Towards Green Transport Optical Networks: Efficiency, Energy Consumption and Emission-Aware Modeling and Optimization

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***Abstract*—The rapid growth in the number of network users and connected devices, along with users' interest in bandwidth- and computation-intensive services, is driving a significant increase in network traffic and computational load at network nodes. That in turn entails rapidly increasing energy consumption in transport optical networks. The growth in demand for electricity often causes an increase in greenhouse gas (GHG) emissions. Current research primarily focuses on network efficiency and cost optimization, while environmental aspects are either treated as secondary objectives or omitted altogether. Furthermore, many existing studies make use of synthetic or significantly simplified datasets of network energy profiles and resulting emissions, which limits the realism and practical usefulness of the results. The proposed doctoral thesis aims to address and fill literature gaps by gathering real datasets on the energy profiles of existing optical networks and by proposing and evaluating a modeling and optimization framework to design and reoptimize a transport optical network, considering simultaneously its efficiency, cost, energy consumption, and GHG emissions (following its operation).**

***Index Terms*—transport optical networks, network optimization, green networking, greenhouse gas emissions**

I. Introduction

The rapid development of information and communication technology (ICT) has made telecommunications networks a key element of modern life. They shape how both the social and economic sectors function. They support our daily work and education, provide us with entertainment, and enable instant communication with people around the world. Additionally, they facilitate or enable operations in sectors such as finance, public administration, healthcare, and industry.

The ever-growing popularity and versatility of telecommunication networks result in a continuous increase in the number of users and networking devices, users' interest in bandwidth-intensive services, as well as complex network-managing systems allowing to keep networks' high efficiency. That in turn entails a rise in network traffic volume and a growth of computationally-expensive operations in network nodes. Nokia estimates that global network traffic will increase by 5 to 9 times between 2023 and 2033 [1]. This, in turn, leads to increased electricity demand and, consequently, higher greenhouse gas (GHG) emissions. According to data presented in [2], in 2020 the ICT sector accounted for approximately 4% of global electricity consumption, which corresponds to about 1.4% of global GHG emissions.

As a result, telecommunication networks need to continually evolve to meet the ever-increasing traffic volume and the requirements of network users. Nowadays, their development is mostly devoted to software solutions controlling their operations. In that area, the application of data analytics and machine learning (ML) brings noticeable improvements in the network performance [3]. However, it also significantly increases network nodes energy consumption and resulting GHG emissions. Increasing energy consumption is an additional operational cost for network operators, while emissions may affect the natural environment. The European Commission has identified reducing GHG emissions as a key priority for the coming years [4]. Therefore, it is crucial to design and optimize transport optical networks considering not only their efficiency but also cost, energy consumption, and emissions. Please note that energy consumption and GHG emissions are related but not equivalent problems. Emissions depend not only on energy use but also on the type of energy source.

II. Review of Existing Approaches

The problem of energy efficiency and the concept of *green networking* in optical networks have been extensively analyzed in the literature, with both static and dynamic scenarios, each defining *green* in a different way [5].

In static approaches, long-term network configurations are usually analyzed, in which the problem is typically defined as minimizing total energy consumption while maintaining acceptable service quality and bandwidth requirements [5]. The objective functions primarily focus on directly reducing total energy consumption or the number of active network elements [6]. Meanwhile, the constraints include, but are not limited to, meeting traffic demands and topological constraints. Here, *green* is defined primarily as minimizing electricity consumption [5]. The proposed methods are dominated by optimization models (mainly mixed integer linear programming (MILP)) and dedicated heuristics that simplify the computational problem [7]. In dynamic problems, fluctuations in traffic demands are considered, leading to more complex formulations of dynamic routing and resource allocation. Objective functions continue to focus on energy consumption, often through adaptive resource management [8]. Constraints are extended to include service continuity requirements and

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system response time. This field is dominated by heuristics and metaheuristics [9]. More recent works also feature approaches utilizing machine learning [10].

Notably, the literature mainly covers one-objective problems, focusing on either energy consumption or network operational efficiency. Only few papers attempt to optimize more than one criterion. In such cases, multi-criteria approaches are used, though most are reduced to a single objective function by weighted aggregation [11], [12]. The definition of *green* in these studies remains mainly limited to energy consumption, while other environmental aspects are marginalized.

The consideration of GHG emissions is rather rare in the literature. When studied, it is usually covered indirectly by converting energy consumption into emissions using fixed conversion coefficients, without accounting for the variability of energy sources or geographic location [13], [14], [15].

III. Limitations of Existing Approaches

Despite the vast literature on green networks, several significant limitations remain evident. First of all, the existing works were designed for much simpler networks (especially those not implementing complex ML-based control systems), while the performed case studies used unrealistic, overly simplified assumptions. In turn, the research suffers from numerous limitations and should be revisited to meet the requirements of modern, sustainable, and ultra-efficient network systems.

Secondly, existing solutions rarely take a comprehensive, multi-criteria perspective into account. When multiple objectives are considered, they are typically limited to energy consumption and, at times, network performance. The authors of [10] and [16] describe methods aimed at improving the trade-off between network throughput and total network energy consumption. Another article that employs a multi-criteria approach is [11], which aims to maximize the use of renewable energy while maintaining quality of service (QoS). The authors of [9] focus on optimizing energy consumption and network efficiency. To the best of our knowledge, there is a lack of approaches that simultaneously account for a broader set of relevant criteria, such as energy consumption, carbon emissions, operating costs, and overall system performance.

Third, a majority of existing research treats green networks primarily as a problem of minimizing energy consumption [6], [7]. While reducing electricity consumption is an important goal, it does not necessarily translate into a smaller environmental impact. In particular, many studies overlook the GHG intensity of energy supplies [14], [17], failing to account for differences between electricity generated from renewable sources and that derived from fossil fuels, such as coal. As a result, solutions optimized solely for energy efficiency may not lead to a significant reduction in emissions.

And lastly, the credibility and practical application of many approaches and case studies are limited by the nature of the data used. A significant part of the research relies on generalized assumptions or synthetic datasets rather than actual measurements and real data gathered. This limits the credibility and practical applicability of the results, as these data often do not reflect the real conditions and variability characteristic of real-world energy systems and network operations.

These limitations underscore the need for more comprehensive and data-driven approaches. Future research should prioritize the use of real-world datasets specific to particular locations that reflect both energy consumption and associated emissions. Furthermore, it is essential to account for time dynamics and technological diversity in energy systems, while refining multi-criteria optimization methods that better reflect the complex trade-offs inherent in the design of green networks. The considered PhD thesis will address these limitations.

IV. Thesis Research Problem

The thesis will address the identified literature gaps. It will address the modeling and optimization of efficient and simultaneously green optical transport networks. The thesis will define and solve multi-objective problems of network design and re-optimization, taking into account network efficiency, cost, energy consumption, and GHG emissions. The work includes three phases: (*i*) elaboration of real network energy profiles, (*ii*) green network design, (*iii*) green network re-optimization.

The first phase will focus on gathering real data for further study on network design and re-optimization. Firstly, we will select several real optical transport network topologies, including national and European ones. Then, we will identify candidate power plants (and their fuel types) to support network nodes. Next, for each power plant, we will gather historical data on its production levels and associated emissions. We will also gather daily energy prices for each country hosting the power plants. Lastly, we will perform data processing and validation, and develop models to forecast energy-related parameters. In turn, we will create and publish a dataset of real optical network topologies and their energy profiles.

The second stage will cover a static network design problem, in which the optimization objective will be related to network efficiency (spectrum usage), energy consumption, operational cost, as well as GHG emissions following the energy consumption and supporting power plant type. For a given set of traffic services and demands, the network design will affect, among others, the selection of routing rules, the location of particular services in data centers, and the location of data centers in network nodes. Considering the objective definition, we will study two cases. Firstly, a multi-objective task (combining several criteria mentioned before – for instance, spectrum usage and emissions) to balance various optimization goals. Secondly, a one-criterion task (considering each of the criteria subsequently) to investigate the influence of a one criterion on other ones. That procedure will provide a vast and useful case study, enabling network operators to select a beneficial or acceptable network configuration.

The third stage will cover an operational network in which reconfiguration actions (e.g., changes of routing rules, relocation of a data center client or a network service) will be periodically run to improve network performance. Similarly to before, we will consider various performance metrics (bandwidth blocking probability (BBP), power consumption, operational cost, emissions), and try to balance them.

V. Thesis Contribution and Research Questions

The thesis main goals and contribution will be three-fold: (*i*) dataset of energy profiles (with forecasting models) of real optical transport networks; (*ii*) models and algorithms to design new and optimize existing network accounting for their efficiency, energy consumption, cost, and emissions; (*iii*) results of methods evaluation and realistic case studies (on the network performance and relationship between evaluation metrics) enriched with conclusions and recommendations. The thesis realization will verify the following research questions:

RQ1: *What are the most important limitations of the current literature on green transport optical networks?*
RQ2: *Which energy grid parameters influence the most performance of transport optical networks (w.r.t. cost, energy consumption, and emissions) and can be used for optimization?*
RQ3: *Which modeling and optimization methods are the most suitable for the multi-objective network design problem w.r.t. spectrum usage, cost, energy consumption, and emissions?*
RQ4: *Which data analysis and optimization techniques are the most suitable for the multi-objective network reconfiguration problem w.r.t. BBP, cost, energy consumption, and emissions?*
RQ5: *How much can multi-objective modeling and optimization improve the overall network performance (w.r.t. operational performance (spectrum usage or BBP), cost, energy consumption, and emissions) compared to traditional one-objective optimization?*

VI. Methodology

The work will be conducted using a comprehensive set of methods and tools for data collection, modeling, optimization, and experiments. **Data gathering:** Data gathering will be performed manually or using self-implemented dedicated scripts from trustworthy sources (like reputable journals and conferences, government organization websites, recognizable universities and researchers, network operators, and equipment vendors). **Design of models and algorithms:** Following techniques will be used: *Mathematical programming* (MILP); *Decomposition techniques* (branch-and-price); *Constructive greedy heuristics*; *Metaheuristics* (like simulated annealing, tabu search); *Multi-objective optimization* (scalarization methods, Pareto optimization); *ML* (supervised and reinforcement learning); *XAI* (like shapley additive explanation (SHAP)). **Experiments:** The approaches will be evaluated through simulations following a standard scheme, incl. parameter tuning and comparison with reference methods. Non-deterministic methods will be run several times to ensure the results' statistical significance. The results will be statistically tested, using e.g., the Student's t-test, Friedman ranking, and Schaffer post-hoc analysis. Efficiency measures will be spectrum usage, BBP, energy consumption, and emissions. Tests will be run for real networks and realistic transmission models. **Tools for research, data processing:** The student will design and implement most software tools for the thesis, incl. tools for: (*i*) gathering, generating, and processing the data, (*ii*) implementing and testing models and algorithms. MILP models will be implemented using the Gurobi solver. Algorithms will be designed using pseudocodes or flow diagrams and implemented in Python using supported packages. **Equipment:** The research and simulations will be performed on personal computers and supercomputers from *PL-GRID* initiative [18].

VII. Ongoing work

At the time of paper writing, the student has completed: the literature review and identification of existing gaps; selection of network topologies; elaboration of network energy profiles (including the design and evaluation of forecasting models); and design of models and algorithms for green network design. Currently, the student implements network design approaches.

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References

[1] "Nokia global network traffic report 2023-2033," March 2025.
[2] J. Malmodin *et al.*, "Ict sector electricity consumption and greenhouse gas emissions–2020 outcome," *Telecommunications Policy*, vol. 48, no. 3, p. 102701, 2024.
[3] F. Musumeci *et al.*, "An overview on application of machine learning techniques in optical networks," *IEEE Commun. Surv. Tutorials*, vol. 21, no. 2, pp. 1383–1408, 2019.
[4] E. Commission, "Strategic agenda 2024-2029." https://www.consilium.europa.eu/en/european-council/strategic-agenda-2024-2029/. [Online: 10-Jul-2025].
[5] A. Bianzino *et al.*, "A survey of green networking research," *IEEE Commun. Surv. Tutorials*, vol. 14, no. 1, pp. 3–20, 2012.
[6] D. Ottenet *et al.*, "On modelling the power consumption of a backbone network," in *IEEE ICC Workshops 2023*.
[7] L. Chiaraviglio *et al.*, "Reducing power consumption in backbone networks," in *IEEE ICC 2009*.
[8] A. B. Vieira *et al.*, "An sdn-based energy-aware traffic management mechanism," *Ann. Telecommun.*, vol. 77, no. 3, pp. 139–150, 2022.
[9] M. Swamidoss *et al.*, "Next-generation energy-efficient optical networking: Dq-rgk algorithm for dynamic quality of service and adaptive resource allocation," *Concurrency Comput. Pract. Exper.*, vol. 36, no. 16, p. e8070, 2024.
[10] R. Martínez *et al.*, "Enhancing network performance and reducing power consumption in elastic optical networks with deep reinforcement learning," in *ONDM 2024*.
[11] R. Nakamura *et al.*, "A heuristic spatio-temporal scheduling for virtual network allocation considering renewable energy," in *GLOBECOM2023*.
[12] B. Nleya and C. Mulangu, "An overview of green networking and power savings in optical backbone networks," in *icABCD 2018*.
[13] Y. Suh *et al.*, "A study on impact of wired access networks for green internet," *J. Network Comput. Appl.*, vol. 57, pp. 156–168, 2015.
[14] M. Hossain *et al.*, "Energy, carbon and renewable energy: Candidate metrics for green-aware routing?," *Sensors*, vol. 19, no. 13, p. 2901, 2019.
[15] K. Duszyńska and R. Goścień, "Towards green and efficient network traffic prediction," in *ICTON 2025*.
[16] R. Martínez *et al.*, "Autonomous control operations for energy-efficient packet optical networks," in *ICTON 2024*.
[17] V. Schie *et al.*, "Optimizing the total energy consumption and co2 emissions by distributing computational workload among worldwide dispersed data centers," in *IBPSA 2015*.
[18] "PLGrid infrastructure." https://www.plgrid.pl/. [Online: 10-Jul-2025].