Comparing Tree and Chain Topologies for Designing Resilient Backhaul Access Network

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***Abstract*—Long-reach passive optical networks (LR-PONs) have been proposed as an economically viable solution for FTTH network architectures. The longer reach allows it to bypass local-exchange (LE) sites. This results in the elimination of the processing of electronic traffic at the metro nodes and the need for a dedicated metro network. Consequently the functionalities of metro and core nodes are merged into metro-core (MC) nodes. An MC node is connected to tens of thousands of end-users via local exchange (LE) sites. Thus any cable cuts or MC node failures can affect tens of thousands of customers. Therefore, each LR-PON is connected to two MC nodes. In this paper we compare two topologies, tree and chain, to interconnect MC nodes and LEs. The tree topology uses cable splicing and allows cable sharing to reduce the cost. In the chain topology a set of exchange-sites are part of a chain whose end-points are two MC nodes. We study these topologies by modelling each one of them as a combinatorial optimisation problem, and present our findings by analysing national networks for the UK and Italy.**

I. Introduction

Continuous growth in the amount of the data transfer within national and global networks over recent decades demands new infrastructures and data transfer technologies. In line with this, the goal of the DISCUS project [1] was to develop an end-to-end design for a network that can provide a high-speed broadband capability of at least three orders-of-magnitude greater than today's network to all users, while being ultra energy efficient and environmentally sustainable, and remain economically viable. Typically, the network of a country has three layers: *access*, *metro*, and *core*. A signal originating at an end-user (or source) traverses through the access layer, then the metro layer and finally the core layer before descending back to the target in the exact reverse order. Using the DISCUS architecture a Long Reach Passive Optical Network [2] is deployed in the access part, the metro part is eliminated and a Transparent Optical Core Network is deployed in the core part [1].

LR-PON provides an economically viable solution for fibre-to-the-home network architectures. In LR-PON the optical reach ranges from 100 to 125 kms. The longer reach allows it to bypass LEs, which eliminates electronic traffic processing in the metro nodes and the need for a dedicated metro network. Consequently, the functionalities of metro and core nodes are merged into MC nodes. The longer reach also reduces the number of active network nodes by as much as two orders-of-4magnitude, while all electronic data processing can be removed from the local exchanges, thereby reducing both cost and energy consumption. Increasing the number of customers per PON from 32 to about 500 increases equipment and fibre sharing thus further reducing cost and making LR-PON an economically viable solution with low Capital Expenditure (CapEx) and short time to positive cash flow.

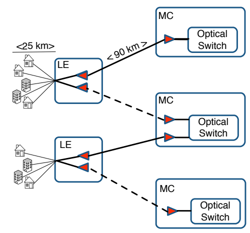


Fig. 1. Backhaul network with dual-homing protection

In the architecture each MC is connected to tens of thousands of customers via tens of hundreds of LEs. A fault in the long distance part of a LR-PON or Optical Line Terminal can therefore affect 500 customers, while a cable cut or a complete failure of an MC node can affect tens of thousands of customers. Therefore protection against equipment failure, MC node failure and cable/fibre cuts is of primary importance for LR-PON-based access networks. Protection can significantly increase network overall cost. The aim of this work is to investigate the impact of tree and chain topologies on the overall cost when designing a resilient backhaul access network.

A basic and effective protection mechanism for LR-PON is to use dual-homing [3]. Figure 1 shows an example where all PONs in an LE are dual parented. The red triangles are the amplifiers and the maximum distance allowed from the MC node to the customers is up to 115 km. In this work we have considered protection links up to the first PON split (which is assumed to be placed in today's LEs), leaving the "last-mile" unprotected. This is a common choice for residential customers, while protection can be extended to the user's premises for business customers. To minimise cost, the protection and primary transmission paths and terminal equipment need to be shared over as many customers as possible. Simply connecting an LE site to two MC nodes is not sufficient to guarantee the connectivity because if a link or a node is common in the routes of fibre going from the LE to its two MC nodes then both MC nodes would be disconnected if that link or node fails. Therefore, the paths from an LE that connects them to their MC nodes must be node-disjoint so that in the case of a fibre cut, amplifier failure, or other equipment failure, an alternative path is available.

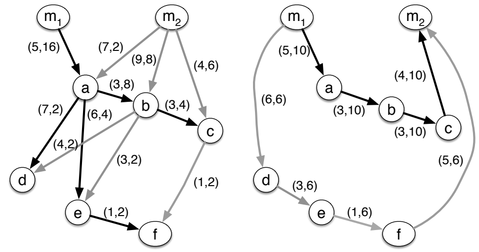
In this paper we focus on designing the cable fibre network between a set of MC nodes to their sets of LE sites such that there are two bounded node disjoint paths from each LE site to its two MC nodes. In particular, we explore the use of two different topologies, namely tree and chain, to provide a backhaul resilient network to the customers. Figure 2 shows an example of the two alternatives; in this example we observe two MC nodes $\{m_1, m_2\}$, and six LE sites. Let us assume that the each LE site in the set $\{a, d, e, f\}$ is associated with one PON, and each LE site in the set $\{b, c\}$ is associated with two PONs. For each PON we need four fibres to connect their two MC nodes, i.e., two fibres per PON per MC since we need one fibre for the upstream communication and another one for the downstream communication.

In the tree topology fibres are distributed from MC nodes to LE sites through cables consisting of fibres that form a tree distribution network. The tree distribution network must be resilient to edge and node failures, that is, the solution allows switching to an alternative path whenever an edge or node in the distribution network fails. Figure 2(a) shows an example. Black arrows show the cable distribution network for MC node m_1 and grey arrows for MC node m_2. The weights associated to edges indicate the length of the link (left) and the minimum number of fibres required (right). For instance, $\langle e, f\rangle$ requires 2 fibres as f has one PON and the distance between e and f is 1 km. The link $\langle a, b\rangle$ requires eight fibres: four fibres for LE b (with two PONs) and four fibres for c (with two PONs) and the distance between a and b is 3 km.

In the chain topology fibres are distributed from the MC nodes to LE sites through cable chains. In this topology LE sites are connected one after another with no branches in the sequence. The first and last LE sites in the chain are directly connected to the MC nodes. Unlike the tree topology where we need fibres from two different cables for a PON to design a resilient network, in the chain topology we only need one cable for dual-homing protection. Figure 2(b) shows a chain solution for our example. In the example we observe two chains: one highlighted with black arrows and another one with grey arrows. Similar to the tree topology, the weights in the edges indicates the length and the number number of fibres for each link. In this example the tree topology requires 306 km of fibre (using 12 cable links) and the chain topology requires 280 km of fibre (using 8 cable links).

II. Constraint Optimisation Formulation

In this section we present the formal definition of the problems we consider. Let M be the set of MC nodes. Let E be the set of LE sites. Let $N = M \cup E$ be the set all nodes. Let E_i be the set of LE sites associated with the MC $i \in M$. Let $N_i = E_i \cup \{i\}$ be the set of nodes in the tree associated with the MC node i. Let T_i be the tree associated with MC node i. Let $C_{ij} = E_i \cap E_j$ be the set of LE sites that are common to MC nodes $i \in M$, $j \in M$ and $i < j$. Let λ be a constant denoting the upper bound in the distance from the MC node to any LE.



(a) Tree topology (b) Chain topology

Fig. 2. Backhaul network example for two MC nodes and 6 LE sites. The weight of the edges indicates the distance in kms of the link (left) and the total fibres required for the link (right).

A. Tree Topology

In the tree topology each LE has two incoming edges and might have zero or more outgoing edges. Let x^i_{jk} be a Boolean variable that denotes whether a link between node $j \in E_i$ and $k \in E_i$ is selected or not. Let y^i_{jk} be a Boolean variable that denotes whether LE j is used by LE k to reach to the MC node i. Each edge $\langle i, j\rangle$ has an associated cost c_{ij} which is by default the distance between i and j, unless otherwise stated. Let f^i_j be a variable denoting the length of the path from the MC i to its LE site j. Let b^i_j be a variable denoting the maximum length of the path from the LE site j to any of the leaf-nodes in the subtree emanating from LE j. Each LE site has only one incoming edge in the tree associated with a given MC node:

$$\forall_{m_i \in M} \forall_{e_k \in E_i} : \quad \sum_{e_j \in N_i} x^i_{jk} = 1. \tag{1}$$

Each MC is connected to at least one of LE site:

$$\forall_{m_i \in M} : \quad \sum_{e_j \in E_i} x^i_{ij} \geq 1. \tag{2}$$

The total number of edges in any tree T_i is equal to $|E_i|$. This is a redundant constraint but its inclusion can improve the quality of the LP relaxation.

$$\forall_{m_i \in M} : \quad \sum_{e_j \in N_i} \sum_{e_k \in E_i, e_j \neq e_k} x^i_{jk} = |E_i|. \tag{3}$$

If an edge from $e_j \in E_i$ to $e_k \in E_i$ is selected then the length of the path from m_i to e_k is equal to the sum of the lengths from m_i to e_j plus the length between e_j and e_k:

$$\forall_{m_i \in M} \forall_{\{e_j, e_k\} \subseteq N_i} : \quad x^i_{jk} = 1 \Rightarrow f^i_k = f^i_j + d_{jk}. \tag{4}$$

If an edge from $e_j \in E_i$ to $e_k \in E_i$ is selected then the length of the path from e_j to any leaf-node through e_k is greater than or equal to the sum of the lengths from e_k to any of its leaf-node plus the length between e_j and e_k:

$$\forall_{m_i \in M} \forall_{\{e_j, e_k\} \subseteq N_i} : \quad x^i_{jk} = 1 \Rightarrow b^i_j \geq b^i_k + d_{jk}. \tag{5}$$

At any node in the tree the length of the path from an MC node m_i to a node e_j and the length of the path from e_j to the farthest LE should be less than or equal to λ:

$$\forall_{m_i \in M} \forall_{e_j \in N_i} : \quad f^i_j + b^i_j \leq \lambda. \tag{6}$$

If an edge from $e_j \in E_i$ to $e_k \in E_i$ is selected then it means that the LE j is used by LE k to reach to the MC node i:

$$\forall_{m_i \in M} \forall_{\{e_j, e_k\} \subseteq N_i} : \quad x^i_{jk} \Rightarrow y^i_{jk}. \tag{7}$$

If a node j is in the path between the MC node i and k and k is in the path between the MC node i and l then it means j is also in the path between the MC node i and l:

$$\forall_{m_i \in M} \forall_{\{e_j, e_k, e_l\} \subseteq N_i} : \quad y^i_{jk} \wedge y^i_{kl} \Rightarrow y^i_{jl}. \tag{8}$$

If m_k and $m_{k'}$ are the MC nodes of LE k, then any node j can only appear in atmost one path: Therefore, we enforce the following constraint:

$$\forall_{\{m_i, m_{i'}\} \subseteq M} \forall_{\{e_j, e_k\} \subseteq E_i \cap E_{i'}} : y^i_{jk} + y^{i'}_{jk} \leq 1. \tag{9}$$

Objective: The objective is to minimize the total cost:

$$\min \sum_{m_i \in M} \sum_{\{e_j, e_k\} \subseteq E_i} c_{jk} \cdot x^i_{jk}. \tag{10}$$

B. Chain Topology

In the chain topology each LE has one incoming and one outgoing edge, and the first and last LE in the chain are connected to MC nodes. Additionally, for each LE we maintain the distance to primary and secondary MC nodes. Let N be the set of all LE sites and MC nodes. Let E be the set of LE sites.

Let w_{ij} be a Boolean variable denoting whether an edge between LE sites $e_i \in E$ and $e_k \in E$ is selected or not. Each edge $\langle e_i, e_j \rangle$ has an associated cost c_{ij}. Let dp_i (resp. ds_i) be a variable denoting the length from LE e_i to the primary (resp. secondary) MC node.

The end-points of each chain must be MC nodes, and each LE site must be connected to either two other LE sites or one LE site and one MC node. We model the chain as a directed graph. In the context of directed graph each LE must have one incoming and one outgoing edge. Without loss of generality we assume that the index of the starting MC node is less than the index of the ending MC node.

$$\forall_{\langle m_i, m_l \rangle \in M^2 s.t.\ m_i < m_l} \forall_{e_j \in C_{il}} : \quad \sum_{e_k \in C_{ij} \cup \{m_l\}} w_{jk} = 1. \tag{11}$$

$$\forall_{\langle m_i, m_l \rangle \in M^2 s.t.\ m_i < m_l} \forall_{e_k \in C_{il}} : \quad \sum_{n_j \in C_{il} \cup \{m_i\}} w_{jk} = 1. \tag{12}$$

The distance from the primary MC to any LE site and the second MC node to any LE site must be included for computing the length of the chains:

$$\forall_{\langle m_k, m_l \rangle \in M^2 s.t.\ k<l} \forall_{e_j \in C_{kl}} : w_{kj} \Rightarrow dp_j = d_{kj}. \tag{13}$$

$$\forall_{\langle m_k, m_l \rangle \in M^2 s.t.\ k<l} \forall_{e_j \in C_{kl}} : w_{jl} \Rightarrow ds_j = d_{jl}. \tag{14}$$

If there is a directed link from $e_i \in E$ to $e_j \in E$ then the length of the fibre from the primary MC node to e_j must be greater than the sum of length of the fibre from the primary MC node to the LE e_i and the distance between e_i and e_j:

$$\forall_{\langle m_k, m_l \rangle \in M^2 s.t.\ k<l} \forall_{\{e_i, e_j\} \in C_{kl}} : w_{ij} \Rightarrow dp_j = dp_i + d_{ij}. \tag{15}$$

$$\forall_{\langle m_k, m_l \rangle \in M^2 s.t.\ k<l} \forall_{\{e_i, e_j\} \in C_{kl}} : w_{ij} \Rightarrow ds_i = ds_j + d_{ij}. \tag{16}$$

The distance from any LE site to the primary and secondary MC nodes must be less than or equal to λ:

$$\forall_{e_i \in E} : dp_i \leq \lambda. \tag{17}$$

$$\forall_{e_i \in E} : ds_i \leq \lambda. \tag{18}$$

Objective: The objective is to minimise the total cost:

$$\min \sum_{\{n_j, n_k\} \in N} c_{jk} \cdot w_{jk}. \tag{19}$$

Complexities. The tree topology relates to the rooted distance-bounded spanning tree for every MC node whose total cost is minimum, this problem is NP-hard [4]. The chain topology relates to the vehicle routing problem with time windows whose total cost is minimum, this problem is also NP-hard [5].

C. DISCUS Architecture

We use the DISCUS architecture described in Figure 1, the maximum distance allowed from the MC node to the customers is up to 115 km. Typically the maximum distance is divided for the backhaul and the optical distribution networks (ODN); the backhaul allows up to 90 km from the MC node to the LE sites, and the ODN allows up to 25 km from the LE site to the customers.

The quality of the signal deteriorates due to the length of the fibre and the splitting of the fibre to connect a number of customers. Depending on the technology used, there is a threshold on the allowed signal attenuation. Consequently, there is a trade-off between the distance and capacity limits, i.e., as the distance limit (or the length of the fibre) increases, the capacity limit (i.e., the number of clients that can be connected to the fibre) decreases. In this paper we use the relationship between size and the maximum length of the PON as described in [1]: $(512, 10)$, $(256, 20)$, and $(128, 64)$. The first number in each tuple refers to the number of customers, and the second to the maximum length of the fibre from the LE to a customer. Additionally, we use a fill factor of 80%, therefore 20% of the PON is free for new customers.

Certainly, the distance from the LE to the customers varies according to the geography of the area. Customers in dense urban areas are expected to be very close to the LE sites, while rural customers are expected to be located further away. We use three geo-types to label LE sites: rural LE sites have at most 2000 customers; sub-urban LE sites have more than 2000 and less than 8000 customers; and urban LE sites have more than 8000 customers. In particular, we observe that 55% (23%), 23% (49%), and 22% (28%) of the population can be categorised respectively as rural, sub-urban, and urban for the UK (resp. Italy).

In this paper we use the cable costs proposed in the DISCUS project [6]. The cost of the cable varies with the number of fibres as follows: (12, €2430), (24, €2716), (48, €3145), (96, €4145), (144, €5145), (192, €6145), (240, €7145), (276, €7859). The first number in each tuple refers to the number of fibres per cable. The second corresponds to cost per km. We assume that the number of fibres in a cable goes up to 276. In the fibre deployment we use the minimum cable cost required to cover the demand. For instance, if 145 fibres are required we use a 192-fibre cable. If 280 fibres are required we use two cables: one with the maximum number of fibres (i.e., 276) and another with the minimum number (i.e., 12).

The cost of installing fibre cable varies considerably with the current duct occupancy and the amount of free duct space. In [7] the authors indicate that in many European countries the duct availability rate per link is about 70%. However, unoccupied duct space might not be usable due to several factors, e.g., unavailability in the middle of the sector, deployment rules, etc. In this paper we assume that the cost for duct and trenching on a trail is €3300 per km.

III. ITERATED CONSTRAINT-BASED LOCAL SEARCH

In this paper we focus our attention on the iterated constraint-based local search technique to solve the rooted distance bounded spanning tree with disjoint paths [8] and [9]. This technique has proven to be a robust alternative for networks with up to thousands of nodes and outperforms CPLEX implementing the MIP model described in Section II.

The local search algorithm comes in two modes. The intensification mode improves the current incumbent solution until a local minimum is reached. In the diversification mode the algorithm introduces noise in the current solution by performing random moves to escape from the local minima. We refer the reader to [9] for a complete description of the algorithm.

A. Tree Topology

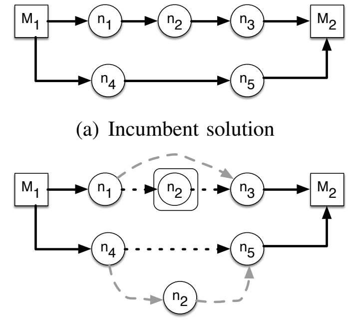
In [9] the authors introduce the subtree operator to drive the search towards near-optimal solutions. The operator uses the following 4-step procedure in the intensification phase:

1) Randomly select a node e_i from a facility m_i from the current solution;
2) Delete the emanating subtree from e_i in m_i;
3) Identify the best location for e_i, i.e., a new predecessor e_{p_i} and a potential successor $e_{n_{s_i}}$ for e_i in m_i satisfying all constraints;
4) Insert e_i as a new successor of e_{p_i}, and if needed, add $e_{n_{s_i}}$ as a successor of e_i.

In the diversification phase the operator selects a random location in the third step to escape from the local minima.

B. Chain Topology

Inspired by the success of LS for the tree-based topology, we use a LS approach to tackle the chain-based topology. Figure 3 shows an example of a move for the chain model. We assume that Figure 3(a) represents the current solution with two chains. The direction of the chain indicates the primary and secondary MC nodes. The first chain contains nodes n_1, n_2, and n_3, and the second one contains LE sites n_4 and n_5. Figure 3(b) shows the output of the move operator. We remove n_2 from the current solution, and reinsert it between LEs n_4 and n_5. Black dashed arrows show the removed links and grey dashed arrows show the new links in the solution after completing the move.



(a) Incumbent solution

(b) Move

Fig. 3. LS for the chain-based topology

For the chain topology we use the same local search framework as for the tree topology. In the intensification the algorithm starts by randomly selecting an LE site e_i from the current solution. Then we delete e_i from the solution and insert it in the best location for it in an alternative chain c'. In c', e_i will be associated with a new predecessor e_p and a new successor e_s in c'. In the diversification phase we select a random location for the selected node.

To design an effective and efficient algorithm we equipped the move-operator with data structures to incrementally update and evaluate the objective function. In a nutshell for each chain we maintain the distance to the furthest customer for the primary and secondary MC nodes. With this information we check whether inserting an LE site in a given location satisfies the length constraint in constant time or not.

Delete: deleting a node e_i from chain c_j requires constant time. Let e_{p_i} and e_{s_i} be the predecessor and successor nodes for e_i. Deleting a node involves removing the links $\langle e_{p_i}, e_i \rangle$ and $\langle e_i, e_{s_i} \rangle$, and adding the link $\langle e_{p_i}, e_{s_i} \rangle$. The objective function is updated as follows:

$$obj = obj + c_{p_i s_i} - (c_{p_i i} + c_{i s_i}).$$

If the problem instance is not satisfying the triangle inequality, it is necessary to check whether adding the link $\langle e_{p_i}, e_{s_i} \rangle$ leads to a feasible solution.

Feasiblity: checking whether a node e_i can be inserted between nodes e_p and e_q in chain c_k involves checking whether the new distance to the primary and secondary MC nodes (i.e., first and last nodes in the chain) is below or equal to λ:

$$dp_k + d_{pi} + d_{iq} - d_{pq} \leq \lambda. \quad (20)$$

$$ds_k + d_{pi} + d_{iq} - d_{pq} \leq \lambda. \quad (21)$$

We recall that the distance constraint goes from the primary (resp. secondary) MC node to the last (resp. first) LE site in the chain. Therefore, if e_p (resp. e_q) is an MC node we assume d_{pi} = 0 in eq. 20 (resp. $d_{iq} = 0$ in eq. 21).

Best location: selecting the best location requires linear complexity in the number of nodes. This operation traverses all chains and computing the cost of adding the node as successor of all nodes in the chain (excluding the last node in the chain). *Insert*: inserting a node e_i in a selected location, i.e., as a successor of a node e_p and as a predecessor of a node e_q, requires constant time complexity as it only involves to update the total distance from the primary (resp. secondary) MC node to the last (resp. first) LE site in the chain as follows:

$$dp_k = dp_k + d_{pi} + d_{iq} - d_{pq}. \qquad (22)$$

$$ds_k = ds_k + d_{pi} + d_{iq} - d_{pq}. \qquad (23)$$

Similar to checking feasibility, if e_p (resp. e_q) is an MC node we assume d_{pi} = 0 in eq. 22 (resp. $d_{iq} = 0$ in eq. 23). Additionally, we update the cost in the objective as follows:

$$obj = obj + c_{pi} + c_{iq}.$$

IV. Experiments

All of our experiments were performed on a 39-node cluster, each node features 2 Intel Xeon E5430 processors at 2.66Ghz and 12 GB of RAM memory. For each instance we use the local search algorithm with a 1-hour time limit. We would like to remark that we evaluated the MIP model described in Section II, but the complete solver does not scale up to more than a few tens of LE sites.[1] In all our experiment we use λ=90, and we use the Euclidean distance with a road factor=1.4 to compute the distance between a pair of nodes.

We experimentally evaluate the tree and chain topologies using our local search algorithms with real instances from two European countries. We start with Table I with a comparison of local search vs. CPLEX (version 12.5.1) implementing the MIP model described in Section II. The objective in this experiment is minimising the trail distance (i.e., sum of the distance between the edges in the solution).

We use small size instances from the UK with two MCs and n LEs and report the performance of the two approaches (LS and CPLEX), the best known lower bound (LB) for each instance, and the GAP with respect to the LB. As it can be observed, LS is always better than CPLEX, except for the smallest instance where both approaches provide the optimal solution. It is also worth noting that for the biggest instance in this experiment (n=70) LS is very close to the optimal solution with a GAP of 5% whilst CPLEX reports a GAP of 29%. Finally, on average, we observe that LS is better than CPLEX with an average GAP of 18% vs. 23% for CPLEX. We would like to remark that our LS algorithm for the tree topology is also considerably better than CPLEX. We refer the reader to [8] and [9] for a comparison of CPLEX vs. LS for the tree topology.

We now move our attention to Table II. Here we report the nationwide cost of our LS algorithms with a 1-hour time limit to deploy the tree and the chain topologies for real instances for the UK (with 5393 LEs and 75, 80, 85, and 90 MCs), and Italy (with 10709 LEs and 100, 120, 140, and 160 MCs). To compute the actual cost, in euro, of the solutions we take into account the fibre cost and duct availability. Certainly, the

[1] We use the big-M method to translate implications into linear constraints.

TABLE I
Trail distance (km) for LS and CPLEX implementing the chain topology with a 5-minute time limit for small size instances

Size	LS	CPLEX	LB	LS-GAP	CPLEX-GAP
22	**1210.4**	**1210.4**	1210.4	**0.00**	**0.00**
25	**839.9**	841.27	839.9	**0.00**	0.01
26	**1068.8**	1156.8	782.8	**0.27**	0.32
34	**1174.9**	1307.2	985.7	**0.16**	0.25
38	**1635.3**	1706.2	1351.5	**0.17**	0.21
41	**1757.2**	1794.3	1494.8	**0.15**	0.17
45	**2215.9**	2337.3	1924.0	**0.13**	0.18
51	**2202.2**	2311.3	1531.5	**0.30**	0.34
53	**2095.6**	2245.9	1675.0	**0.20**	0.25
61	**1848.1**	2003.8	1348.7	**0.27**	0.33
70	**2095.6**	2807.7	1988.3	**0.05**	0.29

idea is to reuse existing infrastructure as much as possible to reduce the deployment cost of the solutions. We study different parameters for the duct availability (from 50% to 100%) to evaluate the cost of the two solutions. We highlight that [7] suggests that for certain areas in the UK there is a probability of 70%-80% of finding enough duct space in a given link.

Let us start with a scenario where fibre-cable is the only cost of the solution (i.e., 100% duct availability). Here we observe that the tree topology is marginally better than the chain topology. This is because the tree topology tends to allow more sharing in a single cable than the chain topology. For instance, on average for the UK the tree and chain topologies deploy respectively 244 and 144 fibres per km, therefore the tree topology deploys, on average, a 144-fibre cable per km, whilst the tree topology deploys, on average, a 276-fibre cable per km.

The chain topology is better when considering existing infrastructure. We attribute this to the fact that the tree topology needs, on average, about 1.5 cables per LE and the chain only needs about 1.1 cables per LE. Therefore, the tree topology increases the cost as it requires to buy more duct space in the distribution network. In the extreme case with only 50% duct availability we observe that the chain topology is up to 18% (UK) and 17% (Italy) cheaper. Finally, considering the suggested 70% available duct space the chain topology is up to 12% (UK) and 13% (Italy) cheaper than the tree topology.

V. Related work

Over the last few years there has been a growing interest in designing resilient networks. Most current work has been devoted to designing mathematical formulations for the edge and node disjoint protection strategies (see [10] for a recent survey with the complexity of the problems). We recall that an edge-disjoint solution protects links in a network, and therefore allows swapping to an alternative path whenever a link fails. Alternatively, protection can be provided at the node level by having node-disjoint paths between pairs of nodes. Certainly, node-disjointness leads to a stronger protection.

In [11], [12], and [13] the authors propose MIP formulations to tackle edge-disjointness with side constraints such as node-degree and hop-constraints, but without considering the

TABLE II
COST IN MIL. OF € TO DEPLOY THE CHAIN (TOP) AND TREE (BOTTOM) TOPOLOGIES VARYING THE DUCT PROBABILITY

Country	|M|	Duct availability per cable 100%	90%	80%	70%	60%	50%
UK |E|=5393	75	93.6	**94.1**	**94.6**	**95.2**	**95.7**	**96.2**
		88.8	**94.1**	98.3	102.5	106.2	109.3
	80	92.3	**92.8**	**93.3**	**93.9**	**94.3**	**94.8**
		89.8	95.1	99.7	103.2	107.1	110.3
	85	88.7	**89.3**	**89.8**	**90.4**	**90.8**	**91.3**
		87.1	92.2	96.3	100.3	103.5	107.2
	90	**84.9**	**85.4**	**85.9**	**86.5**	**86.9**	**87.4**
		86.2	91.2	95.3	98.9	102.5	105.9
Italy |E|=10708	100	132.8	133.8	**134.7**	**135.7**	**136.5**	**137.4**
		124.3	**131.9**	138.1	144.3	150.4	156.1
	120	120.8	**121.8**	**122.7**	**123.6**	**124.5**	**125.4**
		120.5	127.9	134.3	140.3	145.3	150.1
	140	**115.1**	**116.1**	**117.0**	**118.0**	**118.8**	**119.8**
		116.9	124.1	130.2	135.8	141.9	146.6
	160	**110.5**	**111.5**	**112.5**	**113.4**	**114.3**	**115.2**
		111.5	118.4	124.5	129.7	134.9	139.9

distance constraint. Additionally, [14] shows experimental results for the edge-disjoint solutions with the distance constraint for networks with up to 40 nodes. We recall that we are dealing with a stronger protection mechanism, i.e., node-disjoint paths, and nationwide networks with thousands of nodes. In [15] the authors propose an algorithm for node-disjointness without the distance constraint for networks with up to 255 nodes.

In [12] and [16] the authors propose solutions for edge and node disjointness where only a limited number of links in the network are subject to a failure. The former presents a theoretical analysis of an approximation algorithm for the edge-disjointness scenario, and the latter presents an empirical evaluation of two approximation algorithms for the node-disjointness scenario.

In [17] the authors describe a variable neighborhood search approach for the network design problem with distance constraints. Similarly to our approach the authors performs local moves to improve the current solution. The authors rely on a pre-computed backup route from the root-node to any node in the problem. We recall that the use of the pre-computed routes might no lead to valid edge or node disjoint solutions.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we have presented two topologies, namely tree and chain, to design a resilient backhaul network. We use a local search approach to compute the overall required cable and fibres for both solutions and evaluate the deployment cost in euro varying the probability of finding enough available duct space to deploy cable in the solution. Interestingly, in the scenario where there is fully availability of duct space, the tree topology is marginally better. However, as we decrease the duct availability the chain topology becomes a better alternative. In fact, in the suggested 70% duct availability the chain topology is up to 18% cheaper than the tree topology.

In the future we would like to relax the parenting relationship between LEs and MCs to further improve the cost of the solutions. We also plan to consider additional constraints such as minimum and maximum customers associated with the MCs to analyse more realistic scenarios.

ACKNOWLEDGMENT

This work is supported by the European Union 7th Framework Programme (FP7/2007-2013) under grant agreement no. 318137 (DISCUS), Science Foundation Ireland (SFI) under grant 08/CE/I1423. The Insight Centre for Data Analytics is also supported by SFI under Grant Number SFI/12/RC/2289.

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