link usage for the German topology with demand matrix 5.

Metric	Objective A	Objective B	Benchmark
Total spectrum usage	0.4786	0.5326	0.4786
Number of used FSUs	2035	2553	2035
Highest used FSU	192	246	246
Average Utilisation Entropy (UE)	0.0080	0.0080	0.0159
Average Shannon Entropy (SE)	0.8437	0.9235	1.3960
Total cost	840.5	774.4	840.5

Table 3: Metrics with the German topology and demand matrix 5.

4.3 1+1 Dedicated Path Protection

A protection method can be classified as dedicated protection or shared protection depending on whether sharing of network resources is permitted. This kind of security is quite easy to set up, and it behaves predictably. Traffic is sent simultaneously on two different fibers from the source to the destination using the 1+1 dedicated route protection mechanism. No common resource is shared by many protective pathways (such as a fiber line). The failure and activation of one

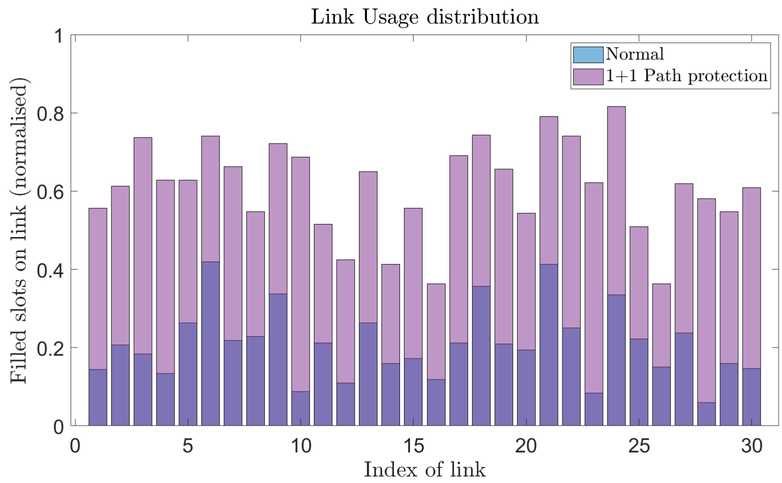


Figure 8: Link Usage Distribution

protection path have no effect on any other protection path when using dedicated protection.

For 1+1 path protection we mainly compared the results of objective A and the corresponding RMSA solution to not make the comparison to broad. The general results for the implementation of 1+1 path protection is that it is costly on the network. The link usage in Fig. 8 shows that the spectrum usage on each link increases drastically, which is expected for the demand is doubled. The path length distrubution is shown in Figure 9. With the path length we see that the mean length of a path increases. This is reasonable because the alternative paths that share no links with main path will naturally be much longer. Taking a look at the cost, the algorithm performs a cost of 669.2 without path protection and 1404.3 with the path protection. As it can be seen from the numbers, path protection mechanism increases the cost, however also provides a more reliable network to failures.

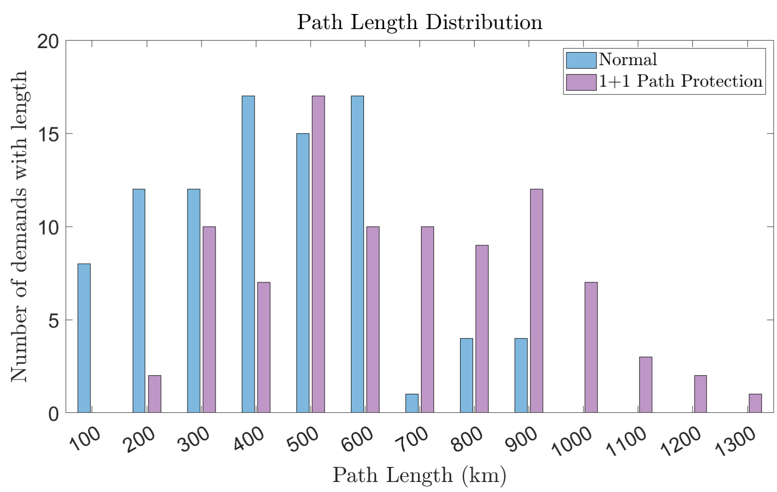


Figure 9: Path length distribution

4.4 Problematic matrices and combinations

Interesting results are that for certain combinations of demand matrix, routing and spectrum assignment the scripts crash. The crashes are a result of certain links being full and therefore certain demands can not be assigned. This typically happens with the benchmarking algorithm for high demand if the algorithm would be path protected. Typically this was not a problem with the seperatly developed RMSA algorithms which shows one weakness of fixed shortest path instead of a K-shortest path alternative.

5 Conclusion

In this report different RMSA algorithms have been compared where each algorithm had its own objectives to optimise, total spectrum usage and total transponder cost. Both algorithms were based on K-shortest paths and a modified first fit spectrum assignment. The algorithms succeeded in their respective objective when compared to a benchmarking RMSA. Concluded is that an optimised spectrum usage often results in more expensive hardware and if the demanded traffic is high this might be needed but for lower demand cheaper transponders with a less optimised spectrum works well. Allowing for more FSUs in the network according to the cost objective also improved metrics such as utilisation entropy and Shannon entropy, which is believed to be a result of more FSUs that create a less sporadic link spectrum. K-shortest paths was further more effective than fixed and gave a bit of redundancy to the system which made it easier to optimise either total spectrum or the cost. 1+1 Path protection set a heavy load on the network and only works for lower demand matrices but is a valid approach if you can afford the higher costs and higher load on the network.

6 Reflection on Group Work

The group members had different reflections about the given objectives. That helped the members to discuss their understandings and learn more about the details. In the early stages of the project, members were not speaking too much about the ideas but as things became clearer, members did not hesitate to speak out.

The project definitely helped members to understand more about the lectures, deepened their knowledge of the network design.

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7 Appendix

7.1 A1

Link index	Source node	Sink node
1	1	2
2	1	3
3	1	7
4	2	1
5	2	4
6	2	7
7	3	1
8	3	5
9	4	2
10	4	8
11	5	3
12	5	6
13	5	6
14	6	5
15	6	7
16	6	9
17	7	1
18	7	2
19	7	5
20	7	6
21	7	8
22	7	9
23	8	4
24	8	7
25	8	10
26	9	6
27	9	7
28	9	10
29	10	8
30	10	9

Table 4: Link indexes and the corresponding source and sink node for each link.