

Software tools for a multilayer network design

Holger Höller and Stefan Voß

Abstract—Today's long haul and metro high-speed networks are mainly based on synchronous digital hierarchy (SDH) or its American equivalent synchronous optical network (SONET) and wavelength division multiplex (WDM). On the other hand, the large amount of traffic growth during the last years has been caused mainly by Internet protocol (IP) traffic. Traditionally, the IP-router based networks and the cross-connect based synchronous networks are often planned and operated separately. However, in line with new developments such as generalized multiprotocol label switching (GMPLS), network providers begin to realize that the convergence of these two worlds promises significant benefits. A set of software tools to support the network designer has been developed and used on various kinds of real world network planning problems arising in the SDH/WDM context. This includes, among others, 1+1 protection planning, static restoration and dual homing issues. These tools are extended with additional features to handle aspects of the IP/SDH interplay in a GMPLS environment. The two main components are an AMPL based integer model (solved via CPLEX) and a heuristic implemented in C++.

Keywords—*network design, GMPLS, SDH, WDM.*

1. Introduction

The term *layer* may be used with different meanings in the context of telecommunication networks. First, there is the well-known ISO/OSI model that divides the communication process into seven distinct layers. The physical layer at the bottom describes the technological means how to transport the data from one place to another while the higher layers handle connections, routing, error-processing, etc. The meaning of the word *layer* throughout this paper resembles this definition but is more based on the client relationships of the different technologies and their protocols. The lowest layer is constituted by the dark fibers. Especially in core networks, WDM systems are usually installed at least on the main routes; they constitute the second layer. SDH/SONET signals are multiplexed in the WDM systems, thus they are clients of WDM and form the next higher layer. IP, as a possible client to SDH/SONET, is the next layer.

Also the hierarchical structure of a network, i.e., the division into access, regional and backbone networks, can be viewed as different layers. Though the software tools are able to support some hierarchical network structures, including dual homing at the borders between regions and the backbone, this kind of layering will not be the focus of this article.

In this paper we aim at describing our current developments in modeling and solution approaches for multilayer network design. The focus is on integrated planning of different layers whose planning was usually performed separately in the past. The technologies and network structures discussed throughout this article are based on the systems that are currently installed or scheduled for large-scale use in the near future. Thus switching in the cross-connects takes places in the electrical domain and WDM is simply used as a high-capacity point-to-point connection. Future developments such as all-optical cross-connects and thus the routing and wavelength assignment problem (RWA) are not considered.

The structure of this article is as follows: Section 2 treats the network design problems and their technological and economical context. Section 3 describes the planning tools that we have developed to cope with these problems and Section 4 sums the article up with some conclusions.

2. The network design problem

2.1. Network structure and demands

The traditional organizational and technological structure of many carriers consists of a transport network department (with its roots in the telephone network) and a separate IP network department (with its roots in packet data networks). They both tend to optimize “their own network” according to their own needs. The result might be two local minima instead of a global one for the combined networks. Even if this description is a bit over-exaggerated, the mutual understanding of people working in the “IP world” and those working in the “transport world” should improve in order to design and operate an integrated multi service network.

In recent years, there has been a tremendous shift in the demands towards IP; meanwhile data traffic has superseded voice traffic. The Internet and together with it also IP are becoming the predominant means for communication, even voice traffic is beginning to migrate to IP. The two technologies are converging on the side of the customers and now also in the core networks. On the other hand, when asking network operators, they often state that most demands in the core networks are leased lines with a fixed capacity. This seeming contradiction might be solved when considering what data is actually transported over these lines. A 155 Mbit/s leased line for a virtual private network (VPN) of a company looks like an ordinary switched

circuit demand. However, one can ask whether it is really used for time-critical circuit switched data or merely for IP-packets groomed in a virtual container (VC) at the customer side. On the other hand, the question arises, if an IP VPN in the core still can benefit from statistical multiplexing. Maybe the traffic between the two customer locations is already so much aggregated before it enters the core network that the statistical gain for the network provider would be close to zero. This would mean that one of the big advantages of IP, the better network usage due to statistical multiplexing, might not work any more. At least during the busy hour, the actual capacity needed for such IP traffic might be almost identical to switched circuit traffic.

Capacity planning for switched circuit networks is comparatively easy, since the demands have a fixed size that does not change over time. Once the appropriate container size is determined, a deterministic routing and capacity planning for these containers can take place. However, IP traffic has a stochastic behavior. A demand cannot be entirely described by a single value for the required bandwidth; its size may change from one second to another. A simple way for capacity planning would be just to take the peak value (or the average value) of the bandwidth requirement and treat it like an ordinary switched circuit demand. For a conventional IP over SDH network with a fixed mapping of an incoming IP stream into SDH containers, this might be suitable. But of course, this does not necessarily lead to an efficient use of the resources since large parts of the containers might be empty most of the time.

A more flexible and resource saving possibility might be achieved by the use of virtual concatenation in combination with the link capacity adjustment scheme (LCAS) (cf. [4, 12]). An IP demand is mapped into a number of virtually concatenated SDH containers and that number is varying over time according to the actual size of the IP demand. Of course, the capacity has to be available in the underlying transport network, but this time it is not wasted if a demand requires less capacity than on average, but it can be dynamically used by other demands that need above average capacity at that moment. However, this requires more knowledge about the IP demands than a traditional static planning. Along with the peak bandwidth requirements, a distribution of the requirements over time has to be known. Otherwise, it is not possible to route the demands such that demands with peaks at different times use the same routes so that they can actually share capacities. If all or at least most of the demands have their peaks at the same time of the considered period (e.g., a day), even the dynamic use of virtual concatenation would not help to save resources. This is a point that has to be considered generally in the discussion about more flexibility and bandwidth on demand in transport networks. The capacity and thus the equipment have to be available in the first place in order to be assigned dynamically. But if this capacity cannot be shared with other demands, a small line with additional bandwidth on demand is not cheaper than a large

dedicated line. In both cases, the extra capacity is wasted outside the busy hour and the costs for the carrier are the same.

2.2. Generalized multiprotocol label switching

An important part in the future integration of transport and IP networks is probably played by GMPLS. Banerjee *et al.* [2, 3] give a versatile description of GMPLS. For the official standards refer to the respective requests for comments from the Internet Engineering Task Force (IETF)¹. The goal is a common control plane for the entire network. Routing, resilience, monitoring, etc., are all performed by a unified management system. It may give the network operator the opportunity to provide new kinds of services and an integrated planning process may reduce the overall network costs while guaranteeing the required service level (cf. [11]). GMPLS can be implemented in two different scenarios called overlay model and peer-to-peer model. The overlay model can be seen as an intermediate step between the current separation of layers or networks and an all-integrated network. The network consists of different clouds that hide their inner structure and communicate via specific interaction points. These clouds can be different layers like SDH and IP. But also the layers themselves can be divided into separate entities, e.g., devices of different vendors or different network providers. The peer-to-peer model opens the entire internal structure of a network to the outside. Thus the edge devices of the adjacent layers or networks mutually know their topologies. Only this knowledge enables a truly common control plane for the different parts of the network. However, the peer-to-peer model should not be seen as the ultimate goal for all networks. There are good reasons to use an overlay approach for some scenarios. For example, the GMPLS standard leaves room for vendor specific features, which of course only work inside its own equipment cloud. Thus it might be impossible to use a common control plane that has all the features the provider needs for the different parts of the network unless the equipment comes from one vendor only. On the other hand, different parts of the network might be operated by different providers, which do not want to reveal their inner structure to a (possible) competitor. While the overlay model can be handled well with existing planning tools, the peer-to-peer model poses a much more complicated task.

2.3. Resilience

Another important aspect in multi-layer networks is the resilience. The question is not just which mechanism should be used, as, e.g., 1+1 protection versus restoration in SDH networks, but also on which layer it should be implemented. Demeester *et al.* [5] discuss this topic for a similar problem, the integrated planning of asynchronous transfer mode (ATM) and SDH/WDM networks. Pongpaibool [10]

¹See, <http://www.ietf.org/rfc.html>

extensively treats survivability with respect to GMPLS networks and gives many useful references. Traditionally, SDH and WDM core mesh networks are often 1+1 protected, which means a distinct backup path for every demand. IP-networks have the inherent ability to reroute the traffic in case of failures, provided that enough spare capacity is available. If the IP network now acts as a client of the transport network, this might lead to a double fold protection and therefore to a massive waste of capacities.

Different approaches might be taken in order to prevent this problem. Two obvious but may be too extreme possibilities are to use only the resilience on one layer. If the IP layer has enough spare capacity, then it might not be necessary to use any kind of protection on the optical layer. The feasibility of this approach, however, depends on the size and structure of the network. It is doubtful whether an IP-router network could handle the simultaneous rerouting of thousands of demands if a WDM link fails. At least it would take a while before the normal state of operation would be reached again. On the other hand, protection could take place only in the optical domain. Fast protection switching would establish a route around the failure before the IP layer would notice it. No spare capacity for rerouting would be needed in the IP layer. A drawback of this approach is the probably high resource consumption. Also the lower layer cannot sense router failures without any additional signaling from the IP layer.

A good solution in the long run might be in between. Both layers, the IP as well as the optical, begin to adopt the advantages of the other one. On one hand, SDH and WDM get fast rerouting or dynamic restoration in order to save resources. On the other hand, multiprotocol label switching (MPLS) introduced circuit like traffic flows for IP, which (among other features) enables a quick rerouting. This might ultimately converge in GMPLS peer to peer networks where a unified resilience mechanism is coordinated between the layers. Low layer failures are directly handled on the optical layer (SDH or WDM) before the IP layer notices the outage. IP layer failures are handled on the IP layer, but the IP layer has knowledge of the available backup resources on the optical layer and can use them for its own recovery operations, e.g., after a router failure. Of course, this mechanism, like many others, works only reliably for single failures. Once the IP layer occupies capacity on layer 1 and layer 2 systems for its backup routes, they are blocked and can no longer be used for recovery of failures on the optical layer.

3. The software tools

The SDH/WDM network design problem, as treated, e.g., in [6, 9], is to decide which combination of equipment and routing will be able to carry the given demands at the lowest cost. It is important to realize that the routing and the equipment assignment cannot be separated. Due to the strong economies of scale, the shortest path is not always the cheapest, it might often be useful to accept

a detour and even additional hops in order to fill large long-haul systems that are very expensive as a whole but very cheap per bit.

The models presented here rely on a set of common network equipment with certain user-adjustable parameters. The network has to carry a certain set of (protected) demands with the objective of minimizing the investment in the equipment. The different layers considered are the fiber-layer, 2.5 Gbit/s SDH-, 10 Gbit/s SDH- and WDM-systems. The integration of IP introduces an additional layer on top of the SDH layer. The tools consist of two major parts, a mixed integer model solved by CPLEX and a heuristic implemented in C++.

3.1. Data and preprocessing

Most realistic network planning scenarios are not a green-field study but they are rather based at least on an existing fiber graph. The laying of new fiber lines is a very expensive task and therefore is avoided whenever possible. Thus the set of fiber lines is considered as static. It is given by the network provider along with its estimated figures for the future demands and the costs for the possible equipment choices. The main data considered for the planning process is the following:

- Fiber lengths and maybe quantities if they are restricted.
- Demands in VC-x units for SDH and Mbit/s for IP (IP demands might also be asymmetric).
- Equipment specifications like capacities, ranges and prices of WDM multiplexers, transponder, amplifiers, regenerators, cross-connects, IP routers, port cards and so on.

Our tools have no direct access to the databases of the network provider; they import the data from EXCEL via the Windows open database connectivity (ODBC) interface or custom ASCII files. AMPL/CPLEX are compatible to these two formats as well. For details on the AMPL ODBC interface refer to the documentation of AMPL optimization LLC [1]. Both, the custom heuristic and AMPL, allow a batch processing in order to quickly evaluate different scenarios (demand matrices, parameter sets, cost functions, etc.) of the same problem instance without any intermediate user interaction.

This common interface also enables an interworking of the two tools without any further data conversion, which opens some interesting opportunities. First of all, it allows an easy use of the same data sets to compare both approaches, which simply saves time. Second it is possible that the output of one method is used as input for the other one. The best solution found by the heuristic may serve as an upper bound for CPLEX. This helps to reduce the run-time and the memory consumption and thus leads to better solutions for some problem instances, especially to those that previously were aborted due to a lack of memory. But interaction may also take place the other way round. For networks

where CPLEX was not able to find an optimal solution, the best feasible solution that it has actually found may be used as an alternative starting solution for the heuristic. However, the latter possibility has not yet been tested.

An important aspect for the input of the data is a sensitivity analysis. Past experience shows, that this data is often erroneous or incomplete due to various reasons. Duplicate links with different lengths and missing links are perhaps among the most common problems. The requirements for the planning tools are twofold. First they should identify such problems if possible and second they should nevertheless try to proceed as normal. While a detailed error reporting is of course helpful, maybe even indispensable, dozens or even hundreds of pop-up windows because of duplicate links are certainly not welcomed by the user. Maybe he is aware of duplicate links in his database and just does not bother if the program chooses any one of them because the length differences are negligible. However, more important is a check for bi-connectivity in case a protection planning should be carried out.

While the AMPL import does not support “silent” sensitivity analysis for such cases, the heuristic contains pre-processing steps where such things are handled and reports may be generated if selected by the user. This might, e.g., include a list of articulation points or a list of duplicate links. The user might choose to completely ignore such things and then the algorithm deletes duplicate edges and adds additional ones in the case of missing connectivity according to simple rules. At this point some more sophisticated algorithm to add links might be included but that is at least currently beyond the scope of our approaches.

3.2. The algorithms and their implementation

The heuristic is a custom development programmed in C++. Figure 1 shows a flow diagram of the core algorithm. It

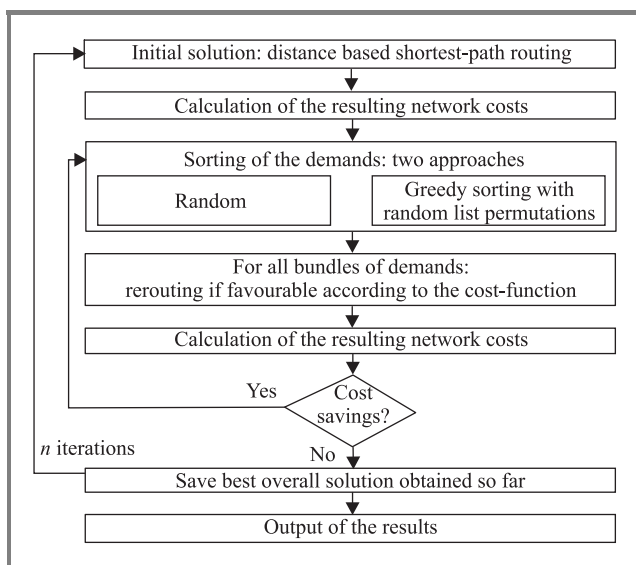


Fig. 1. Flow diagram of the heuristic part.

processes the input data as described in Subsection 3.1 and, starting from a shortest path solution, iteratively improves the routing and the equipment assignment according to the cost and capacity constraints. A detailed description of the algorithms can be found in [7]. Table 1 summarizes some results in comparison to a shortest path routing and a provably optimal solution of the respective integer programming formulation.

Table 1
Comparative results of the best objective value that was found for different networks

| Nodes/edges/demands | CPLEX | Shortest path | Heuristic 2000 runs |
|----------------------------|-------|---------------|---------------------|
| 11/16/19 VC4 grooming | 1231 | 1347 | 1244 |
| 20/33/84 | 9426 | 9728 | 9604 |
| 111/160/243 1+1 protection | – | 333 909 | 313 145 |

One fundamental difference between IP and circuit switched traffic is that IP is unidirectional, thus in principle the size and the routing of the traffic from A to B can be totally different from the size and routing from B to A, the different routings and bandwidths are aggregated for the calculation of the port-cards, they can be freely rearranged in transit nodes as long as the minimum switching granularity is respected. Therefore, the algorithm is able to work with bi-directional demands as well as with arbitrary demand granularity. This can be, e.g., a granularity of 155 Mbit/s for a VC4 switched network or 1 kbit/s for the IP-routers. The statistical multiplexing gain is not yet implemented, largely due to a lack of appropriate data, but is scheduled for the near future.

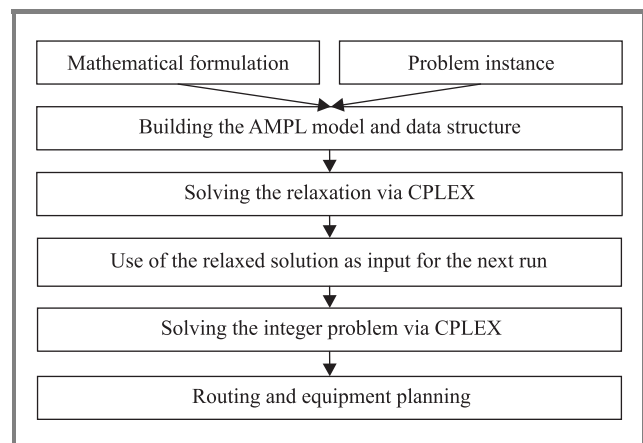


Fig. 2. Flow diagram of the AMPL/CPLEX part.

The sources of the tools are open to the network operator so that the planner knows what he is doing and what the effect of different parameters is. This is an advantage over most commercial tools, which are usually a black box to

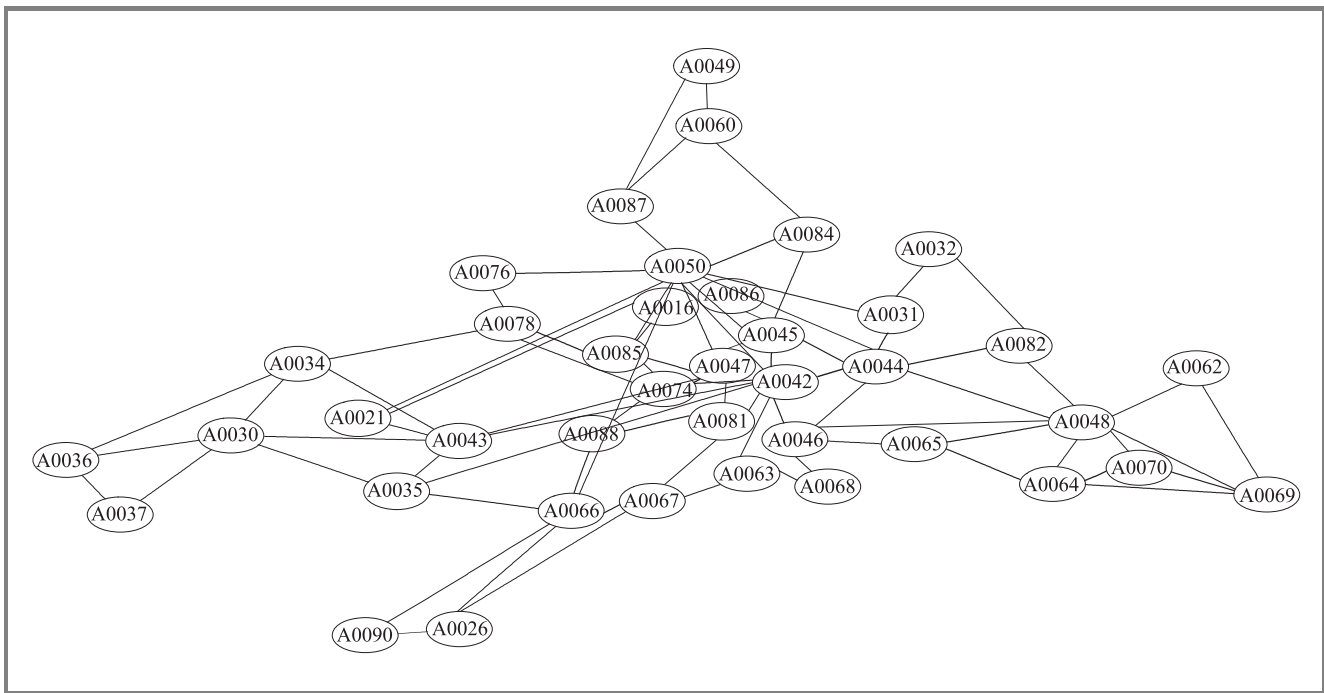


Fig. 3. Graphical output of a network structure.

Table 2
Runtimes for different network topologies

| Runtime [s] for the problem instance, Δ between the best solution that was found and the lower bound | | | | | | |
|---|----------|----------|----------|-----------------------------|----------|----------|
| Number of nodes/links/demands in the network | | | | | | |
| 17/26/28 | 20/22/46 | 20/33/84 | 24/48/36 | 24/48/60 | 27/32/45 | 30/45/60 |
| 16 | 4.5 | 12 300 | 4840 | 36 160 $\Delta = 1.78\%$ | 17 | 5900 |

the network designer. Of course, the companies that develop these tools want to protect their intellectual property and a black box might be suitable for some standard planning or re-planning issues that arise in certain intervals and have therefore been established as well-known routine. But for more advanced problems and for more advanced users, knowledge of the algorithms and their software implementations can be a great help in order to guide the planning process in the desired direction.

The heuristic works with up to 1000 nodes on state-of-the-art desktop PCs. Although run-time is usually not a major concern for such a strategic network planning process, fast processing is necessary for an interactive planning process, where the planner “plays” with different scenarios or configurations. For this purpose, mechanisms like the greedy randomized adaptive search procedure (GRASP) metaheuristic (cf. [7]) have been included that may be used to find good solutions in a short amount of time when it is more important to get results fast than to get a 1% better objective value. Given that it is partly based on forecasts, the general question arises if the input data is accurate enough to justify a comparison of different scenarios with a pre-

cision of a few percent more or less overall investments. This could be pseudo-accuracy.

The integer model is based on classic flow formulations and processes almost the same data as the heuristic. A drawback is the fact that this formulation currently does not support path restoration but only path protection. Figure 2 shows the steps for the use of this approach. First, the mathematical formulation is adjusted to the current real world problem. Then a linear relaxation of the problem is solved. This intermediate step is basically a means to reduce the memory consumption of the following integer calculation that produces the routing and the equipment plan.

The CPLEX calculation works for some dozens of nodes, which restricts it to comparatively small problem instances. However, the maximum network size that can be solved is very dependent on the actual structure of the problem. Specific relationships of the equipment costs or special fiber topologies might be very easy to solve, while other networks that are much smaller cannot be handled. Table 2 gives the runtime of some problem instances and clearly shows that they depend on the specific graph and not on the size alone. It is always a good idea to give the exact

approach a try even for larger problem instances. Furthermore, it is useful as a reference for the heuristic.

3.3. Results of the planning process

The output of the software is a plan of the network that contains the routings for all demands and the equipment that is needed to carry them and of course the overall investment that is necessary for the equipment. Initially, these are large lists and tables, e.g., with load and equipment lists for all nodes and links. It gives the planner a full picture of the scenario but it is not easy to get an overview and draw conclusions from a scenario just with lots of numbers. Some kind of graphical output has been an often-requested feature during the development of the tools. The EXCEL part of the output can easily be converted into diagrams that already give a quick overview of the results. Yet besides these possibilities, a basic graphical output of the network structure (static pictures) with the nodes, the links and their loads can be displayed with the help of the free software package Graphviz². Figure 3 shows such a topology graph. However, full interactive graphical output is beyond the scope of this development and too time-consuming to implement.

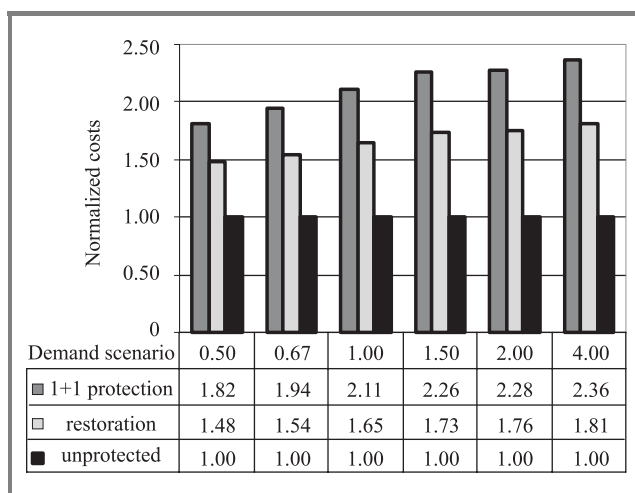


Fig. 4. Scenarios with different demand forecasts.

In principle, this output is a (near) optimal solution of the initial network planning problem with respect to the overall investment in new equipment. However, there are too many simplifications and uncertainties in the underlying data and models, so that these tools should not be misused as an automatic network planning system. The results require an experienced planner for thorough examination and interpretation. In most cases, the planning process will probably be interactive and iterative. A specific scenario is calculated with the help of the tools, the planner analyses the results and then changes some parameters for the next run.

²See, <http://www.research.att.com/~north/graphviz/>

A comfortable feature is the batch mode, which allows pre-defining a set of scenarios and doing the calculations in one run. This is especially helpful for input data with intrinsic uncertainty, e.g., the demand distribution, and may lead to best case/worst case/average case results instead of just a single network design. Figure 4 shows an example from a past study (cf. [8]), where different demand forecasts were compared for a given network topology and three resilience mechanisms.

4. Conclusions

In this article, we have given some background on current multilayer planning problems for IP/SDH/WDM networks, including recent developments like GMPLS. We have presented two complementary tools, a heuristic and an integer programming approach, that started as classic switched circuit network planning tools and are now evolving towards the integration of IP networks. They provide a flexible and promising basis for further developments and have been already successfully used on several different planning problems. However, an integrated planning process that covers all the important aspects like, e.g., unified resilience mechanisms and statistical multiplexing effects, while simultaneously optimizing the routing and the necessary equipment, is still some way to go.

References

- [1] "AMPL optimization LLC. Relational database access", 2000, <http://www.ampl.com/NEW/tables.html> (state: 9.7.2004)
- [2] A. Banerjee, J. Drake, J. Lang, B. Turner, K. Kompella, and Y. Rekhter, "Generalized multiprotocol label switching: an overview of routing and management enhancements", *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 144–150, 2001.
- [3] A. Banerjee, J. Drake, J. Lang, B. Turner, D. Awduche, L. Berger, K. Kompella, and Y. Rekhter, "Generalized multiprotocol label switching: an overview of signaling enhancements and recovery techniques", *IEEE Commun. Mag.*, vol. 39, no. 7, pp. 144–151, 2001.
- [4] Cisco Systems, "Leveraging transport for data services with virtual concatenation (VCAT) and link capacity adjustment scheme (LCAS)", 2003, www.cisco.com/warp/public/cc/so/neso/meso/meipac/lcas_wp.pdf (state: 16.6.2004)
- [5] P. Demeester, M. Gryseels, A. Autenrieth, C. Brianza, L. Castagna, G. Signorelli, R. Clemente, M. Ravera, A. Jajszczyk, D. Janukowicz, K. Van Doorselaere, and Y. Harada, "Resilience in multilayer networks", *IEEE Commun. Mag.*, vol. 37, no. 8, pp. 70–76, 1999.
- [6] H. Höller and S. Voß, "A mixed integer linear programming model for multilayer SDH/WDM networks", Universität Hamburg, 2003.
- [7] H. Höller and S. Voß, "A heuristic approach for combined equipment-planning and routing in multi-layer SDH/WDM networks", *Eur. J. Oper. Res.*, 2004 (to appear).
- [8] H. Höller, S. Voß, M. Fricke, and S. Neidlinger, "Vergleich des Einflusses der Bedarfsstrukturen und Netztopologien von SDH/WDM Netzen auf das eingesetzte Schutzverfahren", in *ITG-Fachbericht 182 "Photonische Netze", Vorträge der 5. ITG Fachtagung "Photonische Netze" in Leipzig*. Berlin: VDE Verlag, 2004, pp. 115–120.
- [9] B. Melian, M. Laguna, and J. Moreno-Perez, "Capacity expansion of fiber optic networks with WDM systems: problem formulation and comparative analysis", *Comput. Oper. Res.*, vol. 31, no. 3, pp. 461–472, 2004.

- [10] P. Pongpaibool, "Survivability of GMPLS-based IP-over-optical networks". Ph.D. thesis, Carnegie Mellon University, Department of Electrical and Computer Engineering, 2004.
- [11] H. Zhang and A. Durrresi, "Differentiated multi-layer survivability in IP/WDM networks", in *8th IEEE-IFIP Netw. Oper. Manag. Symp.*, Florence, Italy, 2002, pp. 681–694.
- [12] K. Zhu, H. Zang, and B. Mukherjee, "Exploiting the benefits of virtual concatenation in optical transport networks", in *Conf. OFC 2003*, Anaheim, USA, 2003.



Holger Höller has studied industrial engineering with focus on electrical engineering at the University of Technology Braunschweig, Germany, and received his diploma in 2002. Since November 2002 he is working as a Research & Teaching Assistant at the Institute of Information Systems, University of Hamburg, Germany. The

main focus of his current research is located in the area of IP/SDH/WDM multi-layer planning problems.

e-mail: hoeller@econ.uni-hamburg.de

Institut für Wirtschaftsinformatik

Universität Hamburg

Von-Melle-Park 5

20146 Hamburg, Germany



Stefan Voß, born 1961 in Hamburg, Germany, is Professor and Director of the Institute of Information Systems at the University of Hamburg. Previous positions include full Professor and Head of the Department of Business Administration, Information Systems and Information Management at the University of Technology Braun-

schweig, Germany, from 1995 up to 2002. He holds degrees in mathematics (diploma) and economics from the University of Hamburg and a Ph.D., and the habilitation from the University of Technology Darmstadt. His current research interests are in quantitative/information systems approaches to supply chain management and logistics as well as public mass transit and telecommunications. He is author and co-author of several books and numerous papers in various journals. Stefan Voß serves on the editorial board of some journals including being Associate Editor of "INFORMS Journal on Computing" and Area Editor of "Journal of Heuristics". He is frequently organizing workshops and conferences. Furthermore, he is consulting with several companies.

e-mail: stefan.voss@uni-hamburg.de

Institut für Wirtschaftsinformatik

Universität Hamburg

Von-Melle-Park 5

20146 Hamburg, Germany