European Journal of Operational Research 240 (2015) 361–371

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Discrete Optimization

Single PON network design with unconstrained splitting stages

Luís Gouveia [a,1], Maria João Lopes [b,c,*], Amaro de Sousa [d,2]

[a] CIO-DEIO, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Instituto Universitário de Lisboa (ISCTE-IUL), Av. das Forças Armadas, 1649-026 Lisboa, Portugal
[c] CIO, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[d] Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:
Received 27 September 2013
Accepted 2 July 2014
Available online 11 July 2014

Keywords:
OR in telecommunications
Network design
Integer linear programming
Passive optical networks

ABSTRACT

A Passive Optical Network (PON) is a network technology for deploying access networks based on passive optical components. In a single PON access network, the client terminals are connected to a Central Office through optical splitters and interconnecting fibers where each splitter splits in equal parts the input optical signal coming from the Central Office over its different output fibers. In this paper, we consider PON topology solutions where the splitting ratio and the number of splitting stages are not constrained to a given target design but, instead, are decided based on the cost of the solutions. We present different Integer Linear Programming formulations to model this problem and provide computational results showing that the optimal solutions can be computed for realistic problem instances. In addition, we describe how the formulations can be adapted for the traditional PON topology approaches and present computational results showing that significant cost gains are obtained with the unconstrained splitting stage approach.

1. Introduction

In access networks based on passive optical components, a Passive Optical Network (PON) connects an output port of an OLT (Optical Line Terminal), located in a Central Office, to a set of ONUs (Optical Network Units), one for each client (herein, designated as client terminals). Such connections (from the Central Office to the client terminals) are based on passive optical components, i.e., optical splitters and fibers. When the number of client terminals is larger than the capacity of a PON, multiple PONs are deployed, each one corresponding to one output port of the OLT.

In this paper, we address the single PON network design problem in the context of densely populated urban scenarios. In these scenarios, client terminals are concentrated on a small number of locations (i.e., buildings) which enables us to model the problem with fewer variables and constraints. In the general case, the length of the path from the Central Office to each client terminal, and the number of splitters on it, is constrained by the maximum optical power that can be sent by the Central Office and the power loss suffered by the optical signal on fibers and splitters. In densely populated urban scenarios, though, distances between the Central Office and the client locations are short and such constraints do not need to be considered. Moreover, network infrastructures, like ducts or fiber cables, are usually available in these scenarios (or can be used from other utility entities) which enable us to model connection costs by a cost per fiber model.

In the single PON network design problem, we have to decide where to install splitters and how to interconnect all network elements (Central Office, splitters and client terminals) through optical fiber connections. Splitters are optical devices that split in equal parts the optical signal coming from the Central Office over their output ports in a power of 2; this is the splitting ratio of the splitter, which can be 1:2, 1:4, 1:8 and so on. There are costs associated with the different splitter types (defined by their splitting ratios) and splitter locations and there are costs associated with fiber connections which are higher for longer fibers. The objective is to determine the minimum cost PON configuration.

Current research dedicated to PON network design usually assumes a PON capacity of 64, i.e., each output port of the OLT hosted in the Central Office can connect a maximum of 64 client terminals to the network. Nevertheless, it is foreseen that in the near future the capacity of the PONs will evolve to 128 or 256 client terminals as pointed out in ITU Standard (2010).

Most of recent works (an overview of these works is presented in next section) address the multiple PON network design problem

* Corresponding author at: Instituto Universitário de Lisboa (ISCTE-IUL), Av. das Forças Armadas, 1649-026 Lisboa, Portugal. Tel.: +351 217 903 228.
E-mail addresses: legouveia@fc.ul.pt (L. Gouveia), mjfl@iscte.pt (M.J. Lopes), asou@ua.pt (A. de Sousa).
[1] Tel.: +351 217 500 409.
[2] Tel.: +351 234 370 052.

http://dx.doi.org/10.1016/j.ejor.2014.07.006
0377-2217/

where a set of clients are to be connected through more than one PON because the total number of clients is higher than the capacity of a single PON. This is a very complex optimization problem since besides the design of each PON, this problem also includes the clustering of client terminals to PONs. Due to its complexity, the multiple PON network design problem is tackled with approximate methods. Such solution techniques are of interest for quickly finding solutions in the evaluation process of many different network scenarios and for deciding which PONs should be implemented and which client terminals should be connected to each PON. Nevertheless, for the final network design, exact methods that can find optimal solutions for each PON are preferable.

In this work, we address the single PON network design case, i.e., we assume that the clustering of client terminals to PONs has been previously decided and each PON design must be individually determined. Unlike most of previous works, we consider a PON topology where the splitting ratio and the number of splitting stages are not constrained to any target design but, instead, are decided by the optimization task based on the minimum cost objective. Unlike the traditional approaches, where the single PON network design is easy for real size problem instances, this is a hard problem as it will be seen in the computational results.

We start by presenting a generic model for the single PON network design problem, which is non-linear. Then, we propose several ILP (Integer Linear Programming) models and test them by solving test instances with up to 256 client terminals (a PON capacity value which is foreseen in the near future). In the context of the computational results, we compare the efficiency of the different models and show that the most efficient modeling alternatives are able to solve to optimality all problem instances.

In addition, we describe how the proposed models can be adapted for the traditional PON topology approaches. We present computational results that compare the obtained optimal costs between the different approaches. These cost comparisons show that significant cost gains are obtained for PONs of larger capacity with the unconstrained splitting stage approach when compared with the traditional approaches.

The paper is organized as follows. Section 2 describes the optimization problem and overviews the recent works on PON network design. Section 3 presents the several modeling alternatives to the problem. Section 4 presents and discusses the problem instances and the computational results. Finally, Section 5 presents the conclusions and the issues for future research.

2. Problem description

Consider the example shown in Fig. 1 defining the location of the Central Office (where the OLT is hosted) and of the client terminals that must be connected in a total of 64 client terminals (numbers close to client locations indicate the number of client terminals). Fig. 1 also shows the potential locations for the splitters.

The simplest possible PON configuration considers a single splitting stage. In this case, the Central Office is connected to a splitter and this splitter is connected to the individual client terminals. Since the number of terminals is 64 in our example, the splitter must have a splitting ratio of 1:64 (as illustrated in Fig. 2). In the downstream, the optical signal sent by the Central Office is split in equal parts by the splitter among all its output ports. This solution minimizes the cost associated with splitters while penalizing the cost associated with fibers. Note that if the number of terminals is lower than 64, but higher than 32, a splitter with splitting ratio 1:64 is still required although some of its output ports are not in use.

Some recent works have considered single splitting stage solutions in the design of multiple PONs in the context of greenfield

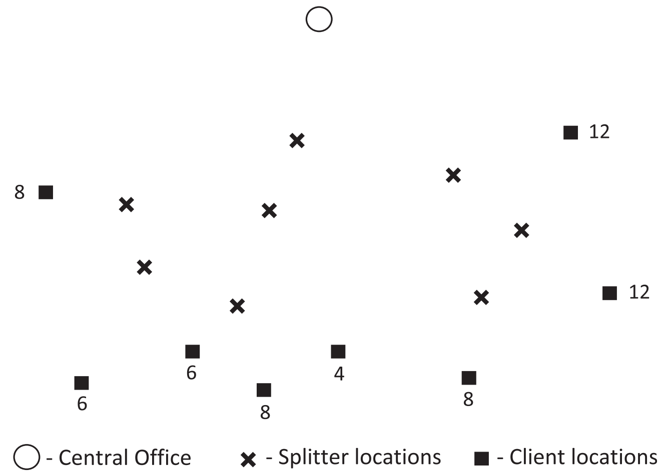

Fig. 1. Central office, splitter and client locations.

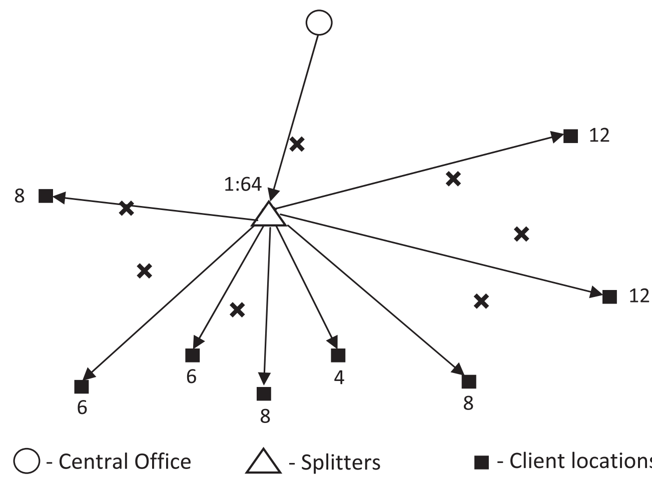

Fig. 2. A single splitting stage solution.

scenarios, i.e., scenarios where no infrastructure exists and its deployment costs must be considered in the optimization task. Approximate solution methods are proposed both in Bley, Ljubic, and Maurer (2013) and in Li and Chen (2009) where this last work also considers maximum length constraints to the fiber lengths of each PON.

A more flexible solution is to consider two splitting stages, which often arises in practice. In this case, the Central Office is connected to a first stage splitter, then this splitter is connected to different second stage splitters and, finally, these splitters are connected to the individual client terminals. In Fig. 3, we illustrate a two splitting stage solution where the splitting ratio is 1:4 in the first stage and 1:16 in the second stage (note that other splitting ratios can also be adopted on each stage). As in the previous case, the optical signal sent by the Central Office must be split in equal parts by 64 before reaching each client terminal. Nevertheless, in this case, the split of the optical signal is distributed by the two splitting stages instead of being done on a single splitting stage (as in the previous case): it is first split by 4 in the first stage (the number of terminals served by each of these output connections is $64/4 = 16$) and, then, each of these output signals is split by 16 in the second stage (the number of terminals served by each of these output connections is $16/16 = 1$).

Note that, in this case, the client terminals in the same location can be connected to the network through different splitters (in