# OPTIMIZATION OF MULTIPLE UDWDM PON DEPLOYMENT BASED ON PHYSICAL RESTRICTIONS AND ASYMMETRIC USERS' CLUSTERING

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## NOTA DE ACEPTACIÓN

Presidente del Jurado

Jurado

Jurado

Definir

# Declaración de originalidad

Medellín, 29 de noviembre de 2016.

**Yo, Germán Vicente Arévalo Bermeo**

“Declaro que esta tesis de grado no ha sido presentada para optar a un título, ya sea en igual forma o con variaciones, en esta o cualquier otra universidad”, Art 18 Régimen Dicente de Formación Avanzada.

Firma

*"To Katy, Adrián and Maty"*

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# Abstract

The problem of finding the optimal topology for a set of users can be treated as a Steiner Tree optimization problem, which is a NP-Hard problem. Therefore it must be employed an heuristic approach in order to find solutions for this type of problems. On the other hand we have the problem related with selecting the PON technology proper to the scenario under consideration, regarding the users' bit rate demand and the desired scalability. The current thesis manuscript details the justification, objectives, and results obtained in my doctoral research work, which is centered in the study of a multiple UDWDM PON deployment, for a very large number of users with different bit rate requirements, taking into account equipment-capacity and physical layer restrictions as well as the costs' comparison of deploying standardized PON technologies vs. an UDWDM PON implementation.

# Chapter 1

# Scope of the project

This chapter describes the objectives and justification of the need and interest that exist regarding the topic of the optimal dimensioning of multiple Ultra Dense Wavelength Division Multiplexing (UDWDM) Passive Optical Network (PON) for a very large number of users with different traffic demands (i.e asymmetric users). First, it is described the problem and then the objectives and contributions of this research work.

## 1.1 General description of the problem

Due to the many unresolved problems currently confronted in the development of next generation optical access networks, Wavelength Division Multiplexing (WDM) PON has been a very popular topic of research in recent years. In this trend of interest it is also popular the techno-economics study of this type of networks looking for cost-effective deployment strategies [69][21][100]. Particularly, UDWDM PON constitute a promising technology because they will be interesting for next-generation after Next-Generation Passive Optical Network - Version 2 (NGPON2). Many research works study and propose new technological solutions for implementing low-cost Optical Line Terminal (OLT) and Optical Network Unit (ONU) equipment in order to render economically feasible such networks in the future [75][85][74][76][88][90][96]. The development of UDWDM PON solutions confront a series of challenges like hardware costs, complexity of the technology required for transmitters and receivers, nonlinear effects due to the close spectral proximity among channels [2][78][15][4][93], among others.

There are many proposals of topologies for next generation optical access networks [103][59]. Nevertheless, regarding PON, the predominant topology type, which is also the only one that has been standardized, is the tree-topology [70]. The most widely deployed PON topology is the splitter-cascaded based tree topology. Therefore, a very popular and interesting topic of research is the study of optimization schemes for optimal tree-topology planning/dimensioning for conventional and next generation PON [94][58][62]. In addition, the only standardized transmission technique, previous to NGPON2 was Time Division Multiplexing (TDM) PON. In fact, a step towards WDM PON is the new NGPON2 standard, which specifies an hybrid TDM/WDM transmission employing four Dense Wavelength Division Multiplexing (DWDM) wavelengths, keeping compatibility with legacy Optical Distribution Network (ODN) [70][68][91]. Also, some research works have reported proposals for an upcoming NGPON3 standard based on WDM PON [96].

However we haven't been able to find any research work report covering the optimal dimensioning of UDWDM PON in confront with the dimensioning of other standardized types of PON. And, due to the the particular characteristics and potential performance of the UDWDM PON. Therefore, the question related with the research covered in this thesis would be: is UDWDM PON the most suitable network-access technology for attending the mid and long term increase of bit rate demands from residential and corporate users of Internet in a large region with many users serviced by multiple central offices?. Based on such question we found out that the study of the optimal dimensioning of this networks constitute a very interesting topic to be covered, specially when considering the implementation of multiple PON in large regions with very large number of users with heterogeneous bit rate requirements [33].

Accordingly, in the doctoral research work presented in this document we consider PON topologies whose ODN is deployed as splitter-cascaded based multilevel trees, and whose network provider's equipments (i.e. the so called OLT) are placed in many different Central Office (CO) buildings. Given that the UDWDM transmission technique permits a very optimal use of the available spectrum, we consider that the OLT is composed with at least $N$ transmitters and receivers tuned to a different wavelength one to each other [85]. Therefore, such OLT is able to service up to $N$ users, where every user send and receive data employing a unique wavelength in the network. The ODN is composed by optical links and switching equipment (also called branching equipment), e.g. splitters, which provide the required physical connectivity between the OLT and the ONU.

## 1.2 Objectives

### 1.2.1 General objective

To propose an algorithm for optimal dimensioning of multiple PON deployment based on physical restrictions and asymmetric users' clustering in wide regions with a very large number of users with different demands of sustained bit rate. And, employ the algorithm for comparing the overall cost of different solutions: Gigabit-capable Passive Optical Network (GPON), 10-Gigabit-capable Passive Optical Network (XGPON), NGPON2 and UDWDM PON.

### 1.2.2 Specific objectives

**Clustering:** To find an effective approach for clustering users in a wide region with very large number of users to be covered through a multiple Passive Optical Network (PON) deployment.

**Optimization:** To develop an street-aware optimization scheme for multiple UDWDM PON deployment in wide regions with very large number of residential and corporate users with different bit rate demands.

**Evaluation:** To evaluate the model in order to characterize its performance and effectiveness by means of performing a cost comparison of multiple UDWDM PON deployment with other standardized PON deployments like GPON, XGPON and NGPON2.

## 1.3 Contributions

This work presents the following contributions:

**Clustering:** An effective approach for clustering a region with randomly placed users, according to the population distribution, in order to optimally assign PON hardware to them.

**Optimization:** An optimization scheme, based on heuristic approaches, for street-aware optimization of multiple UDWDM PON topology planning taking into account the optical fiber data transmission impairments, the PON equipment capacity and a wide area with very large number of users with different sustained bit rate demands.

**Comparison:** A deployment cost comparison between UDWDM PON and other standardized PON like GPON, XGPON and NGPON2, employing the developed optimization scheme, in order to analyze the prospective of each PON technology in the future.

## 1.4 Organization of the manuscript

This thesis manuscript has been organized as follows:

Chapter 1 presents the description and objectives of the problem covered in the thesis. Chapter 2 covers the study of the state of the art regarding recent developments in the optical access networks and current technologies proposed for implementing UDWDM PON. Also, in that chapter, we review the most popular and successful models so far proposed for optimal dimensioning of PON. In Chapter 3 it is described the scenario and reference costs used for developing this research. In chapter 4 the optimization problem formulation is described. Chapter 5 presents a detailed explanation of the heuristic approach employed for resolving the optimization problem. Next, in chapter 6 we present the results obtained in this research by means of employing OTS for processing realistic maps data for different cities: Turin, Rome, Medellín and Quito. Finally, chapter 7 concludes this work.

# Chapter 2

# State of the art regarding UDWDM PON

This chapter describes the state of the art regarding the optimal dimensioning of PON and the most popular technological solutions proposed for UDWDM PON deployment. We focus particularly in the most recent developments for next generation PON transmitters and receivers and the optimization techniques employed for next generation optical access networks.

## 2.1 Next generation optical access networks

Next generation passive optical networks are able to offer data rates beyond 10 Gb/s as is evident in the recently released ITU-T G989 series standards (i.e NGPON2 standards) [43][70]. Then, many research works confirm that a possible future step in PON would be towards pure WDM with more wavelengths in the network [43][77][100]. The downstream (DS) transmission depends on the equipment in the optical line terminal (OLT) and for that reason it is less cost-sensitive than the upstream (US) transmission, which in the other hand depends on the equipment at the ONU. Nevertheless, OLT equipment must also be economically attractive to the service providers. Therefore, one of the most challenging problems related with the commercial deployment of these networks, is the development of low-cost and high-speed colorless optical equipment for implementing OLT and ONU [11][100]. The "COst-effective COhereNt Ultra-dense-WDM-PON for $\lambda$-to-the-user access" (COCONUT) project, supported by the European Union, looks for the development of low-cost coherent technology to allow a future massive deployment of UDWDM PON [96].

Many research works cover the study of low cost solutions for WDM PON [21]. Some propose the use of low-cost tunable lasers [6], other propose the remodulation of the downstream signal [26] and other propose the spectrum slicing of a shared broadband light source (BLS) for seeding the reflective modulators at the ONU. In [52][19] it is reported a low cost WDM PON employing intensity modulation and direct detection up to 10 Gb/s by means of transmitting RZ coded signals with a duty cycle in the order of 75%. In addition, a considerable amount of research is already proposing solutions for UDWDM PON transmitters and receivers in OLT/ONU equipment, mainly using coherent transmission techniques [92][39].

In the research developed by authors in [85], it is reported a system which demonstrates the feasibility of the coherent transmission technologies for supporting the evolution of access networks towards UDWDM PON. In very recent paper [86] authors present trials of UDWDM PON transmission over currently deployed fiber, testing the performance for Long Term Evolution (LTE) backhauling and for coexistence with other networks like GPON and 100 Gb/s systems. In [31][32] authors discuss the use of Reflective Semiconductor Optical Amplifier (RSOA) as low-cost solutions for data coherent transmission at 2.5 Gb/s and 3.125 Gb/s, respectively, in UDWDM PON. It has been evidenced that this technology could enhance the power budget available and, in consequence, provide service in larger geographical areas and for more users, as evidenced in [96]. A very promising low cost solution for rendering commercially available the coherent transmission is avoiding the use of expensive external modulators through the use of directly modulated thermally tuned Distributed Feedback Brag-reflector (DFB) lasers with coherent homodyne receiver, as reported in [18]. Yet, the coherent transmission technologies still need to be enhanced for providing cost-effective commercial solutions [75].

An important limitation of performance in bidirectional UDWDM PON is the cross talk caused by backreflections and nonlinearities, specially Four-Wave Mixing (FWM) and Cross Phase Modulation (XPM) [4]. In [61][81] authors analyze the causes of back-reflections as a phenomenon mainly produced by the propagation of the same wavelength-channel in the same optical fiber and due to defective network equipment. The use of Nyquist pulse shaping combined with multilevel modulation techniques permit optical channels to become stronger in front of crosstalk and nonlinear effects and achieve very high aggregated data rate capacity [17].

In [81] a 192 x 10 Gb/s UDWDM PON is demonstrated. Nevertheless, even when using coherent transmission and Nyquist pulse shaping, UDWDM PON are still highly limited by nonlinear effects [80][79]. In [90][89] it is described a bidirectional PON with 2 x 12 x 10 Gb/s US and DS UDWDM channels by means of using a 16-ary Quadrature Amplitude Modulation (QAM) modulation and Nyquist pulse shaping, avoiding the necessity of a local oscillator (LO) in the laserless-ONU thanks to the use of polarization multiplexed pilot tones. [34] Reports the use of Nyquist-independent-sideband (N-ISB) modulation for improving the throughput in coherent UDWDM PON up to 12 Tb/s, by means of employing 75 sub carriers, each one of them with 16 x 10 Gb/s channels. A method for reducing the impact of inter-channel FWM in UDWDM PON is reducing the splitting factors to 1:8 or lower and employing unequal spacing between channels [82]; however, such solutions means more complexity and sub-optimal reuse of the currently installed ODN.

It also has been studied the problem of rendering technically feasible the use of multiple individually modulated wavelengths out of a single laser source, mainly due to the problems related with frequency offsets. Some advances has been achieved regarding such problems, as the system reported in [84] which describes a solution for transmitting Gigabit-Ethernet-encapsulated real time video in a coherent UDWDM PON including the use of real-time digital signal processing (DSP) techniques in the ONU.

On the other hand, the problem related with the wavelength assignment has two perspectives. First, the perspective based on the premise that there are as many wavelengths as users demanding the transmission of data, in such case the wavelength assignment is a trivial problem since every user is assigned with a different wavelength. Second, the consideration that there are fewer available wavelengths than users and, in consequence, it is necessary to provide a time-slot allocation procedure. The most popular techniques are the Dynamic Bandwidth Assignment (DBA) or Dynamic Wavelength Assignment (DWA) scheduling algorithms (or heuristics) often based on Integer Linear Program (ILP) or Mixed Integer Linear Program (MILP) [101]. Models reported in [98][101] make use of Markov chains in order to assess the dynamic wavelength allocation in TDM-WDM PON.

Some models combine the problem of optimal ODN dimensioning with the routing assignment, as in [65] where the authors describe a dynamic routing and wavelength assignment model for WDM PON, taking into account the crosstalk caused by FWM nonlinear effect as a cost parameter for the best route selection. The approach reported in [55] proposes a scheduling algorithm for WDM PON which employs a Tabu search heuristic, providing near optimal results in short times. Employing the same heuristic approach, this authors further address the problem of WDM PON and 10 Gb/s Ethernet Passive Optical Network (10GPON) coexistence though a scheduling algorithm for wavelength/bandwidth allocation in [54]. In [55] it is also employed a Tabu search heuristic approach for finding a scheduling and transmission grants' joint solution in WDM PON. Regarding nonlinear effects in UDWDM PON, some DWA algorithms consider the mitigation of FWM in the wavelength allocation, as described in [15]. As reported in [87], DWA could be a feasible solution to the limited tunability range of low-cost thermally-tunable DFB lasers. The design of OLT for statistical UDWDM PON (SUDWDM PON) in [88] takes into account a maximum admitance (MA) DWA algorithm in order to efficiently distribute the wavelength spectrum among 256 users. In a similar approach, [20] proposes an ILP formulation for resolving the placement of the so called Base-Band Units (BBU) in order to optimally assign resources to Radio Stations in convergent Fixed/Mobile WDM PON.

Regarding the study of optimization schemes for ODN topology design and planning in PON, the approach most of the optimization models employ is a green-field design-planning model for searching the minimum-cost tree-topology for a set of users, which for practical proposes are randomly placed users. The ODN cost mostly evaluates the Capital Expenditures (CAPEX), related with the optical fiber and switching equipment costs, but some models consider also the Operational Expenditures (OPEX) [60][24].

Hence, generally the problem is confronted as an integer linear programming or mixed integer linear programming optimization problem, subject to some restrictions based on the optical fiber length and on switching equipment amount and capacity (among other physical restrictions like the systems' power budget and flow aggregation) [5][8, 9, 10][22][27][28][29][30].

Under the general conditions regarding the PON deployment in a geographical region, the set of links connecting a set of randomly placed users in the region can be considered as a weighted-bounded graph [71][83]. Hence, the problem related with the optimal topology search for connecting the users' end equipment with the providers' equipment can be considered essentially a weighted Steiner tree problem [104][12][83], which is a well-known NP-hard problem [16][25][37][38]. Therefore, it is generally employed some heuristic approach in order to find a feasible, near-optimal, solution in polynomial time [42][51][67].

Research reported in [94] describes an ILP model for traditional PON optimal deployment based on flow aggregation in order to achieve a better computational efficiency. This model is also suitable for multi-fiber mesh networks with or without wavelength conversion. However, this model is not useful for planning complex next-generation PON since it do not consider the particularities of employing new transmission technologies. Authors in [58] employ a genetic algorithm (i.e. a heuristic approach that applies the natural genetic ideas of natural selection, mutation and survival of the fittest "individuals") and mathematical modeling techniques to optimize a two-hierarchy TDM PON by means of selecting the position of primary and secondary nodes and their split-levels. This model do not consider the use of more than one wavelength in the network.

Research in [62] reports the use of a Recursive Association and Relocation Algorithm (RARA), which employs the Simulated-annealing heuristic for resolving the optimization problem of minimizing the deployment cost of cable and conduit sharing in TDM PON. Paper referenced in [35] describes an ILP model and a heuristic procedure for optimal deployment of two-stage TDM PON taking into account equipment and installation costs (CAPEX) and operational costs (OPEX). The results presented in the paper indicate that OPEX is a very important contributor for the network overall cost. In [63] it is presented an ILP model for minimizing the optical fiber and splitters costs in long-reach PON by means of employing a partition-recursive heuristic approach. Since the cost of the optical fiber installation is by far the most expensive expense in a PON deployment, this paper concludes that a cascaded splitter topology requires lower length of optical fiber and in consequence is less expensive than the single-splitter topology. Figure 2.1 shows an illustration that compares one-stage and multi-stage topologies for the same set of users.

Regarding the optimal deployment of pure WDM PON, a critical parameter constitute the allocation of the remote switching equipment, based in the geographical location of the OLT and ONU, as evidenced in [49]. In that paper, it is used a column generation (CG) algorithm for selecting the best multi-stage topology. The research work reported in [27] propose a cross-layer optimization scheme for greenfield topology planning in the specific case of two-hierarchy WDM PON. The ILP model employed in that paper takes into account power attenuation and splitting ratio (SR), and includes restrictions related with the aggregated-traffic-demands by means of considering in the model the number of wavelengths carried by the optical fibers. Such model do

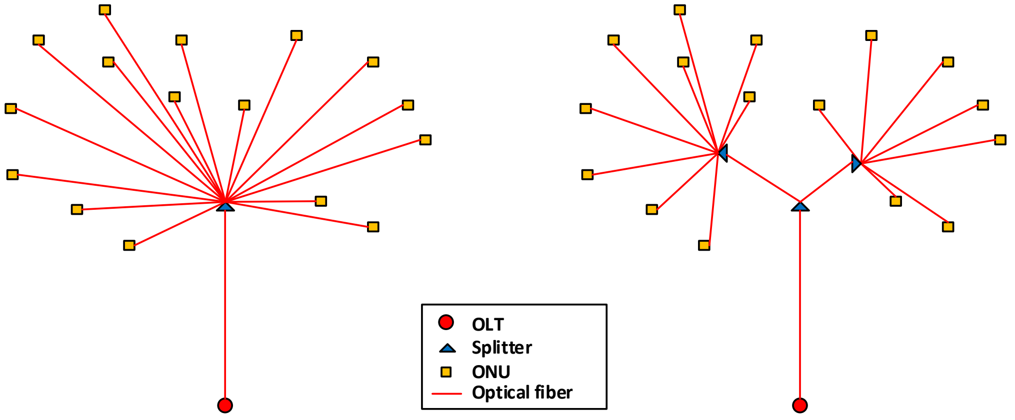

Figure 2.1: Typical PON Tree-Topologies: (a) One-stage (one remote node) Tree-Topology; (b) Multi-stage (cascaded splitter) Tree-Topology [8].

not includes any other type of optical fibers' physical impairment (other than power attenuation) and do not scale to a general multi-hierarchy WDM PON. Authors in [104] propose a divide and conquer heuristic, which is a recursive partition−combination algorithm, for minimizing the cost of arrayed waveguide grating (AWG) and optical fiber deployment in WDM PON. Nonetheless, this work considers a fixed International Telecommunications Union (ITU) WDM grid and is not exhaustive regarding the transmission impairments in the network.

Authors in [33] aim to find an optimal selection of transmission technologies for TDM/WDM and pure WDM PON, as a trade-off among complexity, capacity, and reach. The proposed model uses restrictions related with power budget and the type of passive optical components in the remote nodes. In addition, it employs restrictions related with the cost of the OLT and ONU equipment based on the equipment's level of complexity. The model looks for the lowest total-complexity-cost by means of a heuristic recursive search. The previously mentioned paper concludes that for a large number of users with medium to high traffic requirements, it would be necessary to deploy a pure WDM PON. In [5] authors of the previously described paper extend their work for resolving it through a MILP formulation, instead of employing heuristics. This work provide a cost sensitivity study for the technologies based on coherent detection, remarking the feasibility of their implementation in near future.

In relation to the survivability of PON, some papers propose different techniques, like in [95] where is proposed a long-reach hybrid TDM/WDM PON with mesh topology, based on redundant links connecting the AWG and splitters. Authors of the paper describe a heuristic algorithm called MeshLIP, which starts from a feasible network topology and then improves it by inserting chances in the topology in order to achieve the survivable network while minimizing the total length of fiber deployment. However, this model do not take into account any restriction related with channels' capacity and transmission impairments. Research reported in [53], by means of the use of a MILP based approach and a heuristic algorithm called Locate-ONU-with-Lowest-Availability-Requirement-First (LOWLARF), proposes a model for planning survivable long-reach PON, with 99.999% of availability, aiming to achieve the largest possible area of coverage. The heuristic LOWLARF consists on a recursive search of optimal solution over a weighted matrix, bounded by the problem's related restrictions.

An interesting topic generally not taken into consideration in PON planning is the modeling of the uncertainties regarding who and where the customers will be. Regarding that approach, [22] reports a model for optimal allocation of splitters and routing fibers in Fiber To The Home (FTTH) deployment using a mixed integer linear formulation applying problem size reduction schemes to overcome the NP-hard nature of the problem. That paper suggests it would be interesting to perform the research of optimization problems based on planar graphs in order to confront the factor of uncertainties in the problem.

Some models propose a street-aware solution. In the research referenced in [7] we describe an ILP model for optimal deployment of multi-stage DWDM PON in Manhattan regions. In order to resolve the problem we employed a heuristic approach based on Dijkstra's algorithm for finding the minimum rectilinear Steiner tree (Fig. 2.2). Another paper focused on street-aware topology design is [57] which describes a model for dimensioning next generation optical access networks, based on real street maps. The model proposed in that paper starts from a heuristic clustering algorithm for the assignment of ONU focusing on the conduit sharing optimal deployment.

Most optimization models look for an optimal selection of switching and network equipment locations. [56] Presents an MILP optimization model for PON whose formulation looks for the most cost-effective splitter's location-allocation. The solution approach is based on the "multi-level capacitated

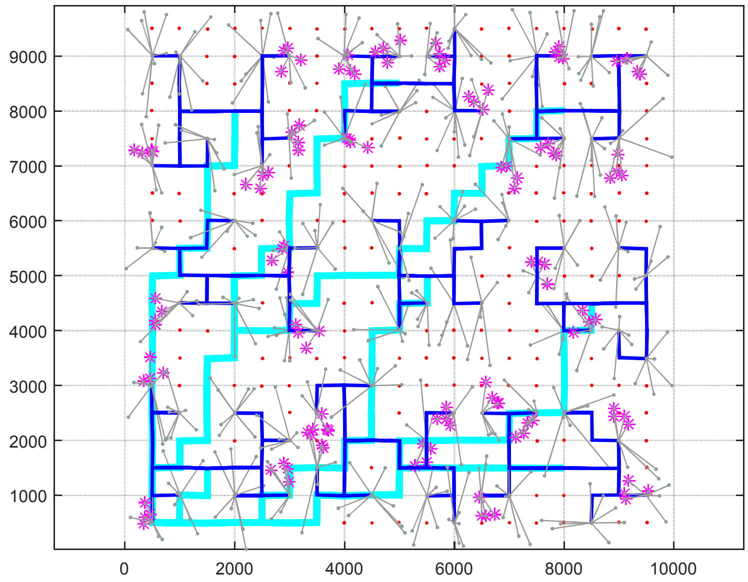

Figure 2.2: Example of PON optimal topology in a Manhattan region, based on the minimum Steiner tree search [7].

facility location problem", considering nonlinear link costs and a local search heuristic procedure. The heuristic algorithm moves splitters toward the root splitting node and then toward the leaf splitting nodes, comparing the overall cost in each movement. In [30] it is reported an algorithm for GPON optimal deployment based on an Ant Colony Optimization (ACO) method combined with post processing metaheuristics for recursive local search of a minimum. In [64] authors use an ILP optimization model for deploying low-cost long-reach PON with cascaded optical amplifiers. For the optimal splitters/optical-amplifiers allocation uses a dimensioning algorithm based on power budget (i.e. fiber attenuation, optical losses in network elements, amplified spontaneous emission, etc.).

Some research works start from finding optimal clusters for the of users set, as the model reported in [97] which employs a heuristic based in the k-means algorithm for building users' clusters in order to optimize the duct sharing and deployment cost in PON. Research in [73] proposes a heuristic approach based on an agglomerative clustering for resolving an ILP model formulated in order to minimize the PON optical fiber costs in a rural areas with sparse users. The agglomerative clustering heuristic employed

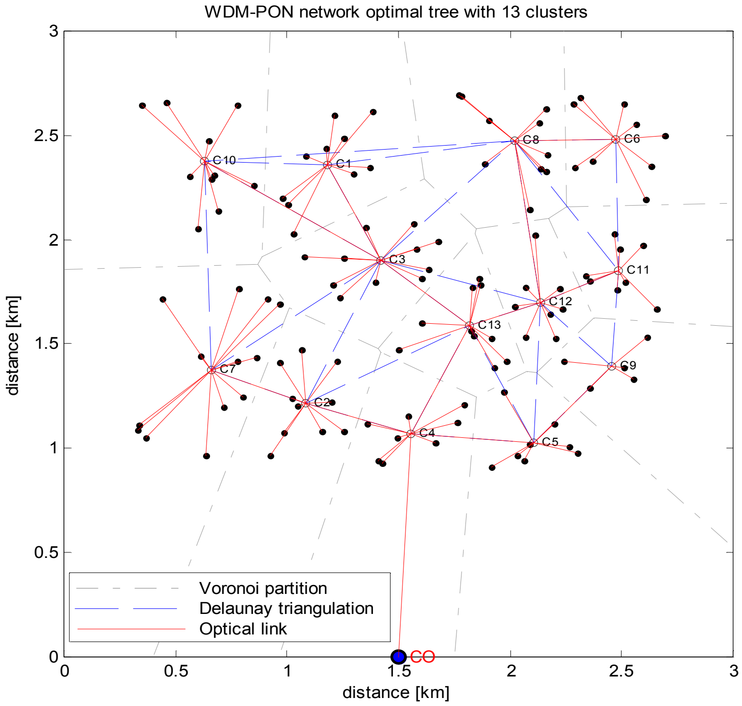

Figure 2.3: Example of PON optimal topology, based on the EMST search over a Delaunay triangulation [10].

in that paper performs a recursive search for the optimal splitter allocation trying to set first the higher capacity splitters and then comparing results when replaced with lower capacity splitters. Research work reported in [66] uses a Simulated Annealing metaheuristic starting from a clustering scheme based on Voronoi's partitions in order to design an optimal tree topology for PON. Using this approach (i.e. focusing first in the users' clustering), we propose in [10] a WDM PON topology deployment model which first performs a Voronoi's partition of the users' region in order to build the clusters. Then, the algorithm builds a Delaunay's triangulation in the region using the clusters' centers of mass. Next, using the Prim's algorithm, we find the EMST over the set of links composed by the Delaunay's triangles. This is possible thanks to the fact that the EMST is a subset-graph of the Delaunay-triangulation graph of a set of points [13]. Figure 2.3 illustrates an example of the results achieved whit this model.

Additionally, research work reported in [28] describes an optimization scheme for greenfield WDM PON based on a two-phase clustering technic employing a p-center mathematical model. The problem resolution is confronted by means of a CG ILP formulation taking into account the fiber attenuation and the unicast/multicast traffic demands. In a recent paper [9] we report an extension of our previous work in [10] proposing a novel UDWDM *Passive Optical Network (PON)* topology optimal deployment model which includes restrictions related with the bit error rate (BER) penalty produced by the data transmission impairments confronted in a UDWDM technique, like the increased strength of crosstalk and nonlinear effects. In order to resolve a problem we use an EMST search over the Delaunay's triangulation of the users regions by means of a modified version of the Prims' algorithm, which evaluates the lower distance based on a cost equation. The cost equation takes into account the fiber length, capacity and BER penalty.

Other particular approaches in the PON's planning formulations reported by the research community are the following: [44] Details a model for long-reach PON planning considering the traffic demand, user requirements and physical constraints. This model employs a two-stage evolutional heuristic, which compares a PON tree-topology with the structure of a chromosome. For resolving the splitter allocation problem, this algorithm uses a Prüfer sequence, which is a mathematical representation of the chromosome links as an N-dimensional vector space. Nonetheless, this approach lacks of flexibility for including other type of optimization restrictions based on new-generation data transmission technologies. In [36] it is described an ILP formulation for optimal PON design focusing on optical cabling constraints. Authors of this paper use a heuristic for decomposing the problem in a simpler fiber-restrictions based problem with warm start (i.e. setting arbitrarily large values to variables in order to satisfy the cable constraints). The PON planning model in [41] present ILP formulations with unconstrained splitting stages (i.e. splitters are not constrained by their previously established capacity but they are decided based on the cost of the solution). Work previously described in [28] was enhanced in [50] and [29] for covering the dimensioning of hybrid PON employing the same p-centered plus a p-median logistics formulation. In [46] we propose an optimal hybrid wireless-optical access network for deploying an advanced measurement infrastructure (AMI) in Smart-Grid Networks.

Very few research works cover the cover the deployment of PON for very large number of users. Research works referenced in [23] and [14] report scalable WDM PON and TDM/WDM PON architectures, using cascaded splitters and AWG, which can accommodate a large and ultra-large number of end users but none of them cover the multiple PON topology design required in a case of a very big deployment. In [3] it is reported a suboptimal solution for large PON deployments in near polynomial time, employing a combination of the Dreyfus-Wagner's algorithm and a clustering algorithm for resolving the related Steiner tree problem, but this work neither considers a multiple PON deployment for very large number of users taking into account the particular features of UDWDM PON.

Table 2.1 presents a summary of the state of the art regarding the topic of optimal dimensioning of PON[1].

From this study of the state of the art, we can conclude that UDWDM PON constitute a very interesting and promising solution for the next step towards new generation optical access networks. However, few research works consider the optimization of topologies for UDWDM PON. Moreover, none of them cover the deployment of multiple UDWDM PON for connecting a very large number of users.

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[1] References [7], [9] and [10] constitute our apport to the state of the art

Table 2.1: Summary of the state of the art for topics regarding optimization schemes for PON's topology design.

| Paper | PON type | | | | Objective | | | | Restrictions | | | | Algorithm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Author | TDM-PON | TWDM-PON | WDM-PON | UDWDM-PON | OF and trenching | Cabinets (splitters) | PON hardware | OPEX | ODN loss | Cluster size | Hardware capacity | PSC/SSC location | ILP/MILP | Problem formulation | Heuristics | Clustering algorithm |
| Tornatore [94] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | | |
| Li [62] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Zhang [104] | | | ✓ | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | |
| Kokangul [58] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Jaumard [49] | | | ✓ | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Kim [56] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Eira [35] | ✓ | | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Kantarci [53] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Chardy [22] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Kipouridis [57] | | ✓ | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Chowdhury [27] | | | ✓ | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Agata [3] | | ✓ | | | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| DeAndrade [33] | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | |
| Arévalo [7] | | | ✓ | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Chu [30] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | |
| Lin [63] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | |
| Lin [64] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Van Logg. [97] | ✓ | | | | ✓ | ✓ | | | ✓ | ✓ | | | ✓ | ✓ | ✓ | ✓ |
| Mitcsenkov [66] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Gu [44] | | ✓ | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Francfort [36] | ✓ | ✓ | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Truong [95] | | ✓ | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Pal [73] | ✓ | | | | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Gouveia [41] | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| Andrade [5] | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | | |
| Arévalo [9] | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Arévalo [10] | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

# Chapter 3

# Scenario of the research

## 3.1 Introduction

In this chapter we describe the general and specific scenarios we use for modeling our optimization problem and for later testing the heuristic we propose in order to find near-optimal solutions in polynomial time. In the first section we describe the reference topology to be used for the multiple PON deployment. Next we present detailed data of reference costs employed for specific and global price evaluations. Such prices have been obtained through direct interaction with network operators and vendors. Finally we include the network parameters to be used for our network deployment evaluations. This parameters have been retrieved from a set of chosen PON's ITU-T standards(i.e GPON, XGPON and NGPON2 standards) and from some reference papers in the case of UDWDM PON.

## 3.2 Scenario

There are different topology proposals for next-generation optical-access-network [103] but the predominant one for large FTTH deployment is today the PON topology, which is the well-know optical tree topology based on splitters. This research work focuses on FTTH deployment planning using only PON, for which we briefly review here the most relevant ITU standards. GPON and XGPON can reach up to 64 users employing TDM as the channel-sharing technique [47],[48]. The recent NGPON2 standard [99], introduced for the first time in PON standards in 2013, uses an hybrid TDM/WDM transmission with four or more DWDM wavelengths for DS and for US, keeping compatibility with legacy ODN [68]. Some relevant research works have already proposed solutions and technologies for manufacturing low-cost NGPON2 equipment, like [68]. The IEEE PON standards: EPON, GE-PON, 10G-EPON and SIEPON, have followed a similar evolution towards higher overall capacity in recent years.

The scenario we use for testing our optimization algorithm is the deployment of multiple passive optical access networks in metropolitan regions in which most of the users turn to FFTH. Therefore, it make sense to have a very large number of potential PON users in the same urban area. Specifically, in order to test our planning model, we have chosen different simulation scenarios with about $10^5$ users.

In addition, a region with such amount of users requires the support of multiple CO. Every CO houses the hardware necessary to service all users inside its subregion, and is thus equipped with a large number of OLT. Thus, we applied our optimization algorithms to very large number of users, like $10^5$ users, connected to more than one central office. We consider in our study, based on data retrieved from real operators, that every CO will have to host on average $2 \cdot 10^4$ users and thus approximately several hundreds of OLT. We assume that the CO are interconnected among them and that such interconnection is performed by a metropolitan optical fiber ring whose study is anyway beyond the scope of our work.

Additionally, we consider every CO constitutes the root of a multiple tree-topology (i.e. every CO's tree-topology is connected with other CO's tree-topologies through the metropolitan interconnection ring). PON splitters are distributed along the streets among a series of primary street cabinets (PSC), which are placed in publicly accessible places like sidewalks, corners, parks, etc., and secondary street cabinets (SSC), which are placed in any building where al least one user must be connected. A set of multi-fiber feeder optical cables connect a CO with its correspondent PSC. The connection between PSC and the correspondent SSC is performed by means of distribution optical fiber (OF) cables. In a SSC there's one or more splitters (depending on the number of PON required to service the users inside the respective building). From the SSC it is routed a single OF connection up to each users' ONU. Figure 3.1 illustrates a general schema of the multiple PON topology employed in this study. The architecture for splitting placement may change depending on the strategic decision of the operators, but the two-level architecture presented here is anyway one of the most commonly used.

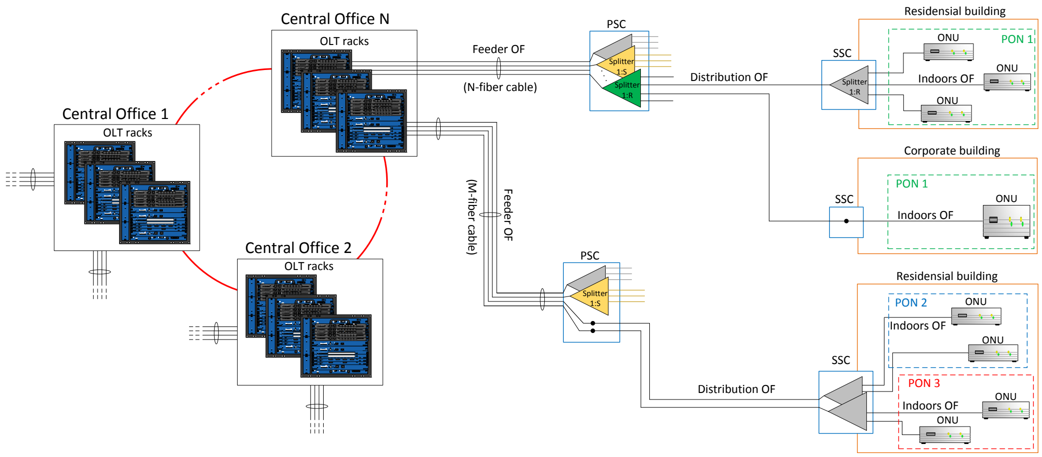


Figure 3.1: Schema of a multiple PON deployment.

We focus our analysis in the comparison of deployment costs using different PON technologies (GPON, XGPON and NGPON2 and the more future-oriented UDWDM PON). While for the existing standards the physical parameters were well known and in some ways also the cost estimate can be obtained from vendors, the situation is less clear for UDWDM PON, so that for the physical layer we took most data from this paper [85], and for the cost we made some reasonable assumptions, as shown in the next section of this chapter.

In order to consider a real scenario for our street-aware optimization algorithm, we developed an add-hoc interface for retrieving real streets and buildings data from OpenStreetMaps (OSM) database [72].

## 3.3 Reference costs

In order to evaluate the deployment cost of multiple PON, we have employed data directly from telecom operators and from equipment vendors. For GPON and XGPON hardware we employ real updated market prices. In the case of NGPON2, the consulted equipment vendors confirmed that the prices of hardware for that technology would be, according to the usual behavior of prices for new technology products, approximately two fold in comparison with the latest technology (i.e. in this case two fold the prices

Table 3.1: Costs of OF cable and trenching.

| COMPONENT | COST ($) |
|---|---|
| Feeder Cable, 2 fibers /km | 600 |
| Feeder Cable, 4 fibers /km | 800 |
| Feeder Cable, 6 fibers /km | 1000 |
| Feeder Cable, 12 fibers /km | 1500 |
| Feeder Cable, 24 fibers /km | 2000 |
| Feeder Cable, 48 fibers /km | 2500 |
| Feeder Cable, 64 fibers /km | 3000 |
| Feeder Cable, 96 fibers /km | 3500 |
| Feeder Cable, 144 fibers /km | 3700 |
| Feeder Cable, 288 fibers /km | 4000 |
| Distribution Cable /km | 2000 |
| Indoor OF installation /user | 50 |
| Trenching and reinstatement/km | 30000 |
| Ducts and fenders /km | 10000 |
| Fusions and slicing /unit | 10 |
| Manholes /unit | 500 |

of XGPON). This trend of price growth for new technology hardware can in fact be appreciated in the prices of XGPON vs GPON (approximately two times the prices of the former in comparison with the prices of the latter). In the network planning model reported in [33] authors propose a complexity-based cost function for assuming the hardware price of non-commercially available technologies like Tunable TDM/WDM PON and Colorless WDM PON. Table 3.1, shows the reference costs we employ for optical-fiber cable and related labor, including the cost of trenching, reinstatement and manholes (employed for the OF cable installation and further maintenance). Table 3.2 details costs for splitters and cabinets and Table 3.3 specifies costs of hardware for the different type of PON considered in this paper. Prices are expressed in United State Dollars (USD).

## 3.4 Network parameters

In this subsection we present a brief description of the network parameter settings we employ for each PON technology, based on the values established in each correspondent standard. Table 3.4 shows the specific network

Table 3.2: Costs of cabinets

| COMPONENT | COST ($) |
|---|---|
| Junction box 144 OF | 500 |
| Junction box 48 OF | 400 |
| Junction box 16 OF | 350 |
| Junction box 8 OF | 300 |
| 1:64 splitter | 120 |
| 1:32 splitter | 70 |
| 1:16 splitter | 45 |
| 1:8 splitter | 28 |
| 1:4 splitter | 24 |
| 1:2 splitter | 20 |
| Cabinet installation | 1600 |

Table 3.3: Costs of PON hardware and related labor.

| COMPONENT | COST ($) |
|---|---|
| OLT chassis - GPON ($10^3$ users) | 16000 |
| OLT chassis - XGPON ($10^3$ users) | 28000 |
| OLT chassis - NGPON2 ($10^3$ users) | 50000 |
| OLT chassis - UDWDM PON ($10^3$ users) | 85000 |
| OLT card - 4xGPON | 9000 |
| OLT card - 4xXGPON | 15000 |
| OLT card - 4xNGPON2 | 25000 |
| OLT card - 4xUDWDW-PON | 40000 |
| ONU residential - GPON | 100 |
| ONU residential - XGPON | 350 |
| ONU residential - NGPON2 | 600 |
| ONU residential - UDWDM PON | 110 |
| ONU corporative - GPON | 350 |
| ONU corporative - XGPON | 600 |
| ONU corporative - NGPON2 | 1100 |
| ONU corporative - UDWDM PON | 2200 |
| Splicing/per splice | 10 |
| OLT installation | 2000 |
| ODF (for each OLT rack) | 3500 |

parameters for each PON technology. In our analysis we focus on the DS transmission because it constitutes the most demanding scenario for the multiple PON dimensioning. In the case of UDWDM PON, we set the parameters based on the work reported by Rohde et al. [85], with few variations in order to be more conservative. For instance, in Rohde's proposal a single OLT is able to service up to 1024 users with a bit rate of 1 Gb/s; instead, we assume only up to 256 users per each OLT with the same bit rate of 1 Gb/s.

Table 3.4: Network parameters for GPON, XGPON, NGPON2 and UDWDM PON.

| Parameter | PON Technology | | | |
|---|---|---|---|---|
| | GPON | XGPON | NGPON2 | UDWDM PON |
| Max. link length [km] | 40 | 40 | 40 | 100 |
| Max. ODN loss [dB] | 35 | 35 | 35 | 43 |
| Users per OLT | 64 | 64 | 64 | 256 |
| Num. of wavelengths | 1 | 1 | 4 | 256 |
| DS bit rate per OLT [Gb/s] | 2.5 | 10 | 40 | 256 |

Other general network parameters we use are:

- Type of OF: standard single mode fiber (SSMF) G652.
- Type or branching device: splitters.
- Attenuation in splitters with SR $k = K_{i,l}$: $\alpha_{i,l} = 3.5\, log_2(k)$ dB [99].
- Maximum number of cascaded splitters: 2.
- Type of users: Residential and Business.
- Number of users in the covered region: $10^5$.
- Reference bit rate (for normalization): $BR_{ref} = 10$ Gb/s.

In the case of the users' Bit Rate (BR) demands, we consider up to six scenarios where residential and corporate users increase the demand of sustained BR from few tens of Mb/s up to many hundreds of Mb/s [1] and even up to one or more Gb/s (in order to include a long-term scenario). Table 3.5 details the six scenarios of BR demands we employ in the analysis. In

Table 3.5: Bit rate scenarios employed in the analysis.

| Scenario | Intervals of demanded bit rate [Mb/s] | |
|---|---|---|
| | Residential users | Corporate users |
| 1 | 10 - 50 | 100 - 500 |
| 2 | 50 - 100 | 500 - 1000 |
| 3 | 100 - 400 | 1000 - 2500 |
| 4 | 100 - 1000 | 1000 - 10000 |
| 5 | 500 - 2500 | 2500 - 10000 |
| 6 | 1000 - 2500 | 5000 - 40000 |

each scenario we defined a BR interval for residential and for business users. The first scenario is already typical today, the second is basically what the European commission requires for supporting demands up to year 2020. The following scenarios are longer term, even though they are not so futuristic in some part or the world like Korea and Japan. As further explained later, for each user we randomly generate the actual BR request, inside the specified interval, using a uniformly distributed probability function. We interpret the randomly generated BR as a minimum guaranteed BR that each user *must* be given.

# Chapter 4

# Problem formulation

## 4.1 Introduction

The current chapter covers the description of the optimization problem formulation. First we specify some required notations for variables and parameters, i.e. the parametrization of the network components regarding its availability, technical features and costs. In the case of the ODN components, we specify the features of hardware componets, candidate sites and details of costs for OF cables (feeder, distribution and indoor), splitters and street cabinets (including their capacity). We also specify ODN's installation related costs and parameters like candidate paths for cables' routing, trenching (including the reinstatement) and ducting. Regarding the PON hardware we specify costs and parameters for the specific features of OLT and ONU depending on the PON technology under consideration. In the final section of the chapter, we give detailed information of the optimization problem formulation based on a cost-related objective function, to be minimized, and a set of restrictions in order to keep the formulation within real-life parameters and render accuracy to the model.

## 4.2 Notations and variables

Any city's region where a multiple PON topology must be deployed can be treated as a weighted connection graph. In this graph streets and street-intersections constitute edges and points which can be used as routing paths from the CO up to their respective PSC, and from PSC up to the SSC.

Now, focussing in a subregion constituted by a single CO, which must be connected to all its serviced users, the objective is to find a topology graph that is optimal under the cost targets that we will describe in detail later in this section.

In order to describe the optimization problem we first define some notations for a set of required parameters, variables and constants.

- $CO$: The Central Offices' set, $CO = \{CO_c\}$, with $c \in \{1, 2, \ldots, C\}$; where $C$ is the number of available central offices.
- $N_c$: The number of users serviced by central office $c$, in such a way that $\sum N_c = N$, where $N$ is the total number of users in the region.
- $O$: The OLT set, with $o \in \{1, 2, \ldots, M\}$, where $M$ is the number of available OLT.
- $U$: The ONU set, with $n \in \{1, 2, \ldots, N\}$, where $N$ is the number of ONU.
- $W$: The wavelengths set, with $w \in \{1, 2, \ldots, L\}$; where $L$ is the number of available wavelengths in one OLT transmitter (per direction). For instance $L = 1$ for GPON and XGPON, while it can be up to $L = 256$ for UDWDM PON.
- $L_i$: The set of splitters available on cabinet placed at the site $i$. We also define $S_{i,l}$ as the $l^{th}$ splitter, on the cabinet $i$, whose SR is given by $K_{i,l} = 2^r$, where $r$ is a positive integer number.
- $B$: Is the set of candidate sites for location of SSC.
- $V$: Is the set of candidate sites for location of PSC.
- $n_{max}$: Is the maximum number of users per OLT.
- $ODN_{loss}$: The maximum loss, in dB, allowed in the ODN.

Parameters related with PON capacity and users' bit rate demands are defined as follows.

- $BR_{ref}$: Reference bit rate (for normalization purposes).
- $BR_{US}/\lambda$: The total US bit rate capacity per each OLT wavelength.

- $BR_{DS}/\lambda$: The total DS bit rate capacity per each OLT wavelength.
- $BR^{n}_{US}$: The US bit rate demanded byONU $n \in U_c$.
- $BR^{n}_{DS}$: The DS bit rate demanded by ONU $n \in U_c$.
- $\Gamma_{US}$: The normalized total OLT's US bit rate capacity, $\Gamma_{US} = (L \cdot BR_{US}/\lambda)/BR_{ref}$.
- $\Gamma_{DS}$: The normalized total OLT's DS bit rate capacity, $\Gamma_{DS} = (L \cdot BR_{DS}/\lambda)/BR_{ref}$.
- $\gamma^{n}_{US}$: Normalized US bit rate demanded by ONU $n \in U_c$, $\gamma^{n}_{US} = BR^{n}_{US}/BR_{ref}$.
- $\gamma^{n}_{DS}$: Normalized DS bit rate demanded by ONU $n \in U_c$, $\gamma^{n}_{DS} = BR^{n}_{US}/BR_{ref}$.

Also, we employ sets of parameters regarding sites, physical paths and costs. Let's say that in the city's region under study, $ST$ is the set of streets, including any physical path suitable for trenching (i.e. for routing the OF cables) and $BL$ is the set of buildings (i.e. any place where users demand connectivity to the PON topology). In this context, the related parameters are.

- $I$: Set of street' (intersections) nodes and buildings' nodes (vertices), $I$=$\{i \in \{ST, BL\}$ / $i$=1,2,...,$T\}$; where $T$ is the number of nodes in streets and buildings.
- $E$: Set of edges $E = \{e_{i,j} \in E \ / \ (i,j) \in I\}$.
- $\alpha^{c}_{o}$: is a binary constant that indicates if the OLT $o$ is placed at the central office $c$ with a value of 1.
- $d_{i,j}$: The distance between two points $(i,j) \in I$. If the points are joined by a single edge, it is the length of the edge. If not, $d_{i,j}$ is the minimum end to end distance calculated by an optimal routing algorithm through several streets and intersections.
- $C^{f}_{OF}$: Cost, per unit length, of a feeder OF cable.
- $C^{d}_{OF}$: Cost, per unit length, of a distribution OF cable.

- $C_T$: Cost of trenching, per unit length.
- $C^{r}_{encl}$: Cost of a street cabinet enclosure with capacity for installing up to $r$ splitters.
- $C_{i,l}$: The cost of the the $l^{th}$ splitter on the cabinet placed at site $i$.
- $C^{rck,\eta}_{OLT}$: The cost of an OLT rack with capacity for $\eta$ users.
- $C^{crd}_{OLT}$: The cost of an OLT line card (single OLT).
- $C_{ODF}$: The cost of an optical distribution frame (ODF).
- $C_{ONU}$: The cost of an ONU.
- $C^{c}_{lbr}$: The cost of labor (i.e. splicing, hardware installation) in a CO.
- $\alpha_{FO}$: The optical fiber attenuation per unit length.
- $\alpha_{i,l}$: The attenuation of the $l^{th}$ splitter placed in the cabinet $i$.
- $\alpha_{ex}$: Other losses in the ODN.

In addition, the optimization model requires the definition of the following binary variables.

$$x_{n,j} = \begin{cases} 1; & \text{if the ONU } n \text{ is connected to the SSC located in site } j \\ 0; & \text{otherwise} \end{cases}$$

$$x_{j,i} = \begin{cases} 1; & \text{if the SSC on site } j \text{ is connected to the PSC in site } i \\ 0; & \text{otherwise} \end{cases}$$

$$x_{i,o} = \begin{cases} 1; & \text{if a splitter in a PSC on site } i \text{ is connected to the OLT } o \\ 0; & \text{otherwise} \end{cases}$$

$$\alpha_{i} = \begin{cases} 1; & \text{if the candidate site } i \in \{V \cup B\} \text{ is active} \\ 0; & \text{otherwise} \end{cases}$$

$$\alpha_{o} = \begin{cases} 1; & \text{if OLT } o \text{ is active} \\ 0; & \text{otherwise} \end{cases}$$

$$S_{i,l} = \begin{cases} 1; & \text{if the } l^{th} \text{ splitter on site } i \text{ is active} \\ 0; & \text{otherwise} \end{cases}$$

$$y_n^{j,l} = \begin{cases} 1; & \text{if the ONU } n \text{ connects to the } l^{th} \text{ splitter placed on site } j \\ 0; & \text{otherwise} \end{cases}$$

$$y_{j,l}^{i,p} = \begin{cases} 1; & \text{if the } l^{th} \text{ splitter located in a SSC placed at site } j \text{ connects} \\ & \text{ to the } p^{th} \text{ splitter located in a PSC placed at site } i \\ 0; & \text{otherwise} \end{cases}$$

$$z_n^o = \begin{cases} 1; & \text{if ONU } n \in U \text{ is connected to OLT } o \\ 0; & \text{otherwise} \end{cases}$$

## 4.3 Optimization problem formulation

The objective function of the optimization problem formulation aims to minimize the total deployment cost of the multiple PON scenario. The function covers the deployment costs in each one of the CO subregions. A main consideration of the problem is the clustering of users among CO based on combinatorial variation of users, i.e. users may be freely distributed among the different CO in order to find the optimal distribution, which constitutes the main advantage of solving the problem for the entire wide region, instead of solving each CO subregion as an independent problem. As further explained, in our heuristic approach we confront this combinatorial problem as a random search moving buildings among CO, in a cost-optimization sense, trying to keep approximately N/$C$ users in each CO region, where $C$ is the number of available CO.

The objective function is defined by Eq. 4.1.

$$\begin{split} min \sum_{c\in CO} \Bigg( C^{c}_{lbr} + C_T \Bigg( \sum_{o\in O} \sum_{i\in V} \alpha^{c}_{o} x_{i,o} d_{i,o} + \sum_{i\in V} \sum_{j\in B} \alpha^{c}_{o} x_{j,i} d_{j,i} \Bigg) \\ + C^{f}_{OF} \sum_{o\in O} \sum_{i\in V} \alpha^{c}_{o} x_{i,o} d_{i,o} \Bigg) + C^{d}_{OF} \Bigg( \sum_{i\in V} \sum_{j\in B} x_{j,i} d_{j,i} + \sum_{j\in B} \sum_{n\in U} x_{n,j} d_{n,j} \Bigg) \\ + \sum_{i\in V\cup B} \sum_{l\in L_i} S_{i,l} C_{i,l} + \sum_{i\in V\cup B} C^{r}_{encl} \alpha_i + \frac{N}{\eta} \Big( C^{rck,\eta}_{OLT} + C_{ODF} \Big) \\ + \sum_{o\in O} C^{crd}_{OLT} \alpha_o + C_{ONU} N \end{split} \tag{4.1}$$

Eq. 4.1 is composed by a global sum operation of the cost for every deployment-component, with respect to each CO. Inside the global sum, the first component take into account costs of the labor related with OF and hardware. Next, there are three components regarding the costs of trenching and the cost of feeder and distribution OF cables. Following there are two components for the costs of the cabinets' enclosures and splitters for PSC and SSC, respectively. The last three components of the function cover the cost of PON hardware. The first and last three terms are actually fixed but we include them in the objective function in order to provide a full evaluation of the total deployment cost.

The constraints that ensure the ILP problem accomplish with the requirements of the proposed optimal network planning, in a real scenario, are the following.

- The variable which defines the path from an OLT $o$ and an ONU $n$ is evaluated as:

$$z^{o}_{n} = \sum_{i\in V} \sum_{j\in B} x_{n,j} x_{j,i} x_{i,o} \quad \forall n \in U, \forall o \in O \tag{4.2}$$

- The sum of users connected to each $c \in$ CO must be equal to the total number of users in the region:

$$\sum_{c\in CO} N_c = N; \tag{4.3}$$

- The number of users connected to central office $c \in$ CO is evaluated as:

$$N_c = \sum_{n \in U} \sum_{o \in O} \alpha_o^c z_n^o; \quad \forall \, c \in CO \tag{4.4}$$

- The number of users (ONU) per OLT must be at most $n_{max}$:

$$\sum_{n \in U} z_n^o \leq n_{max} \alpha_o; \quad \forall \, o \in O \tag{4.5}$$

- The maximum bit rate demand per OLT must not be greater than its US and DS capacity $\Gamma$:

$$\sum_{n \in U} z_n^o \gamma_{US/DS}^n \leq \Gamma_{US/DS} \alpha_o; \quad \forall \, o \in O \tag{4.6}$$

- An ONU must be connected to only one splitter, which is placed in an enclosure at site $j$:

$$\sum_{j \in B} x_{n,j} = 1; \quad \forall \, n \in U \tag{4.7}$$

- A site where a SSC is located must connect to only one site with a PSC if the SSC is active:

$$\sum_{i \in V} x_{j,i} = \alpha_j; \quad \forall \, j \in B \tag{4.8}$$

- A site where a PSC is located must connect to a single OLT if the PSC site is active:

$$\sum_{o \in O} x_{i,o} = \alpha_i; \quad \forall \, i \in V \tag{4.9}$$

- The number of active splitters on site $i$ must be less than the site enclosure capacity:

$$\sum_{l \in L_i} s_{i,l} \leq \alpha_i r_i; \quad \forall \, i \in \{V \cup B\} \tag{4.10}$$

- An ONU can connect to a splitter on site $i$ if there is a physical connection between the ONU and the site $i$:

$$y_n^{i,l} \leq x_{n,i}; \;\; \forall i \in \{V \cup B\}, \forall n \in U, \forall l \in L_i \tag{4.11}$$

- A splitter on a SSC located on site $j$ can only connect to a splitter on a PSC located on site $i$ if there is a physical connection between both sites:

$$y_{j,l}^{i,l} \leq x_{j,i}; \;\; \forall i \in V, \forall p \in L_i, \forall j \in B, \forall l \in L_j \tag{4.12}$$

- The number of ONU that can connect to the $l^{th}$ spliter on a SSC located at site $j$ can not exceed the spliter capacity if the splitter is active:

$$\sum_{n \in U} y_n^{j,l} \leq K_{j,l} S_{j,l}; \;\; \forall j \in B, \forall l \in L_j \tag{4.13}$$

- The number of ONU and the number of splitters located on any SSC that directly connect to the $p^{th}$ spliter on a PSC located at site $i$ can not exceed the spliter capacity if the splitter is active:

$$\sum_{n \in U} y_n^{i,p} + \sum_{j \in B} \sum_{l \in L_j} y_{j,l}^{i,p} \leq K_{i,p} S_{i,p}; \;\; \forall i \in V, \forall p \in L_i \tag{4.14}$$

- The power losses in a link from an OLT up to an ONU must be lower or equal than the PON's allowed ODN loss.

$$\begin{aligned} &\alpha_{FO}\left(\sum_{j \in B} x_{n,j} d_{n,j} + \sum_{i \in V} \sum_{j \in B} \sum_{o \in O} x_{n,j} x_{i,o} x_{j,i} d_{j,i} + \sum_{i \in V} \sum_{o \in O} x_{i,o} d_{i,o}\right) \\ &+ \sum_{j \in B} \sum_{l \in L_j} y_n^{j,l} S_{j,l} \alpha_{j,l} + \sum_{i \in V} \sum_{p \in L_i} \sum_{j \in B} \sum_{l \in L_j} y_n^{j,l} y_{j,l}^{i,p} S_{i,p} \alpha_{i,p} + \alpha_{ex} \\ &\leq ODN_{loss}; \quad \forall n \in U \end{aligned} \tag{4.15}$$

# Chapter 5

# Heuristic approach

## 5.1 Introduction

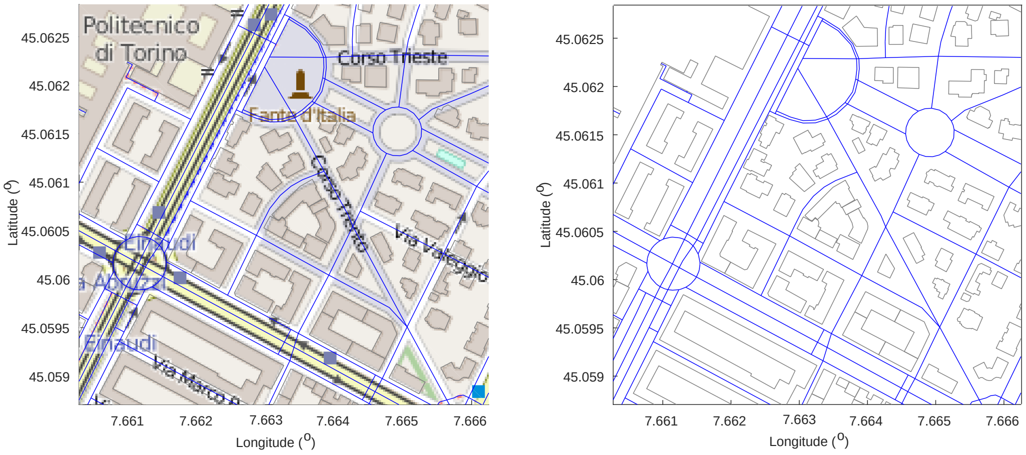
The problem described by Eq. 4.1 and its correspondent constraint equations constitute a Minimal-Steiner-Tree optimization problem, which is NP-hard [37]. Then, in order to find a solution for a very large number of users we propose an heuristic approach based on a primary function (PF) and a set of secondary functions (SF). We have named it Optimal Topology Search (OTS).

In this chapter we make a detailed explanation of the features of OTS and its development process by means of numerical computing environment MatLab™. We employed this developed algorithm in order to find feasible nearly-optimal solutions to the complex optimization problem described in the previous chapter, employing realistic city maps of large regions with many users with very different bit rate demands.

In the following sections we describe the behavior and features of OTS through a description of its main function (i.e the PF) and its secondary functions (i.e. SF).

## 5.2 OTS primary function

The PF first loads the OSM data of the city (i.e. streets' and buildings' data) by means of a routine which calls the OSM's XML data (i.e. the data of the buildings' and streets' coordinates and its tags and attributes). Such information may be used for drawing the profile of streets and buildings of the correspondent city region and of course it can be used for specific data analysis and processing (as we do in this research work). Fig. 5.1 shows the profiles of streets and building in a section of Turin, Italy.



(a)

(b)

Figure 5.1: Illustration of buildings (brown) and streets (blue) profiles in a zone of Turin, Italy. (a) With back map image; (b) Without back map image.

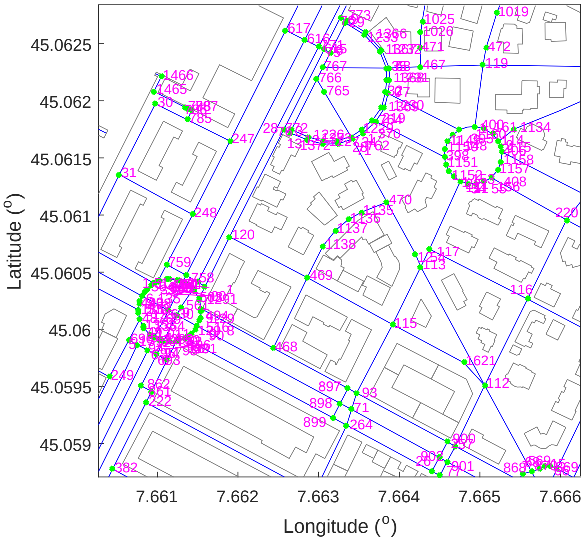
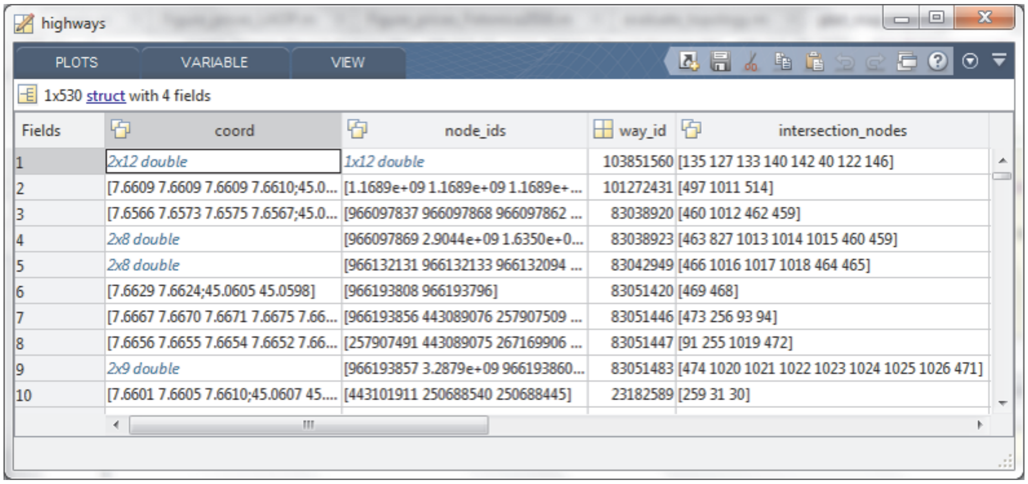


Figure 5.2: Illustration of the intersection-nodes (green dots) found in the streets of a section of Turin's map.

Next, PF finds the streets' intersections and registers them in a data base of streets and its correspondent "intersection-nodes". OTS registers as an intersection-node not only the point where two or more streets intersect to each other but also, for further data processing purposes, it registers the points where an street suddenly change its direction. In Fig. 5.2 it is illustrated a set of intersection nodes and their correspondent index numbers (as they are registered in the intersection-nodes' database). One of the extended databases OTS keeps regarding streets and intersection-node information, is the data of the intersection-nodes contained in every street in the map (along with the coordinates and street ID info), as illustrated in Fig. 5.3.

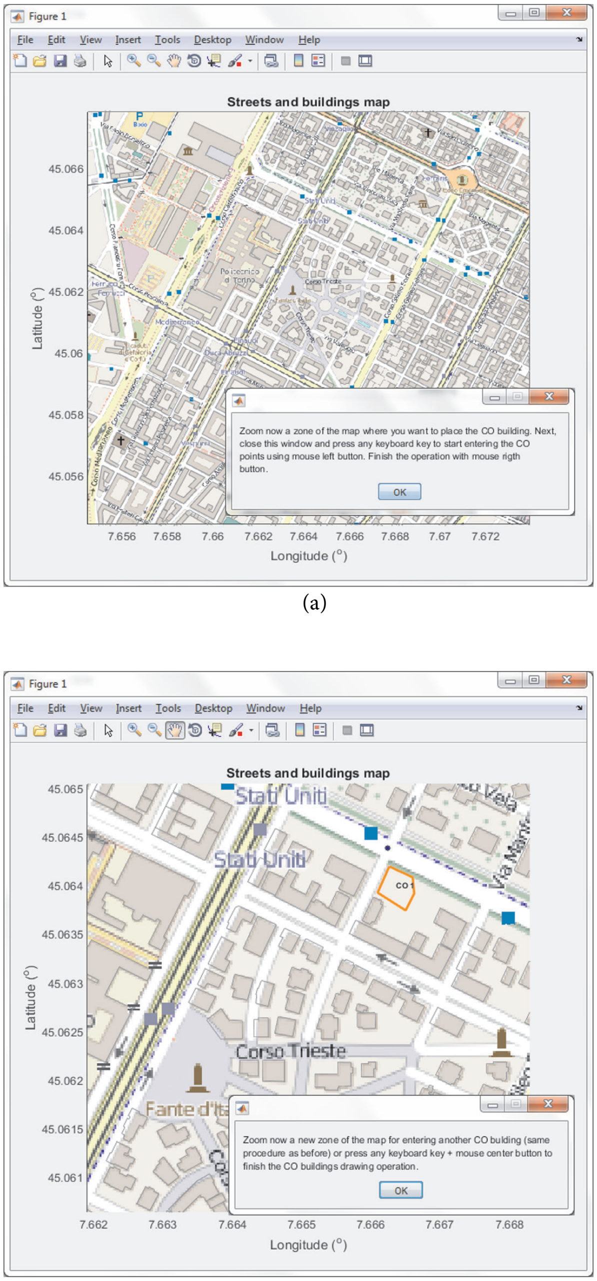


1x530 struct with 4 fields

| Fields | coord | node_ids | way_id | intersection_nodes |
|---|---|---|---|---|
| 1 | 2x12 double | 1x12 double | 103851560 | [135 127 133 140 142 40 122 146] |
| 2 | [7.6609 7.6609 7.6609 7.6610;45.0... | [1.1689e+09 1.1689e+09 1.1689e+... | 101272431 | [497 1011 514] |
| 3 | [7.6566 7.6573 7.6575 7.6567;45.0... | [966097837 966097868 966097862 ... | 83038920 | [460 1012 462 459] |
| 4 | 2x8 double | [966097869 2.9044e+09 1.6350e+0... | 83038923 | [463 827 1013 1014 1015 460 459] |
| 5 | 2x8 double | [966132131 966132133 966132094 ... | 83042949 | [466 1016 1017 1018 464 465] |
| 6 | [7.6629 7.6624;45.0605 45.0598] | [966193808 966193796] | 83051420 | [469 468] |
| 7 | [7.6667 7.6670 7.6671 7.6675 7.66... | [966193856 443089076 257907509 ... | 83051446 | [473 256 93 94] |
| 8 | [7.6656 7.6655 7.6654 7.6652 7.66... | [257907491 443089075 267169906 ... | 83051447 | [91 255 1019 472] |
| 9 | 2x9 double | [966193857 3.2879e+09 966193860... | 83051483 | [474 1020 1021 1022 1023 1024 1025 1026 471] |
| 10 | [7.6601 7.6605 7.6610;45.0607 45.... | [443101911 250688540 250688445] | 23182589 | [259 31 30] |

Figure 5.3: Illustration of the first 10 registers in the streets' data base of Turin's map.

Following, PF asks for a set of central offices in the map. For this purpose PF may call a data file of CO geographic locations and include this data in the city's database; or alternatively it may call a function for manually drawing CO buildings in the map as illustrated in Fig 5.4 (a). OTS permit the drawing of as many CO buildings as needed until the CO buildings drawing process is finished, as illustrated in Fig 5.4 (b). In the CO drawing process, OTS asks for selecting a point in a neighboring street of every drawn CO building (e.g. the blue point near upper-left corner of the drawn CO1 building in section (b) of Fig 5.4) which corresponds to the intersection-node employed by the algorithm for referencing a CO in any further process, like for specifying the CO's location or for evaluating the OLT-ONU path search.



Zoom now a zone of the map where you want to place the CO building. Next, close this window and press any keyboard key to start entering the CO points using mouse left button. Finish the operation with mouse rigth button.

(a)

Zoom now a new zone of the map for entering another CO bulding (same procedure as before) or press any keyboard key + mouse center button to finish the CO buildings drawing operation.

(b)

Figure 5.4: Illustration of: (a) City map loading and initial message for drawing a CO building on the map; (b) CO-buildings drawing process and location of reference intersection-points in the proximity of the CO's buildings (blue point close to the upper left corner of CO1).

Once the buildings, streets and CO data is loaded, and the intersection-nodes have been calculated and registered, PF uses a uniformly distributed random function which generates the users' data (i.e. position and bit rate demands). For doing this it first evaluates the geometrical skull of the buildings' coordinates in order to place users inside each building. The number of users generated depends on the type, area, and levels of the building (i.e. if its a house, residential building, corporate building, industrial building, etc.). In the case a building is a single house it is placed a single ONU on it (i.e. a single user), if it's a residential building, the number of users depends on the number of levels and the area of the building because of the number of users per level is evaluated by means of dividing the floor-area of the building by the reference area. The reference area may be changed depending on the type and features of an apartment in a particular zone of a given city in the world. Fig.5.5 shows a zone of Turin, Italy, where it has been placed random users (illustrated as black points) in each building (e.g. we have used a reference area of 100 $m^2$ for a residential apartment in Turin).

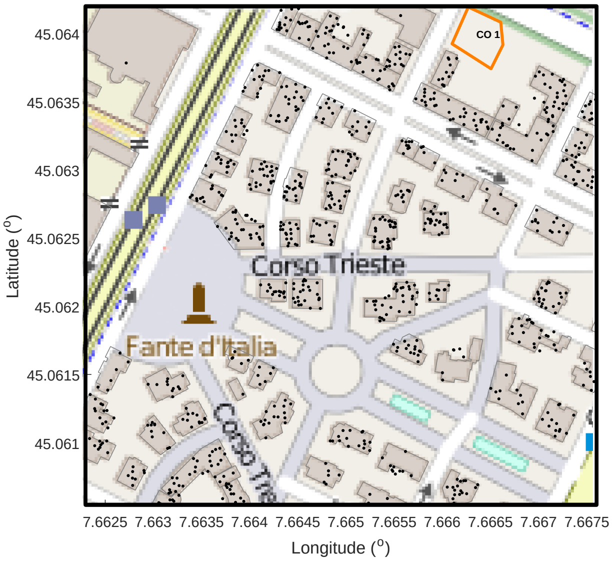


Figure 5.5: Illustration of the random users generation based on the type and area of the buildings.

OTS automatically retrieves from the original OSM data, the type and levels of the buildings. If such information is not present in the map's data, it may be manually included or alternatively it is employed a routine for randomly selecting the levels of a building from a pre-defined range. Such range of building's levels may be changed, by means of an initial variable, in order to reflect the average number of levels of buildings in some region of a given city. Fig. 5.6 shows the map of Turin around *Politecnico di Torino* - POLITO (university). Notice in the figure that POLITO and the building in the upper right section of POLITO's building, which is the *Liceo Scientifico Statale Galileo Ferraris* (high school), are treated as corporate users (i.e. independently of the number of levels and area of the buildings, they are assigned with a single corporate user). The other neighboring buildings, which have a number of levels between 2 and 6, are residential buildings housing many users on them.

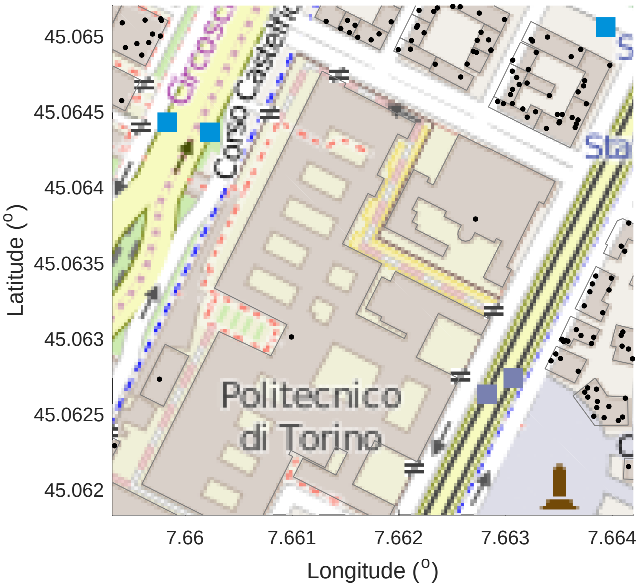


Figure 5.6: Illustration of random generation of corporate and residential users.

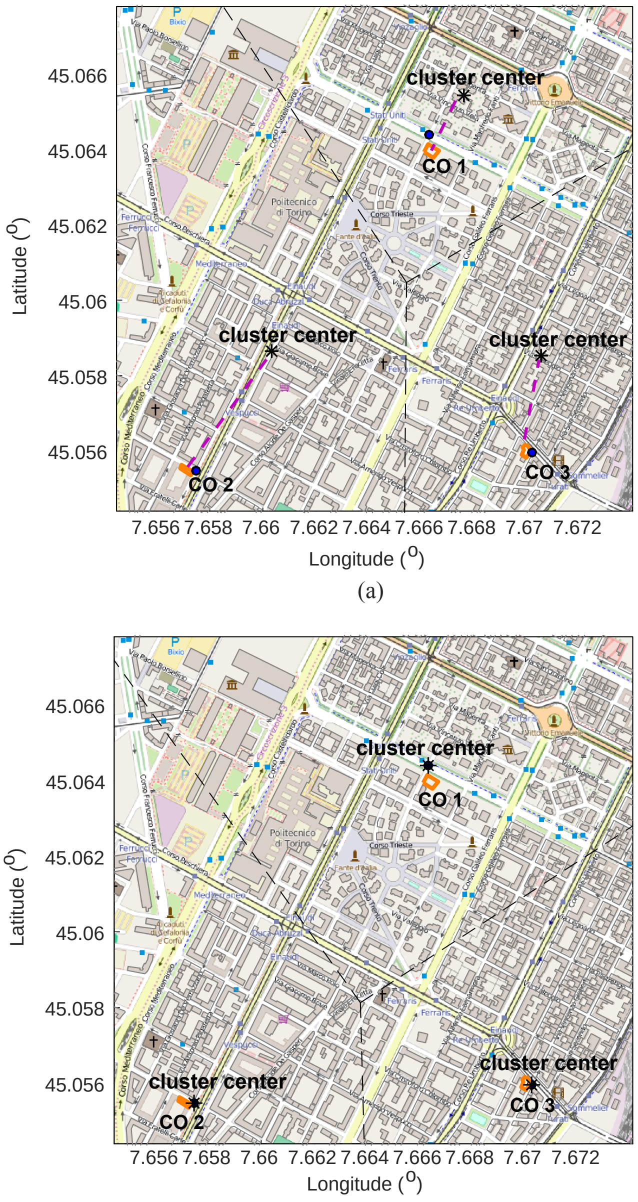
Next, OTS clusters the region in a CO-basis (i.e. distributing the users among the CO) starting from a Voronoi's tessellation of the total region using a $k$-means algorithm [13] for dividing the region in $C$ zones, where $C$ is the number of central offices. With this procedure, the center of a CO subregion is a geometrical center and do not necessarily corresponds to the location of the CO building. Once OTS has completed the evaluation of an optimal topology for this first set of clusters (as further explained in the next section of this chapter, such evaluation is accomplished by a set of SF), it changes the clusters by means of moving buildings from one CO subregion to other based on the variation of the region's geometrical center towards the geographic position of the correspondent CO building. Fig. 5.7 illustrates the fact that as the cluster's centers move towards the CO's locations, the shape of the CO's sub-regions change (i.e. the sub-zones defined by the divisions drawn through the dashed black lines in the map).

Therefore, PF recursively evaluates the total multiple PON topology cost in each iteration comparing the new cost with the previous one and discarding the higher-cost topology. This procedure of iteratively improving the optimal topology cost, using adaptive memory, constitutes a Tabu-search heuristic [40].

## 5.3 OTS secondary functions

The set of SF, called by the PF, perform the following tasks:

- *allocate_ssc*: Identifies users in each building (i.e. if there is at least one business or residential user demanding connection to the PON) and assigns a SSC to the building selecting the closest corner of the building with respect to the nearest street. Fig 5.8 shows a region where *allocate_ssc* function has placed the SSC in each building. Fig. 5.9 presents a detail of some buildings and their correspondent SSC to street connections. Notice in that figure how the SSC in any building is connected to the closest street-point (streets in the figure are remarked in blue) by means of a perpendicular optical-connection-line (drawn in red). We verify the connection from a buildings' corner up to the closest street is performed to an actual street instead of to a street's projection. Such verification is useful in the case a street changes its direction just before arriving to a given building. Every street-point, where a SSC connects to, is included in the intersection-nodes database. Therefore, that intersection-node (i.e. the point where the SSC connects to the closest street) constitutes a reference point for the respective Building. Such intersection-node is later used for finding routes from the building up to the closest PSC (the PSC placement in the neighboring streets is performed by the function *aggregate* which is explained here in the following lines).



(a)

(b)

Figure 5.7: Change of CO sub-regions as the clusters' centers move towards the CO's buildings. (a) Clusters' centers far from the CO; (b) Clusters' centers close to the CO's buildings

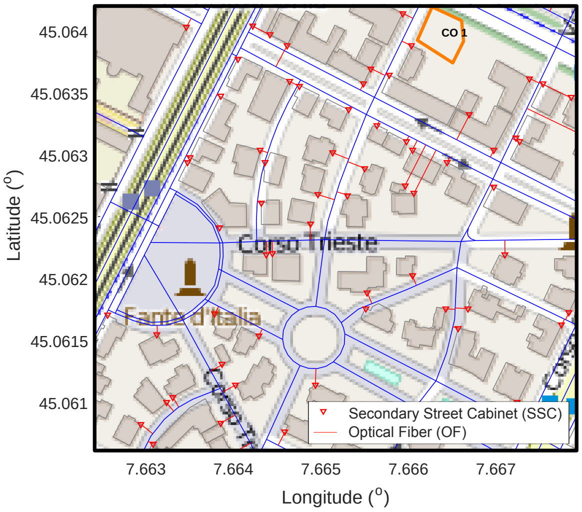


Figure 5.8: Function *allocate_ssc*: Placement of SSC on buildings and connection with the closest street.

- *clustr_build*: It is employed for clustering a CO subregion (among the buildings and users of such subregion) in order to assign one PON to every cluster (here each cluster correspond to a given set of buildings and their correspondent users). Depending on the number of users and the aggregated bit rate demands inside a building this function dimensions the correspondent OLT and ONU hardware. The clustering algorithm we employ is a Shared Nearest Neighbor (SNN) based clustering algorithm [102], which permits a more efficient clustering than the traditional $k$-means algorithm because of it can be tailored for clustering buildings instead of single users. We use the SNN algorithm in such a way that every building is treated as a entity with a distance based on numerical and categorical attributes [45]. Specifically, the distance is evaluated based on: i) the length from the building (using as reference point its SSC) up to the closest PSC or CO and ii) the attributes, which are defined by the number of users inside the building and the normalized total amount of traffic demanded by the users in that building. Every cluster is assigned to a single OLT and must not overcome the upper limit of the following two attributes: maximum number of users and maximum amount of traffic (DS or US) supported by that OLT (i.e. the maximum number of users and the DS/US

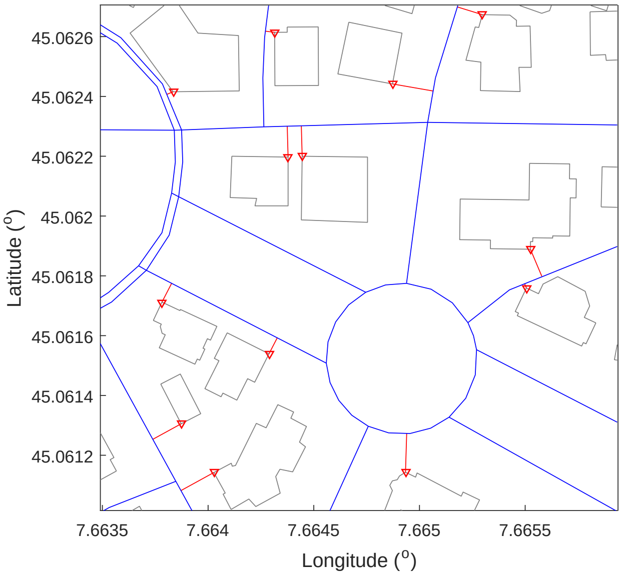


Figure 5.9: Function *allocate_ssc*: Detail of some SSC to street connections.

capacity defined by a given PON technology).

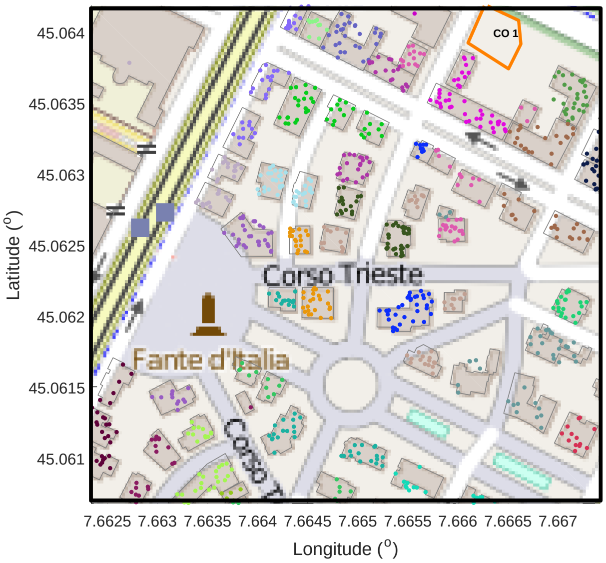


Figure 5.10: Function *clustr_build*: Illustration of the users-building's clustering (every color correspond to a different OLT in the CO).

Therefore, the algorithm looks for an approximation to the upper limit of any of the attributes, and if a building can not be aggregated to a given cluster (due to such aggregation will make that one or both limits be surpassed) such building is aggregated to another neighboring cluster. Fig.5.10 presents a zone of Turin with different clusters. Every cluster (illustrated in the Fig.5.10 as a set of differentially colored users) is serviced by a single assigned OLT (i.e. a single PON) in the CO.

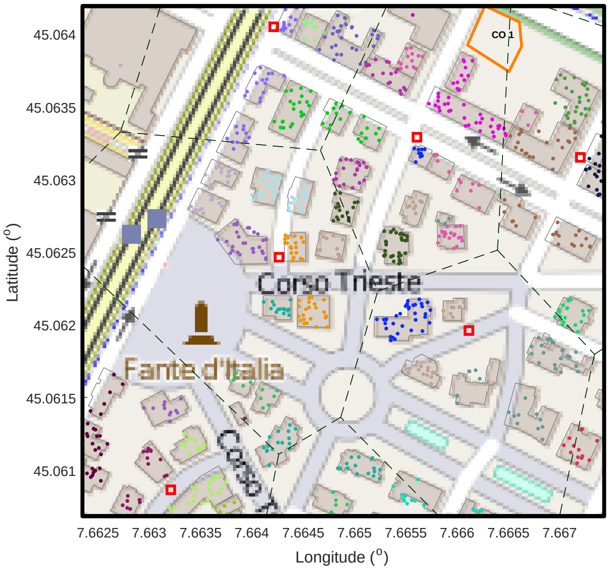
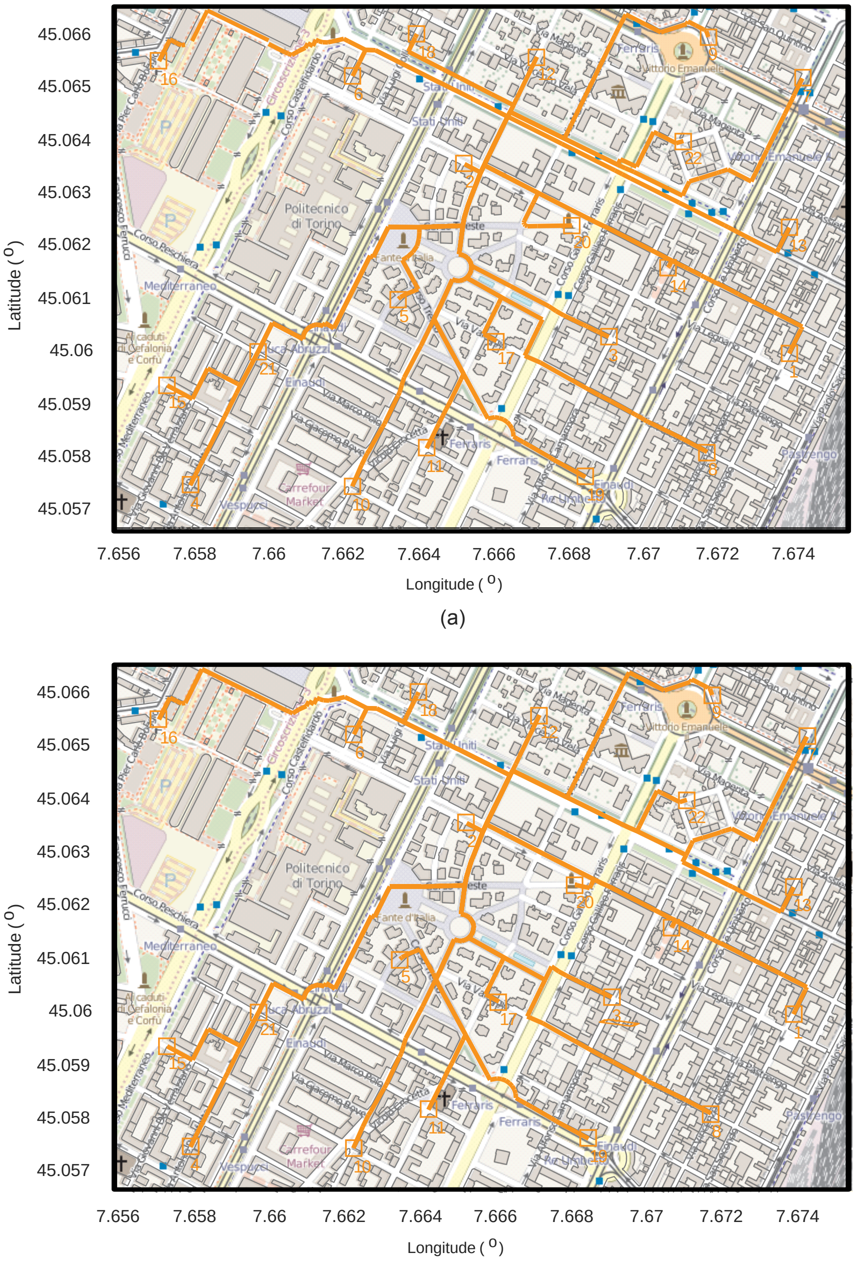


Figure 5.11: Function *aggregate*: PON aggregation by means of a Voronoi's partition (black dashed lines) and optimal location for PSC (red squares).

- *aggregate*: Performs PSC dimensioning and allocation by means of PON aggregation (i.e. clustering PON this time in order to share PSC and therefore optimize their costs of deployment). It starts from a set of initial candidate sites for PSC location and performs again a Voronoi's partition for clustering PON. Next it employs a Tabu search heuristic, which changes the PSC positions based on the closest single move towards the CO given by the Delaunay's triangulation of the current PSC locations (i.e. moving towards the CO in a non arbitrary way but following the closest Delaunay's link). In a similar way than PF, this function in every iteration chooses the best PSC locations (from the overall topology cost point of view). The Voronoi's partition and the optimal locations for the PSC that services a given set of PON (defined approximately by the Voronoi's partition) can be appreciated in Fig 5.11. The optimal location of a PSC is chosen from the candidate sites that are in close proximity to the Voronois' centers.

- $OF\_feeder, OF\_distrb, share$: These three functions evaluate the trenching, duct sharing and searching of optimal routes for OF cables from CO up to PSC and from PSC up to SSC, by means of the Dijkstra's algorithm. $OF\_feeder$ employs a recursive search of optimal routes starting from a first shortest path, and then modifying the metric of the most concurrent routes (the more concurrent the lower the metric becomes) and then running Dijkstra's algorithm again for tailoring the routes in order to share the paths for the feeder optical fibers (i.e. aggregating optical fibers in the same optical cable and thus optimizing the cost of trenching and fiber installation). In Fig.5.12 it can be seen an example of the recursive optimization performed by the $OF\_feeder$ function. $OF\_distrb$ uses the Dijkstra's algorithm for finding optimal routes from a PSC up to the correspondent SSC (notice that such correspondence was already defined by the clustering of users in different single PON and by the PSC-PON correspondence performed by the previously described $clustr\_build$ and $aggregate$ functions). Finally $share$ evaluate the routes in order to assign a single trenching and duct path to any set of feeder optical fibers which share the same route in the city's streets (in order to evaluate only once the cost of the shared trenching paths and ducts).

- $evaluate\_cots$: Evaluates the cost of the multiple PON deployment from the results given by the previous functions. The cost of the OF cabling from SSC up the users' ONU inside every building is calculated based on the average number of the levels in the building, for vertical-cabling dimensioning, and on the average radius of the buildings' geometrical skull, for the horizontal-cabling dimensioning. This function provides detailed specifications of costs (including the labor or installation cost), for every CO and for the complete region's global values. Specifically, OTS gives costs for the following components of the multiple PON deployment: PON hardware, trenching and ducts for feeder and distribution optical cables, optical cables, cabinets and splitters.



(a)

(b)

Figure 5.12: Function $OF\_feeder$: (a) Optimal CO-PSC routes (feeder OF) given by an initial run of Dijkstra's algorithm. (b) Definite optimal CO-PSC routes found by the function by means of metric (cost) modification of concurrent paths.

The general operation of these functions is described in Algorithm 1.

**Algorithm 1:** Optimal Topology Search (OTS)

```
Data: $Data = load\_data(City, Users, CO)$
Result: $Optimal\_Topology = OTS(Data)$
begin
    for $i \in \{Heuristic\_modifier\_counter\}$ do
        $Data_i = i^{th}\_heuristic\_variation(Data)$
        $Data_c = cluster\_CO\_zones(Data_i)$
        for $c \in CO$ do
            $SSC = allocate\_ssc(Data_c)$
            $[OLT, ONU] = clustr\_build(SSC, Data_c)$
            $PON_{hardw} = \{OLT, ONU\}$
            $PSC = aggregate(PON_{hardw}, Data_c)$ $SC = \{SSC, PSC\}$
            $OF\_feeder = Find\_pahts(PSC, Data_c)$
            $OF\_distrb = Find\_pahts(SSC, Data_c)$
            $ODN = \{OF\_feeder, OF\_distrb, SC\}$
            $Trenching = share(ODN)$
            $Topology_i = \{ODN, PON_{hardw}\}$
        end
        $C_i = evaluate\_cost(Data_c, Topology_i)$
        if $C_i < C_{opt}$ then
            $Optimal\_Topology = Topology_i$
            $C_{otp} = C_i$
        end
    end
end
```

## 5.4 General description of the results obtained with OTS

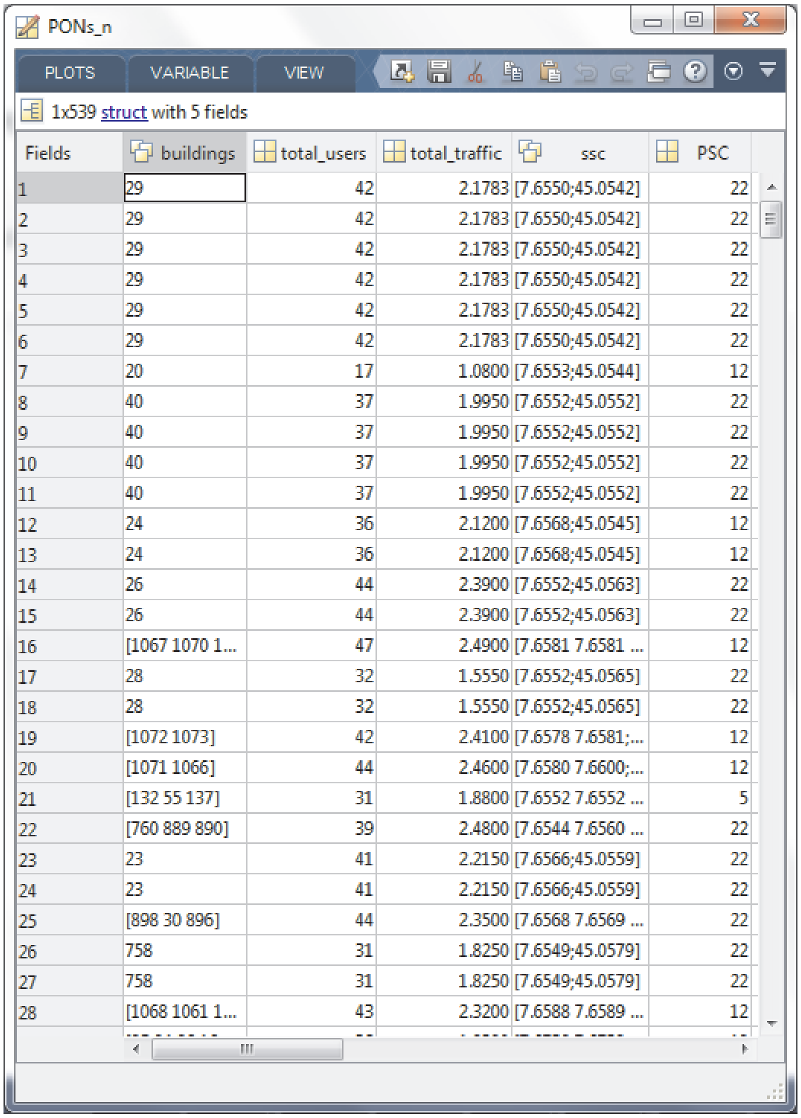
OTS finds optimal low-cost solutions for multiple PON deployments using real city maps. Provided that it is based on heuristic approaches it is not certain that the solution is the most optimal solution but can be considered nearly-optimal. Depending on the time the user is committed to spend OTS may perform lower-cost topology searches with a great level of accuracy (depending on the parameters which permit to tailor the heuristic search like the number of iterations and the size of the steps). As reference, the time OTS spends for resolving a region with $10^5$ users varies from few hours (typically 1.5 hours) to some hours (an average of 6 hours) depending on the iterations and steps employed to tailor the heuristic processes.

OTS can deliver data results and graphical results as following described:

- Building data:
  - Building identifier (ID).
  - ID of the CO sub-region the building belongs to.
  - Type of the users in the building (business or residential).
  - Coordinates of its structure (building's location) including the SSC.
  - Attributes: number of users and bit rate demanded by them.
  - ID of the PON and the CO which service the users in the building.
  - ID of the CO to which its SSC is connected to.
  - Route from the buildings' SSC to the correspondent PSC or CO.
- PON data:
  - PON ID.
  - The number of users serviced by the PON and the sustained bit rate demanded by them.
  - Coordinates of the SSC the PON's ODN connects to.
  - The ID of the PSC employed in the PON's ODN.
- PSC data:
  - Type of the users in the building (business or residential).
  - Coordinates of its structure and SSC location on it.
  - Attributes: number of users and bit rate demanded by them.
  - PON ID and CO ID which service the users in the building.
  - PSC ID to which its SSC is connected to.
  - Number of fibers in the feeder optical cables that arrive to the PSC.

- CO data:
  - ID of the CO.
  - Coordinates of its structure (CO location).
  - Data of the buildings serviced by the CO.
  - PSC employed by the CO (for feeder fiber routing).
  - Data of the PON serviced by the CO.
  - Costs of deployment of the sub-region serviced by the CO.
- Costs data:
  - Cost of OLT hardware in CO.
  - Cost of trenching and ducts for feeder and distribution optical cables.
  - Cost of optical cables (feeder, distribution and indoors).
  - Cost of cabinets and splitters (PSC and SSC).
  - Cost of ONU (business and residential).
  - Total cost of the multiple PON deployment.
- Graphical results:
  - City map (buildings and streets) with latitude and longitude coordinates.
  - Location and index of the different CO in the map.
  - CO sub-regions.
  - Buildings and users location in their respective CO subregion.
  - SSC location.
  - PSC location.
  - Feeder optical cables routes.
  - Distribution optical cables routes.
  - PON distribution in a region or subregion (differentially colored users).
  - Voronoi's partition of the region among the different CO.

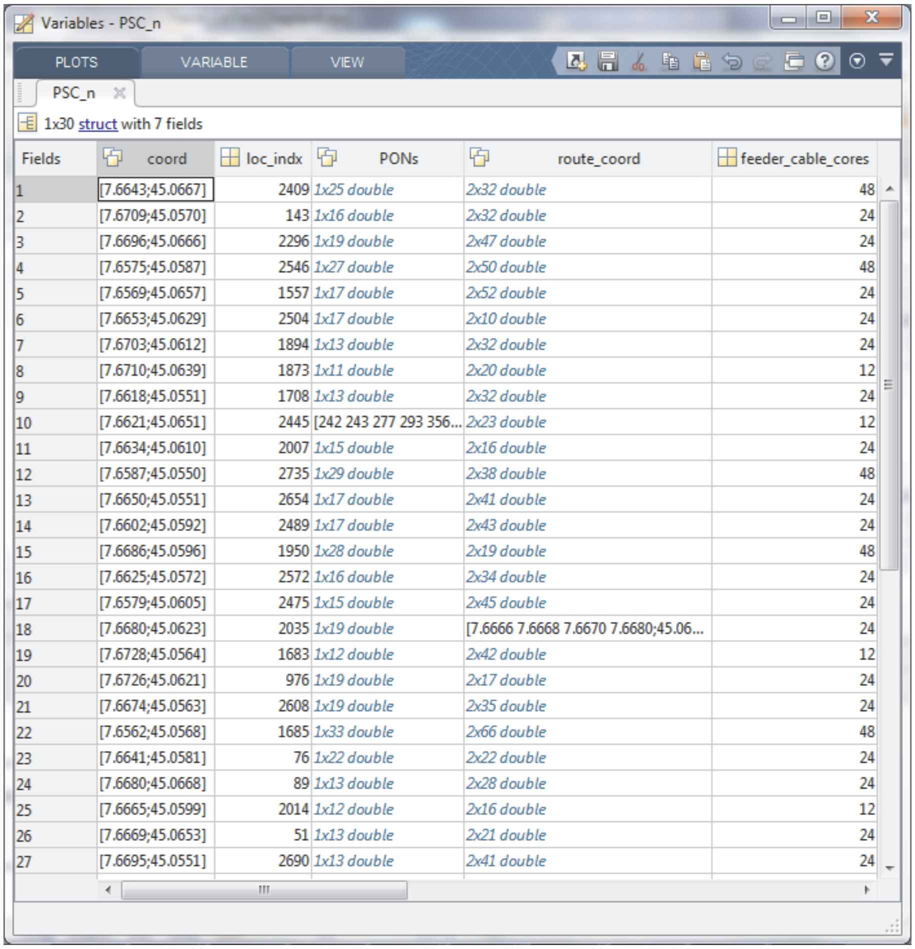
Fig.5.13 and Fig.5.14 show examples of the data results delivered for PSC and PON. Every OTS data table provides detailed information of some component of the deployment. For instance, the table illustrated in Fig.5.13 provides information of serviced buildings, total users, traffic demands, SSC and PSC for the first 28 PON in a region where OTS found a solution for optimal deployment of GPON. In Fig.5.14 it can be seen information of PSC ID and location (coordinates) PON whose feeder OF arrive to the PSC, route CO-PSC, features of the feeder optical cable that arrive to the PSC.



1x539 struct with 5 fields

| Fields | buildings | total_users | total_traffic | ssc | PSC |
|---|---|---|---|---|---|
| 1 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 2 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 3 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 4 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 5 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 6 | 29 | 42 | 2.1783 | [7.6550;45.0542] | 22 |
| 7 | 20 | 17 | 1.0800 | [7.6553;45.0544] | 12 |
| 8 | 40 | 37 | 1.9950 | [7.6552;45.0552] | 22 |
| 9 | 40 | 37 | 1.9950 | [7.6552;45.0552] | 22 |
| 10 | 40 | 37 | 1.9950 | [7.6552;45.0552] | 22 |
| 11 | 40 | 37 | 1.9950 | [7.6552;45.0552] | 22 |
| 12 | 24 | 36 | 2.1200 | [7.6568;45.0545] | 12 |
| 13 | 24 | 36 | 2.1200 | [7.6568;45.0545] | 12 |
| 14 | 26 | 44 | 2.3900 | [7.6552;45.0563] | 22 |
| 15 | 26 | 44 | 2.3900 | [7.6552;45.0563] | 22 |
| 16 | [1067 1070 1... | 47 | 2.4900 | [7.6581 7.6581 ... | 12 |
| 17 | 28 | 32 | 1.5550 | [7.6552;45.0565] | 22 |
| 18 | 28 | 32 | 1.5550 | [7.6552;45.0565] | 22 |
| 19 | [1072 1073] | 42 | 2.4100 | [7.6578 7.6581;... | 12 |
| 20 | [1071 1066] | 44 | 2.4600 | [7.6580 7.6600;... | 12 |
| 21 | [132 55 137] | 31 | 1.8800 | [7.6552 7.6552 ... | 5 |
| 22 | [760 889 890] | 39 | 2.4800 | [7.6544 7.6560 ... | 22 |
| 23 | 23 | 41 | 2.2150 | [7.6566;45.0559] | 22 |
| 24 | 23 | 41 | 2.2150 | [7.6566;45.0559] | 22 |
| 25 | [898 30 896] | 44 | 2.3500 | [7.6568 7.6569 ... | 22 |
| 26 | 758 | 31 | 1.8250 | [7.6549;45.0579] | 22 |
| 27 | 758 | 31 | 1.8250 | [7.6549;45.0579] | 22 |
| 28 | [1068 1061 1... | 43 | 2.3200 | [7.6588 7.6589 ... | 12 |

Figure 5.13: Example of data for the first 28 PON in a CO subregion deployed with GPON.



1x30 struct with 7 fields

| Fields | coord | loc_indx | PONs | route_coord | feeder_cable_cores |
|---|---|---|---|---|---|
| 1 | [7.6643;45.0667] | 2409 | 1x25 double | 2x32 double | 48 |
| 2 | [7.6709;45.0570] | 143 | 1x16 double | 2x32 double | 24 |
| 3 | [7.6696;45.0666] | 2296 | 1x19 double | 2x47 double | 24 |
| 4 | [7.6575;45.0587] | 2546 | 1x27 double | 2x50 double | 48 |
| 5 | [7.6569;45.0657] | 1557 | 1x17 double | 2x52 double | 24 |
| 6 | [7.6653;45.0629] | 2504 | 1x17 double | 2x10 double | 24 |
| 7 | [7.6703;45.0612] | 1894 | 1x13 double | 2x32 double | 24 |
| 8 | [7.6710;45.0639] | 1873 | 1x11 double | 2x20 double | 12 |
| 9 | [7.6618;45.0551] | 1708 | 1x13 double | 2x32 double | 24 |
| 10 | [7.6621;45.0651] | 2445 | [242 243 277 293 356... | 2x23 double | 12 |
| 11 | [7.6634;45.0610] | 2007 | 1x15 double | 2x16 double | 24 |
| 12 | [7.6587;45.0550] | 2735 | 1x29 double | 2x38 double | 48 |
| 13 | [7.6650;45.0551] | 2654 | 1x17 double | 2x41 double | 24 |
| 14 | [7.6602;45.0592] | 2489 | 1x17 double | 2x43 double | 24 |
| 15 | [7.6686;45.0596] | 1950 | 1x28 double | 2x19 double | 48 |
| 16 | [7.6625;45.0572] | 2572 | 1x16 double | 2x34 double | 24 |
| 17 | [7.6579;45.0605] | 2475 | 1x15 double | 2x45 double | 24 |
| 18 | [7.6680;45.0623] | 2035 | 1x19 double | [7.6666 7.6668 7.6670 7.6680;45.06... | 24 |
| 19 | [7.6728;45.0564] | 1683 | 1x12 double | 2x42 double | 12 |
| 20 | [7.6726;45.0621] | 976 | 1x19 double | 2x17 double | 24 |
| 21 | [7.6674;45.0563] | 2608 | 1x19 double | 2x35 double | 24 |
| 22 | [7.6562;45.0568] | 1685 | 1x33 double | 2x66 double | 48 |
| 23 | [7.6641;45.0581] | 76 | 1x22 double | 2x22 double | 24 |
| 24 | [7.6680;45.0668] | 89 | 1x13 double | 2x28 double | 24 |
| 25 | [7.6665;45.0599] | 2014 | 1x12 double | 2x16 double | 12 |
| 26 | [7.6669;45.0653] | 51 | 1x13 double | 2x21 double | 24 |
| 27 | [7.6695;45.0551] | 2690 | 1x13 double | 2x41 double | 24 |

Figure 5.14: Example of data for the first 27 PSC in a CO subregion deployed with GPON.

In Table 5.1 it is also presented an example of information, provided by OTS, relative to buildings belonging to a multiple PON deployment in an CO subregion of Turin downtown. Notice in the table that the buildings' locations are referenced by means of the coordinates of their correspondent SSC. The type of building is referenced by 1=residential, 2=business.

Fig.5.15 presents the optimal topology deployment for a zone of Medellín serviced by three CO buildings. Notice the subregions of each CO in that region of Medellín are differentiated by means of using a different color when drawing the profile of the correspondent buildings.

Table 5.1: Information of the first ten buildings (from a total of 1073) in a CO's subregion in Turin.

| Build. ID | Type | Levels | Numb.of users | BR (Gb/s) | SSC coord [Long;Latd] | PSC ID | Assigned PON |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 8 | 43 | 2.62 | [7.6613;45.0617] | 11 | 437,438 |
| 2 | 1 | 2 | 8 | 0.41 | [7.6603;45.0607] | 14 | 213 |
| 3 | 1 | 5 | 24 | 1.32 | [7.6610;45.0604] | 11 | 403 |
| 4 | 1 | 3 | 17 | 0.95 | [7.6614;45.0611] | 11 | 55 |
| 5 | 1 | 3 | 2 | 0.06 | [7.6568;45.0652] | 5 | 167,168 |
| 6 | 1 | 6 | 61 | 3.1 | [7.6579;45.0650] | 5 | 43,44,45 |
| 7 | 1 | 7 | 91 | 5.2 | [7.6564;45.0572] | 22 | 189 |
| 8 | 2 | 1 | 1 | 0.8 | [7.6589;45.0645] | 5 | 137 |
| 9 | 1 | 2 | 7 | 0.14 | [7.6738;45.0575] | 19 | 137 |
| 10 | 1 | 8 | 7 | 0.42 | [7.6736;45.0572] | 19 | 137 |

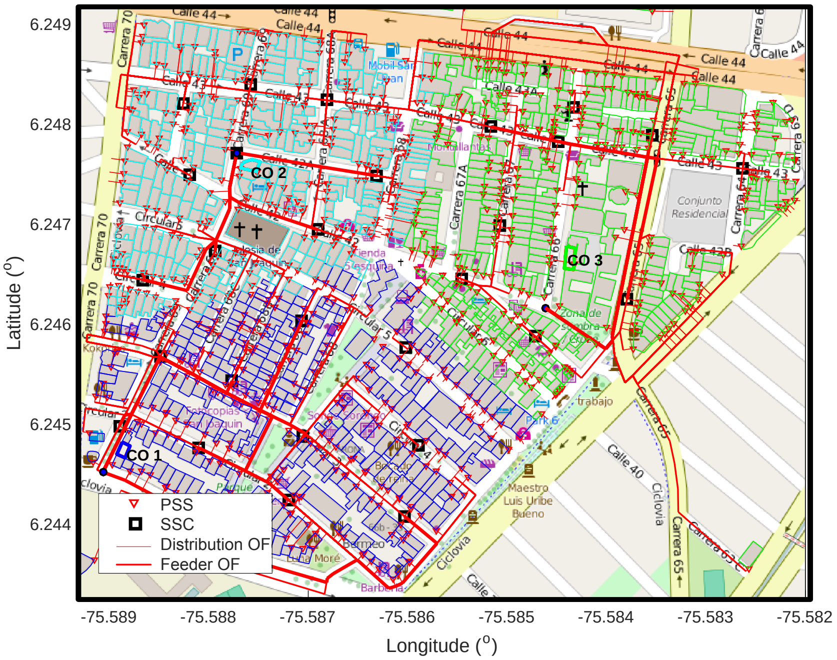


Figure 5.15: Multiple PON deployment, for three CO, in a downtown zone in Medellín.

# Chapter 6

# Results

## 6.1 Introduction

Current chapter contains detailed information of results given by OTS. We carried out a series of multiple PON deployment simulations employing different city maps information retrieved from OSM. In every simulation we assumed a region with many users demanding high-bandwidth FTTH services.

We present three cases of optimal multiple PON deployment: first we present the results obtained in Turin, with six different bit rate demands and four PON technologies (GPON, XGPON, NGPON2 and UDWDM PON). Then we present results of multiple PON deployment in Rome, with three bit rate scenarios and three PON technologies (those used in Turin, excluding UDWDM PON). Finally we present the result given by OTS for Quito. Given the low feasibility of deploying next generation PON in Quito, and the current low demand of high bandwidth access networks in this city, here we simulated a more conservative multiple PON deployment with only two PON technologies: GPON and XGPON, and two bit rate demand scenarios.

## 6.2 Case of study: Multiple PON deployment in a downtown zone of Turin

In order to present a specific complete deployment scenario of costs, in this section we describe the details of OTS simulation results in a down town zone of Turin, Italy. Here we selected a region characterized by the presence of many residential buildings. Buildings in this zone may have from few up to hundreds of apartments. We used a region of 15 $km^2$ with nearly 6500 buildings and a total number of users in the order of $10^5$.

The streets and buildings location that we used in OTS correspond to the real data taken from the OSM database while we did some reasonable assumptions to estimate the actual number of users per building (a data that is not directly available in OSM, but that we statistically derive using such information as the building footprint and number of floors). Moreover, we assumed that the corporate users in Turin's selected region is a 2% of the total users.

With the purpose of guaranteeing uniformity and equity in the results, we employed for every PON technology the same set of users, with their corresponding bit rate demands, and the same CO locations in the region chosen for performing the multiple PON deployment tests.

We ran OTS for every PON technology specified in Table 3.4, sweeping the six bit rate demand scenarios detailed in Table 3.5. In each case OTS found an optimal topology (as demonstrated in the previous section of this chapter) according to the procedure described in chapter 5.

Fig. 6.1 shows a composite plot of a region in Turin with approximately $10^5$ users. In the two insets, we show as an example the plot of the resulting optimal topology solution found by OTS, for UDWDM PON and bit rate scenario #4 (see later for more details on this). Notice that OTS is a street-aware algorithm which finds, among other non-graphical results, the optimal location of PSC, SSC and routes for feeder and distribution OF cables, along through the city's streets. For visibility purposes we have not included the plot of links from SSC up to users inside each building. Zoom above shows the edges of three different CO zones and the correspondent Delaunay's partition. Buildings in different zones are plotted with different color. Zoom below shows a region with about $10^4$ users which includes the plotting of the feeder and distribution OF cables routing and the street cabinets locations.

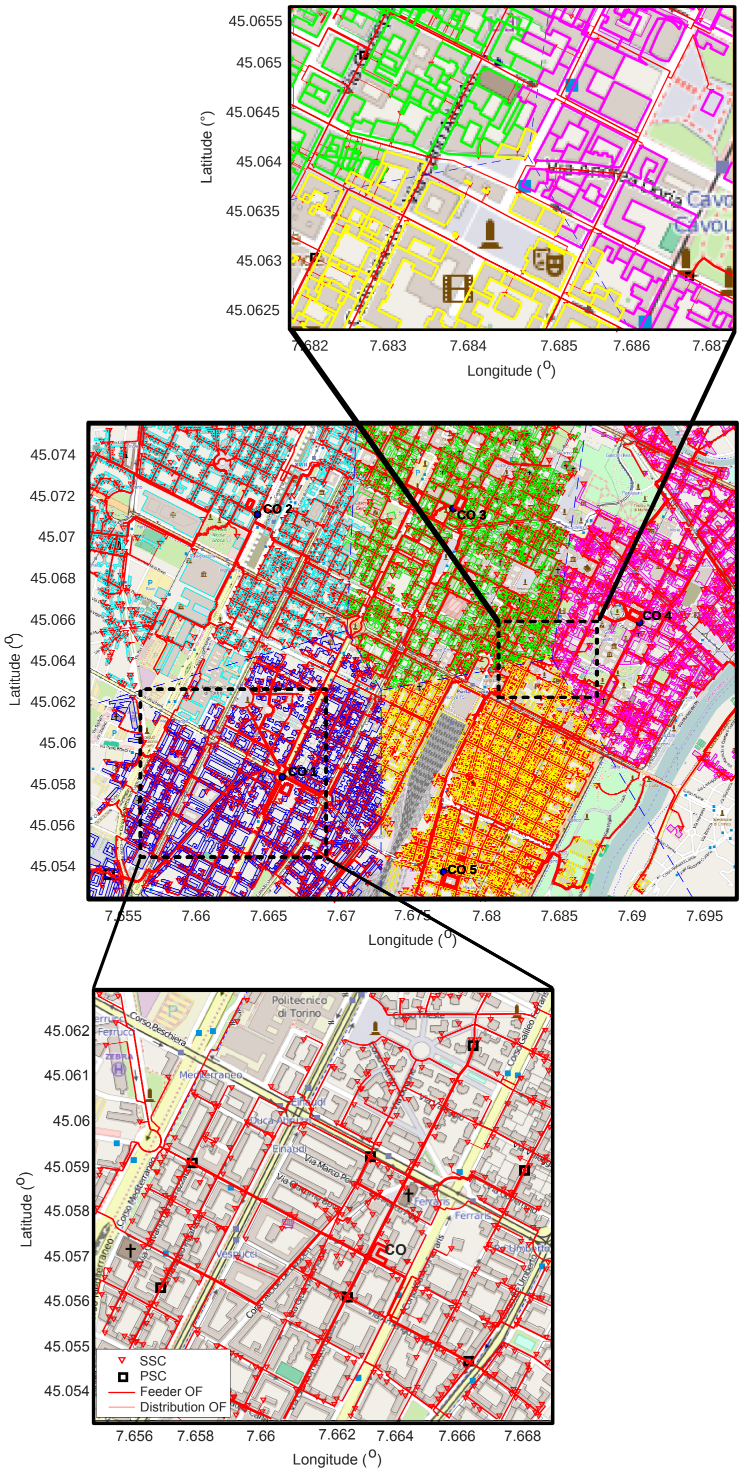


Figure 6.1: Multiple PON deployment for a region with $10^5$ users and 5 CO zones (central figure)

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Table 6.1: Costs of the multiple PON deployment for $10^5$ users

| Bit Rate Scenario | Cost (millon of USD) | | | |
|---|---|---|---|---|
| | GPON | XGPON | NGPON2 | UDWDM PON |
| 1 | 51.4 | 82.2 | 113.3 | 157.1 |
| 2 | 61.0 | 84.2 | 113.3 | 157.1 |
| 3 | 106.6 | 93.3 | 113.3 | 157.1 |
| 4 | 178.7 | 127.9 | 113.3 | 157.1 |
| 5 | 394.6 | 207.8 | 146.8 | 159.9 |
| 6 | - | 250.7 | 168.3 | 164.5 |

In a real-life case, users demand different bit rates depending on their needs and preferences. For that reason we randomly assigned, by means of a uniformly distributed random function, a different minimum guaranteed bit rate for each user, residential or corporative, in the range of the correspondent values of the bit rate scenario under consideration. Table 6.1 specifies the total deployment cost of for GPON, XGPON, NGPON2 and UDWDM PON in every bit rate scenario. An interesting value of the obtained results is the cost of GPON for the bit rate scenario #1, which is approximately the scenario that covers today's typical bit rate demand for residential and corporative users. Such value, 51.4 millon of USD for $10^5$ users, corresponds to a cost of about 514 USD per user (i.e 51.4 millon of USD divided by $10^5$ users), which seems a reasonable result considering the typical cost estimations of current operator's real costs per user for GPON.

The results in Table 6.1 show that, for increasing bit rate demands (i.e. going from Bit Rate Scenario #1 up to #6 in our formalization) the deployment cost significantly ramps up above a given bit rate demand "threshold", whose position depends on each technology capacity. For instance for GPON, the cost ramps up above scenario #2, that requires up to 100 Mbit/s sustained bit rate per user which, given the GPON 2.5 Gbps downstream bit rates, requires to deploy PON having significantly less than 64 users. Basically, this requirement leads to the necessity of deploying a larger number of GPON for the same total number of users, thus significantly increasing cost. As another example, for NGPON2, thanks to a much higher capacity, the cost ramps up only above Bit Rate Scenario #4.

Fig. 6.2 shows a chart of costs for each PON technology deployment, including a detail of the cost of hardware, trenching and ODN components, for the six bit rate scenarios. It can be seen in the figure that when the guaranteed bit rate demand from users is relatively low, i.e. in the order of some tens of Mb/s for residential users and some hundreds of Mb/s for corporative users, like in the scenarios 1 and 2, the cost of GPON is the lowest one in comparison with the cost of the other technologies. Instead, when the bit rate demands from residential users is in the order of few hundreds of Mb/s (scenario 3), XGPON becomes the best choice in front of the increased cost of the deployment for GPON and the still more expensive cost of NGPON2 and UDWDM PON. However, as can be seen for the scenario 4, if the bit rate demands of residential users are in the order of few hundreds of Mb/s up to 1 Gb/s and for corporate users in the order of 1 up to 10 Gb/s, then XGPON becomes also a expensive solution in comparison with NGPON2. Under the consideration we have made about of hardware prices for UDWDM PON, which is about two times the price of NGPON2 hardware and about 4 times the prices of XGPON hardware, in scenario 5 NGPON2 still constitutes a better solution than UDWDM PON, and only in scenario 6 the deployment of UDWDM PON has a similar cost to the deployment of NGPON2. Clearly, Scenario 6, where residential users demand a bit rate of 1 or more Gb/s and corporate users demand bit rates beyond 5 Gb/s, is a long term scenario but it may anyway become interesting in the following years.

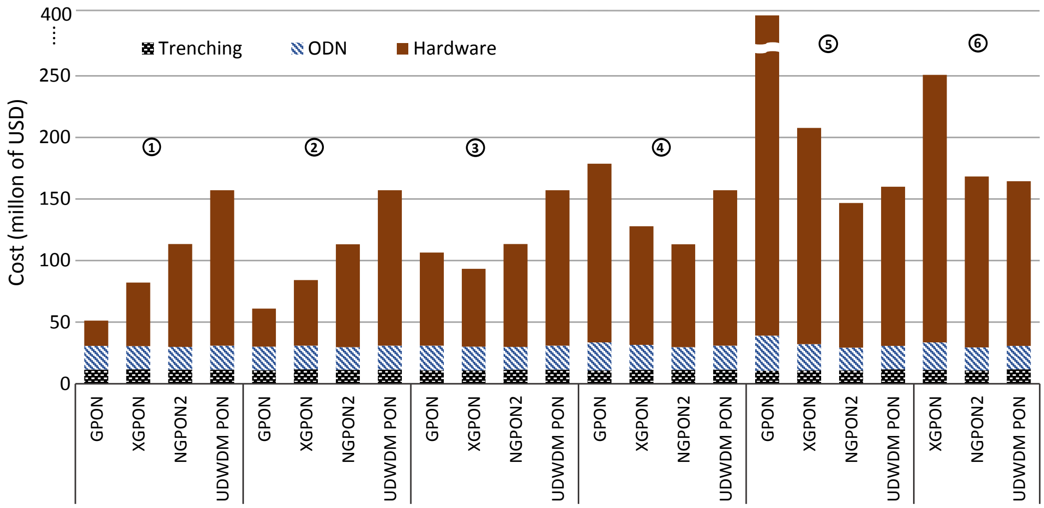

Figure 6.2: Cost of multiple PON deployments for GPON, XGPON, NGPON2 and UDWDM PON in the six bit-rate-demand scenarios specified in Table 3.5.

Analyzing our results, we see that the most important factor for the increase of the total hardware cost is related to the CO hardware. To better point out this result, we plot in Fig. 6.3 the costs of CO hardware for each PON technology. Notice that, due to its capacity for servicing much more users per OLT, the CO hardware for UDWDM PON is overall less costly in a multiple deployment in comparison with the cost of the other PON technologies. Moreover its price is constant in the first four bit rate demand scenarios, and increases only in the fifth and the sixth scenario, but its increase is much lower than the increase of costs for the other PON technologies. These results confirm the fact that a key point for rendering this technology commercially competitive is the reduction of the ONU cost.

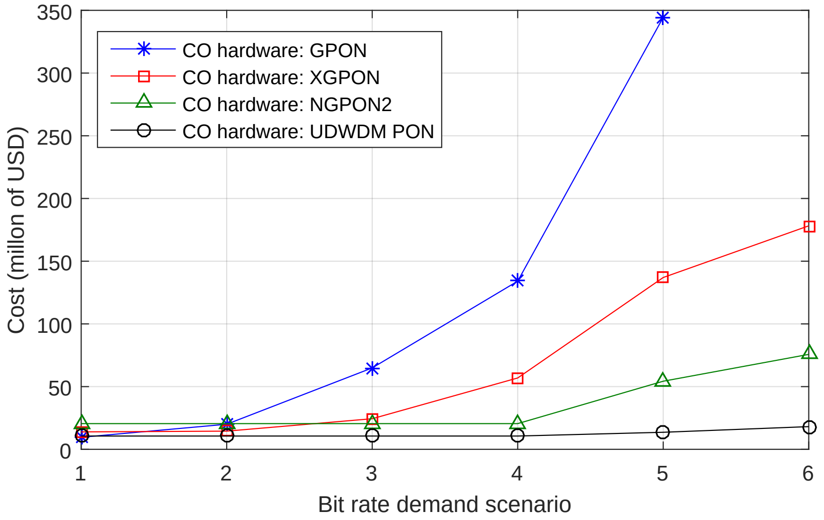

Figure 6.3: Costs of CO hardware for multiple PON deployment, five CO, $10^5$ users.

Even though the cost of the ODN is mostly impacted for the high cost of installation of the distribution optical fiber cables inside buildings (i.e. from the SSC up to the users' ONU), such price is almost constant for all bit rate demands and for any PON technology and thus does not represent a planning decision factor in the techno-economic analysis of PON technology selection. In the other hand, the cost of the feeder fiber (i.e. from CO up to PSC) and the distribution fiber up to every building (i.e. from PSC up to SSC), present a behavior of constant increase from the point where a PON technology have to service a bit rate demand which goes beyond its limits of capacity, as illustrated in Fig. 6.4. This result suggests that for region where users are sparsely located (and thus have opposite characteristics compared to the user distribution considered in this paper, which corresponds to a densely populated urban area), the cost of the ODN might represent an important decision factor in the PON technology selection.

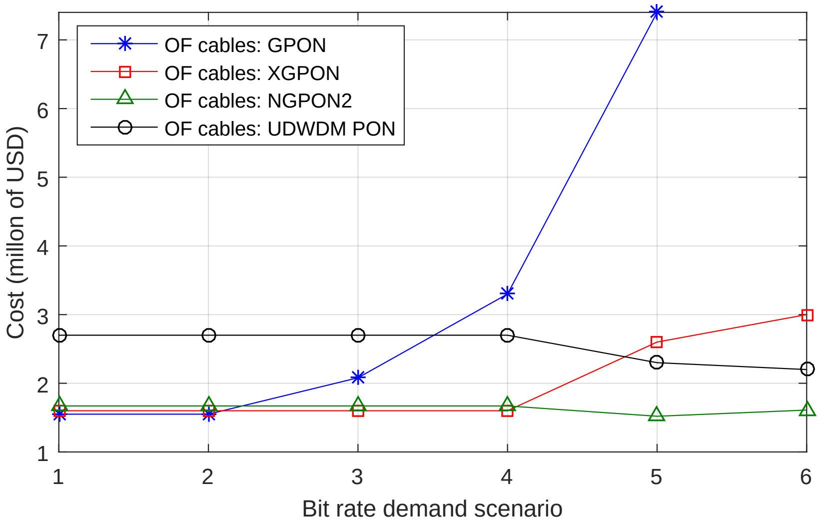

Figure 6.4: Costs of feeder OF plus PSC-SSC distribution OF in the region of about $15km^2$ (Turin downtown), with $10^5$ users.

As we have discussed in a previous Section, the hardware cost assumptions made in this research work for GPON, XGPON UDWDM PON NGPON2 were obtained after interactions with system vendors, while the costs for UDWDM PON were necessarily very approximated since this is only a ”research level” technology, without any standard nor pre-production yet. We have thus performed a further analysis where we take UDWDM PON hardware costs as a variable parameter. Even though the selection of prices in this part of our analysis assumes arbitrary values, we kept such prices of UDWDM PON hardware in a feasible interval of possibilities by means of using as reference the XGPON technology. We consider three cases: first, the case when the UDWDM PON hardware is three times more expensive than the XGPON hardware; second, when it is four times more expensive than the XGPON (which correspond to the prices employed in the analysis previously presented); and third, when it is five times more expensive than the XGPON

Table 6.2: Costs of the multiple UDWDM PON deployment for three scenarios of hardware prices.

| Bit Rate Scenario | Cost (millon of USD) when UDWDM PON's cost is: | | |
|---|---|---|---|
| | $3 \times (XGPON)$ | $4 \times (XGPON)$ | $5 \times (XGPON)$ |
| 1 | 134.0 | 157.1 | 193.5 |
| 2 | 134.0 | 157.1 | 193.5 |
| 3 | 134.0 | 157.1 | 193.5 |
| 4 | 134.0 | 157.1 | 193.5 |
| 5 | 136.5 | 159.9 | 197.4 |
| 6 | 140.0 | 164.5 | 203.3 |

hardware. Table 6.2 presents the results given by OTS for these three situations. It can be observed that the prices of the UDWDM PON deployment is approximately the same for all bit rate scenarios. This is due to the fact that the six bit rate demands scenarios are far from reaching the limits of the performance for the UDWDM PON technology considered in our analysis [85].

Fig. 6.5 plots the prices of Table 6.2 and the prices of XGPON and NGPON2 in Table 6.1. It can be observed that, in the six bit rate scenarios considered in the analysis, the cots of XGPON or NGPON2 deployment increase with respect to the increase of the users' bit rate demands. And, given that the price of UDWDM PON keeps approximately constant, there is a point where UDWDM PON deployment, in any of the three considerations of hardware price, intersects with the curves of XGPON and NGPON2. Such intersection represent the approximate scenarios where a UDWDM PON solution constitutes a better option than the other PON technologies. The intersection point between XGPON curve and the lower UDWDM PON curve, in the near zone of bit-rate-demand scenario 4, suggests that if the prices of a UDWDM PON technology can be kept in a range of up to 3 times the prices of XGPON, UDWDM PON could be a better option in confront with XGPON when the users' bit rate demands reach an average value of some hundreds of Mb/s for residential users, and some units of Gb/s for business users. Instead, confronting UDWDM PON with NGPON2, results observed in the figure suggest that only when demands from users reach or goes beyond values like bit rates of scenario 5, the former could represent a equal or better solution in comparison with the latter.

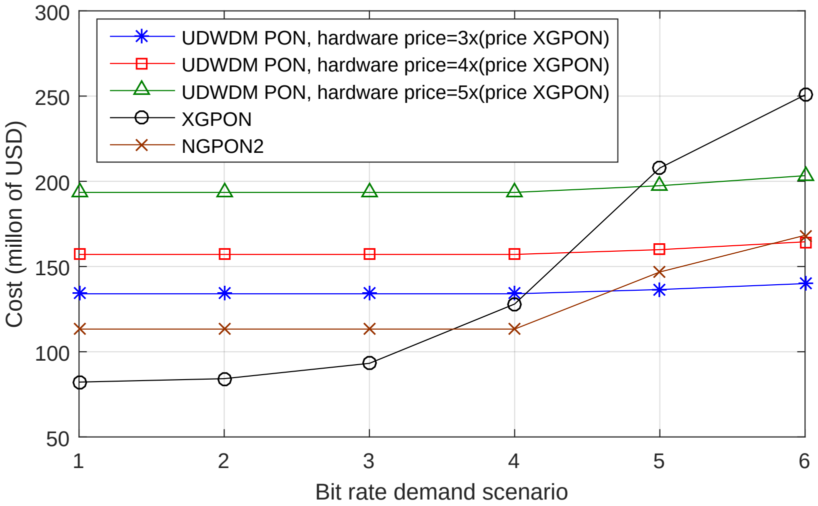

Figure 6.5: Curves of multiple-PON-deployment cost vs bit-rate-demand scenario for XGPON, NGPON2 and UDWDM PON, for $10^5$ users.

## 6.3 Case of study: Multiple PON deployment in a downtown zone of Rome

In this OTS case of study we've chosen a region of Rome of 25 $km^2$ with about $2 \times 10^5$ users serviced by 8 central offices. OTS found optimal topologies which implies optimal paths of OF cable routing and optimal PSC and SSC locations, as shown in Fig. 6.6. Simulation in the selected area of Rome were carried out based on the three different PON technologies: GPON, XGPON and NGPON2. This time we employed a brief scenario of bit rate demands as detailed in Table 6.3. Results show that if users' demand some tens of Mb/s, like in scenario #1, GPON constitute the best option. If the bit rate increase to some hundreds of Mb/s per user (a medium term scenario #2), XGPON constitutes the best techno-economic solution. In a longer term scenario #3, where the bit rate demands are in the order of many hundreds of Mb/s (scenario #3), NGPON2 is the best choice. Such results are detailed in Fig. 6.7 and Table 6.4.

Table 6.3: Bit rate scenarios for Rome's simulations.

| Scenario | Intervals of demanded bit rate [Mb/s] | |
|---|---|---|
| | Residential users | Corporate users |
| 1 | 10 - 100 | 100 - 1000 |
| 2 | 100 - 400 | 400 - 2500 |
| 3 | 100 - 1000 | 1000 - 10000 |

Table 6.4: Total deployment cost for $2 \times 10^5$ users in Rome.

| Scenario | COST (millon of USD) | | |
|---|---|---|---|
| | GPON | XGPON | NGPON2 |
| 1 | 104.08 | 141.51 | 200.31 |
| 2 | 200.84 | 159.82 | 200.26 |
| 3 | 332.94 | 212.78 | 200.25 |

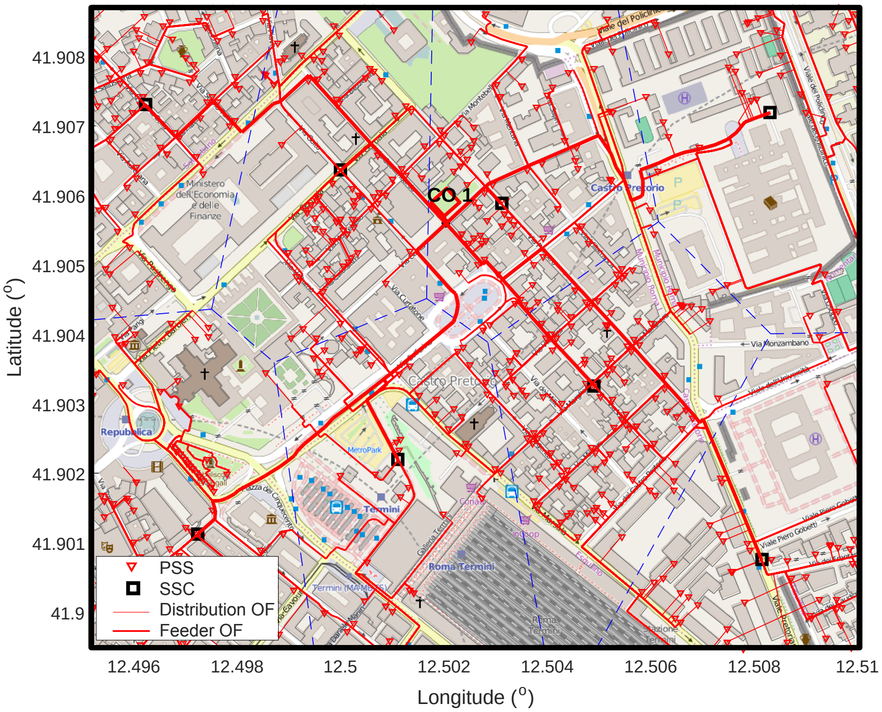

Figure 6.6: Multiple PON deployment in a downtown zone in Rome.

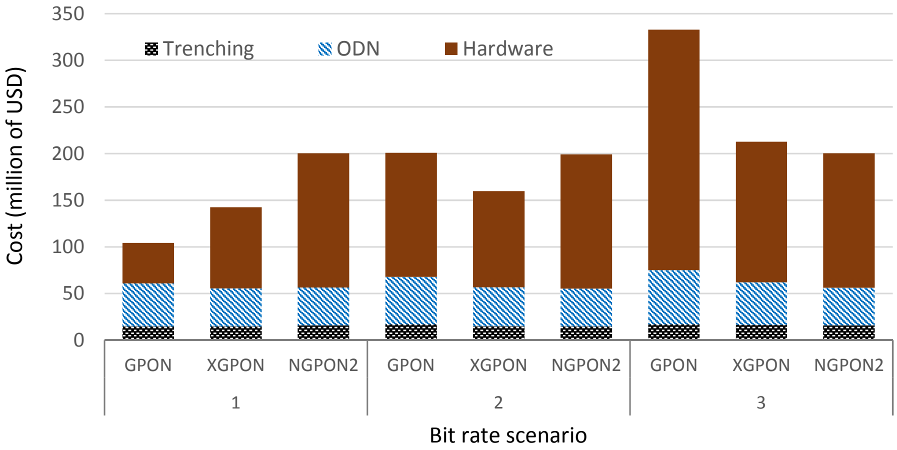

Figure 6.7: Costs of deployment for GPON, XGPON and NGPON2, for $2 \times 10^5$ users, in the three bit rate scenarios specified in Table 6.3.

Fig. 6.8 present the curves of multiple PON deployment for GPON, XGPON and NGPON2. It can be seen that in bit rate scenario #3, NGPON2 constitutes the best technology choice.

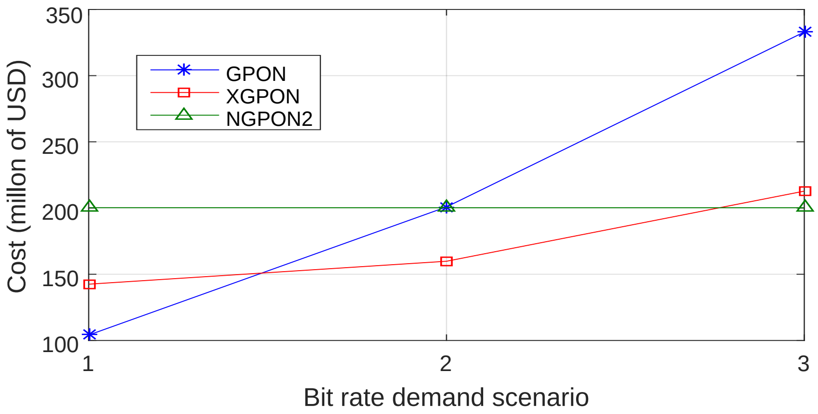

Figure 6.8: Curves of total deployment cost vs bit rate demand scenario for GPON, XGPON and NGPON2, $2 \times 10^5$ users.

In Fig. 6.9 it is considered the cost only of the central offices' PON hardware for multiple PON deployment of the three PON technologies. Notice how in the case of GPON, and in lower grade in the case of XGPON, the CO hardware increases exponentially with the increase of the users' bit rate demands. Instead, the cost of the NGPON2 CO's hardware although it is initially higher, it keeps constant in the three bit rate demand scenarios under consideration.

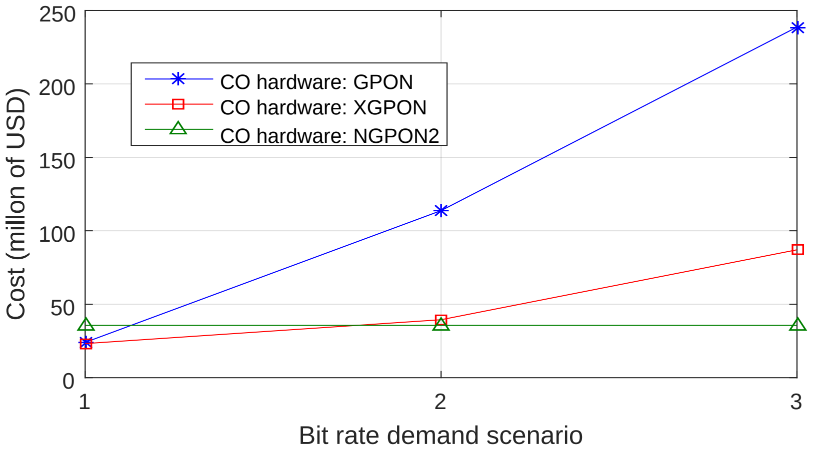

Figure 6.9: Costs of CO hardware for multiple PON deployment, eight CO, $2 \times 10^5$ users.

## 6.4 Case of study: Multiple PON deployment in a downtown zone of Quito

In the case of Quito, the density of potential users requiring FTTH is lower than Turin and Rome. Therefore, in our simulations of multiple PON deployment we use a region of $2 \times 10^4$ users, serviced by two CO. Users were randomly generated in their type, geographic position and bit rate demand. Regarding the type, we again assumed a percentage of corporative users in the order of 2% and residential users in the order of 98%, which also constitutes a real life situation in Ecuador. In the case of the bit rate demands we covered only two scenarios, detailed in Table 6.5: scenario 1 is not a current but a short term bit rate demand scenario in Ecuador. Scenario 2 covers a longer term scenario. In addition, in order to verify and compare results in real life deployment scenarios for Ecuador, we have chosen two technologies which are the most probable candidates for a future massive deployment of FTTH in Quito: GPON and XGPON.

In Quito's simulations OTS found optimal topologies, for the covered

Table 6.5: Bit rate scenarios for Quito's simulations.

| Scenario | Intervals of demanded bit rate [Mb/s] | |
|---|---|---|
| | Residential users | Corporate users |
| 1 | 10 - 100 | 100 - 1000 |
| 2 | 100 - 400 | 400 - 2500 |

zone, including data and graphic information, like optical cable routes and PSC/SSC optimal locations, as illustrated in Fig. 6.10.

Figure 6.10: Optimal topology in a region of Quito covered by a central office (CO 1) with about $10^4$ users (right figure). In the zoom at the left, it can be appreciated the detailed graphical results OTS delivers: Optimal routes for feeder and distribution OF cables, CO location and optimal location of PSC and SSC (notice in Quito's map the SSC are also placed in the buildings while the PSC are located in the neighboring streets).

Table 6.6: Costs of PON deployment in a region of Quito with 21522 users.

| Type of PON | BR scen. | # of PON | COST (Millon of USD) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Hardw. | Trenchig | OF cables | Cabinets | TOTAL |
| GPON | 1 | 522 | 4.87 | 2.96 | 3.99 | 1.82 | 13.6 |
| | 2 | 2616 | 15.29 | 3.05 | 4.45 | 2.35 | 25.1 |
| XGPON | 1 | 382 | 10.66 | 3.10 | 4.19 | 1.91 | 19.9 |
| | 2 | 630 | 12.61 | 3.04 | 4.48 | 1.81 | 21.9 |

Table 6.7: Per-user cost comparison for GPON.

| Scenario | Cost (USD) | | |
|---|---|---|---|
| | Quito | Turin | Rome |
| 1 | 630 | 514 | 520 |
| 2 | 2270 | 1066 | 1004 |

Table 6.6 presents the costs given by the simulation results in the selected area of Quito, in the two bit rate demand scenarios specified in Table 6.5. It can be appreciated that if users' demand some tens of Mb/s, like in the sustained bit rate demand of the first scenario, GPON constitute the best option in confront with XGPON. In fact the cost of the deployment in scenario 1 for GPON results in a per-user cost of about 630 USD, which is a very typical cost in real deployments of GPON in Ecuador. In the other hand, as can also be seen in Table 4, if the sustained bit rate demand per user increase to hundreds of Mb/s, like in second bit rate demand scenario, XGPON constitutes the best solution.

Table 6.7 presents a comparison of the per-user costs for GPON deployment given by OTS in the three different cities: Quito, Turin and Rome. With the purpose of having the same base of reference costs we employed regions with approximately the same number of users, two central offices, and the same costs of network components (even though the prices most probably would not be the same in different countries, we make the assumption of equal prices only for comparison purposes). Notice the cost per-user is more expensive in Quito than in Rome and Turin due to the higher users' density of those cities in Italy.

# Chapter 7

# Conclusions

- Current research work demonstrates the importance of using optimization frameworks for contributing to render feasible the massive deployment of FTTH services through PON. Specially, the next generation PON technologies constitute a promising solution for long term ultra-high bandwidth demands from residential and corporate users.

- The algorithm developed in this work, OTS, constitute a tool able to optimally and confidently dimension a multiple PON deployment in large regions. OTS is based on an effective set of heuristics employed in order to evaluate real life scenarios for deployment of PON taking into account real network parameters and constraints.

- Results obtained with OTS are very realistic (using as reference the current costs of deployment reported by operator and vendors for GPON and XGPON). Thus, we can state that OTS is accurate and versatile. Such accurate results are obtained thanks to the street-aware solutions OTS provides by means of making use of real city maps and very realistic network deployment scenarios, including accurate data of costs. The network components' costs, which were obtained thanks to direct interaction with operators and vendors, may be updated in the future in order to tailor the results according to any change of prices in following months or years.

- OTS is also effective because in a reasonable amount of time (few hours) it is able to find solutions for large city maps with very large number of users, with different bit rate demands and for different PON technologies.

- We have demonstrated that the use of a shared nearest neighbor algorithm constitute an effective approach for clustering users in a wide region with very large number of users in order to assign them to a set of PON available in one or more central office buildings.

- The simulation analysis performed in this thesis have revealed that UDWDM PON could be a promising technology for a future high bit rate scenario but depending on the costs of its hardware. The scenario that constitutes a point of interest for its deployment can be portrait in a users' bit-rate-demand basis. Our analysis suggest that if the price of UDWDM PON hardware, specially the price of the ONU, is in the range of three times the price of XGPON, then UDWDM PON could be an interesting solution when users' demands reach an average of some hundreds of Mb/s for residential users and some units of Gb/s for corporate users. Instead if UDWDM PON hardware is four times or more in comparison with XGPON, then UDWDM PON could be a good solution but in a longer term scenario.

- Results obtained in this research work also demonstrate that the cost of the CO hardware, i.e. the OLT hardware, grows exponentially with the increase of the sustained bit rate demands of the users. Therefore GPON is a technology with much lower scalability, from the prospective of the increase of bit rate demands. In that sense, UDWDM PON offer the greatest scalability but, for the current and near future users' bit rate demands, it would represent a too expensive investment for network operators.

- From results we may confirm that the most feasible solution for the close and mid term scenarios of demand growth of FTTH services and high-bandwidth from users, is NGPON2. The reason is its high bandwidth capability and potentially much lower prices of deployment in comparison with UDWDM PON.

# Glossary

**10GPON** 10 Gb/s Ethernet Passive Optical Network.

**AWG** arrayed waveguide grating.

**BER** bit error rate.

**BLS** broadband light source.

**BR** bit rate.

**CAPEX** Capital Expenditures.

**CG** column generation.

**CO** Central Office.

**colorless** wavelenth/frequency independent (tunable).

**DBA** Dynamic Bandwidth Assignment.

**DFB** Distributed Feedback Brag-reflector.

**DS** downstream.

**DSP** digital signal processing.

**DWA** Dynamic Wavelength Assignment.

**DWDM** Dense Wavelength Division Multiplexing.

**EMST** Euclidian minimum spanning tree.

**FTTH** Fiber To The Home.

**FWM** Four-Wave Mixing.

**GPON** Gigabit-capable Passive Optical Network.

**ID** identifier (or index number).

**ILP** Integer Linear Program.

**ITU** International Telecommunications Union.

**LO** local oscillator.

**LTE** Long Term Evolution.

**MA** maximum admitance.

**MILP** Mixed Integer Linear Program.

**NGPON2** Next-Generation Passive Optical Network - Version 2.

**NP-hard** Non Polinomial-Time Hard: A problem which can not be resolved in nearly linear nor polynomial time.

**ODF** optical distribution frame.

**ODN** Optical Distribution Network.

**OF** optical fiber.

**OLT** Optical Line Terminal.

**ONU** Optical Network Unit.

**OPEX** Operational Expenditures.

**OSM** OpenStreetMaps.

**OTS** Optimal Topology Search.

**PF** primary function.

**PON** Passive Optical Network.

**PON** Passive Optical Network.

**PSC** primary street cabinet.

**QAM** Quadrature Amplitude Modulation.

**RSOA** Reflective Semiconductor Optical Amplifier.

**SF** secondary function.

**SNN** Shared Nearest Neighbor clustering algorithm.

**SR** splitting ratio.

**SSC** secondary street cabinet.

**SSMF** standard single mode fiber.

**TDM** Time Division Multiplexing.

**UDWDM** Ultra Dense Wavelength Division Multiplexing.

**US** upstream.

**WDM** Wavelength Division Multiplexing.

**XGPON** 10-Gigabit-capable Passive Optical Network.

**XML** Extensible Markup Language: is a text-based format used to share data on the World Wide Web.

**XPM** Cross Phase Modulation.

# Bibliography

[1] Cisco visual networking index: Forecast and methodology, 2014–2019, May 2015.

[2] Abdelgader Abdalla, Ricardo Ferreira, Ali Shahpari, Jacklyn D Reis, Mario Lima, and Antonio Teixeira. Improved nonlinear tolerance in ultra-dense WDM OFDM systems. *Optics Communications*, 326:88–93, 2014.

[3] Akira Agata and Kosuke Nishimura. Suboptimal PON network designing algorithm for minimizing deployment cost of optical fiber cables. In *16th International Conference on Optical Network Design and Modeling (ONDM)*, pages 1–6, Colchester, 2012. IEEE.

[4] Gp Agrawal. *Nonlinear Fiber Optics.* Academic Press, Oxford, 5th editio edition, 2013.

[5] Marilet De Andrade, Anna Buttaboni, Massimo Tornatore, Pierpaolo Boffi, Paolo Martelli, and Achille Pattavina. Optimization of long-reach TDM / WDM passive optical networks. *Optical Switching and Networking*, 16:36–45, 2015.

[6] G Arévalo and D Cárdenas. Advantages of the use of VCSEL over RSOA for uplink transmission on WDM-PON networks. In *2012 IEEE Latin-America Conference on Communications, LATINCOM 2012 - Conference Proceedings*, 2012.

[7] Germán Arévalo, Javier Sierra, and Roberto Hincapié. ILP model for Greenfield WDM PON network design based on physical layer constraints.pdf. In G. Groot Gregory; Arthur J. Davis, editor, *Proc. SPIE 8842, Novel Optical Systems Design and Optimization XVI,*

*88420F*, volume 8842, pages 1–6, San Diego, California, United States, 2013. SPIE Digital Library.

[8] Germán V Arévalo. Redes WDM PON: Tendencias y soluciones para viabilizar y optimizar su implementación. *Revista Politécnica*, 35(1):103 – 109, 2015.

[9] Germán V. Arévalo, Roberto C. Hincapié, and Javier E. Sierra. Optimization model for UDWDM-PON deployment based on physical restrictions and asymmetric users' clustering. In *Proc. SPIE 9626, Optical Systems Design 2015: Optical Design and Engineering VI*, volume 9626, pages 1–11, Jena, Germany, 2015. SPIE Digital Library.

[10] Germán V Arévalo, Roberto C Hincapié, and Javier E Sierra. WDM-PON Design Model based on the Minimum Spanning Tree search over Delaunay Triangulations. In *IEEE Asia-Pacific Conference on Computer Aided System Engineering (APCASE)*, pages 68 – 71, Quito, Ecuador, 2015. IEEE.

[11] Kota Asaka and Invited Paper. Consideration of Tunable Components for Next-Generation Passive Optical Network Stage 2. *Jornal of Ligthwave Technology*, 33(5):1072–1076, 2015.

[12] MohammadHossein Bateni, MohammadTaghi Hajiaghayi, and Dániel Marx. Approximation Schemes for Steiner Forest on Planar Graphs and Graphs of Bounded Treewidth. *Journal of the Association for Computing Machinery (JACM)*, 58(5):1–37, 2009.

[13] M De Berg, M Van Kreveld, and M Overmars. Computational geometry: algorithms and applications. *Springer-Verlag, New York,*, 3ra.ed.(ISBN: 978-3-540-77973-5):191–218, 2008.

[14] Chayan Bhar, Goutam Das, Abhishek Dixit, Bart Lannoo, Marlies Van Der Wee, and Didier Colle. A Green Open Access Optical Distribution Network with Incremental Deployment Support. *Jornal of Ligthwave Technology*, 33(19):4079–4092, 2015.

[15] Meihua Bi, Shilin Xiao, Jun Li, and Hao He. A bandwidth-efficient channel allocation scheme for mitigating FWM in ultra-dense WDM-PON. *Optik - International Journal for Light and Electron Optics*, 125(8):1957–1961, apr 2014.

[16] Ahmad Biniaz, Anil Maheshwari, and Michiel Smid. On the Hardness of Full Steiner Tree Problems. *Journal of Discrete Algorithms*, 34:1–12, 2014.

[17] G. Bosco, V. Curri, a. Carena, P. Poggiolini, and F. Forghieri. On the performance of nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers. *Journal of Lightwave Technology*, 29(1):53–61, 2011.

[18] Iván N. Cano, Adolfo Lerín, Victor Polo, and Josep Prat. Direct phase modulation DFBs for cost-effective ONU transmitter in udWDM PONs. *IEEE Photonics Technology Letters*, 26(10):973–975, 2014.

[19] Iván N Cano, Milton N Tipán, and Germán V Arévalo. Optimal Duty Cycle in RZ Codified Data for 10Gb / s Optical Access Networks. In *17th International Conference on Transparent Optical Networks (ICTON)*, pages 4–7, Budapest, 2015. IEEE.

[20] Nicola Carapellese, Massimo Tornatore, Achille Pattavina, Politecnico Milano, and Via Ponzio. Placement of Base-Band Units ( BBUs ) over Fixed / Mobile Converged Multi-Stage WDM-PONs. In *17th International Conference on Optical Network Design and Modeling (ONDM)*, pages 246–251, Brest, France, 2013. IEEE.

[21] F Cavaliere, F Ponzini, and M Presi E Ciaramella. Migration towards High Speed Optical Access Enabled by WDM Techniques. In *Communications and Photonics Conference and Exhibition (ACP), 2009 Asia*, number 1, pages 2–3, Shanghai, China, 2009. IEEE.

[22] M. Chardy, M. C. Costa, A. Faye, and M. Trampont. Optimizing splitter and fiber location in a multilevel optical FTTH network. *European Journal of Operational Research*, 222(3):430–440, nov 2012.

[23] Jiajia Chen, Lena Wosinska, Mohsan Niaz Chughtai, and Marco Forzati. Scalable Passive Optical Network Architecture for Reliable Service Delivery. *J. Opt. Commun. Netw.*, 3(9):667–673, sep 2011.

[24] Jiajia Chen, Lena Wosinska, Carmen Mas MacHuca, and Monika Jaeger. Cost vs. reliability performance study of fiber access network architectures. *IEEE Communications Magazine*, 48(2):56–65, 2010.

[25] Miroslav Chlebík and Janka Chlebíková. The Steiner tree problem on graphs: Inapproximability results. *Theoretical Computer Science*, 406(3):207–214, oct 2008.

[26] Keun Yeong Cho, Student Member, Ui Hyun Hong, Masatoshi Suzuki, and Yun C Chung. 103-Gb / s Long-Reach WDM PON Implemented by Using Directly Modulated RSOAs. *IEEE Photonics Technology Letters*, 24(3):2011–2013, 2012.

[27] Rejaul Chowdhury and Brigitte Jaumard. A cross layer optimization scheme for WDM PON network design and dimensioning. *2012 IEEE International Conference on Communications (ICC)*, pages 3110–3115, jun 2012.

[28] Rejaul Chowdhury and Brigitte Jaumard. A p -Center Optimization Scheme for the Design and Dimensioning of a Set of WDM PONs. In *Global Communications Conference (GLOBECOM)*, pages 2977–2983, Anaheim CA, United States, 2012. IEEE.

[29] Rejaul Chowdhury, Abdallah Shami, Senior Member, and Khaled Almustafa. Designing of Next-Generation Hybrid Optical-Wireless Access Network. In *14th International Conference on Innovations for Community Services: "Technologies for Everyone", I4CS 2014*, pages 9 – 15, Reims, France, 2014. IEEE.

[30] Andrej Chu, Kin Fai Poon, and Anis Ouali. Using Ant Colony Optimization to design GPON-FTTH networks with aggregating equipment. In *IEEE Symposium on Computational Intelligence for Communication Systems and Networks, CIComms*, pages 10–17, Singapore, 2013. IEEE.

[31] G Y Chu, A Lerín, I N Cano, V Polo, J A Tabares, and J Prat. Exploiting RSOA for Uplink Transmission with Coherent Detection for Low Cost UDWDM-PON. In *Asia Communications and Photonics Conference 2014, OSA Technical Digest (online) (Optical Society of America, 2014), paper AF2B.1.*, pages 25–27, Shanghai China, 2014.

[32] Guang Yong Chu, Victor Polo, Adolfo Lerín, Jeison Tabares, Iván N. Cano, and Josep Prat. 1.25 – 3.125Gb/s per user PON with

RSOA as phase modulator for statistical wavelength ONU. *Optics Communications*, 357:34–40, 2015.

[33] Marilet De Andrade, Massimo Tornatore, and Achille Pattavina. Optimization Scheme for WDM-Based Transmission Technology Selection in Future Passive Optical Networks. *Journal of Optical Communications and Networking*, 5(9):1010–1019, 2013.

[34] Ze Dong, Hung-chang Chien, Jianjun Yu, Senior Member, Junwen Zhang, Lin Cheng, and Gee-kung Chang. Very-High-Throughput Coherent Ultradense WDM-PON Based on Nyquist-ISB Modulation. 27(7):763–766, 2015.

[35] António Eira, João Pedro, and João Pires. Optimized Design of Multistage Passive Optical Networks. *Journal of Optical Communications and Networking, OSA Publishing*, 4(5):402–411, 2012.

[36] Stanislas Francfort, C. Hervet, Matthieu Chardy, and F. Moulis. Real life cable constraints in designing Passive Optical Network architecture. In *Federated Conference on Computer Science and Information Systems (FedCSIS)*, volume 0, pages 337–339, Krakow, 2013. IEEE.

[37] M. R. Garey, R. L. Graham, and D. S. Johnson. The Complexity of Computing Steiner Minimal Trees. *SIAM Journal on Applied Mathematics*, 32(4):835–859, 1977.

[38] Elisabeth Gassner. The Steiner Forest Problem revisited. *Journal of Discrete Algorithms*, 8(2):154–163, 2010.

[39] Roberto Gaudino and Invited Paper. Advantages of Coherent Detection in Reflective PONs. In *Optical Fiber Communication Conference (OFC)*, pages 2–4, 2013.

[40] Fred Glover, Manuel Laguna, and Rafael Marti. Principles of tabu search. *Approximation Algorithms and Metaheuristics*, 23:1–12, 2007.

[41] Luis Gouveia, Maria João Lopes, and Amaro de Sousa. Single PON network design with unconstrained splitting stages. *European Journal of Operational Research*, 240:361–371, jul 2014.

[42] Jeff Griffith, Gabriel Robins, Jeffrey S. Salowe, and Tongtong Zhang. Closing the gap: near-optimal steiner trees in polynomial time. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 13(11):1351–1365, sep 1994.

[43] Klaus Grobe. Next-Generation Access/Backhaul based on ITU G. 989, NG-PON2. In *Photonic Networks; 15. ITG Symposium*, pages 1–6, 2014.

[44] Rentao Gu, Xiaoxu Liu, Hui Li, and Lin Bai. Evolutional algorithm based cascade long reach Passive Optical Networks planning. *China Communications*, 10(4):59–69, apr 2013.

[45] Sudipto Guha, Rajeev Rastogi, and Kyuseok Shim. ROCK: A robust clustering algorithm for categorical attributes. In *Proceedings of the 15th International Conference on Data Engineering*, pages 512–521, Sydney, NSW, 1999. IEEE.

[46] E. Inga, G. Arevalo, and R. Hincapie. Optimal deployment of cellular networks for Advanced Measurement Infrastructure in Smart Grid. In *IEEE Colombian Conference on Communications and Computing (COLCOM)*, pages 1–6, Bogotá, 2014.

[47] ITU-T. Recommendation G.984.1 Gigabit-capable passive optical networks (GPON): General characteristics, 2008.

[48] ITU-T. Recommendation G.987.1 10-Gigabit-capable passive optical networks (XG-PON): General requirements, 2010.

[49] Brigitte Jaumard and Rejaul Chowdhury. Location and allocation of switching equipment (splitters/AWGs) in a WDM PON network. In *Proceedings - International Conference on Computer Communications and Networks, ICCCN*, Maui, HI; United States, 2011. IEEE.

[50] Brigitte Jaumard and Shibo Song. Dimensioning Hybrid PONs. In *International Conference on Optical Network Design and Modeling, ONDM*, pages 16–21, Pisa, Italy, 2015. IEEE.

[51] Andrew B. Kahng and Gabriel Robins. A new class of iterative Steiner tree heuristics with good performance. *IEEE Transactions on*

*Computer-Aided Design of Integrated Circuits and Systems*, 11(7):893–902, jul 1992.

[52] Byoung-wook Kang, Kwanil Lee, Sang Bae Lee, and Chul Han Kim. Colorless Amplified WDM-PON Employing Broadband Light Source Seeded Optical Sources and Channel-by-Channel Dispersion Compensators for ¿ 100 km Reach. *Journal of the Optical Society of Korea*, 18(5):436–441, 2014.

[53] B. Kantarci and H.T. Mouftah. Availability and Cost-Constrained Long-Reach Passive Optical Network Planning. *IEEE Transactions on Reliability*, 61(1):113–124, mar 2012.

[54] Mohammad S. Kiaei, Chadi Assi, Lehan Meng, and Martin Maier. On the co-existence of 10G-EPONs and WDM-PONs: A scheduling and bandwidth allocation approach. *Journal of Lightwave Technology*, 29(10):1417–1426, 2011.

[55] Mohammad S. Kiaei, Lehan Meng, Chadi Assi, and Martin Maier. Efficient scheduling and grant sizing methods for WDM PONs. *Journal of Lightwave Technology*, 28(13):1922–1931, 2010.

[56] Youngjin Kim, Youngho Lee, and Junghee Han. A splitter location - allocation problem in designing fiber optic access networks. *European Journal of Operational Research*, 210(2):425–435, apr 2011.

[57] O. Kipouridis, C.M. Machuca, A. Autenrieth, and K. Grobe. Street-aware infrastructure planning tool for Next Generation Optical Access networks. In *6th International Conference on Optical Network Design and Modeling (ONDM)*, pages 1–6, apr 2012.

[58] A Kokangul and A Ari. Optimization of passive optical network planning. *Applied Mathematical Modelling*, 35(7):3345–3354, 2011.

[59] Mukesh Kumar, Prathmesh Pravin, and Ghanashyam Singh. A novel approach to enhance the performance of ring based WDM PON. In *International Conference on Signal Propagation and Computer Technology, ICSPCT*, volume 3, pages 787–794, Ajmer, India, 2014. IEEE.

[60] Christoph Lange, Dirk Breuer, and Ralf Huelsermann. Cost effectiveness of site reduction in optical access network: A capex based comparison of different technologies. In *ICTON 2009: 11th International Conference on Transparent Optical Networks*, pages 1–4, jun 2009.

[61] Domanic Lavery, Milen Paskov, and Seb J. Savory. Spectral Shaping for Mitigating Backreflections in a Bidirectional 10 Gbit/s Coherent WDM-PON. *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, 1:OM2A.6, 2013.

[62] Ji Li Ji Li and Gangxiang Shen Gangxiang Shen. Cost Minimization Planning for Greenfield Passive Optical Networks. *IEEE/OSA Journal of Optical Communications and Networking*, 1(1):17–29, jun 2009.

[63] Bin Lin, Lin Lin, and Pin Han Ho. Cascaded splitter topology optimization in LRPONs. In *IEEE International Conference on Communications*, pages 3105–3109, 2012.

[64] Lin Lin, Bin Lin, and Pin Han Ho. Power-aware optimization modeling for cost-effective LRPON infrastructure deployment. In *21st International Conference on Software, Telecommunications and Computer Networks, SoftCOM*, pages 1–5, 2013.

[65] Adelys Marsden, Akihiro Maruta, and Ken Ichi Kitayama. Routing and wavelength assignment encompassing FWM in WDM lightpath networks. *ONDM 2008 - 12th Conference on Optical Network Design and Modelling*, 2008.

[66] Attila Mitcsenkov, Péter Bakos, Géza Paksy, and Tibor Cinkler. Technology-independent Topology Design Heuristics for Point-to-Multipoint Optical Access Networks. *Optical Network Design and Modeling (ONDM), 2013 17th International Conference on*, pages 298–303, 2013.

[67] Mirzad Mohandespour and Ahmed E Kamal. 1 + N protection in polynomial time : a heuristic approach. In *IEEE Global Telecommunications Conference (GLOBECOM 2010)*, number 978, 2010.

[68] Robert Murano. Optical Component Technology Options for NGPON2 Systems. *OFC2014*, (c):3–5, 2014.

[69] Derek Nesset. Network Operator Perspective on WDM-PON Systems and Applications. *37th European Conference and Exposition on Optical Communications*, (i):Th.12.C.6, 2011.

[70] Derek Nesset and Senior Member. NG-PON2 Technology and Standards. *Jornal of Ligthwave Technology*, 33(5):1136–1143, 2015.

[71] Marc Noy, Vlady Ravelomanana, and Juanjo Rué. On the probability of planarity of a random graph near the critical point. *Proceedings of the American Mathematical Society*, 143(3):925–936, 2015.

[72] OpenStreetMaps. OSM project. `http://www.openstreetmap.org/`.

[73] Saptadeep Pal, Cezary Zukowski, Avishek Nag, David B Payne, and Marco Ruffini. Cable Length Minimisation in Long-Reach-PON Planning for Sparsely Populated Areas. In *International Conference on Optical Network Design and Modeling*, pages 19–22. IEEE, 2014.

[74] J. Prat, M. Angelou, C. Kazmierski, R. Pous, M. Presi, A. Rafel, G. Vall-Llosera, I. Tomkos, and E. Ciaramella. Towards ultra-dense wavelength-to-the-user: The approach of the COCONUT project. In *International Conference on Transparent Optical Networks*, pages 1–4, 2013.

[75] Josep Prat. Technologies for a Cost Effective UDWDM-PON. In *Procceedings of OFC*, pages 1–3, Los Angeles, 2015.

[76] M Presi, R Corsini, M Artiglia, F Bottoni, G Cossu, and E Ciaramella. Low-Cost 6.25 GHz UDWDM-PON based on Direct Intensity-Modulated Transmitters. In *OFC2015: Optical Fiber Communication Conference*, pages 6–8, Los Angeles, California, United States, 2015. OSA Technical Digest (online) (Optical Society of America, 2015).

[77] A. M. Ragheb and Habib Fathallah. Performance analysis of next generation-PON (NG-PON) architectures. In *8th International Conference on High-Capacity Optical Networks and Emerging Technologies, HONET 2011*, pages 339–345, 2011.

[78] Jacklyn D Reis, Darlene M Neves, and António L Teixeira. Weighting nonlinearities on future high aggregate data rate PONs. *Optics Express*, 19(27):26557–26567, 2011.

[79] Jacklyn D. Reis, Darlene M. Neves, and António L. Teixeira. Analysis of nonlinearities on coherent ultradense WDM-PONs using Volterra series. *Journal of Lightwave Technology*, 30(2):234–241, 2012.

[80] Jacklyn D Reis, Ali Shahpari, Ricardo Ferreira, Darlene M Neves, Mário Lima, and António L Teixeira. Performance Optimization of Nyquist Signaling for Spectrally Efficient Optical Access Networks [ Invited ]. *Journal of Optical Communication Networks*, 7(2):200–208, 2015.

[81] Jacklyn D. Reis, Ali Shahpari, Ricardo Ferreira, Somayeh Ziaie, Darlene M. Neves, Mario Lima, and Antonio L. Teixeira. Terabit+ (192 Ã— 10 Gb/s) nyquist shaped UDWDM coherent PON with upstream and downstream over a 12.8 nm band. *Journal of Lightwave Technology*, 32(4):729–735, 2014.

[82] Jacklyn D. Reis and António L. Teixeira. Architectural Optimization of Coherent Ultra-Dense WDM based Optical Access Networks. *Optical Fiber Communication Conference (OFC)*, page OTuB7, 2011.

[83] Gabriel Robins and Alexander Zelikovsky. Minimum Steiner Tree Construction. In Dinesh P Charles J. Alpert, editor, *Handbook of Algorithms for Physical Design Automation*, chapter Chapter 24, pages 487–508. Auerbach Publications, New York, USA, 2009.

[84] Harald Rohde, Erich Gottwald, Pedro Alves, Carlos Oliveira, Ian Dedic, and Tomislav Drenski. Digital Multi-Wavelength Generation and Real Time Video Transmission in a Coherent Ultra Dense WDM PON. In *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, page OM3H.3, Anaheim, CA; United States, 2013.

[85] Harald Rohde, Erich Gottwald, Antonio Teixeira, Jacklyn Dias Reis, Ali Shahpari, Klaus Pulverer, and Jun Shan Wey. Coherent Ultra Dense WDM Technology for Next Generation Optical Metro and Access Networks. *Journal of Lightwave Technology*, 32(10):2041–2052, 2014.

[86] Harald Rohde, Erich Gottwald, Erik Weis, Paul Wagner, Yuriy Babenko, Daniel Fritzsche, and Hacene Chaouch. Trials of a Coherent UDWDM PON Over Field-Deployed Fiber: Real-Time LTE Backhauling, Legacy and 100G Coexistence. *Jornal of Ligthwave Technology*, 33(8):1644–1649, 2015.

[87] Vicent Sales, Josep Segarra, and Josep Prat. An Improved Dynamic Wavelength Assignment in Statistical UDWDM-PONs. In *International Conference on Optical Network Design and Modeling*, pages 22–27, 2015.

[88] Josep Segarra, Vicent Sales, Victor Polo, and Josep Prat. Dimensioning OLT Architectures for UDWDM-PONs Employing Coherent Transceivers. In *ICTON 2015: 17th International Conference on Transparent Optical Networks*, number Ga 318515, pages 2–7, 2015.

[89] A Shahpari, R S Luís, V Ribeiro, J D Reis, R Ferreira, J M D Mendinueta, Z Vujicic, B J Puttnam, M Lima, N Wada, and A Teixeira. Spectrally Efficient Enhanced- Performance Bidirectional Coherent PON With Laserless 10 Gb / s ONU [ Invited ]. *Journal of Optical Communications and Networking*, 7(3):403 – 413, 2015.

[90] Ali Shahpari, Ricardo Ferreira, Vitor Ribeiro, Artur Sousa, Somayeh Ziaie, Ana Tavares, Zoran Vujicic, Fernando P. Guiomar, Jacklyn D. Reis, Armando N. Pinto, and António Teixeira. Coherent ultra dense wavelength division multiplexing passive optical networks. *Optical Fiber Technology*, pages 1–8, 2015.

[91] Gaël Simon, Fabienne Saliou, Philippe Chanclou, Bertrand Le Guyader, and Laurent Guillo. Stimulated Raman Scattering Impairments Induced by NGPON2 Introduction in Co-existing PONs. In *OFC2015: Optical Fiber Communication Conference*, number 1, pages 4–6, Los Angeles, California United States, 2015.

[92] Sylvia Smolorz, Erich Gottwald, Harald Rohde, David Smith, and Alistair Poustie. Demonstration of a coherent UDWDM-PON with real-time processing. In *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*, pages 1–3, Los Angeles, California United States, 2011. IEEE.

[93] José Rodolfo Souza and P. B. Harboe. FWM: Effect of channel allocation with constant bandwidth, and ultra-fine grids in DWDM systems. *IEEE Latin America Transactions*, 9(1):32–39, 2011.

[94] Massimo Tornatore, Guido Maier, Achille Pattavina, and Senior Member. WDM network design by ILP models based on flow aggregation. *IEEE/ACM Transactions on Networking*, 15(3):709–720, 2007.

[95] Dieu Linh Truong, Phan Thuan Do, and Anh T Pham. Optimization of Survivable Mesh Long- Reach Hybrid WDM-TDM PONs. *Journal of Optical Communications and Networking, OSA Publishing*, 6(1):62–76, 2014.

[96] Gemma Vall-llosera, Albert Rafel, Neil Parkin, Marianna Angelou, Dimitrios Klonidis, Ivan Cano, Marco Presi, George Papastergiou, Ioannis Tomkos, Josep Prat, and Ernesto Ciaramella. COCONUT Cost , Power Consumption and Migration Analysis : A Route Towards NG-PON3. In *ICTON 2015: 17th International Conference on Transparent Optical Networks*, pages 1–4. The results of the analysis of the COCONUT (COst-effective COhereNt Ultra-dense-WDM-PON for $\lambda$-to-theuser access) project architectures with respect to their associated cost, power consumption and migration scenarios are presented. COCONUT develops udWDM, 2015.

[97] S. P. van Loggerenberg, M. J. Grobler, and S. E. Terblanche. Solving the passive optical network with fiber duct sharing planning problem using discrete techniques. *Electronic Notes in Discrete Mathematics*, 41:343–350, jun 2013.

[98] John S Vardakas, Ioannis D Moscholios, Michael D Logothetis, and Vassilios G Stylianakis. An Analytical Approach for Dynamic Wavelength Allocation in WDM â€“ TDMA PONs Servicing ON â€“ OFF Traffic. *Journal of Optical Communications and Networking*, 3(4):347–358, 2011.

[99] Jun Shan Wey, Derek Nesset, Maurizio Valvo, Klaus Grobe, Hal Roberts, Yuanqiu Luo, and Joe Smith. Physical Layer Aspects of NG-PON2 Standards â€” Part 1 : Optical Link Design [ Invited ].

*Journal of Optical Communications and Networking, OSA Publishing*, 8(1):33–42, 2016.

[100] Elaine Wong. Next-Generation Broadband Access Networks and Technologies. *Journal of Lightwave Technology*, 30(4):597–608, feb 2012.

[101] Eric W M Wong and Sammy Chan. Dynamic wavelength allocation schemes in WDM-PON. In *PhotonicsGlobal@Singapore, 2008. IPGC 2008*, pages 1 – 4, Singapore. IEEE.

[102] Li Xia Li Xia, Jiang Sheng-Yi Jiang Sheng-Yi, and Su Xiao-Ke Su Xiao-Ke. A Novel Fast Clustering Algorithm. In *International Conference on Artificial Intelligence and Computational Intelligence*, volume 4, pages 284–288, Shanghai, China, 2009. IEEE.

[103] C. H. Yeh, C. W. Chow, S. P. Huang, J. Y. Sung, Y. L. Liu, and C. L. Pan. Ring-Based WDM Access Network Providing Both Rayleigh Backscattering Noise Mitigation and Fiber-Fault Protection. *Journal of Lightwave Technology*, 30(20):3211–3218, 2012.

[104] Jingjing Zhang Jingjing Zhang and N. Ansari. Minimizing the Arrayed Waveguide Grating Cost and the Optical Cable Cost in Deploying WDM Passive Optical Networks. *IEEE/OSA Journal of Optical Communications and Networking*, 1(5):352–365, oct 2009.