Failure Impact, Availability and Cost Analysis of PONs Based on a Network Geometric Model

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Abstract— **Passive Optical Networks (PONs) are considered as the preferred solution for broadband fibre-based access networks. This is because PONs present low cost deployment, low energy consumption and also meet high bandwidth demands from end users. In addition, end users expect a high availability for access networks, while operators are more concerned about reducing the failure impact (number of clients affected by failures). Moreover, operators are also interested in reducing the cost of the access network. This paper provides a deep insight into the consequences that the physical topology and design decisions cause on the availability, the failure impact and the cost of a PON. In order to do that, the physical layout of the PON deployment area is approximated by a network geometric model. A PON deployed according to the geometric model is then assessed in terms of failure impact, availability and cost. This way, the effects of different design decisions and the physical layout on these three parameters are evaluated. In addition, the tradeoffs between availability, failure impact and cost caused by planning decisions and the physical topology are identified and pinpointed.**

Index terms: Availability, failure impact, Capital Expenditures, Passive Optical Networks, network geometric model.

I. Introduction

Fiber to the X (FTTX, X meaning either node, curb/cabinet, building or home) solutions are considered as the most promising architectures for future broadband fibre-based access networks. The need for these broadband fibre-based access networks arises due to the high bandwidth requirements demanded by new services. Nowadays, the preferred technology to implement the different FTTX architectures are Passive Optical Networks (PONs) [1]. PONs are capable of offering high bandwith to end users and present a low cost deployment and low energy consumption. Both currently deployed PONs and Next-Generation PONs (NG-PON) have been the subject of an extensive research to understand and improve the benefits of these fiber access systems [1], [2].

However, higher bandwidth is not the only requirement that users demand. As new services emerge, such as high-definition televison, telesurgery or interactive gaming, users expect access networks (and particularly PONs) to be highly reliable. The importance of Service Level Agreements (SLAs) is also increasing in the access part of the network as users demand a guaranteed level of service availability. In fact, the dependability of PONs has been a subject of discussion over the last years, and several analyses can be found in literature [3], [4]. However, there is still another dimension that heavily affects the dependability of PONs and must be included into the analyses. This dimension is the physical area where the PONs are deployed, and the fact that PONs are not deployed alone, but sharing common trenches and distribution points. In this context, the way the PON is designed plays a major role not only for dependability, but also for the deployment cost.

On the other hand, while availability is closer to the user's perpective, operators are more concerned about the number of users affected by failures (i.e. failure impact). This parameter has also gained importance recently [5] as large outages represent a great loss to operators, not only economically but also in reputation. Failure impact, as availability, is also heavily affected by the physical layout of the deployment area, and the decisions made during the planning phase.

This papers aims at providing a comprehensive insight into the effects that the physical layout, infrastructure sharing and design decisions cause on different dependability-related parameters of a PON. Mainly two dependability-related parameters are considered: failure impact, closer to the operator's point of view, and asymptotic availability, closer to the user's perception. Also the capital expenditures (CAPEX), that affect heavily the PON deployment [6], will be taken into account. By evaluating these three parameters, not only the effects of the physical layout and the fiber deployment are pinpointed, but also important tradeoffs between them are identified.

This paper is organized as follows. Sect. II presents the typical PON architecture and the network geometric model assumed as the PON physical layout. Sect. III describes the failure impact analysis and its results when applied to the network geometric model. Sect. IV introduces the availability analysis based on the geometric model. Sect. V compares the cost of the different scenarios based on the geometric model. Finally Sect. VI gives the conclusions of this work.

II. PON Architecture and Network Geometric Model

This section presents the general PON architecture as well as the network geometric model that will be employed to describe the area under study.

A. PON Architecture

There are several architectures and technologies that can be employed in PONs. The typical architecture of a PON is shown in Fig. 1. This architecture is the most common among PON technologies such as Time Division Multiplexing PON (TDM PON), Wavelength Division Multiplexing PON (WDM PON) and Hybrid WDM/TDM PON.

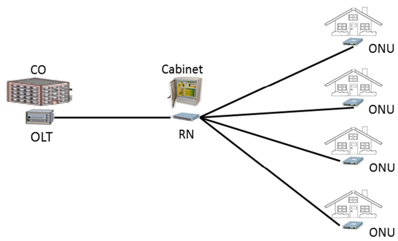

Fig. 1. General PON Architecture.

The equipment located at the Central Office (CO) of the operator is denoted as Optical Line Terminal (OLT) and the OLT ports are accommodated in the OLT chassises. The equipment at the user's side is referred to as Optical Network Unit (ONU). There is also an intermediate point between the CO and the user called Remote Node (RN). Passive elements are accommodated in the RN chassis: splitters for TDM PON, Arrayed Waveguided Gratings (AWGs) for WDM PON or both for Hybrid WDM/TDM PON. The fiber interconnecting the OLT and the RN is denoted as Feeder Fiber (FF) and the fiber interconnecting the RN and the ONU is denoted as Distribution Fiber (DF).

B. Network Geometric Model

In general, geometric models make an abstraction of the area under study, and assume that clients are regularly distributed with an uniform density. As pointed out in [7], geometric models may present a lack of accuracy as they are based on average values. However, the generality of these geometric models makes them well suited for a first analysis, obtaining reasonable results. One of the strengths of the geometric models is that they can be generally applied to many areas, just by tailoring the parameters accordingly. More complex models matching a given street layout in a more accurate fashion could be employed, but then the model will lose its generality. Results will be more accurate, but only for a specific area.

In the context of geometric models, the simplified street length model, shown in Fig. 2, presents a set of features that makes it well suited for the purpose of this paper. This model has already been applied for estimating the cost of FTTH networks in [6] and [8], as it is able to capture the underlaying physical topology of PONs in urban and suburban scenarios quite well. This facilitates the analysis of dependent failures of network elements due to incidents in the physical topology causing failure of more than one element at the same time.

The model assumes that subscribers are uniformly distributed over a regular grid. Subscribers served by a RN are aggregated forming a square on this grid, as depicted in Fig. 2 b). The same way, the set of RNs being served by the CO are aggregated forming a squared array (the feeder level). The CO is located at the center of the grid. RNs are also situated in the middle of each distribution level. Feeder and distribution trenches (containing fibers) are represented by red lines.

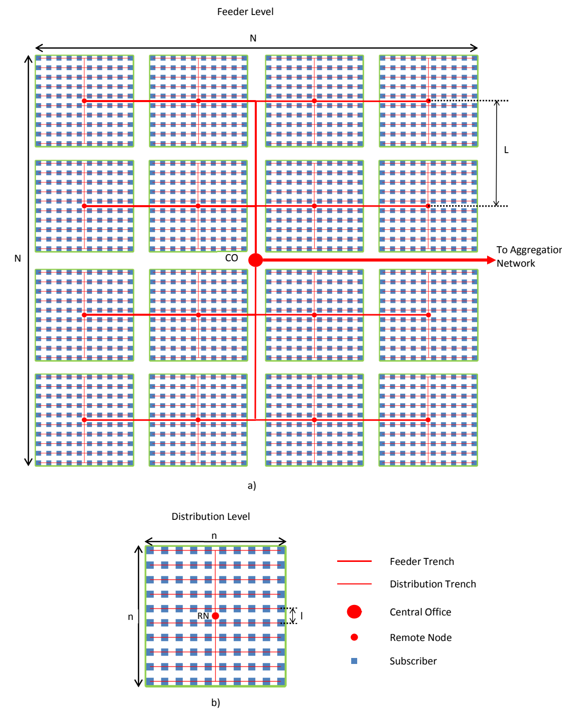

Fig. 2. Geometric model for subscriber and RN distribution.

At the distribution level, a RN serves a set of n^2 subscribers. One side of the distribution level contains n subscribers, where the distance between a subscribers is represented by l (in km). At the feeder level, the CO serves a square array of N^2 distribution level squares, and the distance between RNs is represented by L (in km).

A set of simple equations regarding different parameters can be obtained from this model. These equations will be used later to calculate the failure impact, the availability and the CAPEX. First, it is clear that the total number of subscribers being served by the CO is given by $n^2 * N^2$. Focusing on a distribution level square, it is also straightforward that it contains n horizontal trenches and 1 vertical trench. Each of these trenches is formed by n-1 steps of length l. Thus, the trench length in one distribution level square is equal to $(n^2 - 1) * l$. The same reasoning can be applied to the feeder level, employing N and L in the calculations. This leads to a trench length in the feeder level equal to $(N^2 - 1) * L$.

The number of passive elements at each RN depends on the number of subscribers in a distribution level square (n^2), as well as on the splitting ratio of the passive elements. It follows the expression $\lceil \frac{n^2}{splitting\ ratio} \rceil$. Then, the total number of passive elements is equal to $N^2 * \lceil n^2/splitting\ ratio \rceil$.

Each passive element is connected to an OLT port located at the CO. Thus, the number of OLT ports is equal to the total number of passive elements. The number of OLT chassis needed at the CO depends on the number of OLT ports and on the number of OLT ports per OLT chassis. The number of

OLT chassis follows the expression $\lceil\frac{\lceil\frac{n^2}{splitting\ ratio}\rceil}{OLT\ ports\ per\ chassis}\rceil$.

1) Number of fibers contained by a trench: This parameter will be employed in the following sections to calculate the impact of a failure in a trench, as well as the CAPEX.

Let's focus first on a distribution level square as shown in Fig. 2 b), where every subscriber is connected to the RN by a fiber. As the RN serves n^2 subscribers, the central step of the vertical distribution trench contains $n^2/2$ fibers going up and $n^2/2$ fibers going down, while $n-2$ steps of length l remain to be examined. Then, there are $(n-2)/2$ steps of trench moving up from the RN and $(n-2)/2$ steps of trench moving down from the RN. Moving up from the RN, the number of fibers contained on the vertical distribution trench diminishes by n every time the vertical distribution trench crosses an horizontal distribution trench (as every horizontal trench serves n subscribers). This reasoning continues until the last upper step of the vertical distribution trench, which contains only n fibers. Consequently, the number of fibers contained in a vertical distribution trench diminishes by n subscribers in steps of l km. The same occurrs when moving down from the RN. Hence, the number of fibers contained in a step of a vertical distribution trench can be written as:

$$\frac{n^2}{2} - i*n, i = 0, 1, ..., \frac{n-2}{2} \quad (1)$$

Knowing that for $i = 0$ there is only one step of length l containing $n^2/2$ fibers (the central one), while for $i \neq 0$ there are two steps of length l containing $n^2/2 - i*n$ fibers.

Because of symmetry, the same chain of reasoning can be applied for the horizontal distribution trenches:

$$\frac{n^2}{2} - i, i = 0, 1, ..., \frac{n-2}{2} \quad (2)$$

Knowing that for $i = 0$ there is only one step of length l containing $n/2$ fibers (the central one), while for $i \neq 0$ there are two steps of length l containing $n/2 - i$ fibers.

The same calculations are valid for the feeder level square, but employing N and L instead of n and l. However, every passive element at a RN is connected to the CO by a fiber. Thus, the expressions for the number of fibers contained in a step of vertical or horizontal feeder trench follow equations 3 and 4 respectively.

$$\lceil\frac{n^2}{splitting\ ratio}\rceil * (\frac{N^2}{2} - j*N), j = 0, 1, ..., \frac{N-2}{2} \quad (3)$$

$$\lceil\frac{n^2}{splitting\ ratio}\rceil * (\frac{N^2}{2} - j), j = 0, 1, ..., \frac{N-2}{2} \quad (4)$$

2) Distance between clients and CO: In order to calculate the availability that can be offered to a subscriber, the distance between the client and the CO is needed. Due to the regularity of the model, several subscribers are situated at the same distance from the CO. Hence, the subscribers-CO distance, as well as the number of clients situated at the same distance, must be calculated. Also, the length of fiber needed to be deployed is closely related to the subscribers-CO distance.

Let's focus first on a distribution level square and compute the subscriber-RN distance. It is easy to divide a distribution level square in 4 parts, and perform the calculations for the upper-left part, as the other parts will present the same results due to symmetry. In this upper-left part, there are $n/2$ diagonal subscribers at a distance $(n/2)*l$ from the RN. At the same time, there are $(n/2)-1$ subscribers at a distance $((n/2)-1)*l$ from the RN and other $(n/2)-1$ subscribers at a distance $((n/2)+1)*l$. This reasoning continues till the furthest and closest subscribers, at a distance $(n-1)*l$ and l from the RN respectively. As there are 4 symmetric parts, a general relationship can be found expressing the total number of subscribers that are at a given distance from the RN:

$$4*(\frac{n}{2} - i)\ clients\ at\ a\ distance\ (\frac{n}{2} \pm i)*l\ from\ the\ RN, \\ i = 0, 1, ..., \frac{n}{2} - 1 \quad (5)$$

At this level, each client is connected to the RN by a fiber, so summing up all the previous distances gives the fiber length at a distribution level square.

Moving to the feeder level, the same reasoning can be used to calculate the RN-CO distance, leading to:

$$4*(\frac{N}{2} - j)\ RNs\ at\ a\ distance\ (\frac{N}{2} \pm j)*L\ from\ the\ CO, \\ j = 0, 1, ..., \frac{N}{2} - 1 \quad (6)$$

In this case, it must be considered that each RN is connected to the CO by $\lceil n^2/splitting\ ratio\rceil$ fibers in order to calculate the total fiber length for the feeder level.

Finally, combining the RN-CO distance and the subscribers-RN distance, a relationship expressing the number of subscribers that are at a given distance of the CO can be found:

$$4*(\frac{N}{2} - j)*4*(\frac{n}{2} - i) subscribers\ at\ a\ distance \\ (\frac{N}{2} \pm j)*L + (\frac{n}{2} \pm i)*l\ from\ the\ CO, \\ j = 0, 1, ..., \frac{N}{2} - 1, i = 0, 1, ..., \frac{n}{2} - 1 \quad (7)$$

C. Baseline Scenario

In this subsection, the reference parameters employed as baseline for the geometric model will be presented.

Typically, a currently deployed PON gives service to a number of subscribers around 10 000 [9]. A baseline value of 10 is chosen for both n and N, leading to a total number of 10 000 subscribers. TDM PON is assumed as the baseline architecture, with a splitting ratio of 32 for the splitters (passive elements). The number of OLT ports per OLT chassis could take a wide range of values, but a ratio of 72 OLT ports per OLT chassis is chosen as reference, as then the number of OLT chassis is kept at reasonable values. The linear distance between homes, l, is set by default to 1/24 km, a typical value in suburban areas of the United States [6]. Finally, the linear distance between RNs, L is chosen to be equal to $n*l$.

III. Failure Impact Analysis

In this section, a failure impact analysis of the PON architecture deployed following the geometric model is performed by means of network failure modes.

A. Network Failure Modes

As defined in [10], a network failure mode, Φ_x is defined by the set of elements which have lost their traffic carrying capability. Network failure modes are well suited to study failure impact because they make possible to capture simultaneous failure of network elements due to common causes (e.g. diggings). The set of elements forming the PON encompasses ONUs, distribution trench steps, passive elements, RN chassises, feeder trench steps, OLT ports and OLT chassises. The failure modes related to trench steps imply the failure of all the contained fibers. The same way, a failure mode related to a RN chassis implies the failure of all the passive elements enclosed on it. Finally, failure modes related to an OLT chassis imply the failure of all the OLT ports accommodated on it.

The probability of a failure mode, $P(\Phi_x)$, corresponds to the unavailability of the elements defining the mode multiplied by the availability of all other elements, as shown in equation (8). For the analysis, the availability of each elements has been taken from [11] and [3].

$$P(\Phi_x) = (\prod_{y \in \Phi_x} U_y) * (\prod_{z \notin \Phi_x} (1 - U_z)) \tag{8}$$

In addition, the number of subscribers that have lost service in a given network failure mode can be calculated. This number gives the failure impact of a failure mode, and depends on the failed elements that define the particular failure mode. ONU failures affect only one client. Distribution trench steps affect a number of clients equal to the number of fibers contained in the trench step, thus following equations (1) and (2). RN chassis affect a number of clients equal to n^2. Also, it is assumed that the n^2 clients in a distribution level square are divided among the passive elements in a RN chassis as evenly as possible. Thus, passive elements may affect a varying number of clients. The number of clients affected by a feeder trench steps follows equations (3) and (4), but substituting $\lceil \frac{n^2}{splitting\ ratio} \rceil$ by n^2. OLT ports affect the same number of clients as the passive element they are connected to. Finally, the number of clients affected by an OLT chassis depends on the OLT ports it accommodates, and OLT ports are distributed among OLT chassis in the same fashion as clients are distributed among passive elements. It must be kept in mind that clients affected by more than one failed element are not counted twice in the corresponding failure mode.

B. Failure Impact Results

The results of the failure impact analysis are now presented. In the analysis, only the dominant failure modes (the ones that accumulate the major part of the probability mass) are included. This is because the entire set of network failure modes grows exponentially with the number of elements. Considering failure modes with at most two failed elements is enough to accurately capture the performance of the network, and also keep a reasonable computational effort.

Fig. 3 presents the probability that the number of subscribers affected in a failure mode is equal or bigger than a given percentage of the total number of clients, for different values of n, N and l. By varying the parameters n and N (keeping the total number of clients around 10 000), it is possible to capture the effect of different network planning decisions. Increasing n while decreasing N implies bigger distribution areas covered by a RN, but the number of these areas is smaller. Contrarily, decreasing n while increasing N reduces the region of the distribution part, but the number of distribution areas is bigger. Different values have been chosen for the distance between subscribers. The first value is the reference one explained in Sect. II-C (solid lines in Fig. 3). Other values (dashed lines in Fig. 3) are selected so that the furthest client is located at 20 km from the CO, as this is the maximum reach for TDM PONs [12]. Then, different scenarios with a dense (smaller l) or sparse (bigger l) concentration of subscribers are modeled.

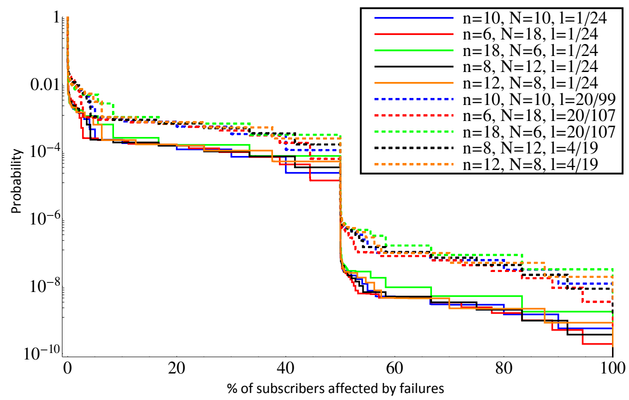

Fig. 3. Probability that the number of clients affected by a failure is equal or bigger than a certain % of the total number of clients for different scenarios.

Fig. 3 leads to several conclusions. First, as dashed lines are above solid lines, the probability of failures is larger in sparse scenarios due to larger fibers and trenches. In addition, the probability of failures affecting more than a 50% of the subscribers is quite low compared to the probability of failures affecting a smaller number of subscribers. This can be seen by the gap that all lines present at this point. This is because the failure modes affecting a large number of subscribers have a small probability, as these failure modes are associated with two failed elements. Consequently, failures affecting a small number of subscribers are much more probable. Also, this gap is larger for dense scenarios. Thus, large service outages (in number of clients) are more probable in sparse scenarios, so the probability of important losses increases.

Moreover, designing the network so that the distribution areas are big implies a higher probability of experiencing failures that affect a large number of clients. In Fig. 3, this fact is pointed out as the green and orange lines are above the others (for the corresponding scenario), although this result is less acute in sparse scenarios. Nonetheless, big distribution areas reduce the cost of the network, as will be explained in Sect. V. In fact, covering larger areas by the CO and the RN (node consolidation) is an on-going trend among operators in order to reduce network costs. Hence, this brings up a tradeoff between failure impact and cost that must be taken into account when designing the access part of a network.

IV. Availability Analysis

In this section, an availability analysis based on the geometric model is carried out. The novelty of this analysis lies in including a general physical layout of the deployment area. Thus, how planning decisions affect the user's availability can be investigated.

Reliability Block Diagrams (RBDs) are employed for the availability analysis. The availability that can be offered to a client can be calculated with the RBD in Fig. 4. The total availability is computed by directly multiplying the availabilities of the different elements. Values for the availability of each element have been taken from [11] and [3]. The availability of the feeder and the distribution fibers depends on their lengths, that can be calculated employing equation (7).

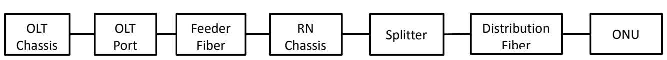

Fig. 4. Reliability Block Diagram for the TDM PON architecture

Fig. 5 shows the percentage of subscribers that could be offered a given availability for different values of n, N when l is fixed to the reference value.

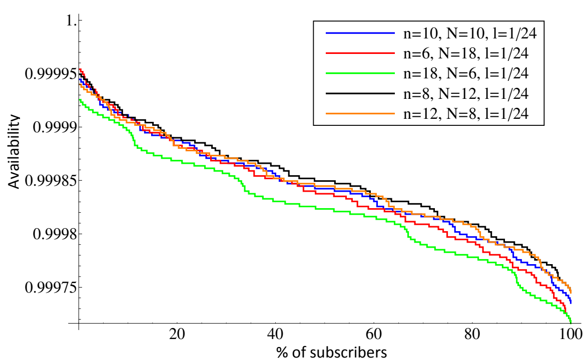

Fig. 5. Availabilty achieved by different % of subscribers in dense scenarios

Mainly, the achieved availability depends on the subscriber-CO distance. The highest availability (achieved by a very low percentage of subscribers) corresponds to the availability that can be offered to the closest subscribers to the CO. Contrarily, the lowest availability (that can be offered to 100% of the subscribers) corresponds to the availability achieved by the furthest subscribers. The difference between the availability of the closest and the furthest subscribers is 0,0002. Although it might seem a small value, it could have heavy implications especially when designing SLAs. Then, special care must be taken when analyzing the availability of an access network, as not all the clients could achieve the same availability. In addition, Fig. 5 reveals that network designs with small distribution areas (smaller n) are capable of offering a better availability to subscribers close to the CO. On the contrary, network designs with large distribution areas (bigger n) offer a worse availability to clients close to the CO. However, in dense scenarios, this trend is not generally true for subscribers situated far away from the CO. For example, the network design with the smallest distribution areas (n=6) offers the best availability to subscribers close to the CO, but offers the same availability to further located clients than the network design with the largest distribution areas (n=18). This reveals that in dense scenarios, the network design and physical layout plays a major role in the achieved availability.

Fig. 6 shows the percentage of subscribers that could be offered a given availability for different values of n, N when l is fixed to the maximum length between subscribers.

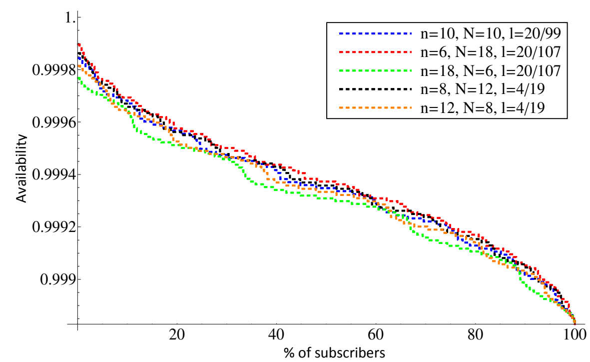

Fig. 6. Availabilty achieved by different % of subscribers in sparse scenarios.

In this case, the achieved availability is quite worse than in dense scenarios, as the distance between subscribers and the CO is larger. In addition, the difference between the highest and the lowest availability is around 0,001 in this case. Thus, the need for including the pyshical layout into the availability analysis is more significant in sparse scenarios, especially if SLAs are involved. Nonetheless, a general trend can be identified for sparse scenarios. The availability offered to the furthest located subscribers is almost the same in all network designs. However, network designs with small distribution areas offer a better availability to subscribers at other distances, as the availability of the feeder fibers dominates the total availability in sparse scenarios. Then, the size of the distribution areas also brings up a tradeoff between availability and cost.

V. Cost Analysis

This section presents the CAPEX associated with the TDM PON deployment. In addition, the effects that design decisions and the physical layout have on the CAPEX are highlighted.

The CAPEX calculation has been performed following the methodology in [4], assuming a take rate of 100% (i.e. all the clients covered by the network subscribe to the service). The number of the different components, as well as the trenching length, can be computed with the expressions in Sect. II-B. The number of fibers and the total fiber length can be calculated by employing equations (1), (2), (3), (4), (5) and (6) accordingly. The cost of each element has been taken from [3].

Fig. 7 shows the cost per subscriber for different values of n, N and l, varying as in previous sections. Layouts $n = 8, N = 12$ and $n = 12, N = 8$ present a lower CAPEX because the OLT ports are almost fully loaded, leading to fewer OLT chassis. Yet, it can be seen that for other layouts the cost per subscriber increases when the distribution areas are small (small n). This is because small distribution areas imply a large number of them. Thus, a large number of feeder trenches is needed, increasing the cost. As shown before, the probability of failures affecting a large number of clients decreases and the availability increases with small distribution areas. Hence, there is an important tradeoff between failure impact/availability and CAPEX when designing the network.

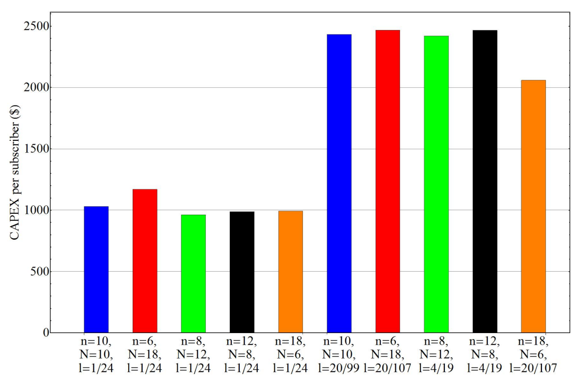

Fig. 7. Cost per subscriber for different physical layouts.

Fig. 7 also reveals that the cost increases considerably for sparse scenarios (large l) due to larger trenches. Again, apart from the effect of fully loaded OLT ports and fewer chassis, larger distribution areas lead to smaller CAPEX. Both the probability of large outages as well as the availability are heavily burdened in this case. To increase the availability and reduce the failure impact, the use of protection mechanisms is needed, but the cost of providing protection can be considerable. Thus, the introduction of protection in the access networks must be included during the design phase, by reusing trenches for deploying protection fibers. With this in mind, the model presented in Sect. II-B can be used to design a more reliable access network without incurring in excessive cost.

VI. Conclusions

In this paper, the failure impact and the availability of a PON, as well as CAPEX, have been evaluated taking into account the physical layout, infrastructure sharing and different design decisions. To reproduce a physical layout as general as possible, a network geometric model has been employed. It has been shown that the physical layout and the design decisions affect the dependability of PONs to a high degree. The failure impact analysis reveals that the probability of more than 50% of the clients being affected by failures is considerable when the area under study is big or has a low density of clients. In addition, reducing the size of the distribution part of the network also reduces the probability of experiencing failures affecting a large number of subscribers. Regarding availability, reducing the size of the distribution areas allows to offer a better availability to end-users in sparse scenarios, while this trend is not always true in dense scenarios. Moreover, there is a big difference in the availability that can be offered to subscribers depending on its distance to the CO. Consequently, the introduction of protection in a PON depends largely on the subscriber-CO distance and the type of user. The CAPEX analysis reveals that the initial investment per subscriber can be reduced if big distribution areas are designed and OLT ports and chassis are fully loaded. Then, there is a direct tradeoff problem between CAPEX and both availability and failure impact when increasing the size of the distribution part that may be solved by employing protection in some areas.

The tradeoffs identified in this work call for further research. The CAPEX-availability/failure impact tradeoff may play a major role when designing the access network, and it can also be affected by the introduction of protection. Yet, the introduction of protection might not be justified for all parts of the access network. Then, the deployment of protection should be further analyzed taking into account not only availability and failure impact, but also the tradeoffs identified here. Client profile, physical topology, infrastructure sharing, losses due to penalties and loss of reputation should also be included.

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