Keywords – Multi-Layer Networks, Mathematical Programming, Computational Study

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MULTI-LAYER NETWORK DESIGN
A MODEL-BASED OPTIMIZATION APPROACH

In this paper, we present a model-based optimization approach for the design of multi-layer networks. The proposed framework is based on a series of increasingly abstract models – from a general technical system model to a problem specific mathematical model – which are used in a planning cycle to optimize the multi-layer networks. In a case study we show how central design questions for an IP-over-WDM network architecture can be answered using this approach. Based on reference networks from the German research project EIBONE, we investigate the influence of various planning parameters on the total design cost. This includes a comparison of point-to-point vs. transparent optical layer architectures, different traffic distributions, and the use of PoS vs. Ethernet interfaces.

1. INTRODUCTION

Our economy is increasingly dependent on reliable access to high-quality broadband services at reasonable cost. Network and service providers face the challenge of offering their services at a competitive price while still being profitable. This calls for innovative network planning methods and optimization tools. To this end, we present a so-called *model-based optimization cycle*, which has been developed in the German research project EIBONE – a cooperative project combing the expertise of operators, like Deutsche Telekom, system vendors, like Alcatel-Lucent, Ericsson, and Nokia Siemens Networks, together with small and medium enterprises, universities, and research institutes.

The proposed framework is based on models with increasing abstraction levels – starting from a detailed *system model* including specifications for the hardware, demand, cost, and network, using an *optimization model* which describes the planning requirements of a particular use-case in a technology independent way, and eventually applying and solving *mathematical models* (mixed-integer programs) to perform an end-to-end optimization of a network design. This approach has the competitive advantage that it is based on a network and system description as it could be stored in the

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[3]This work has been supported by the German research project "EIBONE – efficient integrated backbone"

databases of a network operator and that it uses – albeit the high complexity of today's advanced technology described in the system model – sophisticated mathematical solution methods to compute proven low cost network designs. All results are analyzed and compared on system level.

This framework of increasingly abstract models lays the foundation for solving almost any kind of multi-layer network planning problem. It provides the basis for detailed techno-economic studies, which help to better understand the business implications of technical constraints as well as cost and traffic assumptions. For a network operator, such studies are indispensable for sound long-term decisions about the network architecture or the hardware vendor. Our framework also supports EIBONE partners in other planning tasks for multi-layer NGNs, ranging from tactical expansion planning to reconfiguration tasks to improve the link utilization.

To demonstrate the effectiveness of the approach, we show in a case study how central design questions for an IP-over-WDM network architecture can be answered using our framework. Based on reference networks from the German research project EIBONE we investigate the influence of various planning parameters on the total design cost. The questions addressed in the study are:

- How big are the potential savings by using a more complex transparent optical layer – allowing for ROADMs and OXCs with full optical switching capabilities – compared to a much simpler point-to-point WDM network?
- How big is the influence of the traffic distribution on the optimal network layout and cost? Even for the same total traffic demand, demand predictions stemming from network measurements or from population based geographical traffic models may lead to substantial differences.
- How big is the influence of using more intelligent but also more expensive STM16- and STM64-PoS-interfaces instead of 10Gbit-Ethernet interfaces?

This paper is organized as follows. The overall model-based optimization cycle is presented in Section 2. The different models and some of the transformations are explained. Section 3 is dedicated to the computational case study. We describe the data used in the study and report on the computational results. Eventually, Section 4 provides our conclusion.

2. PLANNING CYCLE

The model-based optimization cycle developed within EIBONE with its three abstraction levels is shown in Figure 1. The specification of a **system model** as a vendor independent *XML-format* has been carried out. It incorporates models of the different hardware, technology layers, cost, and traffic models. It is designed to allow an adequate description of today's as well as tomorrow's multi-layer networks. It facilitates both the mere exchange of data as well as benchmarking all possible aspects within a planning process. Within EIBONE, three reference networks (two German and one US scenario) have been encoded using this XML-format. Together with the different cost and traffic models, these reference networks provide the basis for benchmarking different solution approaches and planning scenarios.

Optimization models, as considered in EIBONE, represent specific planning tasks such as architecture decisions, capacity expansion, or (dynamic) reconfiguration problems in multi-layer transport networks. These optimization problems abstract from the very detailed technological view of the system model to a problem specific view focusing on the functionalities, restrictions, and decisions relevant for the given planning task. The Survivable Network Design data library (SNDlib [9]) can be

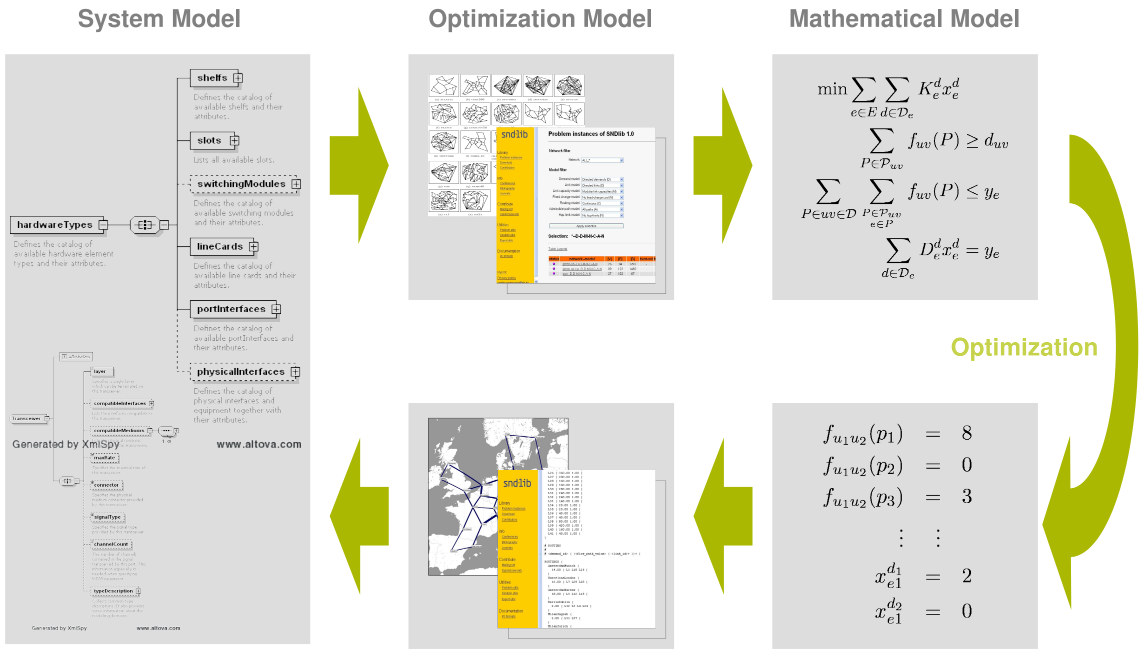


Figure 1: Model-based optimization cycle

considered as a representative of this abstraction level. SNDlib has been compiled out of real-world data from network operators and data stemming from other research projects such as NOBEL [2] and is used by many researchers as a basis for benchmarking their solution approaches by now. The data of SNDlib does not contain information about the particular technological background. It cannot be seen, for instance, whether the links are logical connections between IP routers, whether the link cost includes physical transmission cost, or whether the link capacities are based on ATM, SDH, or Ethernet port capacities. Similarly, we have been developing optimization models which represent the structure of multi-layer networks, including a demand layer, a logical layer and a physical layer. This layering is not coupled with a particular network architecture such as IP-over-OTH, or IP-over-WDM.

Mathematical models and all kinds of algorithmic solution methodologies are used to address the planning problems described by the optimization models. Within EIBONE, two principle approaches have been combined:

- Exact solution methods based on mixed-integer linear programming (MILP) either find a provable optimal solution or a solution within a specified quality guarantee. The running time to close the gap and to prove optimality might increase significantly with the size of the network. Within EIBONE, the efficiency of these methods has been improved through a number of investigations of the underlying fundamental mathematical structure of the problem [7, 10, 11].

- With the second methodology approximate solutions are computed by means of combinatorial heuristics. These can be designed to easily take into account also very special planning requirements and they usually scale better with the size of the network. Heuristics, however, do not provide quality guarantees for the solutions they produce.

Combinations of these two seemingly opposing approaches proved to be very efficient in practice. Heuristics have been integrated into state-of-the-art MILP-solvers to find good quality solutions faster and MILP-based algorithms have been designed to optimally solve critical sub-problems [8].

To close the optimization cycle, transformations are carried out to map the pure mathematical solution to a solution of the considered optimization model and eventually back to a network configuration satisfying the planning task and respecting the hardware and traffic requirements described in the system model. All necessary transformations in the optimization cycle are implemented in Java and fully automated. Network costs are evaluated on system level. The resulting network configuration can be considered to be (close) to optimal with respect to the given cost-model.

3. COMPUTATIONAL STUDY

In this section we present a computational study which is performed using the described model-based optimization cycle. The goal is to give answers to the questions raised in the introduction: the influence of (i) a transparent vs. an opaque optical layer, (ii) the traffic distribution, and (iii) PoS vs. Ethernet interface cards in the IP router.

3.1. NETWORK DATA AND MODELS

We compared two different architectures which differ with respect to cross-connecting channels in the optical layer. Both are an IP-over-WDM architecture. The hardware involved in both alternatives

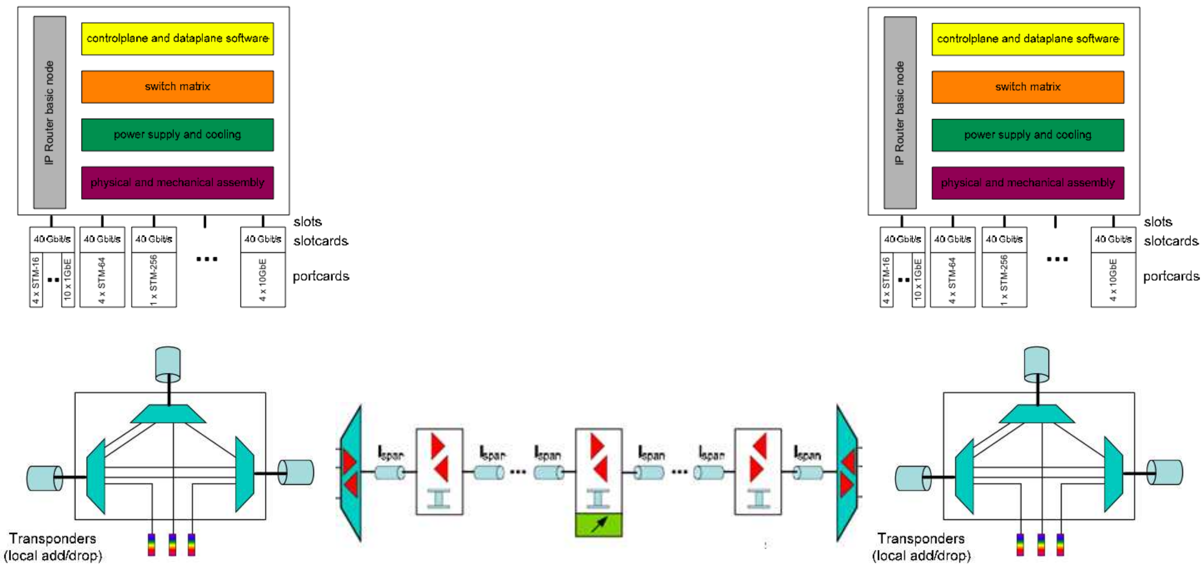


Figure 2: IP layer over WDM layer (Source: NOBEL hardware and cost model [6])

is depicted in Figure 2. In the IP layer, routers are considered having a switching matrix as a central element and slots for slot-cards. The latter host the port-cards which eventually provide capacitated link interfaces. In the WDM layer, the physical link equipment comprises DCFs, DGEs, and OLAs. One WDM-MUX at each end terminates a physical link. For the transparent architecture ROADMs and OXCs can be installed at every node to arbitrarily switch the optical channels, which is not allowed in the point-to-point (opaque) scenario.

Cost values for equipment are based on the NOBEL cost model [6]. The possible capacities at the IP layer nodes range from 640 Gbit/s to 5760 Gbit/s. The cost for the smallest installable router is 16.67, the next larger has a cost of 111.67 which is about 7 times more expensive. The largest one comes at a cost of 315.83. Furthermore, slot-cards, which host the port-cards, are relatively expensive.

It can be seen that the 4xPoS-STM64-SR port-card costs with 18.33 much more than the 4x10GbE-LR port-card with 4.20. The normalizing element in the NOBEL model is the 10G-LH transponder at a cost of 1. The cost of ROADMs and OXCs is about 10, with a degree dependent component. For details, the reader is referred to [6]. The study is performed on:

- the physical (fiber) topology with 50 locations shown in Figure 3, and
- a subset of 17 locations (highlighted in Figure 3) being the traffic sources and the only locations where it is admissible (and mandatory) to install IP router equipment.

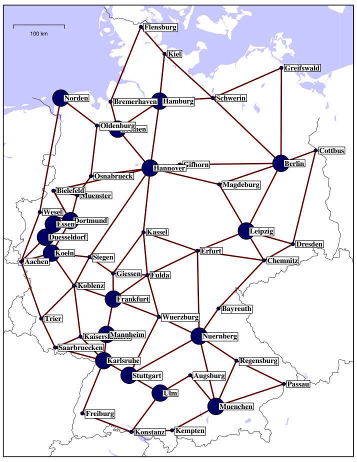


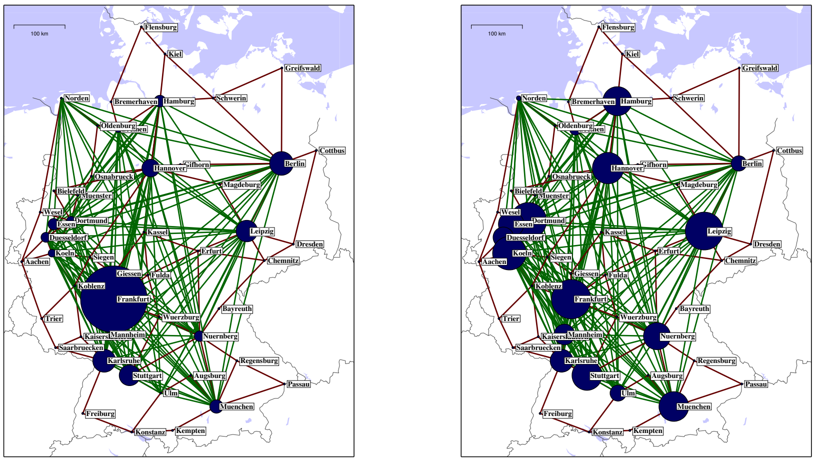
Figure 3: Germany17 over Germany50 reference network

Two types of traffic models are used to create point-to-point traffic matrices, where each of the 17 IP-nodes is a traffic source:

- POP: Dwivedi-Wagner [5], which distributes the traffic classes Voice, Business, and IP dependent on the number of inhabitants, households, and employees. The influence of the distance on the traffic between two locations is highest for Voice and lowest for IP traffic.
- DFN: Measurements of the DFN-Verein [1], which were carried out in 2006 in 5 minute intervals. The measurements over a day, the peak hour over a month, and a year have been used to generate a single point-to-point traffic matrix.

Two traffic matrices have been generated for both models: one with a total traffic volume of 3 Tbit/s (short: 3T) and one with 6 Tbit/s (short: 6T). No survivability constraints have been added for this study. In Figure 4 it can be seen that the traffic is more evenly distributed for Dwivedi-Wagner and that Frankfurt, in particular, is the dominating traffic source for the DFN measurements. It is important to note that the DFN traffic demands reach the limits of the considered router technology, due to its high concentration around Frankfurt. Already for a total traffic volume of 3T it is necessary to install a router with a capacity of 3840 Gbit/s in Frankfurt. There is no feasible network configuration for a total traffic volume of 6T with the DFN traffic distribution, because no router could handle the traffic volumes at the node Frankfurt.

All data (hardware, cost, traffic) has been specified within the system-model. Two optimization models have been defined (one for each considered architecture) that describe abstract two-layer network design problems with discrete capacities for links and nodes of both layers. By introducing



(a) DFN measurements

(b) Dwivedi-Wagner

Figure 4: Source traffic distribution

discrete variables and linear inequalities describing all problem constraints in terms of these variables the optimization models have been formulated as MILPs. See Appendix A for a detailed description of the mathematical models. The MILPs have been solved using the general-purpose solver SCIP 1.0 [3, 4]. To accelerate its performance and to improve solutions and lower bounds several problem-specific preprocessing and cutting plane procedures as well as heuristics have been applied in addition. For theoretical and implementational details on these auxiliary methodologies and plug-ins the reader is referred to [7, 8, 10].

All computations have been carried out on an Intel Core 2 Quad 2.66GHz machine with 4 GB main memory. The total running time for a single optimization has been restricted to 60 minutes. It is noticeable that the average gap (proven quality of the result as the relative difference between the solution cost and a mathematically proven lower bound to this cost) has been 2.5 percent, with a maximum of 8.0 percent.

3.2. TRANSPARENT VERSUS OPAQUE OPTICAL LAYER

In the first study, we investigated how big the cost savings are if it is allowed to use full switching capabilities in the optical layer, compared to classical point-to-point WDM links. For this purpose we computed for both architecture alternatives the network configurations for both demand matrices and for the two total traffic volumes 3T and 6T. The resulting costs are shown in Table 1. As expected, the transparent architecture is always more cost-efficient than its point-to-point counterpart: The savings range between 8.31 and 17.53 percent with an average of 12.48 percent.

For the instance POP-3T-ETH we looked into more details. Surprisingly, 76.1 Percent of the savings are WDM savings (WDM-MUX and Medium), only 25% of savings occur in the IP layer. It is also noticeable that in the point-to-point scenario 75 physical and logical links are used with an average of 1.52 IP/WDM hops per IP demand, while for the transparent scenario, 97 logical links and 25 physical links are used with an average of 4.3 WDM hops per IP link and 1.3 IP hops and 6 WDM hops per IP demand. These values show that the reduction of IP hops per IP demand is minimal and, hence, there are almost no savings in the IP layer for the transparent scenario.

Scenario	Point2Point	Transparent	Savings
DFN-3T-ETH	5819.82	5268.80	9.47%
POP-3T-ETH	6838.73	5639.73	17.53%
POP-6T-ETH	11359.24	9879.98	13.02%
DFN-3T-PoS	7316.29	6708.54	8.31%
POP-3T-PoS	8455.67	7110.41	15.91%
POP-6T-PoS	14134.81	12626.63	10.67%
		Average:	12.48%

Table 1: Cost comparison of point-to-point vs. transparent optical layer

3.3. POS- VERSUS ETH-PORTCARDS IN THE IP-LAYER

The NOBEL hardware and cost model allows to install either PoS- or GbE-interface at IP routers. As already mentioned, the 4xPoS-STM64-SR port-card costs with 18.33 much more than the 4x10GbE-LR port-card with 4.20. This raises the following questions: What is the effect of this cost difference on the overall design of the network and how much more expensive is a design using PoS interfaces? The results of allowing PoS-interfaces only (PoS) and GbE-interfaces only (ETH) are shown in Table 2. As expected, there is a significant increase when using the PoS-interfaces. However, we have

Scenario	PoS	ETH	Savings
DFN-P2P-3T	7346.63	5819.82	20.78%
DFN-TRANS-3T	6708.54	5268.80	21.46%
POP-P2P-3T	8455.67	6838.73	19.12%
POP-TRANS-3T	7110.41	5639.73	20.68%
POP-P2P-6T	14157.73	11359.24	19.77%
POP-TRANS-6T	12626.63	9879.98	21.75%
		Average:	20.59%

Table 2: Cost comparison of PoS- and GbE-interfaces

not encountered any big change in the logical or physical topologies. Both architectures use about the same number of logical and physical links with similar capacities. When comparing the total cost of the PoS-interfaces with the total cost of the GbE-interfaces it can be observed that this difference is almost identical to the difference of the total network cost.

3.4. POPULATION BASED VERSUS CENTRALIZED TRAFFIC DEMANDS

In the last part of the study, two very different distributions of the same amount of total traffic have been generated in order to investigate their influence on the architecture and cost of the networks. As described above, the first one is based on measurements in the German national research and education network (DFN) which is operated by the DFN-Verein, and the second one is based on a population model (POP) suggested by Dwivedi-Wagner [5]. The DFN traffic demands have a higher concentration than the traffic demands stemming from the population model. The emanating demand at node Frankfurt is much higher in the DFN scenario than in the population scenario, while the emanating demands at the other nodes are smaller in the DFN scenario than in the population scenario.

Scenario	Population	DFN	Savings
TRANS-3T-ETH	5639.73	5268.80	6.58%
TRANS-3T-SDH	7110.41	6708.54	5.65%
P2P-3T-ETH	6838.73	5819.82	14.90%
P2P-3T-SDH	8455.67	7346.63	13.12%
		Average:	10.06%

Table 3: Cost comparison for different traffic distributions

The total cost values for the different scenarios are shown in Table 3. To handle the DFN demands, one router with capacity 3840 Gbit/s, six with 1280 Gbit/s, and ten with 640 Gbit/s are required in all solutions. For the more evenly distributed population-based traffic demands, no 3840 Gbit/s router but 13 with capacity 1280 Gbit/s and four with 640 Gbit/s are required. These differences in the IP router platform alone yield an additional cost of 453.33 for the population based demands compared to the DFN demands, independent of the architecture of the underlying optical platform. For the transparent network architecture, the cost difference between the networks optimized for the DFN traffic demands and the population based demands is almost equal to the difference in the IP platform, effects of the chosen transmission technology Ethernet or SDH are negligible. For point-to-point networks, the different IP platforms still account for 50% of the total cost difference.

4. CONCLUSIONS

In this paper, we presented a model-based planning cycle in order to optimize multi-layer IP-over-WDM networks using realistic and very detailed system data. Investigating three different scenarios, the main observation is the following: For the realistic NOBEL hardware and cost model, the 12 percent cost difference between the fundamentally different architectures point-to-point WDM-links and transparent optical switches is on average about the same as the cost difference obtained by varying the traffic distribution. The average difference between the networks designed for the DFN measurements and those for the Dwivedi-Wagner model was about 10 percent. Finally, the difference in card cost between PoS- and GbE-interfaces goes directly into the differences between the network cost.

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A. THE MATHEMATICAL MODEL

This section provides a brief description of the mixed-integer programming model used for the optimization of the transparent architecture which is an extension of the formulation proposed in [12]. It has the advantage of a very compact description of the flow on the logical layer. This is achieved by aggregating all logical flow variables of a node-pair to a single variable. The model for the point-to-point architecture is similar with minor modifications of the parameters.

The physical network is given by the fiber topology depicted in Figure 3 and represented by an undirected graph $G = (W, E)$. The logical network is defined by a subset V of the nodes W and all node-pairs $V \times V$ (the complete undirected graph spanned by the 17 potential IP router locations). For every node-pair $(i, j) \in V \times V$ a set $P_{(i,j)}$ of admissible (light)paths in the physical network is considered. For our calculations we used the 50 shortest paths in G for every node-pair. Let P be the union of all these paths. Each path $p \in P$ has a set M_p of available capacity modules. These modules correspond to interface cards installable at the end-nodes of the path. A path module m consumes c^m channels in the physical fiber layer and has a total capacity (bit-rate) of C^m. Each module can be installed several times on the corresponding lightpath. A physical link can be equipped with an arbitrary number of fibers each supporting a total of B passing channels. For nodes we introduce the sets N and O of admissible logical and physical node modules, respectively. Only one module can be installed at every logical and physical node. A logical node module n has a maximum switching capacity of C^n. A physical node module o has a restricted number of supported fibers C^o_f, overall channels C^o_c, and add-drop channels C^o_t. Every logical link and node module, physical node module and fiber can be installed at a certain cost.

The given traffic matrix defines a set of demands each having source and target in V and a demand value. By aggregating demands at a common source node a set K of commodities is constructed. This transformation reduces the size of the routing formulation (see for instance [7]) and results in commodities having one source and several target nodes. With every commodity $k \in K$ and every node $i \in V$, a net demand value d_i^k is associated such that $\sum_{i\in V} d_i^k = 0$. The total demand starting or ending at node i, is given by $d_i := \sum_{k\in K} |d_i^k|$.

We introduce the following variables. For every node-pair (i, j) the variables f_{ij}^k and f_{ji}^k describe the flow between i and j in both directions w. r. t. commodity $k \in K$ (aggregating the flow for k on all paths in $P_{(i,j)}$). The value y_p^m counts the number of path modules for module m and path p. For every physical link e the number of provided fibers is given by y_e. The logical node module $n \in N$ is installed at node $i \in V$ if and only if the variable x_i^n is set to 1. Similarily, x_i^o decides whether or not to install the physical node module $o \in O$ at node $i \in W$.

The problem of minimizing the cost of a network satisfying the given demand matrix and the capacity restrictions on both layers can be formulated as the problem of minimizing the cost of all module and fiber configurations satisfying the following set of constraints:

$$\sum_{j\in V\setminus\{i\}} (f_{ij}^k - f_{ji}^k) = d_i^k \qquad \forall i \in V, k \in K \tag{1}$$

$$\sum_{p\in P_{(i,j)}} \sum_{m\in M_p} C^m y_p^m - \sum_{k\in K} (f_{ij}^k + f_{ji}^k) \geq 0 \qquad \forall (i,j) \in V \times V \tag{2}$$

$$\sum_{n\in N} C^n x_i^n - \sum_{p\in\delta_P(i)} \sum_{m\in M_p} C^m y_p^m \geq d_i \qquad \forall i \in V \tag{3}$$

$$\sum_{n\in N} x_i^n \leq 1 \qquad \forall i \in V \tag{4}$$

$$By_e - \sum_{p\in P:\, e\in p} \sum_{m\in M_p} c^m y_p^m \geq 0 \qquad \forall e \in E \tag{5}$$

$$\sum_{o\in O} C_f^o x_i^o - \sum_{e\in\delta_E(i)} y_e \geq 0 \qquad \forall i \in W \tag{6}$$

$$\sum_{o\in O} C_c^o x_i^o - 2 \sum_{p\in P:\, i\in p} \sum_{m\in M_p} c^m y_p^m \geq 0 \qquad \forall i \in W \tag{7}$$

$$\sum_{o\in O} C_t^o x_i^o - \sum_{p\in\delta_P(i)} \sum_{m\in M_p} c^m y_p^m \geq 0 \qquad \forall i \in W \tag{8}$$

$$\sum_{o\in O} x_i^o \leq 1 \qquad \forall i \in W \tag{9}$$

$$f_{ij}^k, f_{ji}^k \in \mathbb{R}_+,\ y_p^m, y_e \in \mathbb{Z}_+,\ x_i^n, x_i^o \in \{0, 1\} \tag{10}$$

The flow conservation equations (1) ensure a feasible routing of the traffic demands. The logical link capacity constraint (2) says that the flow between i and j must not exceed the total capacity installed on all corresponding paths. Inequality (3) guarantees that the logical node capacity is not exceeded. The capacity at a logical node is consumed by the total node demand and the capacity of all terminating channels. The physical link capacity constraint (5) restricts the number of channels that can pass a physical link e. Inequalities (6)-(8) are physical node capacity constraints. Attached fibers, overall channels and terminating channels should not exceed the number of provided physical node ports. With (4) and (9) only one logical and one physical node module can be selected for every node in the logical and physical network, respectively.