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PROTECTION IN ADVANCED PON ARCHITECTURE WITH MINIMUM TRENCHING COST

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Abstract

Passive Optical Networks (PON) are widely used for broadband access connectivity, and recent PON technology has evolved the original connections between core network and end user allowing even direct communication between the end users of the network, i.e., the Optical Network Units (ONUs) through the Remote Node (RN), leading to the so called Advanced PON. Since the new services have stringent availability requirements, it is important to study how to extend the existing PON protection scenarios to the Advanced PON architecture to protect traffic between ONUs.

To achieve that, we propose two protection schemes, and compare them focusing on the minimization of the trenching costs, i.e. the cost needed to dig the ditch where the fiber will be laid, and of the total fiber length. In particular, RN-ONU protection scheme protects single communication between ONUs by duplicating two fibers and laying them in different trenches, while ONU-ONU protection protects a single communication between ONUs by reserving only one fiber that links them.

In this work we first we analyze the protected communications types, between end users or between end user and the core network, of both the schemes and the changes needed by them in the state-of-the-art PON protection strategies.

Then, we propose an ILP model that maps primary and backup optical fibers to the candidate trenches and compare two protection schemes in terms of their trenching and fiber costs. We show under which conditions, in terms of inter-ONU communication type, the two protection schemes provide lower cost. We find that in ONU-ONU protection enables, as best case, 10% cost savings increase compared to RN-ONU strategy when all the ONUs require to communicate with only one ONU identified as macrocell.

Abstract in italiano

Passive Optical Networks (PON) sono reti largamente diffuse per acceso a banda larga, e le recenti tecnologie per le PON hanno permesso l'aggiunta, alle originali connessioni tra gli end user e il core della rete, di connessioni dirette tra gli end user, i.e. le Optical Network Unit (ONU) attraverso il Remote Node (RN), introducendo le Advanced PON. Dato che i nuovi servizi sono caratterizzati da stringenti richieste in termini di availability, risulta importante estendere gli scenari esistenti di protezione delle reti PON alle Advanced PON per proteggere anche il traffico tra le ONU.

A questo scopo vengono proposti due schemi di protezione, comparati poi concentrandosi sulla minimizzazione del costo di trenching, i.e. il costo necessario per scavare il fosso dove verrà poi posata la fibra, e sulla lunghezza totale della fibra. In particolare, lo schema di protezione RN-ONU protegge una singola comunicazione tra due ONU duplicando due fibre e posandole in cammini differenti, mentre lo schema ONU-ONU protegge la singola comunicazione tra ONU riservando una sola fibra che colleghi queste due.

In questo lavoro prima vengono analizzati i tipi di connessione, tra due end user oppure tra end user e core network, protette da entrambi gli schemi e i cambiamenti richiesti da questi nelle strategie di protezione delle reti PON.

Successivamente, viene proposto un modello ILP che mappa la fibra primaria e la fibra di backup sui possibili trenching e compara i due schemi di protezione in termini di costi di trenching e di lunghezza totale della fibra. Viene poi mostrato in quali condizioni, in termini di tipologia di connessione tra ONU, i due schemi di protezione forniscono un costo inferiore. Viene scoperto infine che la protezione ONU-ONU, nel migliore dei casi, garantisce un aumento dei costi del 10% rispetto alla strategia RN-ONU, nel caso in cui tutte le ONU richiedono una connessione con solo una ONU definita come macrocella.

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1 Introduction

1.1. Motivation

PON (Passive Optical Network) architecture is widely used to provide broadband access connectivity for residential and business users, and latest evolution of PON technology makes it suitable for more demanding applications, e.g., fronthaul in 5G Radio Access Network (RAN) and intra-datacenter connectivity, thanks to the increased line rate (up to 50 Gbits/s) and higher maximum distance to the end nodes (up to 40 km). Simple point-to-multipoint architecture of PON matches traffic patterns of new applications, however some of them require communication between end users (ONUs) (e.g., traffic between the Centralized Unit and Radio Units is 5G) in addition to standard communication between end users and central office (OLT). Strict latency requirements of new applications cannot be met if ONUs communicate through the OLT, and novel Advanced PON architecture has been proposed [1,2] to allow ONUs to communicate directly through the remote node (RN).

Advanced PON architecture is considered for applications with strong reliability requirements, such as optical fronthaul and backhaul transport, making traffic protection crucially important. Protection schemes in state-of-the-art PON have been widely investigated by the network research community, however, to the best of our knowledge, there has been no attempt to extend those schemes and analyze cost even of protection for traffic between ONUs in Advanced PON.

1.2. Thesis contribution

Inter-ONU communication changes the protection requirements as OLT-ONU and ONU-ONU traffic must be protected. In this thesis we compare two different methods of ONU-ONU traffic protection, namely, RN-ONU protection and ONU-ONU protection, that differ in the strategy to protect the inter-ONU communication: the first try to protect it by reserving a fiber to protect each single fiber of the primary communication, while the second reserve a fiber to protect the entire communication and so that links the source and the destination directly. In Chapter 3 we introduce the two methods and analyze if some changes are needed when they are combined with the traditional PON protection schemes. In Chapter 4, we propose an ILP model that minimize the trenching cost and the total fiber length of primary and backup optical fibers, by selecting the needed trenches between a set of candidate trenches. In Chapter 5 we use the developed ILP model to find an optimal layout of primary and backup fibers in realistic network scenarios and compare two protection schemes in terms of their trenching cost and fiber length.

Cost of the Advanced PON is composed by the cost of components (OLT, RN, ONUs), fibers and trenching cost. Studies [4,5] show that trenching cost dominates the total network cost, but at the same time the total fiber length change depending on which protection scheme is adopted, so in this study we compare cost-efficiency of two different schemes for ONU-ONU traffic protection in Advanced PON by focusing on minimizing trenching cost and the total fiber length.

2 Background on PON Architecture and PON Protection

In this chapter we provide background on PON and PON protection, after this the main Advanced PON evolutions are highlighted.

In Section 2.1 is presented the PON architecture while in Section 2.2 are exposed the PON protection techniques. After these two introductory sections we discuss the evolutions introduced in the Advanced PON in Section 2.3, while inn Section 2.4 a brief literature review over the main topics of this thesis is presented.

2.1. What is a PON

Thanks to their simplicity, reliability and low cost, PONs have become one of the most attractive and widely used broadband access technologies. The physical topology of this architecture is a point-to-multipoint tree network, as shown in Fig. 1.

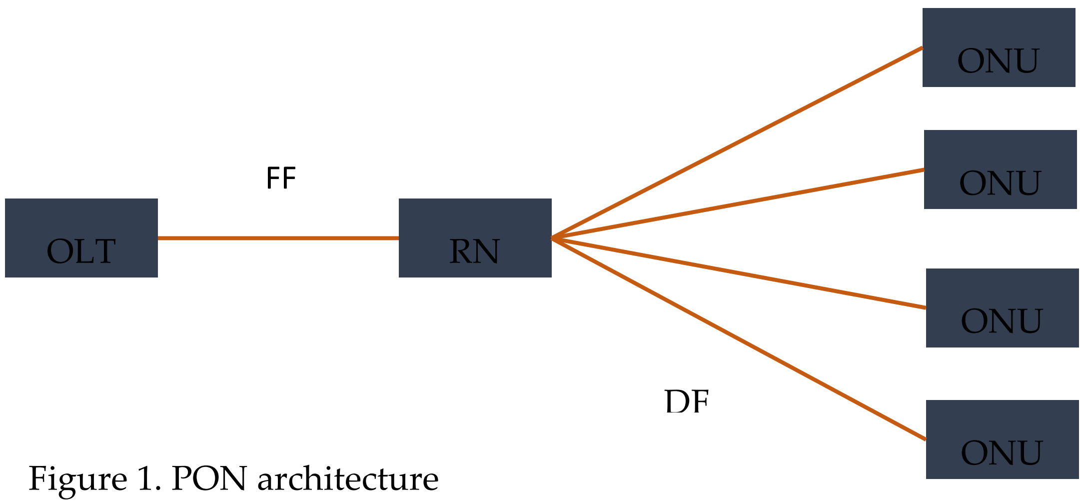


Figure 1. PON architecture

A PON is composed by an Optical Line Terminator (OLT) located at the central office and connected with many Optical Network Units (ONUs) through a Remote Node (RN). At the ONUs the end users of the network transmit and receive traffic to/from the core network, i.e., the OLT. The RN can be implemented as a power splitter (PS) or array wavelength grating (AWG).

The links between these components are optical fibers. Fiber link between the OLT and the RN is known as Feeder Fiber (FF), whereas fiber link between each ONU and the RN is known as Distribution Fiber (DF). In traditional PON architectures, direct communications are established between the OLT and ONUs and not between the different ONUs.

Passive components are inexpensive, reliable and have low energy consumption, and also guarantee high capacity, so they make PON a cost-efficient solution for many applications.

2.2. Protection schemes for PON

PON is a very common network architecture, so traffic protection for this type of networks has been widely explored in literature [3,4,5]. The four standard protection schemes for PON (here referred to as protection type A, B, C, D) guarantee different levels of protection, depending on the Service Level Agreement (SLA) between the user and the network provider. Network operator chooses one of four protection schemes by finding a trade-off between satisfying the SLA and reducing deployment costs.

To guarantee high availability we could duplicate the entire network (OLT, FF, RN, DF, ONU) but this leads to a high network cost and underutilization of network resources. Protection schemes of type A-D provide different levels of duplication of the section between the OLT and the RN. In each of them, DFs can also be duplicated for users that require higher levels of protection.

2.2.1. Protection type A

The FF certainly is the most important element of the network from the availability point of view, since a failure of this link will impact the entire network, thus in protection type A, shown in Figure 2, the only duplicated element of the PON is the optical fiber (both FF and DF). Protected feeder fiber must be link disjoint from the primary one, so protection fiber (PF) and FF are placed in two different trenches. If there is a user that needs additional protection, its DF is duplicated, and an output RN port is reserved for the Protected Distribution Fiber.

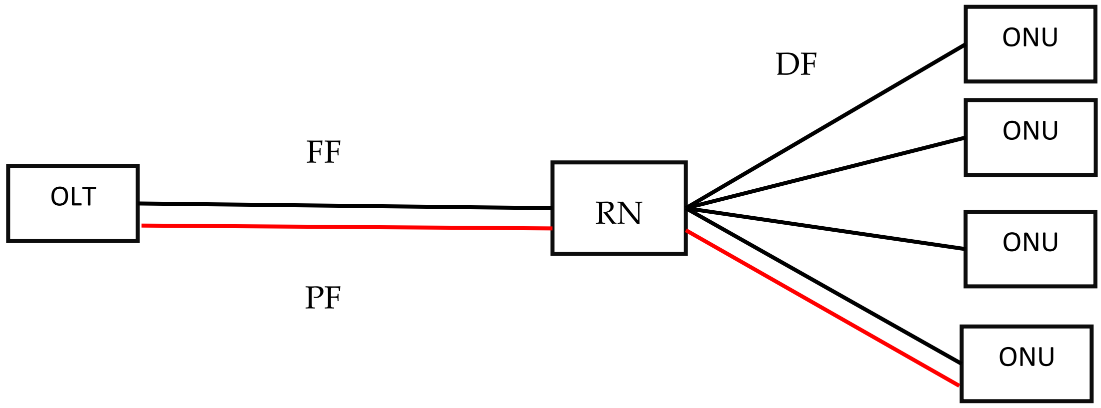


Figure 2: Protection type A

2.2.2. Protection type B

Following the same logic, the second most important element of a PON is the OLT, so in protection type B, shown in Figure 3, in addition to the PF, there is a second OLT that can transmit the same traffic and is activated if the primary OLT fails.

Backup OLT and working OLT are geographically separated and the FF links the working OLT with the RN while the PF connects the backup OLT to the RN, as shown in Figure 3. The inter-OLT signaling is external to the PON and is needed to switch between the primary OLT and the backup OLT. To avoid waste of resources in some cases the secondary OLT is shared between more primary PONs.

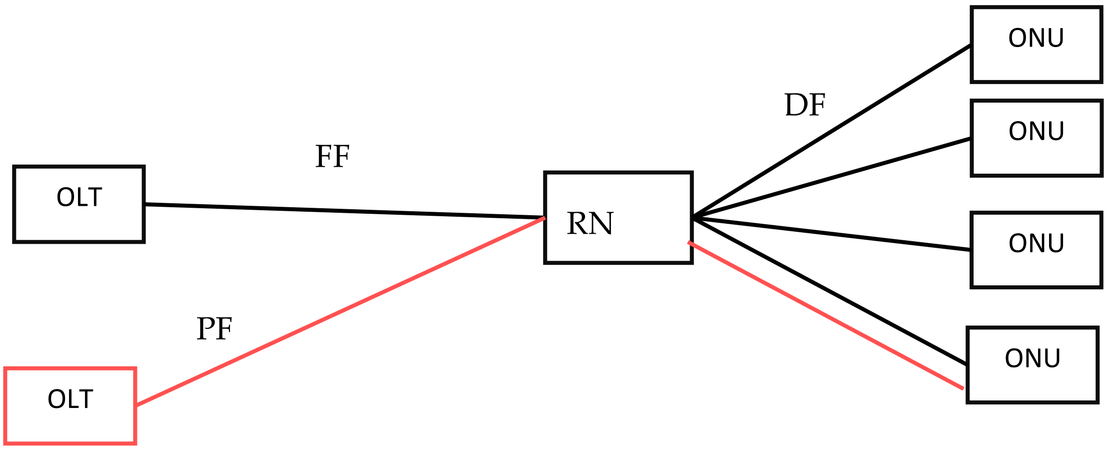


Figure 3: Protection type B

2.2.3. Protection type C

The protection scheme type C depicted in figure 4, increase the availability by duplicating even the RN, other than the FF and the OLT. Doing so, we obtain an entirely duplicated path from the OLT to the RN which acts as the backup path for every protected ONU. At the same time, ONUs that do not require such strong reliability guaranteed are not protected at all, which is the main drawback of this type of protection.

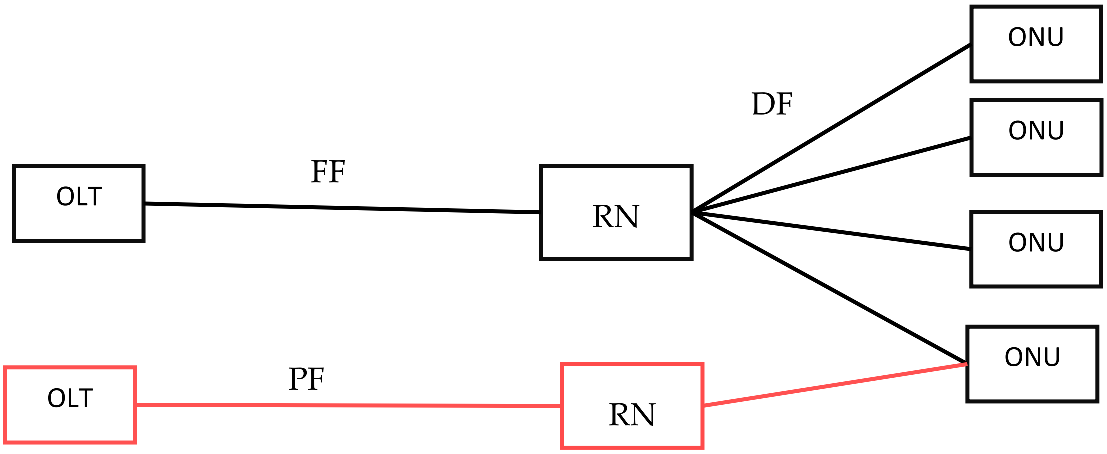


Figure 4: Protection type C

2.2.4. Protection type D

To overcome the limitation of the ONUs with no duplicated elements between OLT and RN, in protection type D an additional link connects working OLT and backup RN, and a link connects the backup OLT to the working RN. As can be seen in Figure 5 with this change also the users that do not require high protection level get a certain level of protection while the others get an entirely duplicated network.

Increasing the protection level, and so increasing the resources which are duplicated, means increasing the costs for the operator. The choice of which scheme to implement is a tradeoff between the availability and the network costs. Since in this last scheme there are lot of duplicated elements, the costs of this solution is relatively high.

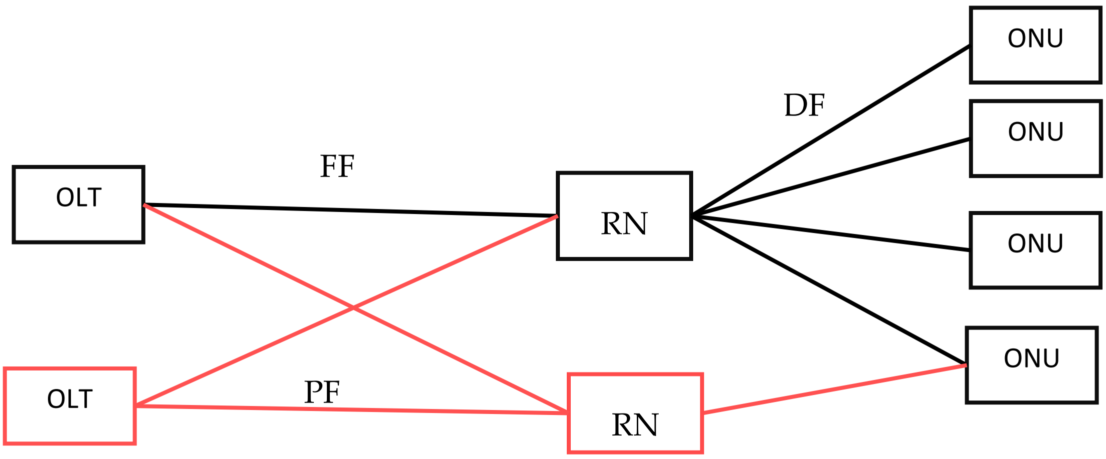


Figure 5: Protection type D

2.2.5. Distribution Fiber Protection

As can be seen in the previous sections, in some cases it is necessary even to duplicate the DF of a specific set of ONUs, in addition to the four protection schemes.

The problem of duplicating OLT, RN and FF is simple and has a small solution space. However, when multiple ONUs require DF protection, the problem of reserving backup fibers for those ONUs while minimizing cost is more challenging.

Works [9] propose an ILP model that takes as input the ONUs location, the RN location and a set of possible trenches where fibers can be placed and minimizes the costs. Since the most relevant cost in the PON deployment is the cost of trenching, one of the most relevant ILP objectives is to minimize that specific cost.

2.3. What is an Advanced PON

All the discussion made so far refers to state-of-the-art PONs which are a widespread solution to bring high capacity to end users, mostly residential, with a relatively low cost for the operator. This technology is limited by the maximum distance from the OLT to the ONU of 20 km and line rate below the 10 Gbit/s. Recent technological advances improve PON capabilities and allow to consider PON architecture not only for residential or small business services, but also for more demanding services (e.g., 5G fronthauling and backhauling).

Some new applications require communication between the end users (ONUs) in addition to standard communication with the central office (OLT), e.g. traffic between the Centralized Unit (CU), Distributed (DU) and Radio Units (RU) in 5G, that come with strict latency requirements. Following the 5G network example, the CU can be physically separated from DU with the so-called F1 interface [1], while RU can be separated from the CU and DU with the Fx interface [1], or all the three 5G network components can be physically separated, and both interfaces are used. Different options have different characteristics under many aspects, but the most relevant is the difference in the transport latency tolerance, since in the F1 interface the latency can be in the range of milliseconds, while in the Fx interface the latency must be in the order of hundreds of microseconds.

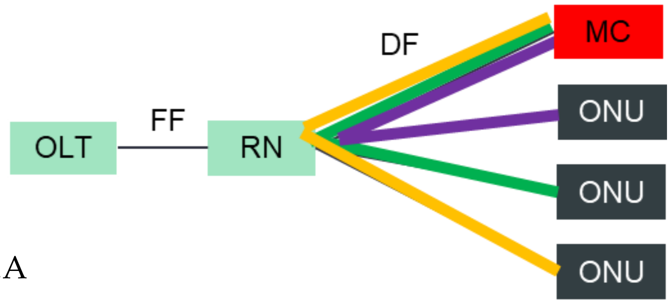
In this work we distinguish three "local interconnects" that allow communications between end users through the RN but differ in traffic patterns: one-to-any, any-to-few, any-to-any. The possibility of local interconnects cannot be achieved with classical implementations of RN. The RN has to propagate the signals from the OLT to each ONU and also signals that originate at ONUs and are destined for other ONUs. To guarantee both functionalities RN structure is modified, depending on the type of the local interconnect.

Another advantage of Advanced PON is in the improved components: until now managing and monitoring of the network is a responsibility only of the edge of the network, but with the new applications there is a need of a more detailed knowledge of the network state. Inserting in the network these components capable to monitor the network leads to what is called "Smart Optical Distribution Network" (smart ODN). Some of the new inserted elements are: the Demarcation Point Monitor (DPM) aimed to verify if there is some failure in the network remaining in the optical domain, the Intelligent Splitter Monitor (ISM) aimed to update the connectivity matrix of the network and hence to memorize which elements is connected to which port, and Smart Branching Nodes (SMN) aimed to introduce a level of reconfigurability in the PON, even if it is only for a small set of practical use cases, and to control the energy consumption.

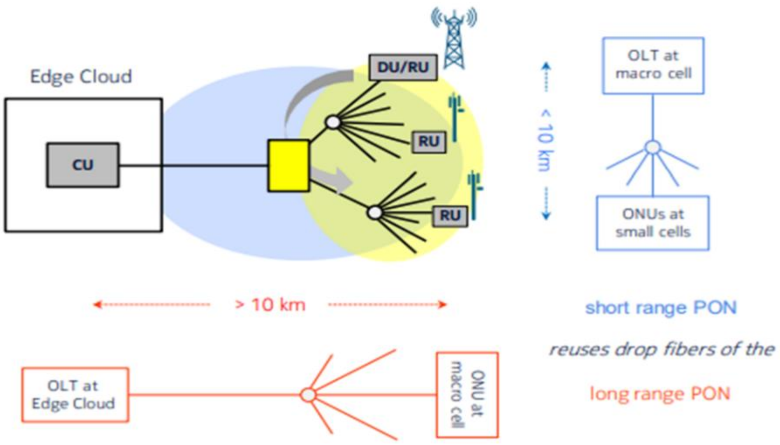
2.3.1. One-to-any local interconnects

In one-to-any scenario a macrocell (MC) and normal cells are the ONUs of the Advanced PON (e.g., connections in 5G-RAN between Distribution Unit and Radio Units). Only the MC communicates directly with the OLT, while low-latency traffic between MC and ONUs passes through the RN. As a result, physical topology is the traditional PON network that supports two logical PONs, as presented in Figure 6b: one for the communication between the OLT and MC, red logical PON in the figure, and one for the low latency services between the MC and ONUs, blue logical PON in the figure.

In Figure 6 we can see how a PON architecture is used to provide not only the traditional communication between OLT and ONUs, but also communication in the local interconnect.



6.A



6.B

Figure 6. One-to-any local interconnect. A. Macrocell connected to the other ONUs through the RN.B. 5G RAN with the two logical PONs built over the physical one [1].

Figure 7 presents one possible RN implementation in the one-to-any scenario. In this case RN is based on a power splitter for the downlink from the OLT, and a diplexer at each ONU port that switches the downlink and the uplink communications. Finally, there is a power splitter for the so called "extension port" which is a RN port dedicated to the communication with other ONUs even if they are not part of the same PON. The crucial elements for the local interconnect are the diplexers that determine if the signal is directed to the OLT or to the other ONUs.

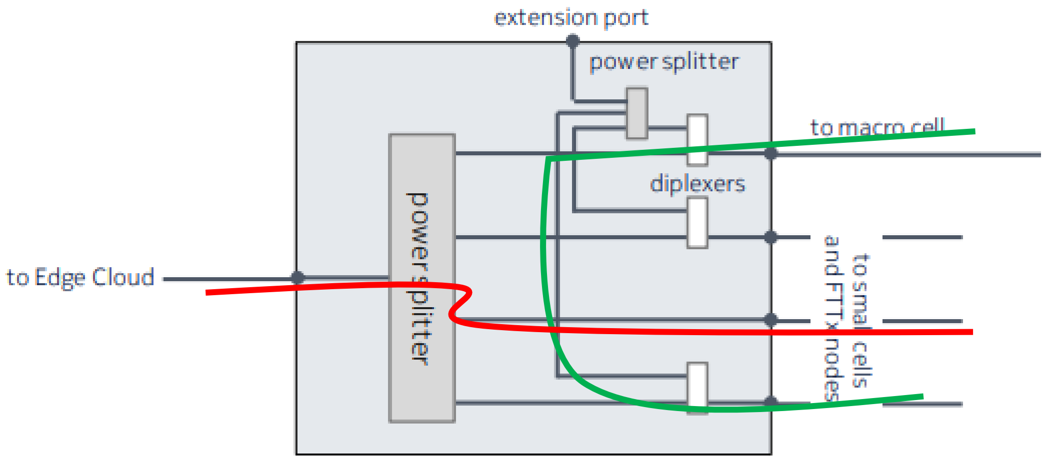


Figure 7. One-to-any RN

2.3.2. Any-to-few local interconnects

In any-to-few scenario, the application built over the PON requires a direct communication between a restricted number of end users, e.g., communications between Base Stations for Inter-cell Interference Mitigation. In this scenario base stations exchange traffic with the neighbouring base stations in order to reduce interference. Each ONU needs a direct communication with low latency to a fixed number of close ONUs through the RN (see Figure 8).

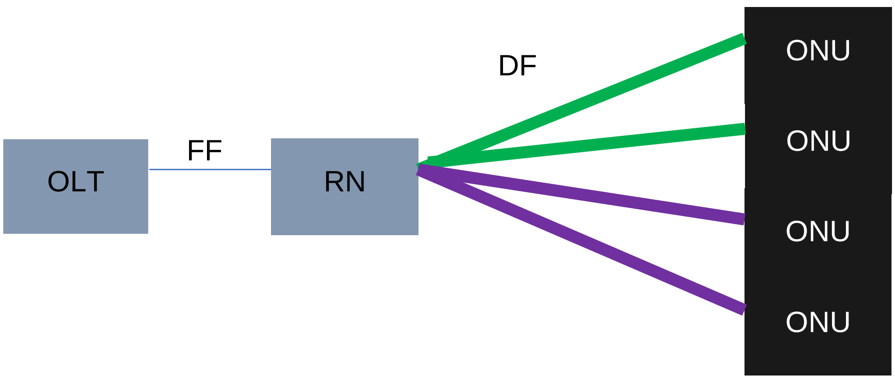


Figure 8. Any-to-few local interconnect

Figure 9 presents possible RN implementation for the any-to-few scenario where we use one power splitter for the communications starting from the OLT and directed to the ONUs, a diplexer for each ONU port that decides if the communication is directed to the OLT or to the other ONUs. Finally, coupling unit is a set of power splitters connected so that they create the communication matrix requested for the specific any-to-few local interconnects.

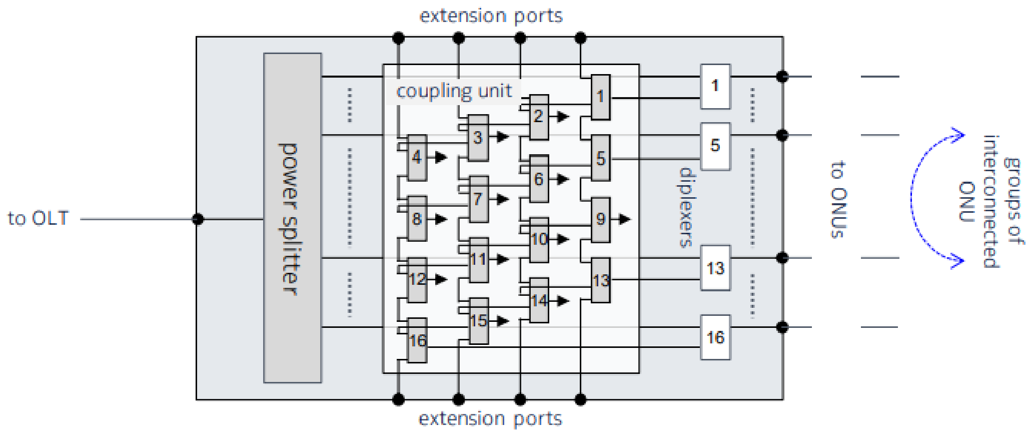


Figure 9. Any-to-few RN

2.3.3. Any-to-any local interconnects

In any-to-any scenarios applications require communications between every pair of ONUs (e.g., intra-datacenter traffic between servers in a rack) (see Figure 10).

Figure 11 presents the possible RN implementation for the any-to-any local interconnects, in particular, for the intra-datacenter communications. In this case a star coupler is used instead of a power splitter, that allows to connect each ONU's port directly to all the other ONU ports.

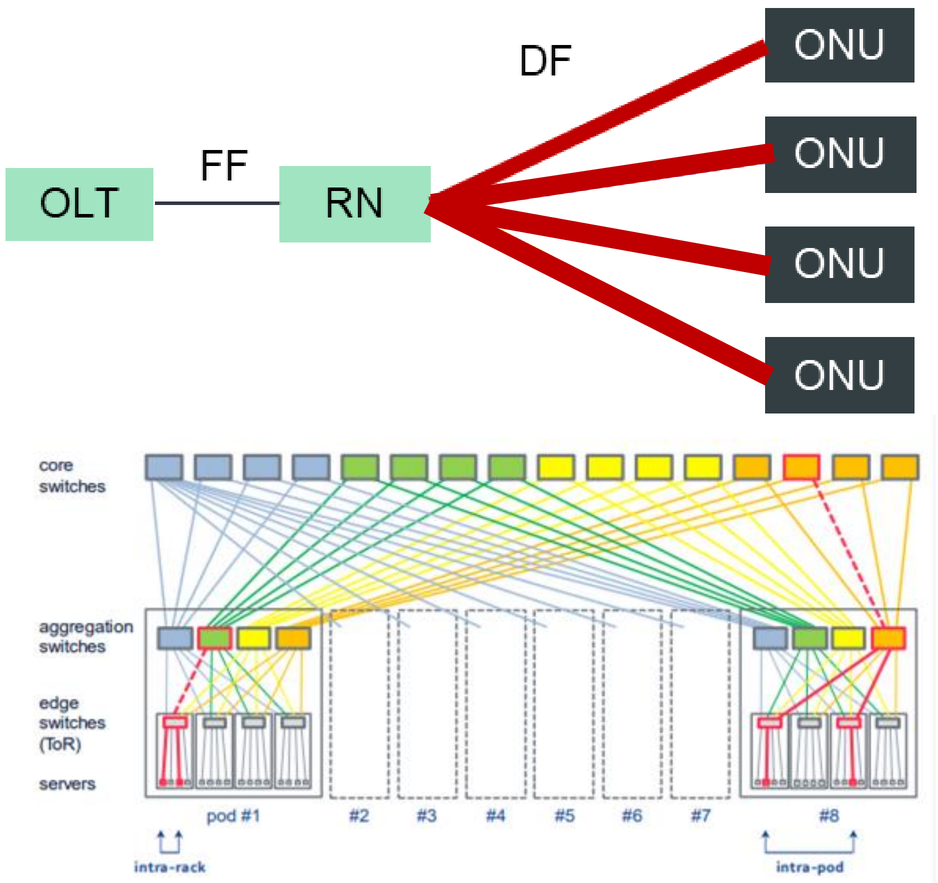


Figure 10. Any-to-any local interconnect. A. All the ONUs connected to the other ONUs through the RN. B. Intra-datacenter traffic between servers in racks, with the PON structure to interconnect them.

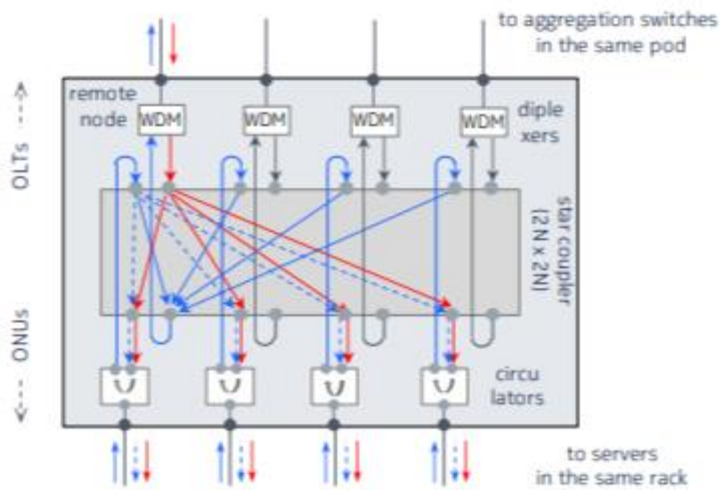


Figure 11. Any-to-any RN

2.4. Literature review

In the recent years, PON has been widely used since network operators can benefit from this network architecture: it allows high capacity and line rate with a relatively low cost. These great advantages suggest to use PON technology for more demanding applications like wireless networks [7,8].

In [1,2] authors analyze the requirements and modifications necessary to support the new services with the PON architecture and propose the definition of a new architecture called Advanced Passive Optical Network.

New applications carry large amounts of traffic over Advanced PON, and require a higher level of availability, as more traffic can be lost in case of a failure than in traditional PONs.

However, protection requires duplicating network components and increasing network cost, which undermines the traditional advantage of PON.

Protection in PON is well standardized [3]. We have presented four protection schemes (type A, B, C, D) in Section 2.2. These four protection schemes, as presented in Chapter 2, duplicates the network elements in order to react to OLT, FF or RN failures, hence in [9] the authors present how it is handled the protection against a DF failure. In [4] the protection schemes necessary to protect a NG-PON2, which is the passive optical network from which starts the Advanced PON introduction, are presented.

In [4, 5, 9] the authors analyze how the main costs for the network operator in deploying a PON is related to the labor cost for trenching and laying the fiber; and plan the protection in the network while reducing the cost related to the trenching and to the fiber.

However, to the best of our knowledge, there has been no attempt to analyze the protection of traffic between ONUs in Advanced PON.

For the Advanced PON protection we start from state-of-the-art PON protection schemes and analyze whether modifications are required to guarantee protection for the new services with ONU-ONU traffic. We present an ILP model that maps primary and backup optical fibers to the candidate trenches. Then we compare cost-efficiency of two different approaches to protection of ONU-to-ONU traffic in Advanced PON.

3 Advanced PON protection

In this chapter two Advanced PON protection schemes will be presented, in order to consider not only OLT-ONU communication but also the local interconnects. In Section 3.1 the two possible schemes will be exposed and analyzed. The Section 3.2 studies how the two new techniques coexist with the protection type A-D in the same topology. Finally in Section 3.3 a comparison between the main advantages and disadvantages of the two protection schemes presented before will be highlighted.

3.1. Proposed Advanced PON Protection Schemes

In the transition from the PON to the Advanced PON architecture, the main difference from the protection point of view is in the local interconnects. As discussed above, local interconnects allow the direct communication between ONUs of the same Advanced PON. To protect such ONU-ONU traffic, in general, we must reserve a backup fiber that allows to maintain the ONU-ONU services in case of a DF failure.

In this thesis we present two schemes for the inter-ONU protection: RN-ONU protection and the ONU-ONU protection. In the first case to protect traffic between ONU1 and ONU2 (see Figure 12a) we propose to reserve a backup fiber, mapped over a different set of trenches, between ONU1 and RN and one between ONU2 and RN, so that we duplicate the primary path and guarantee connectivity between the ONUs through the RN even in case of a DF failure. In the second case to protect traffic between ONU1 and ONU2 (see Figure 12b) we propose to reserve a backup fiber that directly links ONU1 and ONU2 and guarantees connectivity between the ONUs without passing through the RN. Second approach uses less fiber and avoids the RN in the protection path.

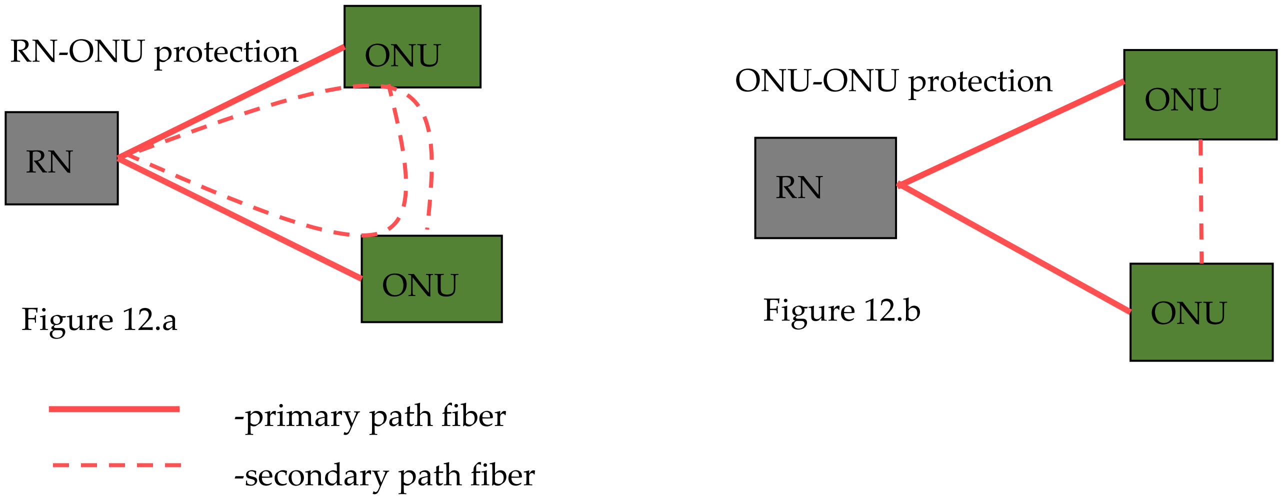


Figure 12. a. RN-ONU protection b. ONU-ONU protection

To compare the two protection schemes we must first make sure that they provide the same level of protection. As we can see from Figure 13.a if we use RN-ONU protection, in case of a DF failure the RN-ONU protection scheme guarantees a backup path that facilitates both OLT-ONU and ONU-ONU communication.

Differently, in the case of the ONU-ONU protection, if the DF of one ONU fails, since the working fiber share the same trench, even the second will probably fail, hence there is no fiber that links the ONUs to the RN and so there is no connection to the OLT. This happens when the working path of the ONUs that need to communicate are mapped over the same trench: in this case if the shared trench is compromised both ONUs are isolated from the rest of the network. To avoid this limitation and obtain the same level of protection (both the schemes protect OLT-ONU and ONU-ONU communications) we require that in the ONU-ONU protection scheme the primary paths of the ONUs between them use link disjoint trenching. In Figure 13.c we can see that if the primary path of one ONU fails we can still communicate with the OLT using the backup fiber of the inter-ONU communication and the primary fiber of the other ONU. This additional constraint becomes a very strong limitation when there are many ONUs that require protection in the local interconnect.

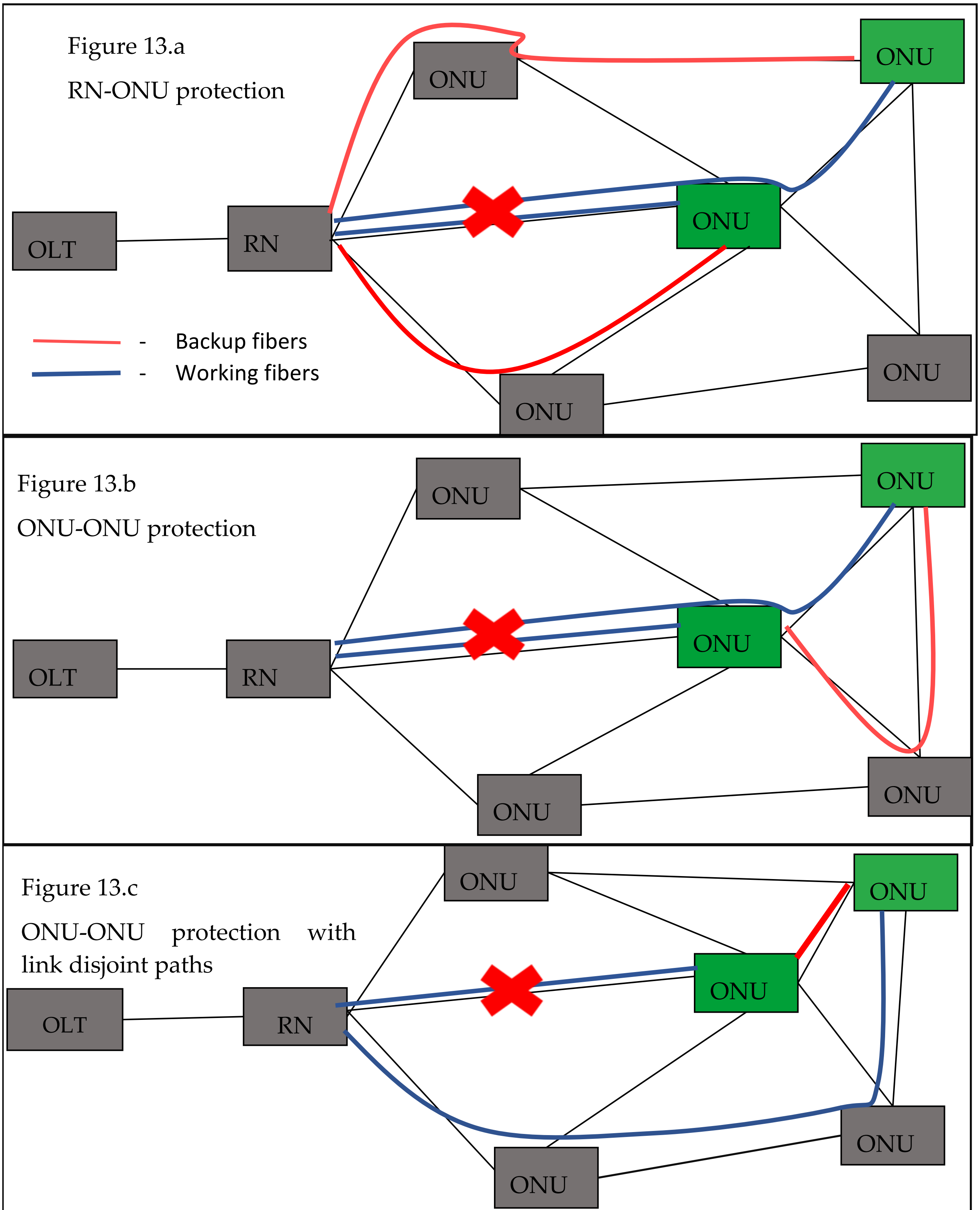


Figure 13.a. With RN-ONU protection there is a path to OLT. b. with ONU-ONU protection there may be no path to OLT. c. If primary paths are link-disjoint, there is a path to OLT even with the ONU-ONU protection

3.2. Modification required in A-D protection schemes for Advanced PON

The two schemes presented in the previous section are two possible ways to protect traffic in Advanced PON against DF failure. However, Advanced PON also have legacy connectivity between OLT and ONU, and we need to consider protection for the OLT-RN section of the PON, which is crucial, since failure of one of these components impacts traffic to each ONU.

Advanced PON does not change the architecture before the RN and so there is no changes for protecting this part of the network as can be seen by the Figure 14, however protection schemes proposed for ONU-ONU traffic protection have some implications.

Protection types A and B do not influence ONU-ONU traffic protection, while protection types C and D require that backup fibers are connected to the backup RN.

No changes are needed if RN-ONU protection is used: all the four state-of-the-art protection schemes (A, B, C, D) can be applied to protect the OLT-ONU traffic exactly like in traditional PON protection. Also, if a DF fails, communications between ONUs and OLT are not interrupted thanks to the backup fiber that links the ONU to the RN.

If ONU-ONU protection is used, protection schemes C and D are not possible, as there are no backup fibers going to the RN. However, ONU-ONU traffic is protected against RN failure in all schemes A-D, as protection paths do not go through the RN.

In conclusion, RN-ONU protection is compatible with all four traditional PON protection schemes, while with ONU-ONU protection OLT-ONU traffic cannot be protected in case of a RN failure.

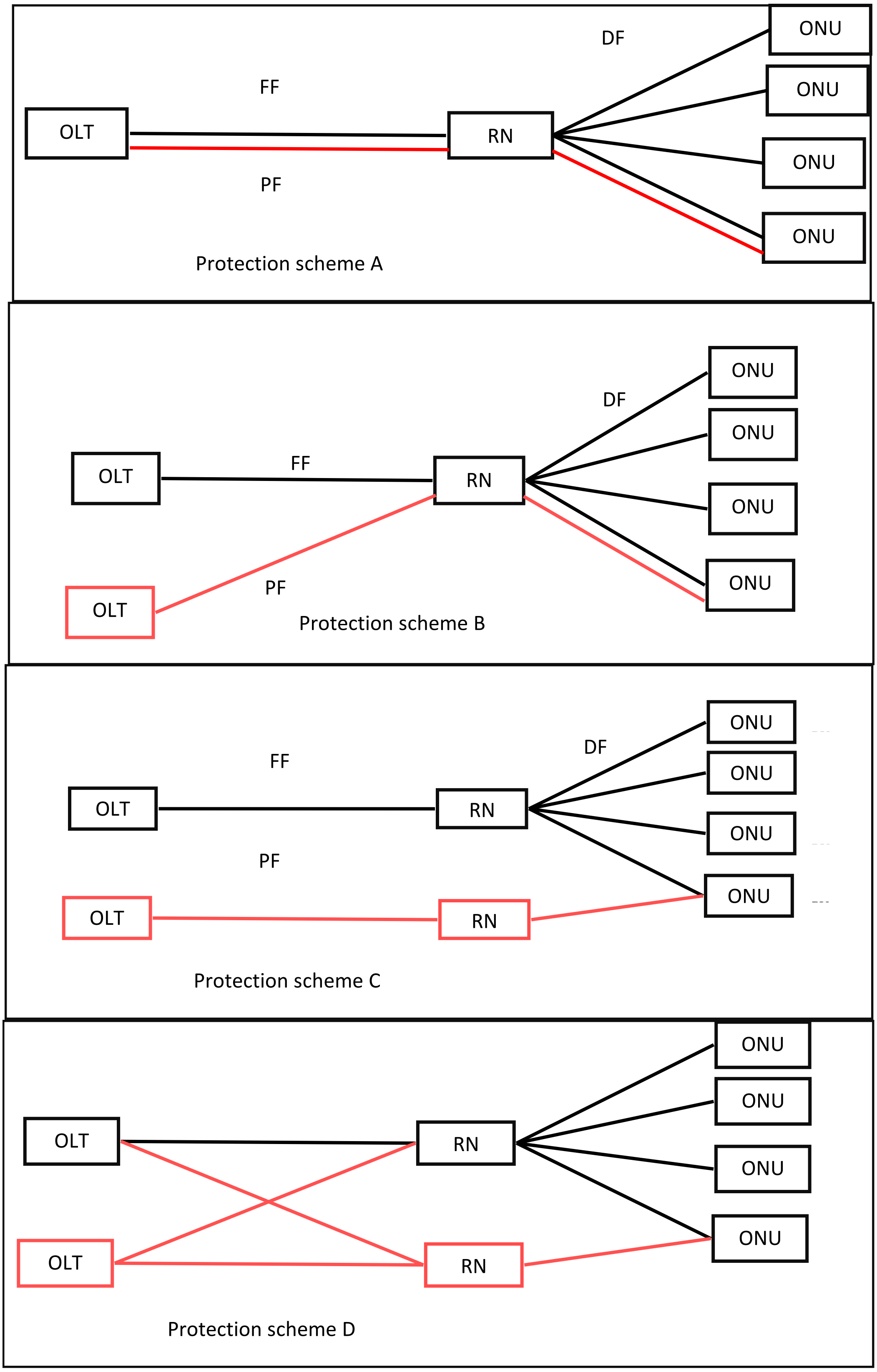


Figure 14. Four protection schemes in the case of local interconnects protection (the protection type C and D refers only to the RN-ONU protection). In black are represented the primary path while in red the secondary path.

3.3. Comparison of RN-ONU and ONU-ONU protection

Now that we have introduced two inter-ONU traffic protection schemes and analyzed their compatibility with the traditional OLT-ONU traffic protection schemes, we can compare them to identify the main drawbacks and advantages.

The main advantage of the ONU-ONU protection is that ports in the RN are not reserved for backup fibers, and either more ONUs can be connected to the same RN, or DF can be longer if RN with a lower splitting ratio is used.

RN-ONU protection scheme is limited by the RN port density, but it is compatible with all four schemes of the OLT-ONU traffic protection and thus resilient to a RN failure for OLT-ONU communications. It also does not require disjoint primary paths to guarantee OLT-ONU traffic protection in case of DF failure (see Figure 13).

4 Mathematical Modelling for Protection Strategies in Advanced PONs

In this chapter we will concentrate on the problem of minimizing the trenching and fiber costs when deploying an Advanced PON with the two protection schemes presented in the previous chapter, i.e., ONU-ONU and ONU-RN.

In Section 4.1 the problem statement is exposed. In Section 4.2 we describe how to generate a topology of all the possible trenches and in Section 4.3 we present an ILP model, that selects the set of trenches for primary fibers between the ONUs and the RN and backup fiber for the ONUs that require DF protection, while minimizing the total trenching and fiber costs.

4.1. Problem Statement

The problem of Fiber Trenching for protected Advanced PON (FTAP) is defined as follows. *Given* the set of ONUs and the location of the RN, we *find* the trenches over which to map the working and the backup fibers between the RN and the ONUs to minimize the trenching and fiber costs, *so* that each ONU is connected to the RN, the maximum length between RN and ONU is limited and, in case of ONU-ONU protection, primary paths between two connected ONUs are link disjoint.

The problem of FTAP is solved by a two-step approach: at the beginning we create a topology whit as nodes the ONUs and the RN while as link a set of possible trenches over which the fibers can be mapped, and after we apply an ILP model aimed to minimize the total trenching costs and the total fiber length.

4.2. Trenching topology

Optical networks are usually planar, which means that links do not intersect on a 2D plane, and so should be the topology of possible trenches between the nodes in our work

It is important to emphasize that the links of the topology that we are going to generate are not the real links of the Advanced PON but are the possible trenches in which DF of the network can be placed.

To generate a planar graph with the largest number of possible trenches, we use Delaunay Triangulation (DT). As presented in [6], DT is a maximum planar partition, which means that no link can be added to the graph while keeping it planar. The main characteristic of the DT is that for each triangle identified by three links of the DT there is no other nodes, excluding the three vertices included in the circle that circumscribe the triangle.

DT takes as input the locations of the ONUs we need to link to the RN. The algorithm is based on the "void circle test" and on the "arc flip". The void circle test is used to verify if a point is in the circumcircle of a triangle or not. We take the coordinate x and y of the triangle's point A, B, C and of the point to verify D, and build the following matrix with their coordinates:

$$\begin{vmatrix} X_A & Y_A & X_A^2+Y_A^2 & 1 \\ X_B & Y_B & X_B^2+Y_B^2 & 1 \\ X_C & Y_C & X_C^2+Y_C^2 & 1 \\ X_D & Y_D & X_D^2+Y_D^2 & 1 \end{vmatrix}$$

We then compute its determinant and based on its value we conclude if point D is in the circumcircle of the triangle ABC or not: if it is greater than zero the point is in the circle. If we identify a point that is in the circumcircle of a triangle we apply the arc flip and obtain a DT. As we can see from Figure 15 the arc flip consists of changing the diagonal of the quadrilateral generated by the four points: in the figure we can see how the yellow point is in the circumcircle of one triangle so we apply the arc flip in order to obtain the two new triangles where there is no node in the circumcircle of a triangle.

The algorithm takes as input the nodes, with their coordinates, that needs to be connected, which include the ONUs and the RN. The algorithm first generates a void topology G (N, L) with no nodes and no links and at each iteration add a node from the set of input nodes I.

Now that we have defined the void circle test and the arc flip we summarize the DT algorithm (see Figure 16):

1. We start with a void topology and add three random nodes, from the set of input nodes I, and the edges between them to G (N, L)
2. Now we add a random node v to G removing it from I and identify the smallest triangle T_i that contain this node
3. Then the edges that link v with the nodes of T_i are added to the edges of the graph
4. Now each triangle of the triangulation is tested with the void circle test and the arc flip is performed if needed
5. When the void circle test is verified over the entire graph and there are no remaining nodes to add from I the algorithm stops and we obtain the DT. Otherwise we restart from the point 2.

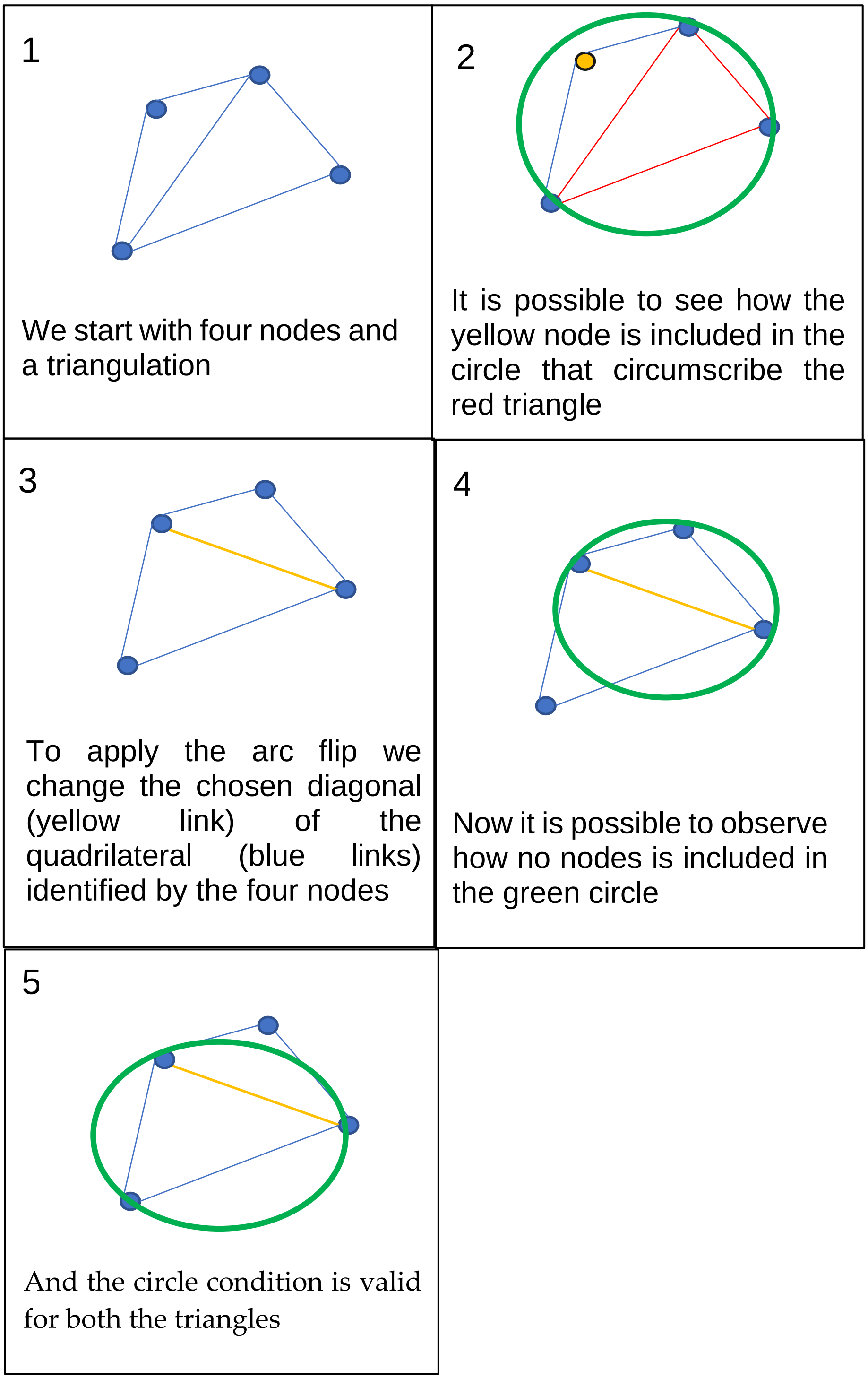


Figure 15. Example of arc flip

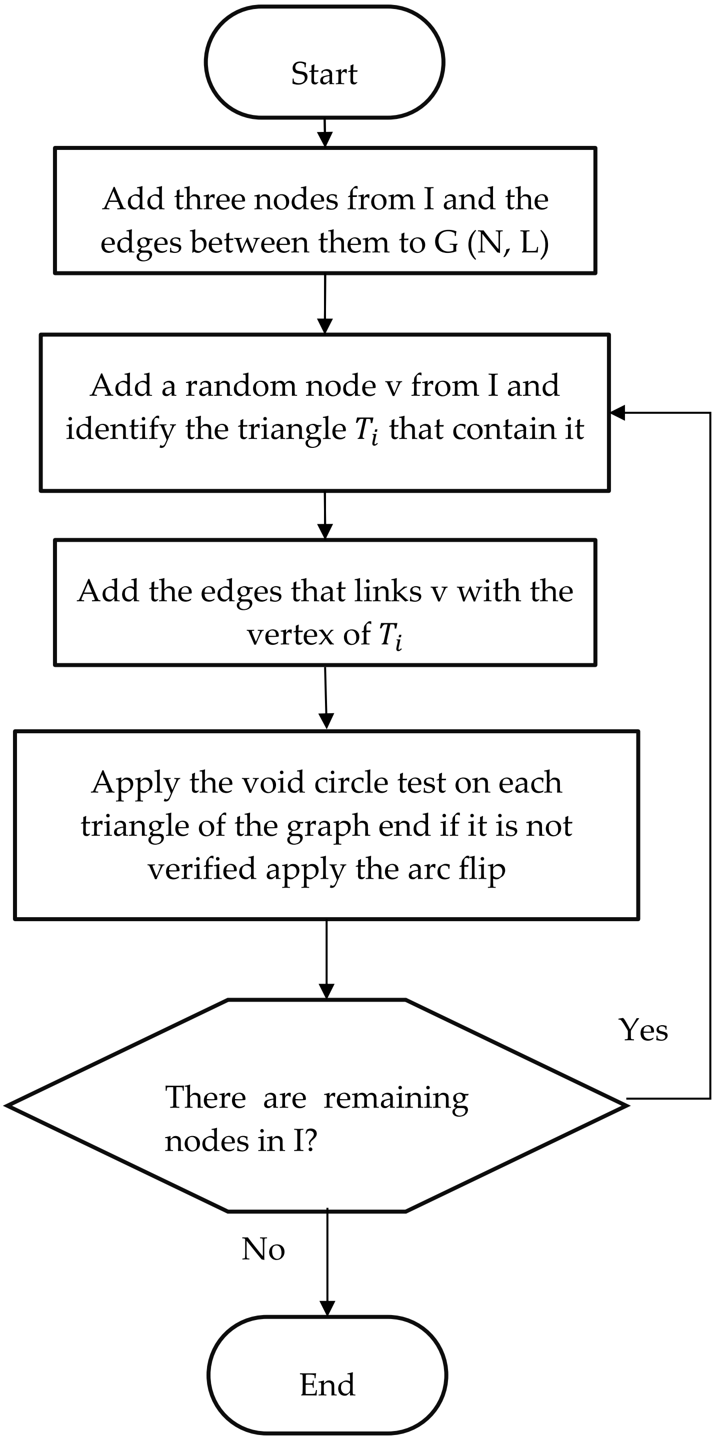


Figure 16. Generation of a DT flow chart

4.3. ILP model for the protection of Advanced PON

We now formalize the problem of FTAP with an ILP model that finds the solution at minimum trenching cost in the local interconnects.

The details of the ILP formulation are discussed in the following:

1. Sets:
   a. N: the set of optical network nodes, that includes the RN, conventionally located at the node 0, and the ONUs
   b. L: the set of links $(i, j) \in L$, that are the candidate trenches obtained by the Delaunay Triangulation
   c. W: set of working demands $(s, d) \in W$. Each demand is expressed as a pair of nodes (RN and ONU) that needs to be connected by a fiber.
   d. B: set of backup demands. Each demand is characterized by a source-destination pair that needs to be connected by a fiber s. In case of RN-ONU protection the source is always the RN and the destination is a ONU that needs protection, while in the ONU-ONU protection the source and destination are a couple of ONUs whose local interconnects has to be protected.
2. Parameters:
   a. l_{ij}: length of link $(i, j) \in L$
   b. D_{RN-ONU}: maximum distance between the RN and the ONU allowed by the technology used for the Advanced PON (40 km)
3. Decision variables:
   a. y_{ij}: identifies if a trench is used or not, takes value 1 if the link $(i, j) \in L$ is included in the solution and 0 otherwise
   b. x_{ijsd}: takes value 1 if the fiber that satisfies the request $(s, d) \in W$ is mapped over the link $(i, j) \in L$ and 0 otherwise
   c. z_{ijsd}: takes value 1 if the backup fiber that satisfies the request $(s, d) \in B$ is mapped over the link $(i, j) \in L$ and 0 otherwise
4. Objective: minimize the total trenching distance, the total fiber distance between the RN and the ONUs, the total distance of primary paths in order to have primary paths shorter than backup paths.

$$min \quad \alpha \sum_{(i,j)\in L} y_{ij} l_{ij} + \beta \left[\sum_{(i,j)\in L} \sum_{(s,d)\in W} x_{ijsd} l_{ij} + \sum_{(i,j)\in L} \sum_{(s,d)\in B} z_{ijsd} l_{ij} \right] + \delta \sum_{(i,j)\in L} \sum_{(s,d)\in W} x_{ijsd} l_{ij} \tag{1}$$

Subject to:

$$\sum_{(i,j)\in L} x_{ijsd} - \sum_{(j,i)\in L} x_{jisd} = \begin{cases} 1 & i = s \\ -1 & i = d \\ 0 & otherwise \end{cases} \qquad \forall i \in N, \forall (s,d) \in W \tag{2}$$

$$\sum_{(i,j)\in L} z_{ijsd} - \sum_{(j,i)\in L} z_{jisd} = \begin{cases} 1 & i = s \\ -1 & i = d \\ 0 & otherwise \end{cases} \qquad \forall i \in N, \forall (s,d) \in B \tag{3}$$

$$z_{ijsd} + x_{0isd} + x_{0jsd} \le j_{ij} \qquad \forall (i,j) \in L, \forall (s,d) \in B \tag{4}$$

$$\sum_{(i,j)\in L} x_{ijsd} l_{ij} \le D_{RN-ONU} \qquad \forall (s,d) \in W \tag{5}$$

$$\sum_{(i,j)\in L} z_{ijsd} l_{ij} \le D_{RN-ONU} \qquad \forall (s,d) \in B \tag{6}$$

In objective function (1) the three terms are respectively the total trenching length, the total fiber length and the total length of primary fibers, each with its weight cost α, β and δ that reflect their respective relevance in the network deployment costs. Equation (2) is the flow constraint for the working paths which guarantees that the fiber for the request $(s,d) \in W$ starts in node s and ends in node d. Equation (3) is the flow constraint for the backup paths which guarantees that the fiber for the request $(s,d) \in B$ starts in s and ends in the node d. Equation (4) guarantees the link disjointness condition between the working and backup path. In addition for ONU-ONU protection it guarantees that working paths of the two ONUs that require local interconnects are link disjoint. Equations (5) and (6) guarantee that the maximum distance between the RN and the ONUs is respected by each working, for equation (5), and backup, for equation (6), fibers.

The complexity of this ILP model is identified by the number of variables and by the number of equations expressed as:

- Number of variables: $(|W| \times |L|) + (|B| \times |L|)$
- Number of equations: $(|N| \times |W|) + (|N| \times |B|) + (|L| \times |B|) + |W| + |B|$

Where |S| means the dimension of the set S. While the dimension of working demands depends only over the network topology, the dimension of working demands can change over the same topology. So it is clear how the ILP complexity depends over the topology dimension and over the set of backup demands.

5 Numerical Results

This chapter compares the two different protection schemes proposed in Chapter 3, using the ILP presented in Section 4.3. The chapter is organized as follows: in Section 5.1 we summarize evaluation settings and different case studies, while in Section 5.2 we present and analyze protection costs and other metrics in different case studies.

5.1. Evaluation settings

In this section we describe the case studies and settings used to compare RN-ONU protection and ONU-ONU protection.

Figure 17 depicts the three planar topologies, with different minimum node degree, obtained with the Delaunay Triangulation and used to map primary and backup fibers of the Advanced PON. Each topology is composed by twenty nodes including the RN.

Length of each link of the topology is computed using coordinates, taken as input of the DT algorithm, of the two edges of the link.

For each topology we generate five random traffic matrices composed of ONU pairs, with a dimension which varies over the number of nodes that require protection. For each matrix we run the ILP model 5 times to find 5 different solutions, considering that 0%, 25%, 50%, 75% and 100% of ONUs require protection.

In one-to-any scenario macrocell is assigned to node with higher degree, other than the RN.

The results are expressed as difference in cost (or fiber length) in ONU-ONU protection with respect to RN-ONU protection in %, i.e.:

$$cost\ difference\ ,\% = \frac{Cost_{ONU-ONU} - Cost_{RN-ONU}}{Cost_{RN-ONU}} * 100$$

We average these metrics across 5 traffic matrices for each topology.

Once the number of ONUs to protect is fixed, RN-ONU protection solution is the same for the three local interconnects, since once the fibers are reserved between the RN and the ONUs all the local interconnects can operate over them. Differently ONU-ONU protection solution changes depending on traffic pattern of the local interconnect (see Figure 18).

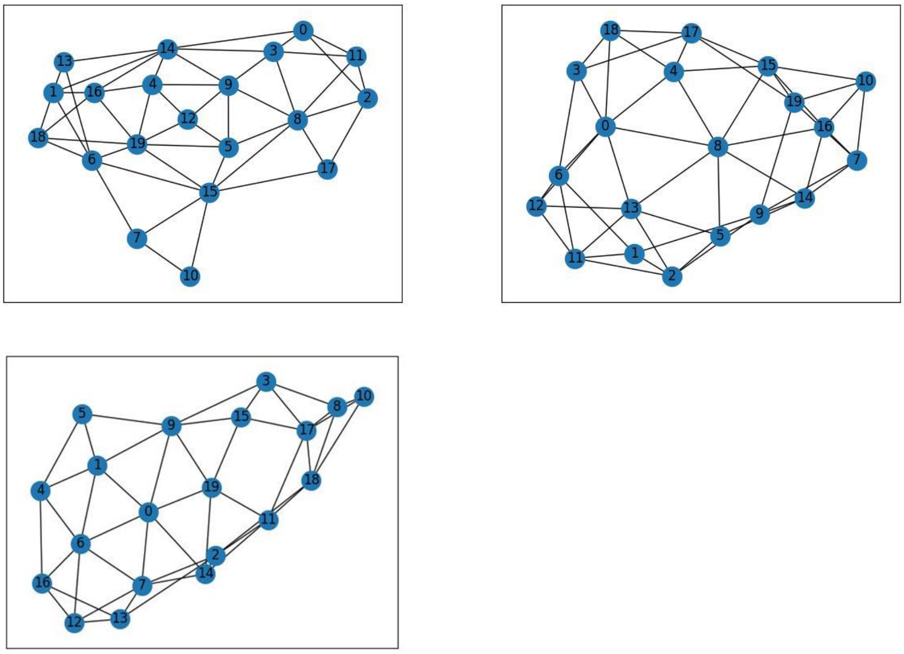


Figure.17 Three topologies used to obtain numerical results

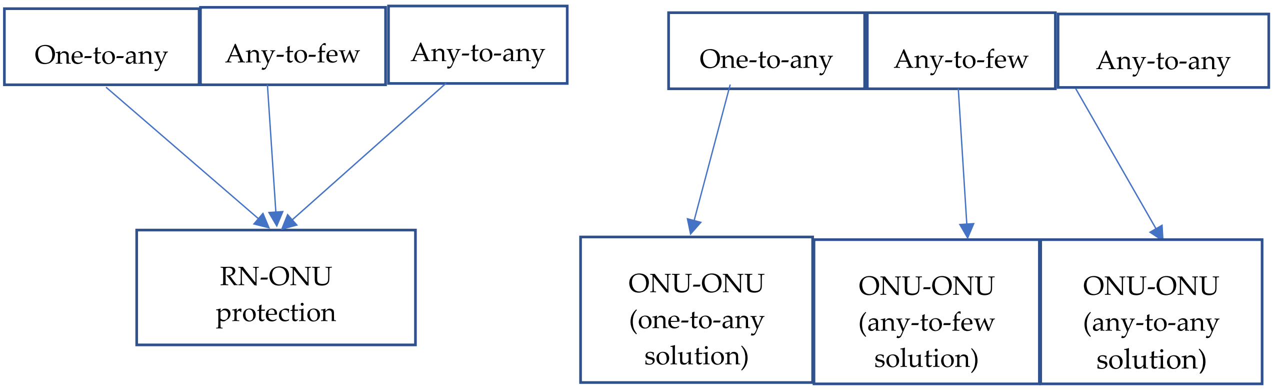


Figure 18: Case studies

Therefore, we will consider one solution for the RN-ONU protection as a baseline reference and compare it in terms of cost and fiber length with one ONU-ONU protection solution per local interconnect.

We use the same ILP model presented in Section 4.3 for both RN-ONU and ONU-ONU protection, but the set of demands changes: in the RN-ONU case they are expressed as connection requests from RN to ONUs, in the one-to-any case – from macrocell to ONUs and for the any-to-any and any-to-few case – from ONU to ONU.

The maximum distance between OLT and ONU is assumed to be 40 km. The weights of the objective function are taken from [4,5]. The simulation of the Delaunay triangulation for the network is implemented using Python and related Python libraries [10,11]. The commercial software package AMPL/CPLEX is used to solve the ILP problem.

5.2. Illustrative numerical results

In this section we numerically compare the trenching cost and deployed fiber length for RN-ONU protection and the ONU-ONU protection to analyze the trade-off between the two protection schemes.

5.2.1. Trenching costs for different percentage of protected nodes

Figure 19 illustrates the increase in trenching costs with ONU-ONU protection with respect to RN-ONU protection under different percentage of nodes to protect (0%, 25%, 50%, 75%, 100%). For the RN-ONU there is only one solution for every local interconnects, that will be the reference solution, and for the ONU-ONU protection there is one solution for each type of local interconnects and so one column that represent the increase of costs with respect to the RN-ONU case.

X symbol is used to indicate that no solution has been found by the ILP, because in that cases the nodes with low connectivity degrees do not allow enough link-disjoint paths.

We can observe ONU-ONU protection has higher cost for all interconnects, up to 10-15% in one-to-any and up to 30-40% in any-to-few and any-to-any scenarios. This is justified by the fact the link disjointed condition requires a higher number of used trenches for ONU-ONU protection. Cost increases with the number of protected nodes, which is also reasonable.

We can conclude that ONU-ONU protection can be practical in one-to-any and any-to-few scenarios with low % of protected nodes where its advantage in terms of lower RN degree can outweigh the 5-8% increase in trenching cost.

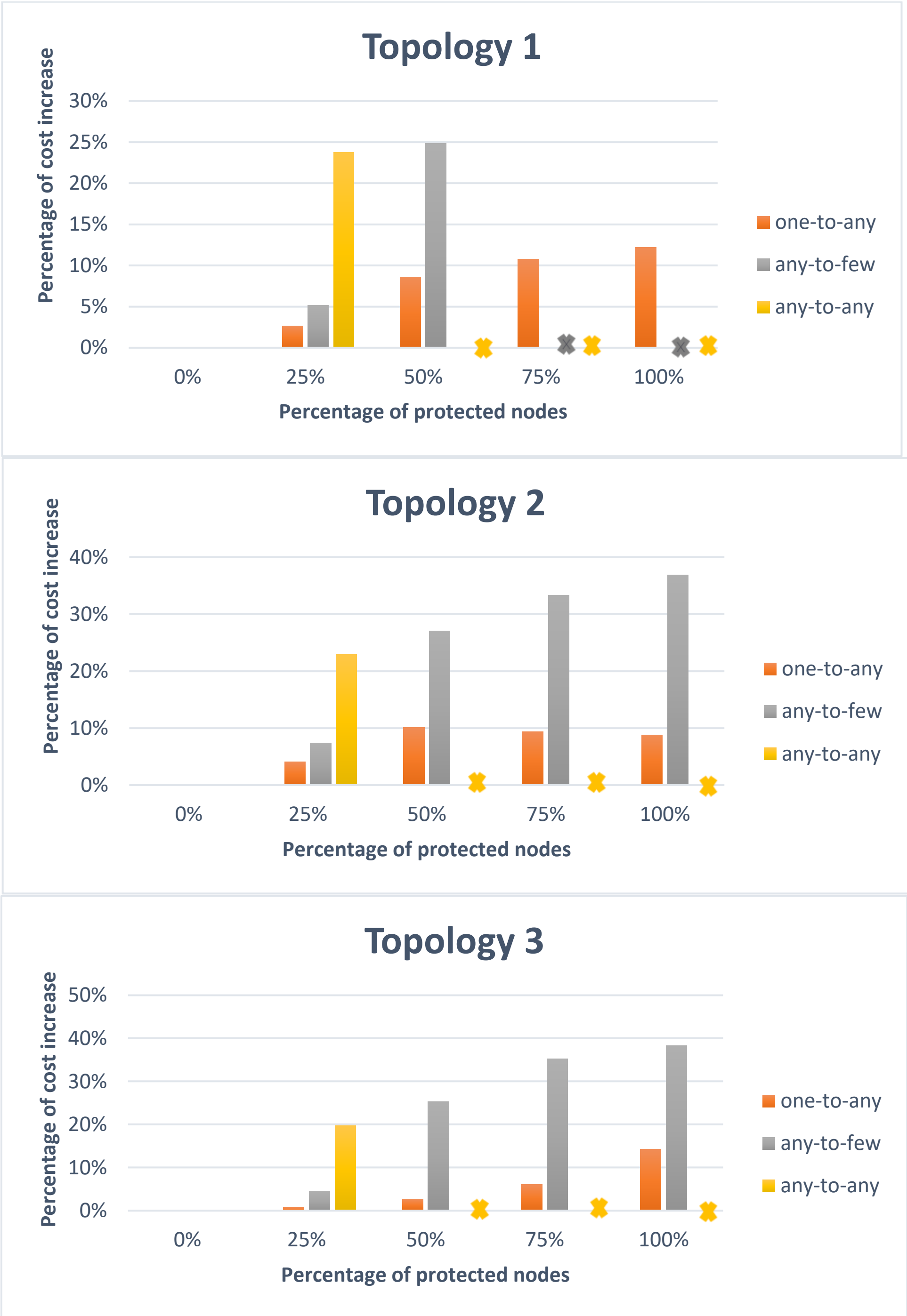


Figure 19. Trenching cost increase for the three topologies in different local interconnects and different % of protected nodes with ONU-ONU protection with respect to RN-ONU protection

5.2.2. Fiber length for different percentage of protected nodes

Figures 20, 21 and 21 illustrate the difference in total length of deployed fibers for the two different protection schemes. It separately depicts the changes in total length of working and backup fibers for different percentage of nodes that require protection and for the three topologies. These results take relevance since over a single trench can be mapped more than one single fiber and so it could be interesting to see if the ONU-ONU protection require less or more fiber than the RN-ONU protection.

ONU-ONU solutions tend to require more fibers for the primary paths due to link disjointness condition, with 50-100% increase in one-to-any if high % of nodes must be protected. However, as protection paths do not pass through the RN, in one-to-any scenario their length reduces by 50-80%.

In any-to-few scenario, the behavior is different, and length of working fiber decreases w.r.t. RN-ONU protection. With 50-100% of protected nodes, length of backup fibers increases by 20%, as longer paths are chosen.

Finally, for the any-to-any case the necessary node degree is so high that for 50%-100% of protected nodes no feasible solutions are found, while for the 25% the solution is feasible but presents an increase of both working and backup fiber in the order of a few %.

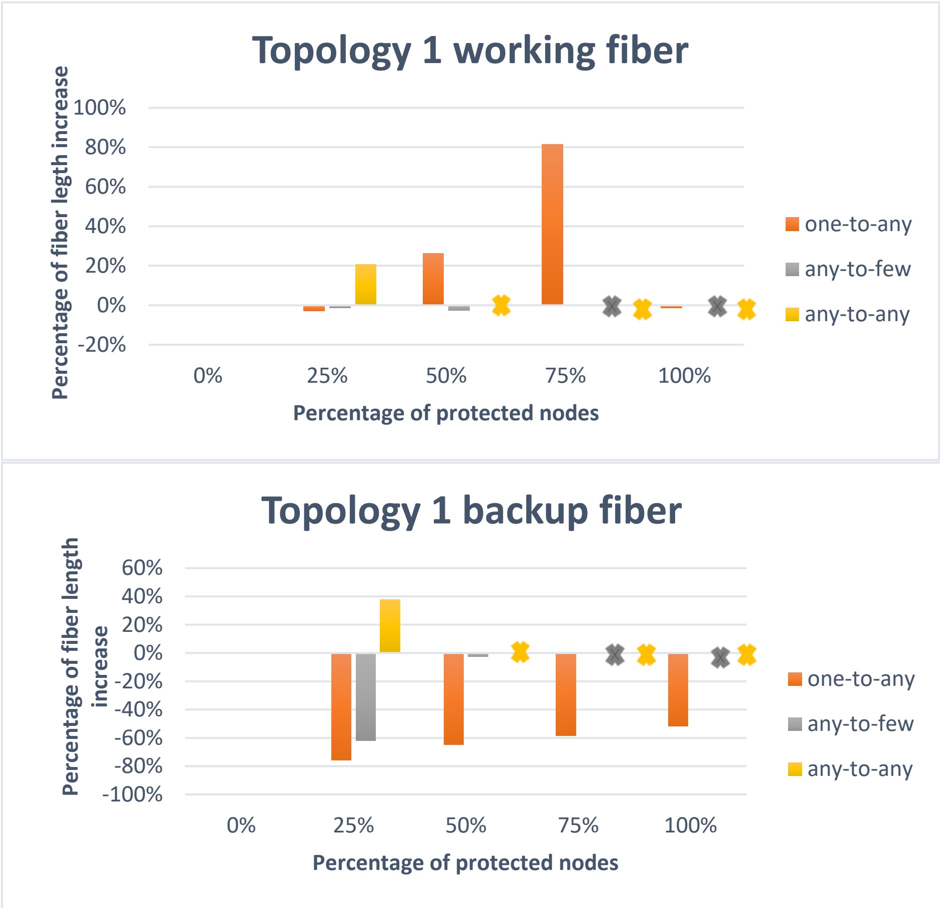


Figure 20. Total working and backup fiber length increase for topology 1 in different local interconnects and different % of protected nodes with ONU-ONU protection with respect to RN-ONU protection

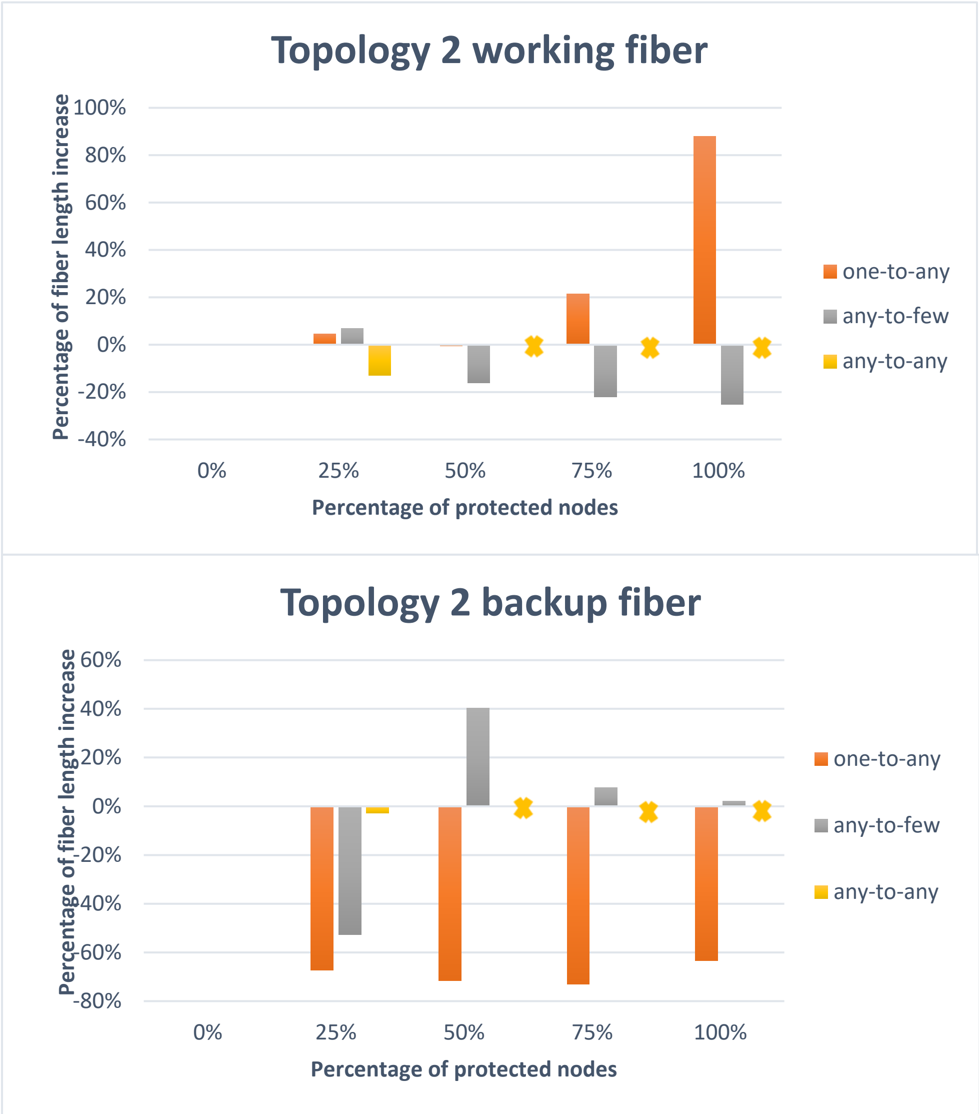


Figure 21. Total working and backup fiber length increase for topology 2 in different local interconnects and different % of protected nodes with ONU-ONU protection with respect to RN-ONU protection

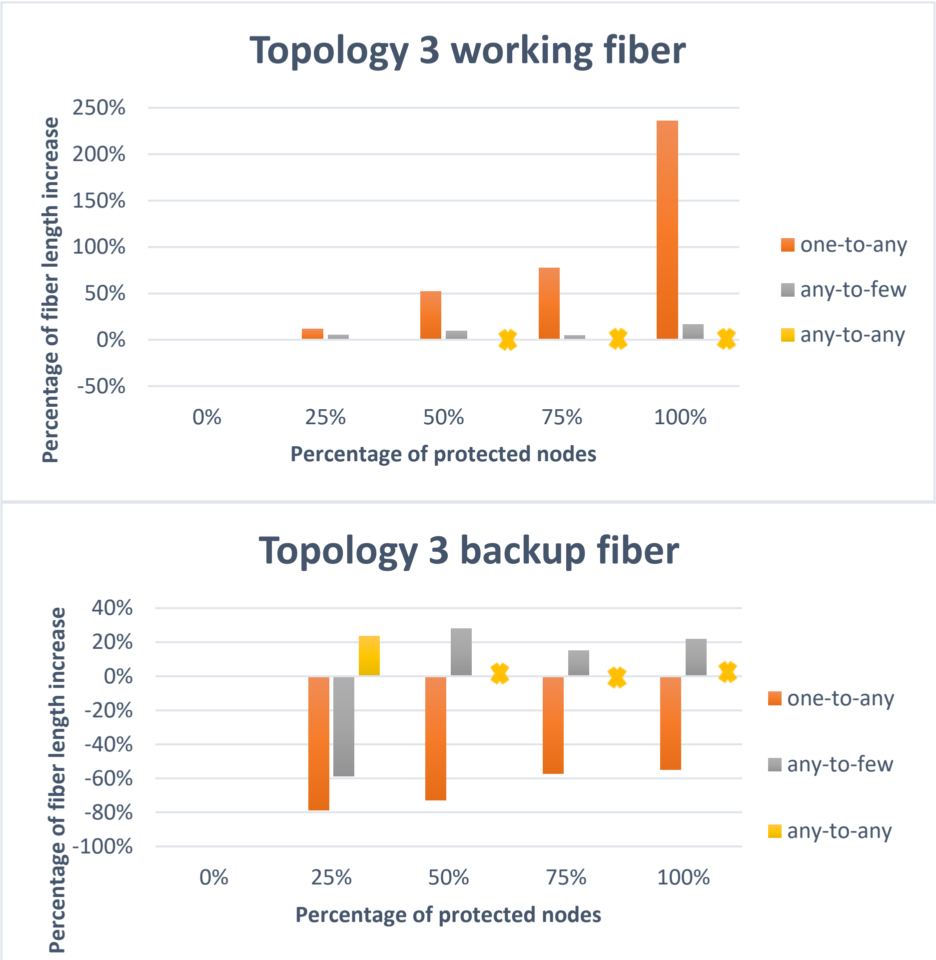


Figure 22. Total working and backup fiber length increase for topology 3 in different local interconnects and different % of protected nodes with ONU-ONU protection with respect to RN-ONU protection

6 Conclusion

We have proposed and analyzed two protection schemes for inter-ONU traffic protection in Advanced PON: RN-ONU and ONU-ONU protection. We have analyzed their compatibility with four state-of-the-art PON protection types.

We have proposed an ILP model that maps primary and backup optical fibers to the candidate trenches while minimizing trenching cost. Finally, we have compared two protection schemes in terms of their cost in different network scenarios and % of protected users.

Numerical results show that ONU-ONU protection requires higher trenching costs for all the network scenarios. However, cost increase in the one-to-any scenario is below 10%, so that ONU-ONU protection can still be considered by the network operators due the benefits that come with the lower RN degree. We also demonstrate different behaviour of working and backup fiber length in different network scenarios.

A possibility of future work could be to analyze the total deployment costs decrease introduced by the possibility of serve a larger number of ONUs with the same RN if the adopted protection scheme is the ONU-ONU, or even to study the distance increase between the RN and the ONU allowed by the ONU-ONU protection. These analysis allow to compare them with the total trenching cost increase, in order to better compare the two protection scheme.

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List of Acronyms

acronym	**meaning**
PON	Passive Optical Network
RU	Radio Unit
CU	Central Unit
DU	Distribution Unit
DF	Distribution Fiber
FF	Feeder Fiber
OLT	Optical Line Terminator
ONU	Optical Network Unit
RN	Remote Node
PF	Protected FF
PS	Power Splitter
ILP	Integer Linear Programming
DT	Delaunay Triangulation
FTAP	Fiber Trenching of protected Advanced PON
MC	Macrocell

A Appendix A

The ILP model for the protection of the Advanced PON presented in Section 3.3 was modelled and solved in the commercial software package AMPL/CPLEX

A.1. AMPL model for protected Advanced PON

```
param n;
param m;
set N=0..n;
set L within {i in N, j in N};
set S = {i in N, j in N: (i,j) in L or (j,i) in L};
set W within {s in N, d in N};
set B within {s1 in N, d1 in N};
param l {L};
param D >=0;
var y {L} binary;
var x {S, W} binary;
var z {S, B} binary;

minimize totalcost: 9000*sum{(i,j) in L} (l[i,j] * y[i,j]) +4*sum{(s,d) in W}(sum{(i,j) in L}(x[i,j,s,d]*l[i,j])) +
0.01 *sum{(s,d) in W}(sum{(i,j) in L}(x[i,j,s,d]*l[i,j])) ;

s.t. flow1 {(s,d) in W, i in N: i=s}: sum{(i,j) in S} x[i,j,s,d] - sum{(j,i) in S} x[j,i,s,d] = 1;
s.t. flow2 {(s,d) in W, i in N: i=d}: sum{(i,j) in S} x[i,j,s,d] - sum{(j,i) in S} x[j,i,s,d] = -1;
```

```
s.t. flow3 {(s,d) in W, i in N: i<>s and i<>d}: sum{(i,j) in S} x[i,j,s,d] - sum{(j,i) in S} x[j,i,s,d] = 0;

s.t. flow4 {(s1,d1) in B, i in N: i=s1}: sum{(i,j) in S} z[i,j,s1,d1] - sum{(j,i) in S} z[j,i,s1,d1] = 1;

s.t. flow5 {(s1,d1) in B, i in N: i=d1}: sum{(i,j) in S} z[i,j,s1,d1] - sum{(j,i) in S} z[j,i,s1,d1] = -1;

s.t. flow6 {(s1,d1) in B, i in N: i<>s1 and i<>d1}: sum{(i,j) in S} z[i,j,s1,d1] - sum{(j,i) in S} z[j,i,s1,d1] = 0;

s.t. link_usage {(i,j) in L, (s,d) in W}: x [i,j,s,d] <= y[i,j];

s.t. link_usage1 {(i,j) in L, (s,d) in W}: x [j,i,s,d] <= y[i,j];

s.t. link_usage_backup {(i,j) in L, (s1,d1) in B}: x [i,j,0,d1]  + z[i,j,s1,d1] + x [j,i,0,d1] + z[j,i,s1,d1] <= y[i,j];

s.t. link_usage_backup2 {(i,j) in L, (s1, d1) in B}: x [i,j,0,s1] + x [i,j,0,d1] + z[i,j,s1,d1] + x [j,i,0,s1] + x
[j,i,0,d1] + z[j,i,s1,d1] <= y[i,j];

s.t. link_usage_backup4 {(i,j) in L, (s1, d1) in B}: x [i,j,0,s1] + x [i,j,0,d1] + z[i,j,s1,d1] + x [j,i,0,s1] + x
[j,i,0,d1] + z[j,i,s1,d1] <= y[i,j];

s.t. distance1 {(s,d) in W}: sum{(i,j) in L} x[i,j,s,d] * l[i,j] <= D;

s.t. distance2 {(s1,d1) in B}: sum{(i,j) in L} z[i,j,s1,d1] * l[i,j] <= D;
```

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