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Optimal Deployment of Next-Generation PON for High and Ultra-High Bandwidth Demand Scenarios in Large Urban Areas

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ABSTRACT

This paper proposes a techno-economic analysis of the optimal deployment of multiple PON networks with different technologies, including the newest next-generation standards, such as GPON, XGSPON, NG-PON2 and 50G-EPON, within a large urban area in Quito. On this zone, we simulated a population of around 20000 customers, distributed between two central offices. We assume that customers demand different bitrates considering present and future bitrate-demand scenarios. This analysis uses an algorithm called OTS (Optimal Topology Search) which employs a nested set of heuristics in order to find the optimal topology for the deployment of PON in large areas with many potential customers. Results obtained in this research describe an accurate projection of the optimal deployment cost and the most suitable PON technology for each bitrate demand scenario, taking into account not only the cost of the entire hardware, but leasing, labor-hours, pole-works and trenching/recapping-works.

Keywords: optimal topology search, optical distribution network, passive optical network, GPON, XGSPON, NG-PON2, 50G-EPON.

1. INTRODUCTION

The new demand of high and ultra-high bitrates driven by the advances in information and communication technologies (ICT), the take-off of social networks, and the new era of internet of things (IoT) and internet of everything (IoE), requires the migration to next-generation (NG) technologies for transport and access networks. The main feature of the NG increased capacity for managing very high volumes of information in upstream (US) and downstream (DS) links.

The only transmission media able to cope with such demands is the optical fiber. Within the different network topologies that are used to provide internet access in urban environments PON currently represent the best solution because of the simplicity of its splitter-based tree-topology optical distribution network (ODN), and for its lower cost in comparison with other optical networks like point to point, ring and mesh networks.

The last two decades of development have lead us to several PON standard, were GPON [1] is still currently the most world-widely developed PON technology. Nonetheless, new standards for PON networks have been emerging in recent years, like XGSPON [2], and NG-PON2 [3], which have enough capacity for offering high and ultra-high bit rate to the users. In addition, other NG standards are in phase of development, like the new 25 – 50 Gb/s Ethernet PON (EPON) standard the IEEE Task Force is working on: the 802.3ca [4].

This paper presents a novel techno-economic study about the use of different PON technologies, GPON, XGSPON, NG-PON2 and 50G-EPON, for providing FTTH access in an urban zone of with about 20000 customers. The main feature of this study is to present an accurate portrait of the performance of each of the former mentioned PON technologies for providing the future high and ultra-high bit rete demands of users. For this research we employed the OTS (Optimal Topology Search) algorithm, which allows to find optimal topologies for PON deployments using real city maps, including not only the cost of the entire hardware, but the costs of leasing and costs of the pole-works and the trenching/recapping-works.[5].

The next sections of this paper are organized as follows: Section 2 describes the network scenarios and the reference costs for this study; Section 3 describes the optimization problem for the FTTH deployments. Section 4 describes the results obtained in this research and, finally, section 5 present some relevant conclusions.

2. SCENARIO AND COSTS

2.1 Scenario

GPON [1] and XGSPON [2], employ TDM/TDMA in the downstream (DS) and upstream (US) links, respectively. XGSPON includes the use of forward error correction (FEC) and APD diodes or semiconductor optical amplifiers (SOA) in the optical network units (ONU), at the end user side, to improve the power budget and the reception sensitivity. NG-PON2 [5] and 50G-EPON combines TDM with WDM for increasing the bitrate capacity of the optical line terminals (OLT), combining four 10Gb/s wavelengths for reaching 40 Gb/s, in NG-PON2 [3] and two 25 Gb/s wavelengths for achieving 50 Gb/s, in 50G-EPON [4]. Table 1 presents a summary of the main features of the four PON technologies to be considered in this study.

Table 1. Network parameters.

Parameter	PON Technology			
	GPON	*XGSPON*	*NG-PON2*	*50G-EPON*
Max. link length [km]	40	40	40	40
Max. ODN loss [dB]	30	35	35	35
Number of wavelengths	1	1	4	2
DS bitrate per OLT port [Gb/s]	2.5	10	40	50
Users per OLT port	64	64	64	64

We chose an urban area of Quito, Ecuador, with a density close to 2,500 of users per kilometer, for simulating the presence of 20000 potential customers distributed in about 98% of residential and 2% of corporate users [6]. In order to establish a real-life scenario for the optimization problem, we employed the OpenStreetMaps® platform for retrieving the real coordinates of streets and buildings profiles [7]. In the simulations, customers were assigned with random service plans, sweeping five different bitrate demand scenarios, as detailed in Table 2, considering today bit rate demands in Ecuador (i.e. average bitrates between 50 and 100 Mb/s for residential users, and from 100 up to 500 Mb/s for corporate users) and future high and ultra-high bitrate demands, like the fourth and fifth scenarios of the table.

Table 2. Bit rate demand scenarios.

Scenario	Bit rate intervals [Mbps]	
	Residential users	*Corporate users*
1	50-100	100-500
2	100-400	100-1000
3	100-600	1000-2500
4	500-1000	2500-10000
5	1000-2500	10000-20000

2.2 Referential costs

The PON network deployment analysis for this study employs costs in Ecuadorian territory. We were able to access real and updated information of costs by means of direct consults to manufacturers, vendors, service providers, and government regulation departments. Tables 3 and 4 show the costs of the ODN components and Table 5 details the costs of the PON hardware. It should be noticed that in the Ecuadorian case, government covers the cost of civil works of the telecommunications infrastructure, because it is considered that impacts some non-renewable resources, like subsoil, the radio electric spectrum, etc. [8].

Table 3. Costs of cables, ducts and civil works.

Component	Cost ($)
Feeder Cable 2 fibers per km	132
Feeder Cable 4 fibers per km	168.96
Feeder cable 6 fibers per km	213.33
Feeder Cable 12 fibers per km	261.36
Feeder Cable 24 fibers per km	369.60
Feeder Cable 36 fibers per km	479.16
Feeder Cable 48 fibers per km	587.40
Feeder Cable 72 fibers per km	798.60
Feeder Cable 96 fibers per km	1059.96
Feeder Cable 144 fibers per km	1586.64
Distribution Cable per km	147.84
Drop Cable per km	47.52
Indoor OF installation per client.	80
Trenching and reinstatement (km)	19806
Ducts per km	28120
Fusion and slicing per unit	6.65
Manholes per unit	922

In the case of equipment for GPON and XGSPON technologies, actual costs were used, but for NG-PON2, although it is already standardized, there aren't any product available yet on the market. Therefore, it was considered the cost of the NG-PON2 hardware as twice the cost for XGSPON hardware, which is a typical tendency for the state-of-the-art technology. In the case of 50G-EPON, given that it is expected to reach bit rate demands per OLT a similar to NG-PON2, we considered the cost of this technology as the of the NG-PON2.

On the other hand, private providers of telecommunications services must pay a rental cost of public infrastructure (underground ducts and lighting poles. This fee is proportional to the cost of installation of this infrastructure and the State control it by a regulatory entity called ARCOTEL. In the case of Quito the costs for infrastructure leasing are, in the case of poles, $9 per supplier, per pole and per-year, while in the case of underground ducts, it is $ 3.71 per meter of duct per-year [8].

Table 4. Costs of cabinets.

Component	Cost ($)
Junction box 8 OF	11.88
Junction box 16 OF	11.95
Junction box 48 OF	19.67
Junction box 96 OF	39.60
Junction box 144 OF	46.20
1:2 splitter	15.44
1:4 splitter	19.00
1:8 splitter	22.97
1:16 splitter	31.68
1:32 Splitter	62.04
1:64 splitter	88.44
Cabinet installation	200.00

Table 5. Costs of PON-hardware.

Component	Cost ($)
OLT chassis for GPON (14336 clients)	1846
OLT chassis for XGSPON (14336 clients)	2485
OLT chassis for NG-PON2 (14336 clients)	4970
OLT chassis for 50G-EPON (14336 clients)	4970
OLT card 16×GPON	886.08
OLT card 16×XGSPON	1775
OLT card 16×NG-PON2	3550
OLT card 16×50G-EPON	3550
ONU residential - GPON	62
ONU residential - XGSPON	106
ONU residential - NG-PON2	212
ONU residential - 50G-EPON	212
ONU corporative - GPON	181
ONU corporative - XGSPON	231
ONU corporative - NG-PON2	462
ONU corporative - 50G-EPON	462
Splicing per splice	6.50
OLT Installation	1840
ODF (por each OLT rack)	1820

3. PROBLEM FORMULATION

Given the set of parameters, constants and variables described in the following table:

Table 6. Parameters and variables.

Element	Description
CO	Central Offices set, CO = $\{CO_c \mid c=1,2,3,\ldots,M\}$, where M is the number of central offices.
N_c	Number of users serviced by the central office c
O	Set of OLT transceivers
U	ONU set, U = $\{ONU_u \mid u=1,2,3,\ldots,N\}$ where N is the number of ONUs
B	Set of candidate sites for location of secondary street cabinets (SSC)
V	Set of candidate sites for location of primary street cabinets (PSC)
n_{max}	Maximum number of users per each OLT transceiver
α^c_o	Binary constant that indicates if the OLT o is placed at the central office c
$d_{i,j}$	The distance between two points 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 l^{th} splitter in the cabinet placed at site i
C_{ODF}	The cost of an optical distribution frame
C_{ONU}	The cost of an ONU
C^c_{lbr}	The cost of labor in a Central Office c
$x_{n,j}$	Binary variable, indicates if the ONU n is connected to the SSC located in site j
$x_{j,i}$	Binary variable, indicates if the SSC on site j is connected to the PSC located in site i
$x_{i,o}$	Binary variable, indicates if a splitter on PSC placed on site i is connected to the OLT transceiver o
α_i	Binary variable, indicates if the candidate site i is active
α_o	Binary variable, indicates if OLT transceiver o is active
$S_{i,l}$	Binary variable, indicates if the lth splitter on site i is active
z^o_n	Binary variable, indicates i fan ONU n is connected to OLT o
η	The total capacity (the number of OLT transceivers) of an OLT chasis

We formulated the problem of finding the optimal cost of deployment of multiple PON as an optimization problem whose objective function to be minimized is the one described in (1). As it is done in real-life deployments we divided the big region in some sub-regions, where different Central Offices would come to operate. In the objective function there are considered all the elements, parameters and sets of the deployment, including the equipment and installation costs, the characteristics of the terrain and the variables of the problem, as defined in Table 6. The elements shown in (1) have values that are limited to the restrictions inherent to the characteristics of PON network structures, i.e. technical limitations of each technology and the limitations of the passive components of the ODN. Such set of restrictions are the same as the ones reported in [5].

$$\min \sum_{c\in CO}\left(\begin{array}{l} C^{c}_{lbr} + C_T\left(\sum_{o\in O}\sum_{i\in V}\alpha^{c}_{o} x_{i,o} d_{i,o} + \sum_{i\in V}\sum_{j\in B}\alpha^{c}_{o} x_{j,i} d_{j,i}\right) + C^{f}_{OF}\sum_{o\in O}\sum_{i\in V}\alpha^{c}_{o} x_{i,o}d_{i,o} + C^{d}_{OF}\left(\sum_{i\in V}\sum_{j\in B} x_{j,i}d_{j,i} + \sum_{j\in B}\sum_{n\in U} x_{n,j}d_{n,j}\right) \\ + \sum_{i\in\{V\cup B\}}\sum_{l\in L_i} S_{i,l}C_{i,l} + \sum_{i\in\{V\cup B\}} C^{r}_{encl}\alpha_i + \frac{N}{\eta}\left(C^{rck,\eta}_{OLT} + C_{ODF}\right) + \sum_{o\in O} C^{crd}_{OLT}\alpha_o + C_{ONU} N\end{array}\right) \tag{1}$$

The problem in (1) is a minimum Steiner-tree optimization problem [9], which may be resolved only with heuristic techniques, like the ones employed by OTS. OTS is an algorithm composed by a main function and several secondary functions [5]. The main function collects the city information, specifies the location of the central office or offices, the position of the clients and their respective demand plans. It also generates Voronoi tessellation areas [9] according to the number of central offices and evaluate for the total topology cost. The secondary functions modify the geometry of the Voronoi tessellation areas in each iteration of the algorithm to evaluate again the topology costs and so on until reaching a convergence point (i.e. until achieving the best possible solution the algorithm is able to find).

For this study, clients were simulated according to population density and were evenly distributed within the regions and buildings. Their demanded bitrate was randomly assigned using a normal distribution using the limits stated in the set of scenarios described in Table 2. Clients were grouped into regions given by a Voronoi tessellation [9]. In each region, it was initially used the location of the Central Offices as the center of mass for performing the users' clustering.

4. RESULTS

By means of using OTS we found the optimal topology for each PON technology and each bitrate demand scenario, as shown in Fig. 1. In this figure, it can be seen that OTS is a street-aware algorithm which, among other results, it present, for each scenario, a graphical diagram where it can be identified the optimal routes for the ODN components. This includes the feeder and distribution fibers and the optimal location of the PSC and SSC. We used underground routes for feeder and distribution cables as required by the Ecuadorian regulation.

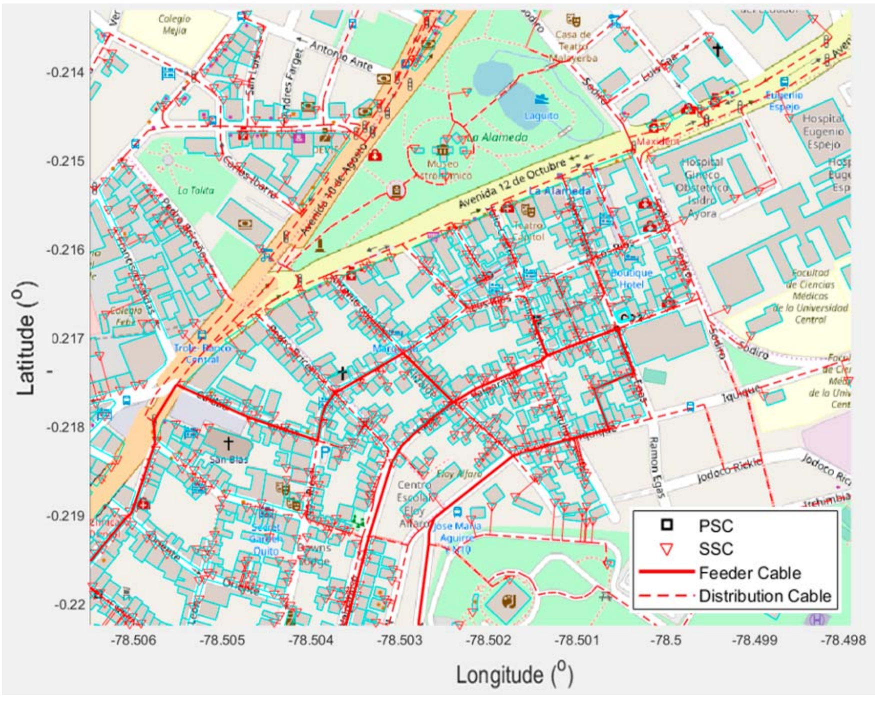

Figure 1. OTS's graphical results in a fragment of the urban zone of Quito, where the study was conducted.

Figure 2 presents the total cost of deployment for each PON technology and for each bitrate demand scenario. Notice that in the deployment costs it is graphically differentiated the individual costs of the Trenching, ODN and Hardware components. In the case of civil works costs (trenching), even if they are an important cost, they are somewhat invariant throughout the change in the simulation conditions and the increase of bit rate demand (especially in the case of the NG PON technologies). It is different the case of the other two components.

The civil works costs are taken on by the State, through public companies, but the costs of the other two components are assumed by the service providers.

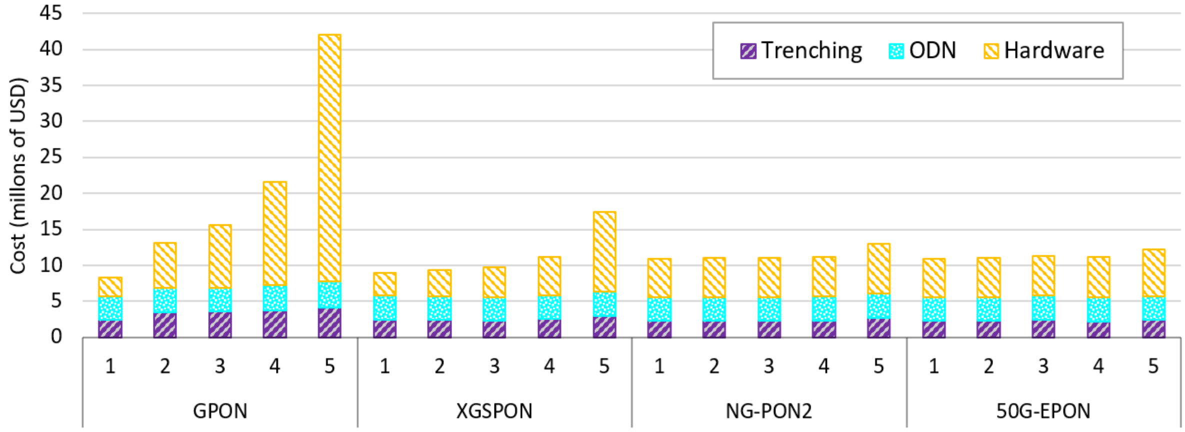

Figure 2. General cost of implementation separating civil works, ODN elements and Hardware.

In the case of GPON, it is evident in Fig. 2 that the deployment cost of this technology exponentially increases with the increment of the users' bitrate demands. For an ultra-high bitrate demand scenario, like the scenario number 5, the cost of using this technology is four times more than the cost of using technologies like NG-PON2 and 50G-EPON. This is due to the fact that the limited bitrate capacity of a GPON transceiver (up to 2.5 Gb/s) is not suitable for servicing users who are demanding high, very-high and ultra-high bitrates. For example, if all users where demanding 2.5 Gb/s, each user must be assigned with a point to point link from an individually assigned GPON OLT, in the CO, up to the ONU in the user's home or office. As expected, XGSPON performs better than GPON, but from the third bitrate demand scenario, the behavior of the deployment cost is also clearly exponential, although with a much lower rate than GPON. Thus, as well XGSPON is not a suitable solution for the most demanding bitrate scenarios.

On the other hand, the cost of deployment of NG-PON2 and 50G-EPON is almost invariable for the first four bitrate demand scenarios. Only in scenario 5 there is an appreciable increment in the deployment cost for both technologies, having 50G-EPON a slightly lower cost of deployment in this ultra-high bitrate demand scenario. However, we are assuming that 50G-EPON hardware have the same cost of NG-PON2 hardware, which could not be necessarily the case. No doubt this two NG PON technologies are the best solution for the near-future ultra-high bitrate demands that users may be starting to demand. Even though for lower bitrate demands, like the ones portrayed in scenarios number 1, 2 and 3, current generation PON like GPON and XGSPON are less costly, the current deployment of NG PON will provide of much better scalability.

The main component that exponentially increases in cost, with the increase of bitrate demand, is the PON hardware in the CO, as is detailed in Fig. 3.

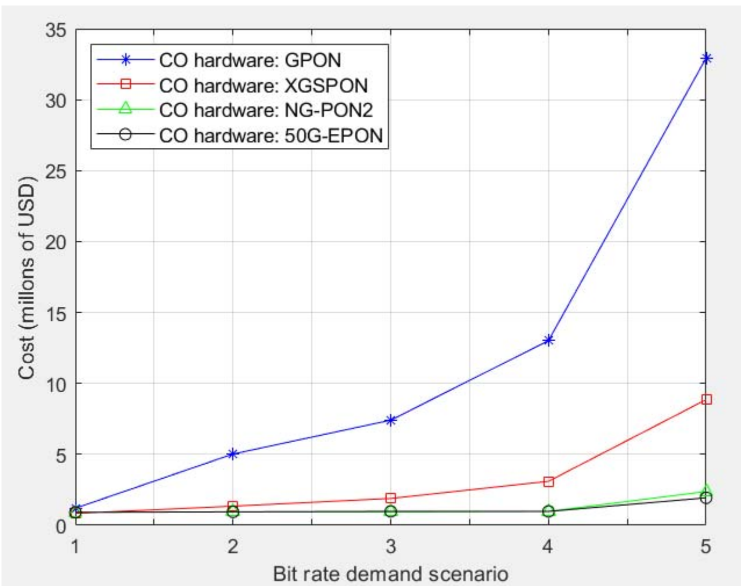

Figure 3. Central office hardware cost by technology and scenario.

5. CONCLUSIONS

This techno-economic analysis evaluated the total costs of deployment of multiple PON in a large urban region with many users having heterogeneous bitrate demands. We considered current generation and next-generation PON technologies within five different bitrate demand scenarios. Our optimization framework took into account not only the cost of the ODN but also the PON hardware. In the case of the ODN costs, we included the civil works for underground routing of cables instead of aerial routing.

Results demonstrated that GPON is still a better cost-effective solution for lower bitrate demands, i.e. when the bitrate is in the order of some tens up to one-hundred Mb/s. When the bitrate demands increase to some hundreds of Mb/s, XGSPON constitute a better solution than GPON. But, when the bitrate demands increase from many hundreds of Mb/s up to more than 1 Gb/s, it is mandatory the use of NG PON technologies, like NG-PON2 and 50G-EPON, because using current generation PON represent a much more expensive solution. Thus, in a mediate future, technologies such as XGSPON may appear to be the best solution to replace the GPON infrastructure but if we are looking for a long-term solution, NG-PON2 and 50G-EPON technologies can offer to the Communications providers the better cost-performance results. However, there is no certainty regarding which of these two technologies will be the one that manufacturers will prefer to implement.

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