BMBF Project ROBUKOM: Robust Communication Networks

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I. Introduction

The cost-effective operation of communication networks requires a network planning and network configuration, which takes into account the temporal and spatial variations in traffic, the complex architecture and the functional behavior of modern communication technologies and protocols, and, last but not least, the requirement for high network availability. Until recently, there was neither practical mathematical models nor satisfactory algorithmic approaches to tackle these increasingly complex optimization problems. New mathematical concepts, such as the methodology of robust optimization [1], [2] or convex formulations for problems with chance constraints [3], are promising approaches to address the traffic fluctuations. Major challenges also arise from the interaction of different aspects of the problem, such as the simultaneous failure of multiple connections in multi-layered network architectures caused by a single hardware failure. A particular difficulty in this case constitutes the high dimensional problem, which arises from the combination of all these aspects in networks of realistic size. One way to master this challenge is the appropriate combination of different methodological approaches, such as the combination of combinatorial approximation algorithms with exact procedures or the adaptive coupling of models with different levels of accuracy.

Within the BMBF joint project ROBUKOM (part of the program "Mathematics for Innovations in Industry and Services") novel and practical mathematical methods for the planning of robust communications networks are being developed. From a mathematical and methodological point of view the following topics are addressed:

- Combinatorial and polyhedral models to account for traffic fluctuations (project 1)
- Non-linear mixed-integer chance-constraint models to account for traffic fluctuations (project 2)
- Scalable, adaptive models and methods for optimization of traffic flows in accordance with the routing protocols and resiliency requirements (project 3)
- Combinatorial and approximation algorithms and their integration into exact optimization methods for designing multi-layer resilient networks (project 4)
- Modelling and optimization of novel multi-layer and multi-technology network scenarios (project 5)

In the following, results of these five subprojects are briefly discussed.

II. Project 1: Robust Network Design under Demand Uncertainties

In this project, the design of a single layer network under demand uncertainty is studied. The basic problem studied in both project 1 and 2 can be modelled as chance constrained optimization problem as follows. Let $G = (V, E)$ be a graph representing the network. For every pair of vertices $s, t \in V$, the random variable (in the sense of stochastics) d^{st} denotes the traffic volume to be routed from s to t. For simplicity, the traffic can be splitted by any means across paths between s and t. Capacity can be provided on the edges $ij \in E$ in discrete amounts C at a cost of k_{ij}.

Let $f_{ij}^{st} \geq 0$ be *flow* variables describing the percentage of traffic between $s \in V$ and $t \in V$ routed along arc $(i, j) \in A$. Further, let $x_{ij} \in \mathbb{Z}^+$ denote the capacity variables and $\eta \in [0, 1]$ (z.B. $\eta = 0.995$) a probability level. Then the problem can be formulated as:

$$\min \sum_{ij \in E} k_{ij} x_{ij} \tag{1}$$

$$s.t. \sum_{j \in \delta(i)} (f_{ij}^{st} - f_{ji}^{st}) = \begin{cases} 1 & i = s, \\ -1 & i = t, \\ 0 & \text{otherwise} \end{cases} \quad \forall s, t, i \in V \tag{2}$$

$$\mathbb{P}\left(\sum_{s,t \in V} d^{st}(f_{ij}^{st} + f_{ji}^{st}) \leq C x_{ij} \right) \geq \eta \; \forall \{i, j\} \in E \tag{3}$$

$$f_{ij}^{st} \in [0, 1], x_{ij} \in \mathbb{Z}^+ \tag{4}$$

The essential difference with classical network design models is the chance-constraint (3), which, depending on the probability distribution of d yields to difficult problems, even if no integrality of x is required.

The goal of project 1 is to transform the chance constraints (3) in such a way that the problem can be solved by integer linear programming techniques. In [4]–[7] the approach of Bertsimas and Sim [1], [2] is followed, yielding cost savings compared to maximum demand planning, without losing the robustness of the network. An extension of the Bertsimas and Sim approach is developed in conjunction with project 4 [8].

III. Project 2: Convex Chance-Constrained Models for Robust Communication Networks

In this project, a similar problem as in Project 1 is treated (single-layer design of IP networks under traffic uncertainty). However, here is another mathematical modeling of demand uncertainty stands in the foreground. The chance-constraints are reformulated as second-order cone constraints [9], yielding a mixed integer nonlinear model.

IV. Project 3: Scalable Optimization Methods for Survivable IP-Networks

Project 3 focuses on the development of practical methods available for route optimization in IP networks. The mathematical optimization formulations not only model the behaviour of the routing protocols used in IP networks in normal situations, but also in case of link and node failures in the optical layer.

Further, in conjunction with project 4, the problem of migrating a network from one technology to another is studied. During the operation of large telecommunication networks, it is sometimes necessary to replace components in a big part of a network. Since a network resource, such as a router or an optical fiber cable, is usually in shared use by several connections, all of these connections will have to be shut down while the component is being replaced. Since the number of workers that perform the upgrade is limited, not all of the affected connections can be upgraded at the same time, and disruptions of service cannot be avoided. The goal is to schedule the replacement of the fibers in such a way, that the number of workers necessary in each period of the discretized planning horizon does not exceed the given budget, and the sum of all connections' disruption times is minimized. This problem is provided by DFN Verein [10] and first results are forthcoming.

V. Project 4: Efficient Algorithms for Survivable Multi-Layer Networks

Project 4 primarily deals with the integrated planning of multi-layer networks with failure safety requirements. The network design should be able to survive (regarding prespecified quality of service requirements) the failure of optical fibers, routers, or transponders. In a second step, the results of Project 3 are combined with those of Project 4, to enable an integrated topology, capacity, and route optimization for IP-over-WDM networks. More information on the topics studied in project 3 and 4 can be found in [11].

VI. Project 5: Robust Design of IP-Networks with Multiple Transport-Technologies

In Project 5 the cost-efficient design of robust multilayer networks under traffic uncertainty is considered, with special attention directed to the question in which layer IP traffic can be routed the cheapest. Currently, a mixed-integer linear programming approach for a multi-layer network design problem under traffic demand uncertainty is studied. This problem arises in the planning of IP (Internet Protocol) based networks, where the IP routers are interconnected by logical links that are paths in an underlying transport network. The transport network in turn might consist of different layers and technologies, e.g., an OTN layer (with electrical switching capability on ODU granularity) and a DWDM layer (with pure optical switching capability on wavelength granularity) which allows for optimum grooming and layer bypassing. Demand uncertainty results from daytime usage fluctuations, user behavior and external effects like BGP route flapping or server load balancing mechanisms. The work is based on modifications of the robust optimization approach of Bertsimas and Sim [1], [2] and the *Path over Path* concept for multi-layer planning [12]. Contrary to existing approaches the model considers multi-path routing, traffic grooming and layer skipping in parallel.

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