

Including Energy Efficiency Aspects in Multi-Layer Optical Network Design

Steffen Gebert, David Hock, Matthias Hartmann, Joachim Spoerhase, Thomas Zinner, Phuoc Tran-Gia
University of Würzburg, Institute of Computer Science
{steffen.gebert,david.hock,hartmann,spoerhase,zinner,trangia}@informatik.uni-wuerzburg.de

Abstract—This paper investigates the influence of the network planning process on a higher energy-awareness of optical multi-layer core networks. In particular, we propose to remove redundant links in the network, and to route corresponding network traffic on other links. Based on the reduced network topology, we compute the required network equipment for realistic traffic demands using a network planning tool. Due to the lack of an accurate model for operational expenditures and energy consumption, we choose the link length as cost function. We show the applicability of our idea and demonstrate the energy saving potential using realistic network topologies.

I. INTRODUCTION

Access networks are currently dominating the power consumption of the Internet [1]. With increasing access speeds, the core network's capacity and thus also the power consumed in the core network is expected to increase continuously. In 2017 [2], the power consumption of the Internet core shall exceed the power consumption of access networks. This results in higher operational expenditures (Opex) for large ISPs, if the network stays unchanged in terms of its energy-awareness.

Several approaches to adjust energy consumption of network devices based on their usage already exist, like stand-by modes or rate-adaption. However, these approaches require a continuous monitoring and dynamic reconfiguration of the network. Operators, however, tend to avoid such reconfigurations to their highly critical network infrastructure during operation.

Core networks are based on optical, often multiplexed, transmission on lower layers, with electrical layers like SONET or Carrier Ethernet in between, and MPLS and IP technology on top. Accordingly, the planing and configuration of multi-layer networks with respect to given traffic demands can become very complex. This is due to the sheer amount of possible realizations for routing specific traffic demands using the different available layers. Hence, the planning process is crucial for operators, since on the one hand a smooth and resilient operation of the network has to be assured, and on the other hand the costs for the network equipment have to be minimized. The resulting software-supported optimization process selects appropriate equipment out of a list of available components which is then used to connect the fibre topology.

A network's costs are split up in capital expenditures (Capex) and operational expenditures (Opex). While the Capex

for network equipment can be estimated quite accurate, calculating Opex is complex. Besides the rent for the buildings where equipment is located or for the dark fiber, Opex also include the wages for staff managing the equipment, and costs for the power consumed by the equipment. Due to its complexity, network planning software is highly specialized and often solely focuses on the Capex calculation [3].

By reducing the number and overall length of fiber links, the network's energy consumption and thus Opex can be reduced. Additionally, reducing the number of the active fiber connections not only avoids energy costs, but also lowers the rent for a fiber infrastructure, if not owned by the operator. By including these factors already in the planning process, the network's utilization can be increased through aggregation of the traffic to fewer links. Expenses for equipment can not only be safed, but also the energy consumption [4] can be reduced.

Therefore, the approach followed in this work is to reduce energy consumption by reducing the network topologies. From a given fiber topology, edges are removed before starting the network planning process. Such a removed edge is later not used in the network and no energy is consumed for line/port cards in routers, multiplexers, as well as amplifiers. In order to guarantee resilience in case of an outage, we assure that each site is still connected via two links at least. Due to the lack of publicly available Opex models for network equipment, we choose the link length as cost function. This cost metric was chosen, as the energy consumption for signal refreshes on WAN links very likely outperforms the energy consumption of the sending and receiving transmitters [2]. Based on this cost function, we evaluate the effect of our proposed mechanisms on the Opex and compare them with the original topology.

The remainder of this work is structured as follows: Section II lists related work. The problem formulation as well as the metrics applied to network topologies are given in Section III, followed by Section IV explaining the used *Mixed Integer Linear Program* (MILP). Results of applying the mechanisms to realistic network topologies are shown in Section V. Finally, Section VI draws conclusions.

II. BACKGROUND & RELATED WORK

This section highlights related work in multi-layer network planning and energy efficiency mechanisms for core networks.

A. Planning of Multi-Layer Networks

The topic of multi-layer network design is on planning the equipment required to set up a network consisting of multiple

This work has been performed in the framework of the CELTIC EUREKA project SASER-SIEGFRIED (Project ID CPP2011/2-5), and it is partly funded by the BMBF (Project ID 16BP12308). The authors alone are responsible for the content of the paper.

layers, i.e. different optical multiplex layers and MPLS/IP on top. Based on the traffic demands in the network, a multitude of possible hardware and routing decisions have to be taken into account for optimization. This includes different technologies, i.e., the specific layer in the multi-layer topology where a traffic demand is routed, as well as heterogeneous equipment of different vendors. Optimization tools, typically based on MILPs or heuristics, mainly aim at minimizing the capital expenditures of the equipment [3], usually because no Opex models are available. However, it is possible to adjust the objective function to take other objectives or mixed objectives into account.

B. Energy Efficiency of Core Networks

A survey on green networking [5] categorizes research work into four categories: *Adaptive Link Rate*, *Interface Proxyming*, *Energy Aware Infrastructure* and *Energy Aware Applications*. Our work touches the first category *Adaptive Link Rate*, with sleep modes and rate switching of network interfaces as well as the category of *Energy Aware Infrastructure*.

That only a few reconfigurations per day (three in the example) allow already 10% energy savings while making use of stand-by modes is shown in [6]. In contrast, dynamic adaptation of the rate speed is more complex, not only from technical side, but also from network planning effort. A similar study is [7], in which the authors state that 25% energy can be saved, if primary paths are aggregated over fewer links and links exclusively used for backup paths are switched into stand-by mode. In contrast to these work, ours focuses on the planning phase using an energy-unaware planning software.

Energy efficiency in IP-over-WDM networks is observed in [8] and three mechanisms are suggested: *Fixed Upper Fixed Lower* (FUFL), *Dynamic Upper Fixed Lower* (DUFL) and *Dynamic Upper Dynamic Lower*, which determine the freedom of dynamically rerouting traffic either on lower (the WDM) or upper (the IP) layer. After traffic aggregation through rerouting, they suggest unused line cards to be switched off. The authors mention that dynamics, esp. in the lower layer where a coordinated reconfiguration of optical cross-connects has to be done, are technically more challenging than rerouting to parallel paths, as suggested with FUFL. Nevertheless, the authors report energy savings in a simulation based on day/night traffic demands also for the simple FUFL scenario, while bigger savings are reported for the DUFL approach, where rerouting takes place on IP layer. This MILP-based network planning approach requires abstractions, and thus differs from our work, in which we do not make such abstractions, as the design process and software for the network is not touched, but stays in the way it was before.

III. PROBLEM FORMULATION

This section first elaborates on properties of network topologies and metrics that influence the performance and reliability of a network. Afterwards, the four observed types of minimal subgraphs of a network topology graph are presented.

A. Network Topology Characteristics

For the presented use case, the following characteristics of network topology graphs are considered the most:

Opex Costs. The number of active links and their total length result in the energy and thus Opex costs. We set the Opex costs for a link proportional to the edge length in the network graph. If an edge is removed from the topology graph, the fiber link is not used and thus no energy consumed (neither on the way through amplifiers, nor at the endpoints through interface cards).

k -connectedness. In order to ensure fault-resilience in case of link or node failures, disjoint backup paths have to be available. In this work, we set $k = 2$, which means that we require two separate paths between any pair of nodes. This later allows the planning software to establish a primary, as well as a node-disjoint backup path between any two nodes.

Network Diameter. The network diameter denotes the longest of all shortest paths between any two node pairs in the network.

B. Network Configuration Characteristics

A network planning or network design software computes a solution for a configuration given the input of a topology, a component list and end-to-end traffic demands. For computing this solution, the following metrics are of interest:

Routed Demands. For every source/destination pair $(u, v) \in V \times V$ there exists a traffic demand D_{uv} with a certain bandwidth requirement. The paths for routing these demands are planned by the design software and later established either as MPLS paths or on lower layers, e.g. translucent optical paths. If no such path can be established due to capacity shortage, the demand is seen as *not routed*.

Protected Demands (Protection). Besides a primary path, also a backup path has to be planned and later established for every demand. While two-connectedness of a network graph is required for disjoint primary and backup paths, two-connectedness is not a sufficient criterion, as the capacity of particular links or equipment can be exceeded. The share of protected demands out of all demands results in the degree of *protection*.

Accepted Solution. This true/false criterion sums up the degree of routed and protected demands. A planned solution (the result of the network planning process) is accepted only if a degree of 100% protection is reached, which implies that all demands are routed. A solution is not an accepted solution, if the degree of protection is lower than 100%.

C. Computing Accepted Solutions

The goal of reducing the energy consumption under the premise that the planning software is able to find an accepted solution is approached from two sides:

ADD. Starting with a reduced topology graph, edges are added, until an accepted solution is found.

DEL. Starting with the original topology (G_{ORIG}), as many edges as possible are removed, as long as the solution stays acceptable.

Both algorithms use repeated invocations of the planning software, always with a varied network topology as input.

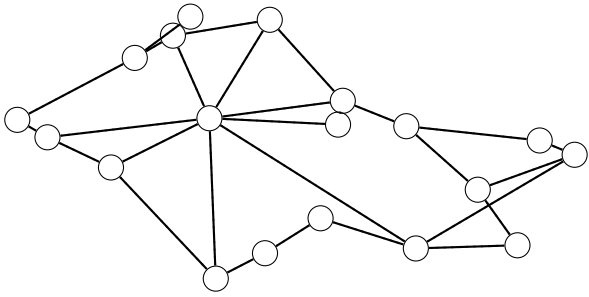


Fig. 1: Original topology (G_{ORIG})

1) *Removing Edges (DEL)*: The topology given to the design software as input is modified in each iteration and the longest active and not yet examined edge of the topology is removed prior to starting the planning. From a topology (V, E) , E' denotes the list of edges ordered descending by their length. In every step of the algorithm, the first (longest) edge $e \in E'$ is moved to the set of inactive edges E_i . If the planning software returns an accepted solution based on the reduced topology $(V, E - E_i)$, then e is kept within E_i . In case that not all demands can be protected, e is removed from E_i again (and will be active in the final topology). The process ends after all edges were examined once ($E' = \emptyset$).

By checking the two-connectedness of the topology, the DEL algorithm can be accelerated, as planning runs that certainly cannot end up with full protection can be avoided, if the removal of an edge e leads to a one-connected topology.

2) *Adding Edges (ADD)*: The planning software is invoked with a reduced topology graph (V, E') with $E' \subset E$. Suggested algorithms for creating these subgraphs are described in the next paragraphs. In case that the planning software is not able to compute an accepted solution, the following algorithm is executed: For every edge $e \in (E - E')$, an extended subgraph $(V, E' \cup \{e\})$ is given as input parameter to the planning software, which is then executed $|E - E'|$ times. The edge e that increased the degree of protection the most is kept for the further planning and added to E' . This is repeated as long as the result of the planning software is not yet giving full protection, thus not an accepted solution.

A trivial and quicker alternative instead of planning the network for every potential edge e would be to pick the shortest edge, thus the configuration that leads to the smallest increase in Opex. However, tests have shown that this quickly leads to most or all links being set to active and therefore was not regarded any further.

D. Reduced Topology Graphs

The following reduced topologies are subgraphs of the original topology G_{ORIG} shown in Figure 1. All proposed subgraphs have the aim to fulfill one or more of the characteristics of well-suited topologies defined in III-A and thus enabling the planning software to create a solution fulfilling the characteristics described in III-B.

1) *Minimum Spanning Subgraph, two-connected (G_{MSS})*: The first subgraph, the *Minimum Spanning Subgraph*, is a two-connected graph connecting all nodes with each other with the minimal total edge length. The result is shown in Figure 2a, where the gray links of the original topology are deactivated,

while the solid black ones stay active. The number of active links in a subgraph G_{MSS} of a graph $G = (V, E)$ is $|V|$.

The resulting subgraph has tendencies to form one or more rings. While a ring topology is common for networks, the downside of this approach is that the paths between two nodes can grow very large, especially in case of a single link failure.

2) *Minimum Spanning Tree, two-connected (G_{MST+})*: To counter the limitations of the G_{MSS} and to decrease the primary path lengths, all nodes are first connected using a minimum spanning tree (MST). Afterwards, two-connectedness is ensured in the same way as with the G_{MSS} , namely by adding the edges resulting in the shortest total length. Figure 2b illustrates this with solid black lines showing the MST and the dashed lines being the edges added for two-connectedness. The grayed out edges denote edges of G_{ORIG} that are deactivated in the example for this subgraph.

The availability of more links in the topology in comparison to G_{MSS} leads to shorter paths, as more direct paths are available in most topology types. However, due to the additional edges added, the total length of active edges, and thus the Opex costs, are increased.

3) *Minimum Diameter Subgraph, two-connected (G_{MDS})*: As long paths traversing multiple hops can result in diminished network performance, the objective of the G_{MDS} is to lower the network diameter, i.e. the longest shortest path between any two nodes in a network.

The Minimum Diameter Subgraph (G_{MDS}) is illustrated in Figure 2c. Like the G_{MSS} , it has a tendency to form large rings because of the two-connectedness criterion. However, not the shortest edges are picked, but instead the edges leading to minimal network diameter, in order to achieve a trade-off between low Opex costs and good network performance.

4) *Minimum Diameter Tree, two-connected (G_{MDT+})*: As last suggestion for energy efficient subgraphs, we introduce the two-connected Minimum Diameter Tree. Similar to the G_{MST+} , the initially calculated minimum diameter tree minimizes the distance between nodes for primary paths, while still forming a tree, thus keeping the Opex costs low. Routing of additional backup paths is enabled through additional links being added to make the topology two-connected with the measure of further shrinking the paths between nodes.

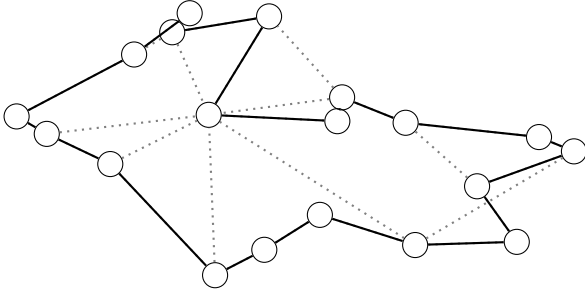
So we suggest the G_{MDT+} as a combination of the G_{MST+} and the G_{MSS} . Combining a prioritization for primary paths over backup paths, saving energy due to a reduced number of the active links (respectively shorter links), as well as avoiding degradation of network performance by avoiding increased network diameters as well as possible.

Figure 2d illustrates the G_{MDT+} with the minimum diameter tree in solid black and the additional edges added for two-connectedness in dashed black.

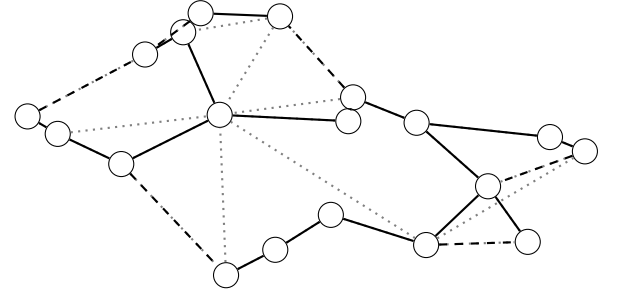
IV. MATHEMATICAL DEFINITIONS

A. Network Flow Model

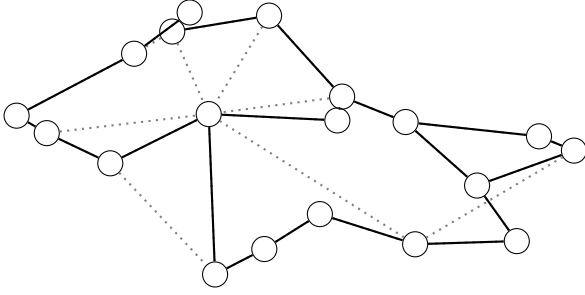
A *Network Flow Model* [9] can be used to model traffic flow and capacity in communication networks using constraints and an objective function, forming a *Mixed Integer Linear*



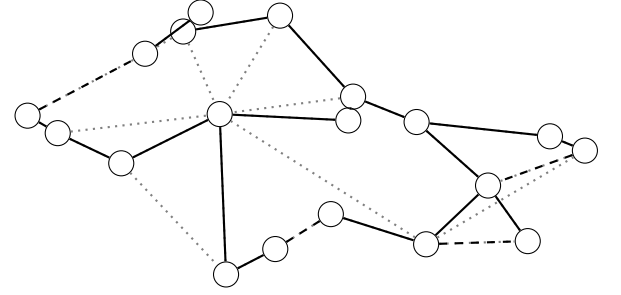
(a) Minimum Spanning Subgraph, two-connected (G_{MSS})



(b) Minimum Spanning Tree, two-connected (G_{MST+})



(c) Minimum Diameter Subgraph, two-connected (G_{MDS})



(d) Minimum Diameter Tree, two-connected (G_{MDT+})

Fig. 2: Reduced network topologies

Program (MILP). The following MILP formulations are used to compute the energy-efficient subgraphs as presented before.

Such traffic flows can be seen as a flow with a certain capacity from a source to a destination, potentially passing intermediate nodes. Like with e.g. a flow of water, a network link carrying reserved bandwidth demands can only be “filled” until its maximum capacity.

In the following, the variables and constraints used by all of the introduced subgraphs are explained. These are the most basic constraints which ensure common requirements, like node-two-connectedness for disjoint backup paths.

1) Input Data:

- Graph $G = (V, E)$ consisting of a set of vertices V and a set of edges E .
- k -connectedness ($k = 2$). Two-connectedness is used to require two disjoint paths between any two nodes.
- $weight_{uv}$: weight of the edge from u to v . The weight is denoted by the geographical distance between u and v .

2) Variables:

- x_{uv} : 1, if the edge from u to v is used, 0 otherwise.
- f_{uv}^{st} : 1 if the flow between s and t is using the edge uv , 0 otherwise. Note that we are using integral flows.

3) *Constraints:* We pick an arbitrary set $S \subseteq V$ of cardinality k and impose for any node pair $s \in S$ and $t \in V$ the following constraints. These constraints ensure that there are at least k node-disjoint paths between s and t . Note that this suffices to ensure k node-disjoint paths between any node pair $s, t \in V$.

k -Connectedness. An integral flow f^{st} between any two vertices s and t symbolizes the traffic demand from s

to t . This constraint ensures that at least k units of flow are sent to vertex t - or in other words at least k paths reach the destination node. Setting $k = 2$ ensures the possibility of reserving disjoint backup paths by ensuring the two-connectedness of the resulting subgraph.

$$\sum_{vt \in E} f_{vt}^{st} - \sum_{tw \in E} f_{tw}^{st} \geq k \quad (1)$$

Flow Conservation. Every flow that flows into a vertex v also has to completely flow out of v except for the $v \in \{s, t\}$.

$$\sum_{uv \in E} f_{uv}^{st} - \sum_{vw \in E} f_{vw}^{st} = 0 \quad \forall v \in V - \{s, t\} \quad (2)$$

Vertex integrity. Every vertex can be used only once by the flow f^{st} . This ensures that node-disjoint primary and backup paths are computed.

$$\sum_{uv \in E} f_{uv}^{st} \leq 1 \quad \forall v \in V - \{s, t\} \quad (3)$$

Flows and Edges. If there is a flow using an edge uv , then this edge has to be used.

$$0 \leq f_{uv}^{st} \leq x_{uv} \quad \forall uv \in E \quad (4)$$

B. Minimum Spanning Subgraph, two-connected (G_{MSS})

Abovementioned constraints are sufficient to form the most simple of the observed subgraphs, which ensures all nodes being two-connected. In order to minimize the overall length of active links (edge weight in the MILP), we define the following objective function:

$$\min \sum_{uv \in E} weight_{uv} \cdot x_{uv} \quad (5)$$

C. Minimum Spanning Tree, two-connected (G_{MST+})

As described in Section III-D2, we first construct a minimum spanning tree, e.g. by using Kruskal's algorithm. Compared to the MILP of G_{MSS} , the variable x_{uv} is set to 1 for all edges uv that are contained in the minimal spanning tree to enforce them being available.

D. Minimum Diameter Subgraph, two-connected (G_{MDS})

For this problem, we use the same constraints and variables as the G_{MST+} . For any two distinct nodes s, t we additionally introduce two unit flows f^{st} , f''^{st} modeling the primary and the backup path, respectively. Both flows satisfy all flow constraints described in Section IV-A for $k = 1$.

The flow f^{st} models the sum of the two flows f^{st} and f''^{st} .

$$f_{uv}^{st} + f''_{uv} = f_{uv}^{st} \quad \forall uv \in E \quad (6)$$

The variable z is an upper bound on the lengths of the primary and the backup path, i.e. it models the diameter.

$$\sum_{uv \in E} f_{uv}^{st} \cdot weight_{uv} \leq z \quad (7)$$

$$\sum_{uv \in E} f''_{uv} \cdot weight_{uv} \leq z \quad (8)$$

Forcing a Low-Diameter Spanning Tree: For each edge $e \in E$ we introduce a binary variable $x'_e \in \{0, 1\}$ indicating whether this edge is used by a primary path or not. This can be ensured by imposing the constraint (4) for the primary flow f' and x' . We also add a constraint to ensure that the subgraph spanned by the primary flow forms a tree.

$$\sum_{uv \in E} x'_{uv} \leq |V| - 1 \quad (9)$$

Objective Function: We minimize a linear combination of the diameter and the total length of the network.

$$\min z + \sum_{uv \in E} x_{uv} \cdot weight_{uv} \quad (10)$$

E. Minimum Diameter Tree, two-connected (G_{MDT+})

We use the same constraints, variables and objective function as in the previous section. Additionally, we precompute a minimum diameter spanning tree and the $x_e = x'_e = 1$ for all edges e of this tree.

V. EVALUATION

To evaluate the effects of providing the reduced topologies as input parameter to a network planning software, we reduce five realistic network topologies prior to supplying it to a network planning software according to the four minimal subgraphs presented in Section III-D.

The evaluated networks are listed in Table I. As resilience mechanisms require two-connected topologies, the original topologies are modified by removing the one-connected nodes so that the observed topologies are fully node two-connected.

The column *Size* of Table I lists the number of nodes $|V|$ and edges $|E|$ of the resulting topologies, after $|V_A|$ one-connected nodes were removed from the original topology.

As exemplary network planning software MuLaNEO (Multi-Layer Network Engineering and Optimization) [10] is used for this evaluation. Based on a supplied fiber topology and the Capex model from the IST NOBEL project [11], MuLaNEO plans the network and emits the resulting costs.

TABLE I: Networks under study.

| Network name and date | | Size | | | Degree d | | Geo location |
|-------------------------------------------------------------------|---------|-------|-------|---------|------------|------|--------------|
| | | $ V $ | $ E $ | $ V_A $ | avg. | max. | |
| Commercial Network Topologies from Topology Zoo [12]. | | | | | | | |
| China Telecom | 2010/08 | 20 | 88 | 18 | 4.40 | 14 | CH |
| NTT | 2011/03 | 25 | 112 | 22 | 4.48 | 11 | Global |
| Research and Education Network Topologies from Topology Zoo [12]. | | | | | | | |
| CESNET | 2010/06 | 19 | 60 | 26 | 3.16 | 8 | CZ |
| GARR | 2010/12 | 22 | 72 | 22 | 3.27 | 8 | IT |
| Rediris | 2011/03 | 18 | 60 | 1 | 3.33 | 10 | ES |

A. Precomputed Subgraphs

Based on the four subgraphs G_{MSS} , G_{MST+} , G_{MDS} and G_{MDT+} , we evaluate the success of MuLaNEO in computing an accepted solution without applying the ADD algorithm.

Table II lists the intermediate results for the five networks. It can be seen that, compared to the original topology G_{ORIG} , Opex costs are reduced for all topologies with all subgraph types, as with each of them at least one edge is removed. However, in most cases, not all demands can be protected using disjoint backup paths, thus resulting in a degree of less than 100% of protected demands. Therefore, except for the China Telecom topology, the returned solutions are almost never acceptable.

However, for the cases when an accepted solution can be computed, Opex savings of 9 to 43% can be achieved compared to the original topologies G_{ORIG} .

B. Evaluations of Accepted Solutions

After evaluating the ability for a planning software to compute solutions based on the pre-computed subgraphs, we apply ADD and DEL from Section III-C. Using DEL, the original graph is reduced step by step. Using ADD, the minimal subgraphs are extended with additional edges until 100% protection is achieved, meaning a primary and secondary path can be determined by the planning software for every traffic demand. The results are shown in Figure 3.

It can be observed that all mechanisms lower the resulting Opex costs. The savings for the GARR topology (red) are with 9-18% already notable, although very low compared to NTT (yellow), which shows potential savings between 39 and 54% because of the high node degrees and thus big potential that links can stay unused. Regarding the resulting Capex, for most of the topologies (except Rediris and GARR based on G_{MDT+}) an increase can be observed compared to the original

| Topology | G_{ORIG} | | G_{MSS} | | G_{MST+} | | G_{MDS} | | G_{MDT+} | |
|---------------|------------|---------|------------|--------|------------|--------|------------|--------|------------|--------|
| | Protection | Opex | Protection | Opex | Protection | Opex | Protection | Opex | Protection | Opex |
| CESNET | 100,00% | 100,00% | 70,76% | 52,72% | 98,83% | 66,64% | 98,54% | 59,65% | 100,00% | 75,05% |
| China Telecom | 100,00% | 100,00% | 100,00% | 56,59% | 100,00% | 59,27% | 100,00% | 56,59% | 100,00% | 67,40% |
| GARR | 100,00% | 100,00% | 99,78% | 79,13% | 100,00% | 91,11% | 99,35% | 85,15% | 100,00% | 87,29% |
| NTT | 100,00% | 100,00% | 66,17% | 37,47% | 96,50% | 45,39% | 64,50% | 37,67% | 99,83% | 60,90% |
| Rediris | 100,00% | 100,00% | 99,67% | 66,43% | 99,67% | 66,43% | 99,67% | 66,43% | 99,67% | 67,71% |

TABLE II: Opex costs relative to G_{ORIG} and degree of protection (configurations not acceptable marked red).

topologies. In these cases, aggregation of traffic requires more expensive equipment for the higher data rates. However, these values are results of the underlying Capex model and not the primary objective of this study. Furthermore, depending on the absolute Opex and Capex costs, this might be acceptable for operators, as higher initial costs can be returned through high savings during operation.

Furthermore, it can be seen that neither the DEL method, nor subgraphs enhanced with the ADD method, show clear advantages for any of the mechanisms. The (dis)advantages of the different subgraph types were explained previously, so that in topologies with characteristics similar to the NTT topology, where the simplistic G_{MSS} results in lower Capex and Opex costs, this graph type might require closer inspection and comparison with the results of more expensive solutions like G_{MDT+} , which tends to result in better network performance through shorter paths.

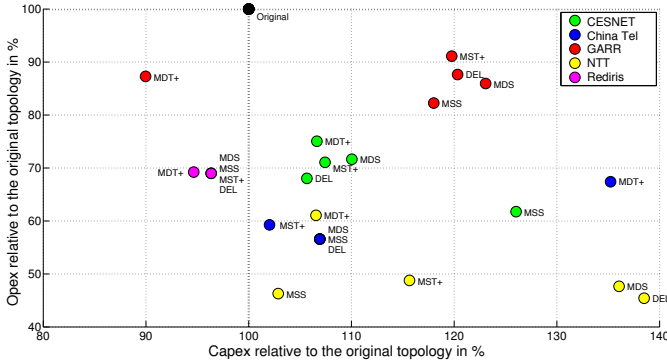


Fig. 3: Comparison of reduced topologies with original one.

VI. CONCLUSION

In this paper, we proposed to modify the planning process for core communication networks in order to reduce the energy consumption and Opex costs. The presented mechanisms avoids a modification of the network planning software and reduce the complexity of the planning software runs, as the size of the network topology used as input parameter is reduced.

By reducing the network topology, the traffic is aggregated to fewer links, as some of the links are removed and thus not available for the planning software. However, our evaluations have shown that pre-computed, minimal two-connected subgraphs are mostly not sufficient. A lack of capacity of the available equipment leads to a lack of resilience in form of backup paths that cannot be realized during the planning process. Therefore, the second part of this work extended these minimal subgraphs by adding the links required to achieve resilience for the given traffic demands.

Our results indicate Opex savings between 9% and 54%. Depending on the applied methods and the observed topology,

the Capex costs ranged between 90% and 140% compared to the original, unmodified topology. Furthermore, while not related to energy savings, unnecessary rent for dark fiber can be avoided, if the network topology still allows equipment to be set up that is able to route and protect all traffic demands.

A definite conclusion, which of the suggested subgraphs minimizes the energy consumption is not possible. Given the fact that the subgraphs show different characteristics regarding performance and resilience metrics, a closer inspection of the resulting topology is required for a particular network topology. However, we showed that our modification always leads to a reduction of the operational expenditures for the given topologies.

VII. ACKNOWLEDGEMENTS

This work was conducted within the Internet Research Center (IRC) at the University of Würzburg. We thank Florian Mayer and Michael Rürger for their programming efforts.

REFERENCES

- [1] K. Hinton, J. Baliga, M. Z. Feng, R. Ayre, and R. Tucker, "Power consumption and energy efficiency in the internet," *Network, IEEE*, vol. 25, no. 2, pp. 6–12, 2011.
- [2] C. Lange, D. Kosiankowski, R. Weidmann, and A. Gladisch, "Energy consumption of telecommunication networks and related improvement options," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 17, no. 2, pp. 285–295, 2011.
- [3] M. Duelli, X. Qin, and M. Menth, "Greedy design of resilient multi-layer networks," in *Next Generation Internet (NGI), 2010 6th EURO-NF Conference on*, June 2010, pp. 1–8.
- [4] F. Idzikowski, "Power consumption of network elements in ip over wdm networks," Telecommunication Networks Group, Technical University Berlin, TKN Technical Report Series TKN-09-006, July 2009.
- [5] A. P. Bianzino, C. Chaudet, D. Rossi, and J.-L. Rougier, "A Survey of Green Networking Research," Institut TELECOM, TELECOM Paris-Tech, CNRS LTCI UMR 5141, Paris, France, Tech. Rep., 2010.
- [6] L. Chiaraviglio and A. Cianfrani, "On the effectiveness of sleep modes in backbone networks with limited configurations," in *Software, Telecommunications and Computer Networks (SoftCOM), 2012 20th International Conference on*, 2012, pp. 1–6.
- [7] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, and A. Tzanakaki, "Energy-efficient wdm network planning with dedicated protection resources in sleep mode," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, Dec 2010, pp. 1–5.
- [8] F. Idzikowski, S. Orłowski, C. Raack, H. Woesner, and A. Wolisz, "Dynamic routing at different layers in ip-over-wdm networks maximizing energy savings," *Optical Switching and Networking*, vol. 8, no. 3, pp. 181 – 200, 2011.
- [9] M. Pióro and D. Medhi, *Routing, Flow, and Capacity Design in Communication and Computer Networks*. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2004.
- [10] M. Duelli, E. Weber, J. Ott, and X. Qin, "Mulaneo: Planung und optimierung von mehrdienstnetzen," *PIK-Praxis der Informationsverarbeitung und Kommunikation*, vol. 34, no. 3, pp. 138–139, 2011.
- [11] "IST Project NOBEL," http://cordis.europa.eu/projects/rcn/71203_en.html.
- [12] "The Internet Topology Zoo," <http://www.topology-zoo.org/>, 2013.