Project assignment EEN115

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The project is focused on the problem of the design and dimensioning of optical communication network infrastructure. The students will be investigating the routing, modulation, and spectrum assignment (RMSA) problem in optical networks. Different approaches to RMSA, and an analysis of the trade-offs to the different performance parameters of interest is at the heart of this project.

Routing, modulation format and spectrum assignment (RMSA)

RMSA is one of the fundamental problems in network design. The problem can be described as follows:

- **Inputs.** There are two inputs to the static version of the problem, which will be considered in this project:
    - The physical network infrastructure, comprising a set of nodes and links. Each link has a finite capacity, that may be divided into frequency slots of fixed or varying size. If the fiber bandwidth is divided into fixed slots of, typically, 100 GHz width, we are considering a so-called fixed spectrum grid. In the second variant, called flex-grid or elastic optical networks, which we consider in this project, the spectrum is divided into smaller-sized frequency slot units (FSUs), e.g., each 12.5 GHz.
    - The set of communication requests. Each request is characterized by a source and one or multiple destinations, as well as the requested traffic volume. In addition, the service class may also be associated to each service (e.g., priority, type of resilience mechanism, connection availability requirements expressed in terms of maximum allowable yearly down time, etc.).
- **Outputs**. To solve the RMSA problem, each communication request must be assigned a physical path through the network, as well as appropriate spectral resources. The service requirements need to be satisfied through, e.g., allocation of backup paths to ensure resilience.
- **Objective**. The RMSA process is typically aimed at minimizing the network resource usage. This can be modelled by minimizing, e.g., the total number of used FSUs in the network, or the highest index of FSUs used on any link in the network (assuming the available FSUs are indexed, and spectrum allocation always starts from the lowest indexed FSU).
- **Constraints**. When assigning spectrum to individual connections, the following constraints must hold:
    - *Spectrum continuity constraint*: the same spectrum slots must be assigned to a connection on all the links included in its physical path
    - *Spectrum contiguity constraint*: the spectrum slots assigned to a connection must be contiguous (i.e., adjacent).

- *Spectrum clash constraint*: if two or more connections share the same fiber (modeled as a common directed physical link), they cannot use overlapping spectrum slots.

Heuristic algorithms for RMSA

The constraints related to spectrum usage make the RMSA problem highly complex. The problem belongs to the NP-complete class of combinatorial problems. To address this, there exist many different approaches to solving this problem. These approaches include integer linear programming (ILP) models that can find optimal solutions for smaller problem instances but suffer from excessive complexity and cannot be solved in reasonable time for problem instances of realistic sizes. Approaches based on heuristic algorithms can find good-quality solutions in reasonable time. The simplest form of heuristic algorithms is called greedy algorithms. They build the final solution incrementally (e.g., processing one communication request at a time) and (*greedily*) select the best solution at the current step. Other algorithms may work in an iterative way by constructive multiple complete solutions to the problem, evaluating their quality and possibly further improving these solutions in subsequent steps.

The heuristic algorithms may also perform RMSA jointly or sequentially:

- **Joint RMSA**: route, modulation format and spectrum are assigned to each connection request before moving on to process the next request until all requests are processed.
- **Sequential RMSA**: routing and spectrum assignment are assigned to all requests in two separate phases. For example, all requests are first routed, then they are assigned the modulation format and after that this solution is forwarded to the SA phase where spectrum is assigned to the entire batch of requests.

RMSA often entails trade-offs between different performance metrics and solution qualities. Some of these trade-offs are well known in the literature, while others are less studied. For example, routing strategies that don’t use the shortest path result with longer paths, but may have a beneficial effect on the spectrum usage.

Some of the well-known routing strategies from the literature include:

- Fixed shortest path routing
- Alternative (K-shortest) path routing
  - Least-loaded routing
  - Highest-loaded routing
- Adaptive routing
- Random routing

Some of the well-known spectrum assignment strategies from the literature include:

- First Fit
- Best Fit
- Least used
- Most used
- Last Fit

The assignment

Each project group needs to perform the following tasks. For the given network topology instances and traffic demand matrices, use different strategies to solve the RMSA, analyse the impact and report on the findings.

Table 1 Group assignment specification

<table>
<tr><th>Group number</th><th>Optimization objective A</th><th>Optimization objective B</th><th>Performance parameters of interest</th><th>Benchmarking algorithm</th></tr>
<tr><td>1</td><td>Maximum used FSU</td><td>Minimize the path length</td><td rowspan="8">Highest used FSU on any link
Total number of used FSUs
Link usage distribution
Path length distribution
Distribution of transponder cost
Spectrum fragmentation metrics: utilization entropy and Shannon entropy</td><td>Fixed shortest path + First Fit SA</td></tr>
<tr><td>2</td><td>Total spectrum usage</td><td>Minimize the maximum link load</td><td>Fixed shortest path + First Fit SA</td></tr>
<tr><td>3</td><td>Maximum used FSU</td><td>Minimize the difference between the load on the highest and least loaded link</td><td>Fixed shortest path + First Fit SA</td></tr>
<tr><td>4</td><td>Total spectrum usage</td><td>Minimize Shannon entropy</td><td>Fixed shortest path + First Fit SA</td></tr>
<tr><td>5</td><td>Maximum used FSU</td><td>Minimize the average link load</td><td>Fixed shortest path + Least Used SA</td></tr>
<tr><td>6</td><td>Total spectrum usage</td><td>Minimize the difference between the longest and the shortest path lengths</td><td>Fixed shortest path + Least Used SA</td></tr>
<tr><td>7</td><td>Maximum used FSU</td><td>Minimize utilization entropy</td><td>Fixed shortest path + Least Used SA</td></tr>
<tr><td>8</td><td>Total spectrum usage</td><td>Minimize the transponder cost</td><td>Fixed shortest path + Least Used SA</td></tr>
</table>

1) Implement an RMSA algorithm of your own design, with the optimization objective A given in Table 1. Run the algorithm for the given problem instances. Analyze and present the performance of the network in terms of the parameters of interest specified in the table.
2) Modify your algorithm to consider the optimization objective B specified in Table 1. Analyze and present how the network performance in terms of the same parameters of interest has changed when objective B is considered instead of A.
3) Implement the benchmarking algorithm specified in Table 1. Perform a comparative analysis of the benchmarking algorithm vs your own designed algorithm for optimization objectives A and B).
4) Extend your designed algorithm to consider 1+1 dedicated path protection. Evaluate the impact of protection in terms of the network resource consumption.

Given:

- Two topologies, 7-node German and 10-node Italian topology are given in the text files. You should consider the fourth and fifth columns of the files as sources and destinations, respectively. The sixth column shows the length of the link (km).

- The realistic traffic matrixes are given for 5 different loads for each topology in the text files (the unit is 10 Gbps). Sort the traffic demands in ascending and descending order based on their size, and report simulation for both scenarios.
- Consider the number of paths for all scenarios as K=5.
- The number of available slots is 320. We assume 12.5 GHz slot width.
- Modulation formats are described in the Table 2 below.

Table 2 Modulation formats

Modulation format	Line rate (Gbps)	Channel Bandwidth (GHz)	Maximum length (km)	Cost (a.u.)
Dual Polarization Quadrature Phase Shift Keying (DP-QPSK)	100	50	2000	1.5
Single Carrier Dual Polarization Quadrature Phase Shift Keying (SC-DP-QPSK)	100	37.5	2000	1.5
Single Carrier Dual Polarization 16 Quadrature Amplitude Modulation (SC-DP-16QAM)	200	37.5	700	2
Dual Polarization 16 Quadrature Amplitude Modulation (DP-16QAM)	400	75	500	3.7

The project comprises of the following deliverables, deadlines and scores:

Assignment	Due date	Assessment type	Points
Team agreement	Optional	None	
Planning report (1 per group)	February 6	Peer review	5
Peer review of the planning report (individual)	February 10	Teacher & TA	Pass/Fail
Half-way progress report (1 per group)	February 19	Peer review	5
Peer review of the planning report (individual)	February 24	Teacher & TA	Pass/Fail
Final report + code submission (1 per group)	March 3	Teacher & TA	15
Final presentation in class (1 per group)	March 7	Teacher & TA	5

Literature

The definition of fragmentation metrics can be found in this paper and the references cited therein:

M. Quagliotti et al. SPECTRUM FRAGMENTATION METRICS AND THEIR USE IN OPTICAL CHANNEL ALLOCATION ALGORITHMS
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8362033

The values for the modulation formats can be found in this paper:

E. Archambault et al. Routing and Spectrum Assignment in Elastic Filterless Optical Networks
https://ieeexplore.ieee.org/document/7423798