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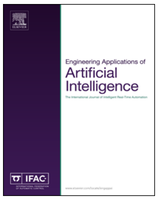

# An evolutionary approach with surrogate models and network science concepts to design optical networks

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Physical topology design of optical networks is frequently accomplished by using evolutionary approaches. However, fitness evaluation for this type of problems is time consuming and the overall optimization process presents a huge execution time. In this paper we propose a new method that uses a multi-objective evolutionary approach to handle the design of all-optical networks. We focused on the simultaneous optimization of the network topology and the device specifications in order to minimize both the capital expenditure of the network and the network performance. Our method uses surrogate models to accelerate the fitness evaluation and a novel network generative model based on preferential attachment to generate the seeds for the evolutionary process. Our approach can provide high quality solutions with a very small execution time when compared to the previous approaches. In order to assess our proposal we performed a set of simulations aiming to analyze the convergence ability and the diversity of the generated solutions for scenarios considering uniform and non-uniform traffic matrices. From our results, we obtained an evolutionary approach that presents better solutions than previous proposals for all analyzed scenarios. Our proposal presents an execution time that is up to 84% and 88% lower than the execution time needed by the previous approaches for uniform and non-uniform traffic, respectively.

## 1. Introduction

The infrastructure of transport networks to provide Internet and other telecommunication services with high bit rate is built mainly by optical technology. Wavelength-routed optical networks (WRON) have been pointed as a promising and economic solution for transport networks. WRONs use reconfigurable high-speed circuit-switched connections, named lightpaths (Ramaswami and Sivarajan, 2010). Each lightpath can be described as an optical channel in a route between a pair of source–destination nodes and may pass through intermediate optical nodes. The possible routes depend on the physical topology. The physical topology design of an optical network implies in choosing which nodes of the network should be connected by using optical fibers. This choice should consider that a higher number of connections between pairs of nodes lead to higher capital expenditure (CAPEX), but can support a higher traffic load (*i.e.* more lightpaths) if these physical connections are properly defined. In all-optical networks, the signal remains in the optical domain through the whole path between source and destination nodes, without any optical–electronic–optical (O–E–O) conversion. Although this type of network presents lower cost, the accumulation of impairments in longer lightpaths can mitigate the quality of transmission (QoT) of the signals due to several physical impairments. Some of the important impairments present in these networks are amplified spontaneous emission noise (ASE), polarization mode dispersion (PMD), chromatic dispersion, crosstalk and nonlinear effects (Ramaswami and Sivarajan, 2010). In general, the signal degradation is related to the quality of the optical devices deployed in the network, and therefore, to the cost of these devices. In fact, the optical network design regards on the trade-off between cheaper devices that present lower performance and expensive devices that present higher performance. Thus, physical topology design of all-optical networks with device specifications is a typical multi-objective problem.

Recent studies in different fields demonstrated that contemporary soft computing techniques can be used to simulate or to forecast behaviors in real-life applications (Taormina et al., 2012; Wu et al., 2009; Zhang et al., 2009; Chau, 2007). Taormina et al. (2012) present an application of artificial neural networks for long period simulations of hourly groundwater levels in a coastal unconfined aquifer sited in Venice. Wu et al., 2009 analyze the accuracy performance of monthly streamflow forecasts when using data-driven modeling techniques on

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the streamflow series from different locations in China. Zhang et al. (2009) used a novel multi-sub-swarm particle swarm optimization (MSSPSO) to find multi-solutions for a multilayer ensemble pruning model and they applied their proposal to a series of experiments using the UCI dataset. Chau deployed a particle swarm optimization (PSO) model to train perceptrons for predicting the outcome of construction claims in Hong Kong (Chau, 2007).

On the other hand, real world optimization problems, such as the design of networks, present specific challenges that should be addressed. First, this kind of problem often presents many conflicting objectives that should be optimized simultaneously. Second, the task of evaluating candidate solutions is usually time consuming and/or expensive for real world problems. It has been shown that evolutionary algorithms can efficiently be used to solve problems with more than one objective (Coello-Coello et al., 2007). These algorithms are called Multi-objective Evolutionary Algorithms (MOEAs). MOEAs generate a set of non-dominated solutions and most of them use the dominance concept. Some MOEAs have also been used to solve problems related to topology design (Knowles and Corne, 2001; Kumar et al., 2005; Zhanga et al., 2011) and to design optical networks (Chaves et al., 2010b; Araújo et al., 2011b; Bastos-Filho et al., 2011). However, multiobjective approaches that consider physical layer impairments present a huge computational cost, because the physical layer impairments are usually evaluated by time consuming network Monte Carlo simulations. For example, the proposal of Chaves et al. (2010b) takes several days to finish a network design process for a 14-node optical network. Thus, despite the recent advances in the design of optical networks, there is not a suitable planning tool for practical purposes due to the high execution time of the current solutions. New studies should consider the trade off between a detailed modelling to design of optical networks and a fast response of the planning tool. On the other hand, recent studies had focused in using surrogate models to assess solutions in evolutionary algorithms in order to decrease the overall time of the evolutionary process (Jin, 2011). Surrogate models are alternative functions that can be used to replace an original fitness function. However, no previous work attempted to use the concept of surrogate models to represent the evaluation of an optical network design. There is an intrinsic difficulty to model the evaluation of an optical network by using surrogate models. This occurs due to the high dimensionality inherent to these types of applications and because the performance of a network under dynamic traffic is closely related to the dynamics of the deployed network and suggests the use of simulations. Thus, the proposal of suitable surrogates for this type of problem is a new and challenging field.

Another important research area that became valuable to analyze several real world problems is the Network Science (Lewis, 2009). Several studies have been proposed to represent the network structure and to analyze the topological features of the network in terms of topological metrics. Topological metrics are quite important to obtain a comprehensive understanding on the impact of the network structure in the network dynamics. One of our hypothesis in this work is that one can map the complex relationships between the parameters of a WRON (including the values for topological metrics) and its performance in terms of blocking probability (*BP*). This could generate a lightweight and accurate surrogate model to be used as a fitness evaluator for evolutionary algorithms deployed to design optical networks. Besides, Network Science can provide useful heuristics to obtain physical topologies that are similar to the ones presented by real networks. Araújo et al. (2013) proposed a first attempt to evaluate *BP* of optical networks based on a machine learning approach, but there is not still any effective way to use this kind of approach as a surrogate model in evolutionary algorithms.

In this paper we propose a new multi-objective evolutionary based approach to handle the physical topology design of optical networks. We use concepts of Network Science to provide an improved initialization operator and we propose an efficient surrogate model. We believe that this work is the first to propose a surrogate model that really works for evaluation of dynamic networks in an evolutionary algorithm. Our proposed method to build and to update the surrogate model is generic and can be deployed to any problem that can be modeled as a graph when a global performance measure is available. The remainder of this paper is organized as follows: Section 3 presents a background about Design of Optical Networks, Network Science and Multi-objective Optimization; Section 4 presents the problem description and representation; Section 5 presents a detailed description of our proposal. Sections 5, 6 and 7 present the simulation setup, results and the conclusions, respectively.

## 2. Theoretical background

This section aims to provide theoretical foundations related to Design of Optical Networks, Network Science and Multi-objective Optimization in order to allow one to better understand our proposal. Section 2.1 provides the theoretical background related to design of optical networks and includes an explanation about recent advances in this field. Section 2.2 provides the theoretical background related to topological metrics of networks and generative procedures to create network topologies with specific properties. Section 2.3 provides the theoretical background related to multi-objective optimization.

### 2.1. Design of optical networks

The design of optical networks can be classified as physical topology design (PTD) and virtual topology design (VTD) (Ramaswami and Sivarajan, 2010). VTD is usually accomplished by embedding the lightpaths over an already deployed physical topology. PTD consists in proposing a fiber topology and optical components. In this work we address the design of optical networks under a PTD perspective. Thus, we provide a more detailed literature review on PTD in this section.

PTD is classified as a NP-hard problem and because of this one cannot find optimal solutions for medium and large networks in a reasonable time (Ko et al., 1997). The computational complexity of the algorithms proposed to solve PTD has an exponential dependency with the number of network nodes. Thus, in order to design real-life networks that present dozens of nodes, several works aim to propose sub-optimal solutions by using heuristics (Xiao et al., 2001; Grover and Doucette, 2001; Liu and Tobagi, 2008) and meta-heuristics (Ko et al., 1997; Morais et al., 2011; Banerjee and Kumar, 2007; Altiparmak et al., 2003). Heuristics techniques use some specific information related to the problem in order to find sub-optimal solutions. Variations of the methods branch exchange (BE) (Gerla and Kleinrock, 1977) and cut saturation (CS) (Boorstyn and Frank, 1977) are very common in previous works related to heuristics approaches for PTD. On the other hand, meta-heuristics are general purpose algorithms that can be used for a given family of problems. In this line, we can cite some meta-heuristics used in previous works to tackle the PTD problem, such as simulated annelling (Xiao et al., 2001; Grover and Doucette, 2001; Liu and Tobagi, 2008; Altiparmak et al., 2003) and genetic algorithms (Ko et al., 1997; Morais et al., 2011; Banerjee and Kumar, 2007; Sayoud et al., 2001).

Although PTD has been studied for many years for electronic networks, we can cite only few works that aim to propose specific solutions to design optical networks. Besides, most of the works related to design of optical networks uses a modelling that considers static traffic (Xiao et al., 2001; Xin et al., 2003; Liu and Tobagi, 2008; Morais et al., 2011). Another simplification in modelling is to propose methods to minimize only one objective function, such as the network cost (Xiao et al., 2001; Sayoud et al., 2001) or the number of used wavelengths (Xin et al., 2003; Liu and Tobagi, 2008). When only one objective function is considered, we are ignoring that a network design presents conflicting objectives (cost *versus* network performance or energy