Protecting PONs: a Failure Impact, Availability and Cost Perspective Based on a Geometric Model

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Abstract— **Passive Optical Networks (PONs) are regarded as the preferred technology for broadband access networks. PONs provide high capacity and low-power consumption at a low-cost deployment. Besides, the dependability of PONs is becoming more important as end-users also expect access networks to be highly reliable. Operators, on the other hand, are more concerned about reducing the number of clients affected by failures (i.e. failure impact) while keeping the costs at reasonable values. This paper identifies the best suited protection schemes for PONs, and gives a deep insight into how the access network layout and design decisions affect the performance of these schemes. To achieve this goal, the PON deployment area is described by means of a network geometric model. Then, different protection mechanisms are deployed following this model and evaluated in terms of failure impact, availability and cost. In this manner, the performance of the protection schemes is assessed, taking into account the effects of the network layout on these three parameters. Moreover, the trade-offs between failure impact, availability and cost caused by design decisions are also pinpointed.**

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

I. INTRODUCTION

Nowadays, the significance of broadband fibre-based access networks is arising in order to meet the increasing bandwidth demands required by new services. Among several Fiber to the X (FTTX, with X meaning either node, curb/cabinet, building or home) solutions, Passive Optical Networks (PONs) are regarded as the best suited technology to implement fiber access networks [1]. PONs are flexible, scalable and not only provide high bandwidth to end-users, but also present a low-cost deployment and low energy consumption. Due to these features, both PONs and next-generation PONs are envisioned as the most promising solution for future broadband fiber-based access networks [2].

Yet, as new services emerge, such as telesurgery or interactive gaming, end-users are not only concerned about higher bandwidths. Both business and residential users also demand reliable service delivery and business continuity. Thus, the increase in dependability requirements calls for providing protection in the access network. In fact, the dependability of PONs has been a case of concern over the last years, and several protection mechanisms and dependability analyses can be found in literature [3], [4]. However, most of these studies do not include the network layout where PONs are deployed. When designing PON-based access networks, several PONs share trenches and distribution points to reduce the CAPEX. This infrastructure sharing may lead to simultaneous failures due to common causes, affecting the dependability. Thus, design decisions and network layout must be taken into account when deploying protection in PONs.

Availability, meaning readiness for correct service [5], is an attribute commonly used to assess the dependability of a system. In Service Level Agreements (SLAs), users typically demand a guaranteed level of service availability. Operators, however, are much more interested in reducing the number of clients affected by failures (i.e. failure impact). As large outages typically involve great loss to operators, both economically and in reputation, the significance of the failure impact has increased recently [6].

This paper aims at giving a deep insight into the best suited protection mechanisms for PONs. Based on [7], where an unprotected PON was analyzed, this work also provides a comprehensive understanding of how the physical layout, infrastructure sharing and design decisions affect the protection schemes. Besides the CAPEX, which plays a major role when deploying a PON [8], two dependability-related parameters are analyzed. Namely, failure impact, capturing the operator's perspective, and asymptotic availability, closer to the user's point of view. These analyses lead to the identification of the most efficient protection schemes, and pinpoint the effects that the network layout causes on them. Also, they reveal important trade-offs between failure impact, availability and CAPEX.

This paper is organized as follows. Sect. II explains the general PON architecture and the geometric model assumed as the PON physical layout. Sect. III introduces the considered protection mechanisms and their deployment options. Sect. IV presents the failure impact of the different mechanisms, based on the network geometric model. Sect. V introduces the availability analysis of the protection schemes deployed following the geometric model. Sect. VI compares the CAPEX of the schemes under the assumptions of the geometric model. Finally Sect. VII gives the conclusions of this work.

II. PON ARCHITECTURE AND NETWORK GEOMETRIC MODEL

This section presents the typical PON architecture and the network geometric model describing the area under study.

A. PON Architecture

The typical architecture of a PON is shown in Fig. 1. At the operator's Central Office (CO), the Optical Line Terminal (OLT) is deployed, where OLT ports are accommodated in the OLT chassis. The equipment at the user's side is referred to as Optical Network Unit (ONU). The intermediate point between the CO and the user premises is called Remote Node (RN). Each RN is equipped with a RN chassis housing a set of passive elements. These passive elements can be splitters for Time Division Multiplexing (TDM) PON, Arrayed Waveguide Gratings (AWGs) for Wavelength Division Multiplexing (WDM) PON, or both for Hybrid WDM/TDM PON. Finally, the fiber that interconnects the OLT and the RN is denoted as Feeder Fiber (FF), while the term Distribution Fiber (DF) is used for the fiber between the RN and the ONU.

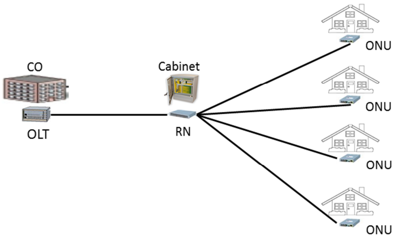


Fig. 1. Schematic diagram of PONs architecture.

B. Network Geometric Model

To describe the PON deployment area, a network geometric model called simplified street length model, or Manhattan model, is employed. In general, geometric models are based on the assumption of a uniform distribution of subscribers over the considered area. Although this may lead to a lack of accuracy [9], it makes these models generally applicable to many different areas. By tailoring their parameters appropriately, general reasonable results for a first analysis can be obtained. Among geometric models, the Manhattan model is especially convenient for the purpose of this paper. Besides its generality, this model captures the underlying physical topology of PONs in urban and suburban areas quite accurately. Regarding CAPEX, this property allows for an easy calculation of the infrastructural needs of PONs. Hence, this model has been widely employed for estimating the cost of PONs in previous studies [8], [10]. On the dependability side, this property facilitates the analysis of dependent failures, as it is possible to seize the effect of incidents in the physical topology causing more than one element to fail simultaneously.

In the Manhattan model, subscribers are uniformly distributed over a regular grid, as shown in Fig. 2. Each RN serves a set of subscribers that are assembled forming a square (the distribution level) on this grid, as can be seen in Fig. 2 b). Similarly, the set of RNs served by the CO form a square array (the feeder level), as in Fig. 2 a). The RNs and the CO are located at the center of the corresponding levels. Both feeder and distribution trenches (containing fibers) are depicted with red lines and can only be laid horizontally or vertically.

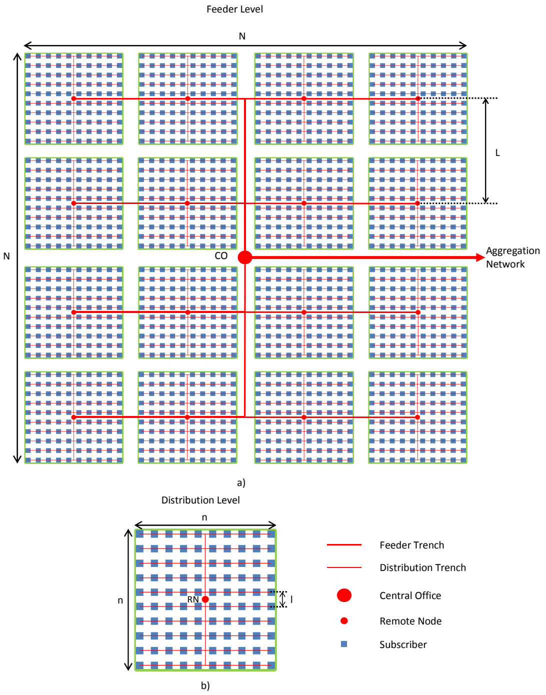


Fig. 2. Geometric model for subscriber and RN distribution.

Regarding the distribution level, one side of each distribution level square contains n subscribers, where the distance between subscribers is represented by l. Thus, each RN serves n^2 subscribers. At the feeder level, N distribution level squares are contained on one side, and the distance between RNs is denoted as L. Then, the CO serves N^2 distribution levels (RNs), and a total of $N^2 * n^2$ subscribers (ONUs).

Dealing with the calculations at the distribution level, a distribution level square encompasses n horizontal trenches and 1 vertical trench. Each trench is composed by $n-1$ steps of length l. Thus, the trenching length in one distribution level square is equal to $(n^2 - 1) * l$, while the total distribution trenching length is $N^2 * (n^2 - 1) * l$. The number of passive elements at each RN chassis depends on its splitting ratio, as well as on the number of subscribers served by a RN. It follows the expression $\lceil \frac{n^2}{splitting\ ratio} \rceil$, while the total number of passive elements can be calculated as $N^2 * \lceil \frac{n^2}{splitting\ ratio} \rceil$.

At the feeder level, the trenching length follows the same reasoning as before. Thus, the total trenching length at the feeder level is equal to $(N^2 - 1) * L$. Concerning the equipment at the CO, each passive element has to be connected to an OLT port. Hence the number of OLT ports is equal to the total number of passive elements. Finally, the number of OLT chassis is determined by the number of OLT ports and the number of OLT ports per OLT chassis as $\lceil \frac{N^2 * \lceil \frac{n^2}{splitting\ ratio} \rceil}{OLT\ ports\ per\ chassis} \rceil$.

1) Number of clients served by a trench: This parameter is employed in following sections as part of the failure impact analysis, and can be calculated as follows.

As for a distribution level square, the RN serves n^2 clients. The central step of the vertical distribution trench serves $n^2/2$

clients going up and $n^2/2$ clients going down, while $n-2$ steps remain to be examined. Then, there are $(n-2)/2$ steps moving up from the RN and $(n-2)/2$ steps moving down from the RN. Up from the RN, the number of clients served by the vertical distribution trench diminishes by n every time it crosses a horizontal distribution trench (horizontal trenches serve n clients). This continues until the uppermost step of the vertical distribution trench, serving only n clients. The same occurs when moving down from the RN, the number of clients served by a step of a vertical distribution trench is

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

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

The same reasoning can be applied for the horizontal distribution trench steps, following

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

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

The same line of thinking is valid for the feeder level. At this level, the number of RNs served by a step of a vertical or horizontal trench follows (3) and (4) respectively. Multiplying (3) and (4) by n^2 gives the number of clients served by a vertical or horizontal feeder trench step respectively.

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

$$\frac{N}{2} - j, j = 0, 1, ..., \frac{N-2}{2}. \quad (4)$$

2) Distance between clients and CO: This subsection deals with the distance between clients and CO, as it heavily affects the availability that can be offered to a subscriber. Besides, the length of fiber needed to be deployed (as part of the CAPEX) is also derived from the client-CO distance.

Let's focus first on the distribution level. Due to symmetry, each distribution level square can be divided in four equivalent quadrants. In each quadrant, there are $n/2$ diagonal clients at a distance $(n/2)*l$ from the RN. Also, there are $(n/2)-1$ clients at a distance $((n/2)-1)*l$ from the RN and other $(n/2)-1$ clients at a distance $((n/2)+1)*l$. This reasoning continues till the furthest and closest clients, located at a distance $(n-1)*l$ and l from the RN respectively. Considering the four quadrants, (5) expresses the number of clients that are at a given distance from the RN, for one distribution level square.

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

Also, the fiber length in one distribution level is given by the sum of all the previous distances, as each client is connected to the RN by one fiber.

At the feeder level, the same logic applies and leads to the number of RNs at a given distance from the CO, given in (6).

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

At this level, each passive element hosted in a RN is connected to the CO by one fiber. Thus, each RN is connected to the CO by $\lceil n^2/splitting\ ratio \rceil$ fibers, and this must be considered when calculating the fiber length at the feeder level from (6).

Finally, combining (5) and (6), the number of clients that are at a given distance of the CO can be expressed as:

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

3) Baseline Scenario: In order to reproduce a currently deployed PON as accurately as possible, the following values have been chosen for the parameters.

Typically, the number of clients covered by a CO is around 10 000 [11]. Because of that, the values of n and N will vary but keeping the total number of clients ($n^2 * N^2$) close to 10 000. Splitters are assumed as passive elements (TDM PON) with a splitting ratio of 32. Regarding the equipment at the CO, the number of OLT ports per OLT chassis is fixed to 72 [12]. Concerning the linear distance between homes, l, a value of 1/24 km is chosen as baseline, as it is a typical value in suburban areas of the United States [8]. Finally, the linear distance between RNs, L, is set to $n*l$.

III. PON PROTECTION MECHANISMS

This section introduces the analyzed protection mechanisms, as well as the chosen deployment options for each mechanism.

A. Protection Mechanisms

In this study, five PON protection schemes have been analyzed. The schematic diagrams of the five protection variants are shown in Fig. 3. Schemes a), b), c) and d) are taken from literature, while scheme e) is a new proposed mechanism.

Schemes a) and b) in Fig. 3 (taken from [4] and [13] respectively) cover protection of the feeder fibers only. Scheme a) employs a protection feeder fiber in parallel with the working feeder fiber. These fibers must be deployed in disjoint trenches. On the other hand, scheme b) tries to reduce the CAPEX by reusing the feeder fiber of different PONs for protection. This requires the use of additional coarse wavelength division multiplexing (CWDM) couplers at the CO and the RN, and interconnection fibers (and trenches) between RNs. Besides, PONs protecting each other must employ different wavelengths.

Variants c), d) and e) in Fig. 3 protect both feeder and distribution fibers. In c), described in [4], all the elements between the CO and the customer are duplicated. A coupler is

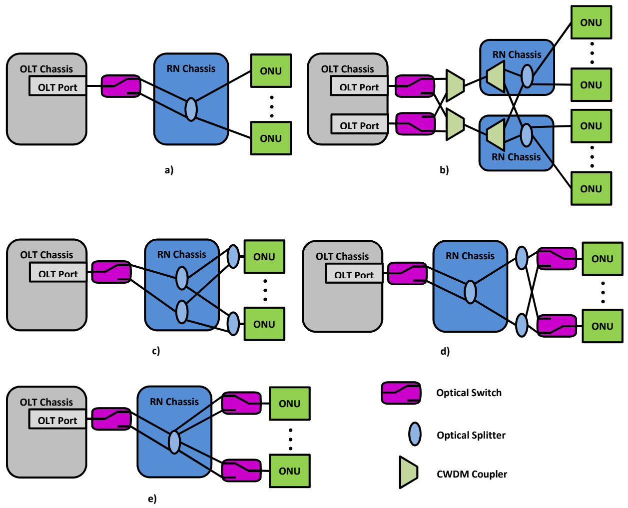


Fig. 3. Schematic diagrams of the protection mechanisms.

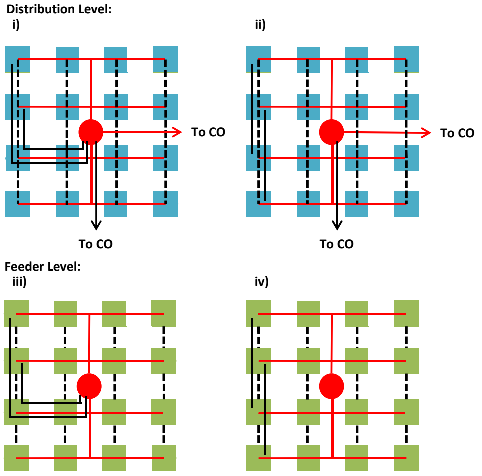


Fig. 4. Deployment approaches for the protection schemes.

needed at the client's side, while protection and working fibers must be deployed in disjoint trenches. However, it presents a lack of flexibility as it is not possible to switch between protection and working paths at the RN. Scheme d), introduced in [3] is based in the same concept as b). ONUs in the same PON protect each other in pairs, reusing the distribution fibers for protection. In addition to the interconnection fibers and trenches between ONUs, a coupler and an Optical Switch (OS) is needed at the user's side. Besides, this scheme does not present the same lack of flexibility as scheme c).

Finally, scheme e) is a newly proposed variant. It duplicates the feeder and distribution fibers, but not the passive element at the RN. Again, working and protection fibers must be deployed in disjoint trenches. Optical switches are needed both at the CO and at the user's side. If a failure occurs at the working distribution fiber, the OS at the ONU switches to the protection distribution fiber. If a fiber break takes place in the feeder part, then the OS at the CO switches. This way, this scheme presents the same flexibility as scheme d).

B. Deployment of Protection Mechanisms

The different ways of deploying the protection mechanisms in the network geometric model are shown in Fig. 4. Approaches i) and ii) refer to the distribution level, where the blue blocks represent clients. Approaches iii) and iv) refer to the feeder level, where the green blocks depict distribution levels. Dashed black lines represent new trenches, while solid black lines denote protection fibers. For the sake of clarity, some protection fibers are omitted, but they follow the same pattern as the ones shown in Fig. 4.

At the distribution level, approach i) is employed by protection schemes c) and e). Protection fibers run vertically till they cross the middle of the distribution level. Then, the protection fibers follow the first working trench (in red) up to the RN. This approach requires n new trenches of length $(n-1)*l$. Also, the length of the protection fiber for each client is equal to the length of its working distribution fiber plus l. Approach ii) is employed by protection scheme d), where ONUs are protected in pairs. Protection fibers run vertically till the paired ONU, and then the working fiber of the paired ONU is reused up to the RN. This approach also requires n trenches of length $(n-1)*l$, and the length of the protection fiber is always $(n/2)*l$. The length of the protection path for one client is equal to the length of the working path of the paired ONU plus $(n/2)*l$. In Fig. 4, both i) and ii) show the path that protection fibers from the RN follow along the vertical distribution trench. This is just to indicate that the vertical distribution trench is reused for protection of the feeder fibers.

At the feeder level, approach iii) is applied for protection schemes a), c), d) and e). This approach uses the same concept as approach i) but at the feeder level. Yet, as the vertical distribution trench is reused for hosting the protection fibers (explained before), only the sections between distribution levels require new trenches. Thus, the protection trenching length is equal to $N*(N-1)*l$. Also, the length of the protection fiber for each passive element at the RN is equal to the length of its working feeder fiber plus L. Finally, approach iv) is employed by protection scheme b). It follows the same idea as approach ii). The protection trenching length is equal to $N*(N-1)*l$, while the length of the protection fibers is always $(N/2)*L$. The length of the protection path for each passive element is equal to the length of the working path of the paired passive element plus $(N/2)*L$.

IV. FAILURE IMPACT ANALYSIS

This section presents the failure impact analysis, performed by means of network failure modes, of the protection schemes deployed as explained in Sect. III-B.

A. Network Failure Modes

A network failure mode, Φ_x is defined by the set of elements which have lost their traffic carrying capability [14]. Failure modes are suitable for the failure impact analysis as they are able to capture simultaneous failure of network elements due to common causes (e.g. diggings). The set of elements covers

ONUs, distribution and feeder trench steps (protection and working), passive elements, RN and OLT chassis and OLT ports. Splitters, OS and CWDM couplers are considered when needed. Failure modes related to trench steps imply failure of all the contained fibers. Modes related to a RN chassis imply failure of all the elements in it; and modes related to OLT chassis imply failure of all the hosted OLT ports.

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 in (8). The availability of each element is taken from [12] and [3].

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

Hence, the number of clients that have lost service in a given failure mode gives the failure impact of that mode. Clients lose service if, in a given failure mode, the failed elements make it impossible to establish a connection between them and the CO. Elements at the user's side affect (in scheme d), splitters affect and protect) one client. Clients affected or protected by trench steps are easily calculated from (1), (2), (3), (4) and explanations in Sect. III-B. RN chassis affect (or protect) n^2 clients, where these n^2 clients are distributed among the passive elements as evenly as possible. Thus, passive elements may affect (or protect) a varying number of clients. OLT ports, CO OS and CWDM couplers affect (or protect) the same number of clients as the passive element they are connected to. Finally, the clients affected by an OLT chassis depend on the hosted OLT ports, and OLT ports are distributed among OLT chassis in the same fashion as clients among passive elements.

B. Failure Impact Results

In this 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. 5 presents the probability that the number of clients affected in a failure mode is equal or bigger than a given percentage of the total number of clients, for the different schemes. A value of 10 is chosen for both n and N. Two values are chosen for the distance between clients, l. Solid lines depict the baseline value in Sect. II-B.3. The other value (dashed lines) is selected so that the furthest clients are located at 20 km from the CO (maximum reach for TDM PONs [15]). This value is obtained by making the maximum distance in (7) equal to 20 km. Then, scenarios with a dense (smaller l) or sparse (bigger l) concentration of clients are modeled.

From Fig. 5, it is easy to see that schemes a), c), d) and e) perform very similar regarding failure impact. In fact, lines corresponding to schemes a), c) and d) are hidden behind the green line (scheme e)). The probability of affecting more than 17% of the clients is quite low, as all lines present a gap around this value. In [7], where the unprotected case was analyzed, this gap was present around 50%. This reveals that protection of the feeder fibers is of uttermost importance, reducing considerably the failure impact. Failures affecting more than 17% of the clients are related with two failed OLT chassis or two failures in the vertical feeder trench. In [6], the importance of protection the OLT is also examined. Scheme b) is revealed as the worst option, due to larger protection paths. Hence, laying all the protection fibers in the same trench is actually better, as long as they are physically disjoint from the working fibers. Schemes c) and e) are slightly better than the others for small percentages. However, providers are interested in reducing the probability of large outages, thus protection of distribution fibers is not significant as few clients are affected. The probability of large outages is larger in sparse scenarios (bigger l), as trenches are longer, and the differences between schemes are more noticeable.

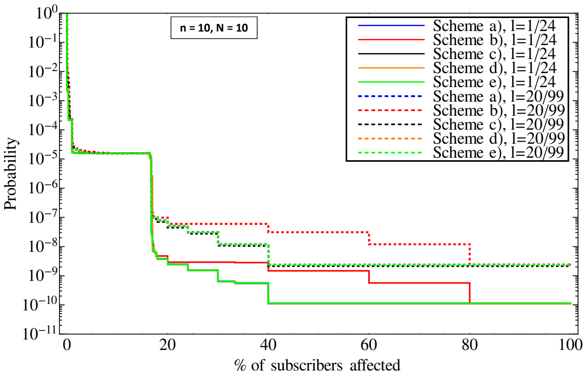


Fig. 5. Probability that the number of clients affected by a failure is equal or bigger than a certain % of the total number of clients for different schemes. $n = 10, N = 10$.

Fig. 6 shows how scheme c) is influenced by the network layout. All the schemes perform in a similar way, so the results in Fig. 6 are analogous for all of them.

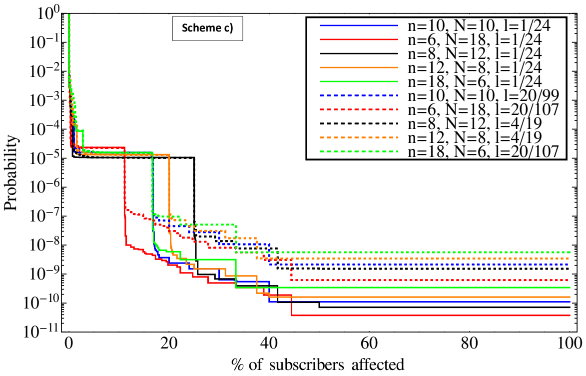


Fig. 6. Probability that the number of clients affected by a failure is equal or bigger than a certain % of the total number of clients for different network layouts. Scheme c)

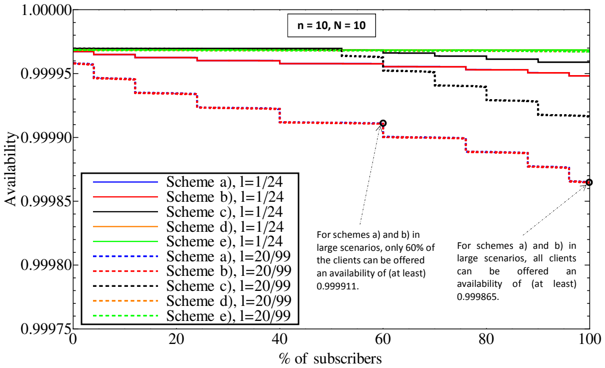
Different planning decisions are captured by varying n and N. Increasing n while decreasing N implies bigger distribution areas, but the number of these areas is smaller. The opposite leads to more, though small, distribution areas.

Parameter l varies as explained before. In general, protection of the feeder fibers reduces the effect of the physical layout on the failure impact. Instead, it is heavily influenced by the physical granularity of the chassis, mainly by the arrangement of OLT port and chassis. This arrangement makes the gap between the most and least probable outages occur at different percentages. E.g. the probability of two OLT chassis failing at the same time is around 10^{-8}, but the number of clients affected varies considerably depending on the previous arrangement. Yet, the physical layout still has an effect on the failure impact (especially for large outages). Bigger distribution areas (larger n), for the same subscriber density (same l) lead to a larger probability of large outages (around one order of magnitude). Also, sparse concentration of clients (larger l) has approximately the same effect.

V. 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, so that how different planning decisions affect the user availability is investigated. Reliability Block Diagrams (RBDs) have been employed for the availability analysis, where the availability values have been taken from [12] and [3]. The availability of feeder and distribution fibers depends on their lengths, calculated from (7) and explanations in Sect. III-B.

Fig. 7 shows the percentage of clients that could be offered a given availability, for the different schemes and values of l ($n = N = 10$). The availability not only depends on the protection scheme, but also on the client-CO distance. The highest availability (achieved by a very low percentage of clients) corresponds to the availability that can be offered to the closest clients to the CO. The lowest availability corresponds to the availability achieved by the furthest clients (thus, it can be offered to 100% of the clients). An example is given in Fig. 7.



For schemes a) and b) in large scenarios, only 60% of the clients can be offered an availability of (at least) 0.999911.

For schemes a) and b) in large scenarios, all clients can be offered an availability of (at least) 0.999865.

Fig. 7. Availability achieved by different % of clients for $n = 10, N = 10$.

It is clear, from Fig. 7, that protection at the distribution level does become relevant when dealing with availability. Schemes d) and e), where fibers are fully protected, perform similarly, with the lines for scheme d) hidden by the lines for scheme e). These schemes are much better than the others (with e) being the best) and achieve almost the same availability in sparse or dense scenarios. Schemes a) and b) also perform in the same way, the lines for scheme a) hidden behind the lines for scheme b). They do not have protection at the distribution level. Still, for dense scenarios, the availability is kept above 0.99994, enough for most of the clients. Hence, the additional protection does not represent a huge improvement in dense scenarios. Yet, in sparse scenarios, only 65% of the clients can be offered an availability of at least 0.9999 in schemes a) and b). This calls for differentiated dependability in sparse scenarios, not only in the traditional sense of business and residential users, but also based on the client-CO distance. Close located clients achieve an acceptable availability without distribution fibers protection, while faraway clients require it. Scheme c) is a special case that illustrates the importance of flexibility at the RN. A failure in a vertical distribution trench may produce a failure in working distribution fibers and protection feeder fibers (Fig 4 a) and b)). Although scheme c) may seem more reliable than schemes d) and e) (as it duplicates the passive element at the RN), it cannot switch from working and distribution paths at the RN, leading to a drop in availability. From the RBD point of view, vertical distribution trenches become a single point of failure for scheme c), while a bridge structure in schemes d) and e). Then, scheme c) becomes inappropriate when trenches are reused, which is a common practice to reduce costs.

Fig. 8 shows how the availability of scheme a) is affected by the network layout. Scheme b) behaves exactly the same, while schemes d) and e) (fully protected) are almost not influenced by the network layout, thus uninteresting. Scheme c) is of no interest also as it is not appropriate for protection.

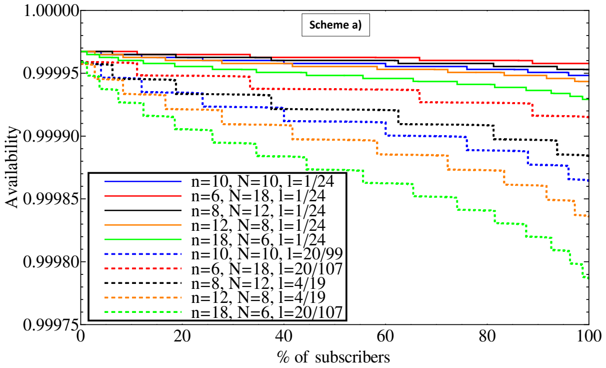


Fig. 8. Availability achieved by different % of clients in distinct network layouts. Scheme a)

Parameters n, N and l vary in the same way as in the previous section. As scheme a) do not provide protection at the distribution level, Fig. 8 shows how the availability (in contrast to the failure impact) is burdened by the distribution fibers. The general trend is that designs with larger distribution areas offer a worse availability. Also, the bigger the distribution area, the larger the drop in availability. This is not a case of concern in dense scenarios (solid lines), as the availability is above 0.9999 in all the cases. However, the network layout does plays a major role in sparse scenarios. Sparse scenarios with small distribution areas ($n = 6$) perform well (from the availability point of view) even without protection at the distribution level. Yet, for sparse scenarios with very large distribution areas ($n = 18$), the offered availability falls more than one order of magnitude. Nonetheless, big distribution areas reduce the CAPEX of the network, as is explained in Sect. VI. In fact, node consolidation (covering larger areas by the CO and RN) is an on-going trend among operators to reduce costs.

This reveals a trade-off between failure impact, availability and CAPEX, that may be solved by differentiated dependability based on the clients-CO distance. Large distribution areas may be employed for reducing costs, where some of them may be left unprotected (the closest to the CO). Still, faraway located distribution areas should be provided with protection at the distribution level. However, not very large distribution areas can be designed (e.g. $n = 18$) because, as pointed out in Sect. IV, the probability of large outages is one order of magnitude larger than in designs with small distribution areas.

VI. CAPEX Analysis

In this section, the CAPEX associated with the different protection schemes is calculated. Also, how the physical network layout influences the CAPEX is highlighted.

For the CAPEX calculation, it is assumed that all the clients covered by the network subscribe to the service (i.e. a take rate of 100% is assumed). The cost of each element has been taken from [3]. The number of the working components and the working trenching length is computed with the expressions in Sect. II-B. The working fiber length can be calculated with Eq. (5) and (6), the latter multiplied by $\lceil n^2/splitting\ ratio \rceil$ as described in Sect. II-B.2. The number of the protection components, the protection trench length and the protection fiber length are computed with the explanations in Sect. III.

In Fig. 9, the CAPEX per subscriber (in \$) is shown, for the different schemes with different network layouts in dense scenarios (l is equal to the baseline value). Exact values for the case $n = 10, N = 10$ are given in Table I for easy comparison (it follows the same trend for other network layouts).

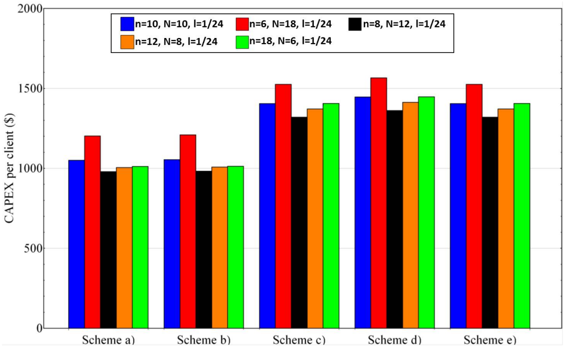


Fig. 9. Cost per subscriber for different physical layouts in dense scenarios.

In dense scenarios (see Fig. 9 and Table I), for a given network layout, there are no big differences between the protection schemes at the same level (feeder or distribution). Also, compared to the CAPEX of an unprotected PON discussed in [7], the cost of protection at the feeder level is quite inexpensive. Yet, the CAPEX increases as more protection is added, but the difference is affordable in dense scenarios. This is because the working trenching and CO-related costs, that are the main contribution to the CAPEX, are the same in all the cases. Hence, the reutilization of fibers (schemes b) and d)) does not provide additional savings. In fact, schemes reutilizing fibers, i.e. b) with respect to a) and d) with respect to c) and e), are more expensive in dense scenarios due to the additional components needed to reutilize fibers. Then, although protection at the distribution level is affordable, it is not needed unless very large distribution areas are designed or a very high availability is required (the probability of large outages is not affected by protection at the distribution level).

TABLE I

CAPEX per client (in \$) for the different schemes with $n = 10, N = 10$.

Scheme	$l = 1/24$	$l = 20/99$
Unprotected [7]	1 030	2 432
a)	1 051	2 524
b)	1 054	2 517
c)	1 405	4 043
d)	1 446	4 059
e)	1 405	4 043

As for the network layout, Fig. 9 reveals two main effects. The first effect is the arrangement of OLT ports and chassis, as the CO-related costs are predominant. Layouts $n = 8, N = 12$ and $n = 12, N = 8$ present fully loaded OLT ports and fewer chassis, leading to smaller CAPEX. If the OLT ports and chassis arrangement is the same, as in the other three layouts, the second effect is the size of the distribution areas. CAPEX per client increases with smaller distribution areas. Small distribution areas entail a large number of them, increasing the number of feeder trenches and fibers and the associated CAPEX. Yet, small distribution areas lead to a larger availability and to a decrease in the probability of large outages. Thus, there is a trade-off between availability/failure impact and CAPEX when designing the access network.

Fig. 10 depicts the CAPEX (in \$) per client for different schemes and network layouts in sparse scenarios. Also, Table I show the values for the case $n = 10, N = 10$.

First, it is obvious that the CAPEX increases considerably compared to dense scenarios, due to larger distances implying larger trenches and fibers. As in dense scenarios, the variations in the CAPEX for the different schemes (at the same level) in a given network layout are quite small. The inclusion of protection at the feeder level is also inexpensive in sparse scenarios if trenches are reused. However, this is not true for protection at the distribution level. In contrast to the dense case, reutilization of fibers entails savings at the feeder level (scheme b) is cheaper than scheme a)) but not at the distribution level (scheme d) is the most expensive).

The impact of the network layout in the CAPEX for sparse scenarios is only dominated by the trench and fiber costs.

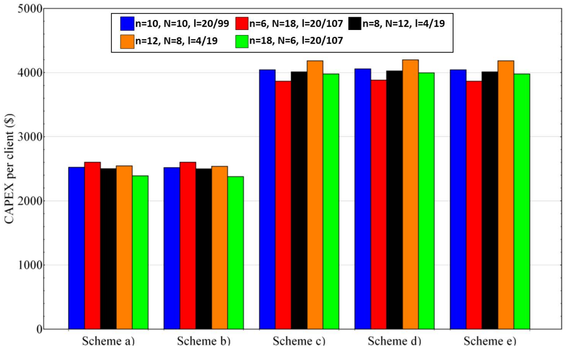


Fig. 10. Cost per subscriber for different physical layouts in sparse scenarios.

When protection is present only at the feeder level, the feeder trenches and fibers dominate the CAPEX. Thus large distribution areas reduce the CAPEX, but burdens both the failure impact and the availability. When protection is present at both levels, the distribution trenches and fibers dominate, reversing the trend. Now larger distribution areas lead lo higher CAPEX. Although at maximum reach the layout $n = 18, N = 6$ does not present the highest CAPEX, it would become the most expensive for larger values of l. Then, with protection at both levels in sparse scenarios, there is no dependability-CAPEX trade-off with respect to the network layout.

VII. CONCLUSIONS

In this paper, the failure impact, availability and CAPEX of different PON protection architectures have been evaluated. In the evaluation, the network physical layout, infrastructure sharing and design decisions have been taken into account by means of a network geometric model. It has been shown that protection at the feeder levels is almost compulsory in order to reduce the probability of large outages, while protection at the distribution level has little effect on it. Besides, feeder fiber protection achieves acceptable availability values for areas with a high density of clients. The availability provided by this protection is also enough for clients located close to the CO in areas with low density of clients. Protection at the feeder level has been proven to be quite inexpensive, due to reutilization of common trenches. Yet, this trench reutilization requires some flexibility in the protection mechanisms in order not to hinder the availability. Although clients situated far away from the CO in sparse areas require protection at the distribution level, this protection leads to large CAPEX. It may be effective if business clients are present and/or if only a subset of the distribution areas is protected. Also, schemes reutilizing fibers are not well suited for providing protection. At the feeder level, they lead to the worst failure impact results, and at the distribution level imply the highest CAPEX.

Design decisions regarding the network layout have been found to affect both the performance of protection schemes and the CAPEX. In dense scenarios, fully loading the OLT ports and chassis reduces the CAPEX but hinders the dependability. The same is true when designing the PON with large distribution areas, which is an on-going trend nowadays. This also applies in sparse scenarios with feeder level protection, as the CO-related costs do not dominate the CAPEX. Hence, there is a direct trade-off between failure impact, availability and CAPEX regarding the size of the distribution areas. The negative impact of this practice in the availability can be overcome by deploying protection at the distribution level. Then, the CAPEX will be higher and the CAPEX trend with respect to the distribution level size is inverted. However, protection of the distribution fibers do not provide any benefits regarding failure impact. Thus, both the availability-CAPEX and failure impact-CAPEX trade-offs are still open.

The two trade-offs identified in this work call for further research. The availability-CAPEX trade-off can be influenced by other aspects such as migration towards next-generation PONs. Also, the achieved availability may still not be acceptable for business users. The failure impact-CAPEX trade-off plays a major role when deciding the size of the distribution part. This trade-off must be further analyzed taking into account also loss due to penalties and loss of operator reputation. Finally, the analyses presented here should be extended to other PON architectures, with more accurate network models.

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