N:1 Protection Design for Minimising OLTs in Resilient Dual-Homed Long-Reach Passive Optical Network

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***Abstract*—Long-reach passive optical networks (LR-PONs) prove to be a suitable candidate for future broadband access networks. The longer reach of the feeder fiber in a LR-PON enables to consolidate a large number of end users. The longer reach also eliminates a degree of electronic processing by eliminating the metro network and connecting the local exchanges (or the central offices) directly to a consolidated metro/core (MC) node.**

However, longer reach makes the feeder fiber more vulnerable to failures and therefore for resiliency purposes a dual-homed architecture is proposed. For an usual case of 1+1 protection, the dual-homed secondary MC node would contain duplicate resources that would take over the failure of each individual working OLTs or the entire primary MC node in case of a catastrophe.

In this work we propose an N:1 protection mechanism to reduce backup OLTs in a resilient dual-homed LR-PON deployment. We model the problem as an Integer Linear Program and solve it for Irish and UK network deployments. Our results show that the percentage of backup OLTs can be reduced by 6 times for Ireland and by 4 times for UK compared to 1+1 protection deployment scenario.

***Index Terms*—Dual Homing, Long-Reach PON, N:1 Protection, Optimisation.**

I. Introduction

Bandwidth-intensive services e.g., high-definition television (HDTV), cloud computing, large file transfers, online video gaming, etc. are overloading the capacities of the access networks. Fiber to the premises (FTTP) technologies have effectively supported the increasing bandwidth demands in the access networks. There have been further efforts to support this increasing access capacity at low cost and low energy consumption and long-reach passive optical networks (LR-PONs) have been proposed as a solution [1], [2].

LR-PONs long optical reach (about 100 km) facilitates consolidation in the number of central offices. This provides an effective technology to simplify the PON architecture which also allows a higher split and hence a larger user base (up to a thousand)[3]. Since longer reach is achieved mainly through a longer feeder fiber (see Fig. 1), failures on this part of the network, e.g., due to a fiber cut, become more probable. In addition, the larger number of users served per PON means that a cable cut can affect thousands of customers. Network protection through dual-homing becomes thus essential to guarantee satisfactory network availability. At the same time, methods that can assure lowest cost per user are likely to be adopted. For this reason, as shown in Fig. 1, we consider the case where only the feeder fiber of every PON is protected (i.e., from the metro/core (MC) node up to the first stage splitter). It is only the feeder fiber that is shared among all users in a PON, and is most vulnerable to failures. This protection therefore, represents the best trade-off between network availability and cost [4]. Higher levels of availability can be assured by protecting the fiber up to the user premises but this is expensive and only suitable for a few business users.

The protection costs can further be reduced by employing $N:1$ protection schemes, at the OLT level [5], which allows reserving one standby OLT for every N active OLTs. Figure 1 shows how $N:1$ protection is enabled by the use of an optical switch between the feeder fiber and the OLT at the MC node. The switch can connect any OLT to any feeder fiber in an agile way. In an initial working configuration, the optical switch connects a set of

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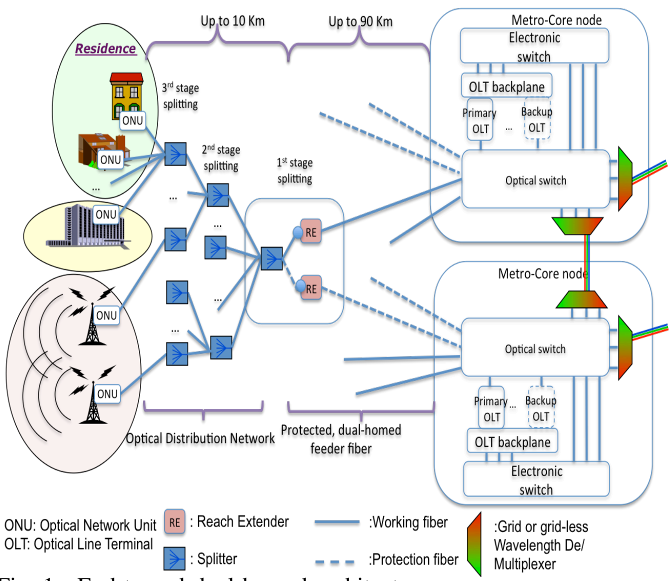

Fig. 1. End-to-end dual-homed architecture.

OLTs to the feeder fibers of the primary PONs. But if and when there is a single or multiple primary OLT failure, the optical switch can connect the corresponding PONs to the available backup OLTs.

This paper mainly models the OLT backup problem for a realistic network deployment, and minimises the number of backup OLTs required in the network to assure satisfactory protection. The worst-case scenario for our assumption is the failure of any one MC node, each covering a geographical area with maximum radius of over 100 km. This could occur for example, if all electronics in a MC node fail simultaneously (e.g., due to catastrophic events such as fire, flooding, earthquakes, etc.).

In addition, we also introduce a new idea where active OLTs might also take part in the protection strategy. This can bring significant advantages by allowing backup OLTs to protect failures occurred in far away MC nodes. Since, all backup OLTs can protect for any node failure, our results show that their overall number is greatly reduced. In this context, it is worth mentioning that this concept of minimising backup capacity for an LR-PON was tested for the IP layer through heuristic algorithms [6] and optimised solutions [7]. Our work models the problem by defining the LR-PON capacity in terms of OLT loads. The results presented in this paper includes some of our preliminary studies presented in [8] for Irish network deployments. This work completes the analyses by including results for a realistic deployment for both Ireland and UK. The entire analysis for UK and some of the supporting results for both Ireland and UK to establish our hypothesis are additional contributions to this extended version.

The rest of the paper is organised as follows. We present the details of our mathematical models in Section II and illustrative numerical results in Section III. Finally, we conclude in Section IV.

II. Problem Description and Formulation

We minimise the number of backup OLTs that provide dual homing of every first-stage splitter, by optimal placement of MC nodes. Dual-homing can reduce the number of backup OLTs, since during complete failure of a MC node (worst case), the number of backup OLTs can be shared among the MC nodes adjacent to the failed node. This is shown in Fig. 2, where we assume that MC-2 suffers a catastrophic failure. We can see that the two adjacent nodes, MC-1 and MC-3 can both protect for the PONs in MC-2 (three in this case). Thus if the sum of the backup OLTs in MC-1 and MC-3 is equal to the number of active OLTs in MC-2, such catastrophic failure can be protected. Note that, if we had employed 1+1 OLT protection, then a larger number of backup OLTs would be required both in MC-1 and MC-3 (since there would be a one-to-one relation between active and backup OLTs).

It should be noticed however that, even if MC-4 has an available backup OLT, this cannot be used, since MC-4 does not protect directly for any PON in the failed MC-2 node. In order to further increase the ability for MC nodes to share their backup OLTs, we have introduced a novel idea, which is represented in Fig. 3. If we allow MC-3 to redirect one of its active OLTs to protect for a PON in MC- 2 without causing noticeable disruption to the end users (which we will discuss in Section III), then MC-4 can use its backup OLT to service that PON (the red arrows indicate the changes). In this way we allow MC-4 to share its OLT for a failure that occurred in MC-2, and as a result we are able to further decrease the number of backup OLTs available in the system.

This is a ripple effect of "spreading" the load from one MC node to other and this concept can be extended across the entire network. For a large geographical area with multiple overlapping MC nodes (as shown in Fig. 4), this concept of offloading the OLTs can be spread across the entire network diameter over multiple hops and as we keep spreading the load of the failed MC node further away to its one-hop neighbours, two-hop

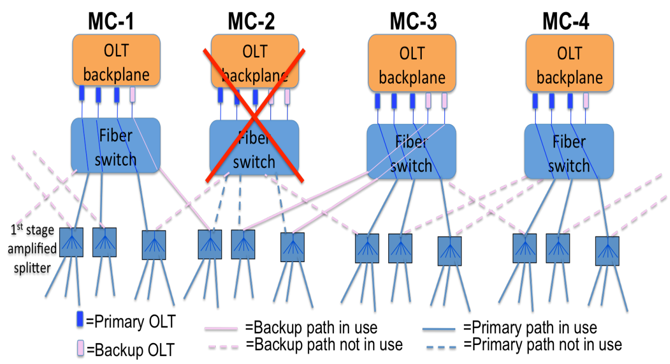

Fig. 2. Example of MC node sharing for feeder fibre protection.

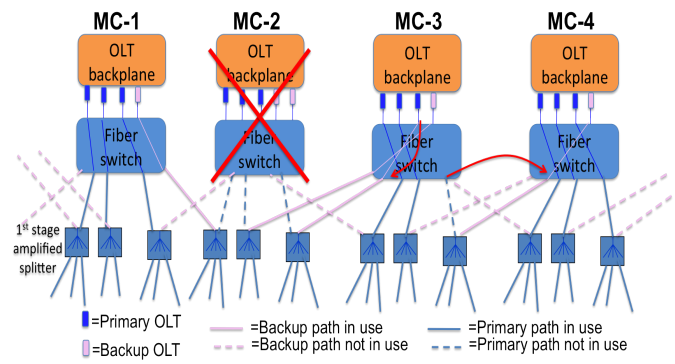

Fig. 3. Example showing our OLT offloading strategy.

neighbours, three-hop neighbours, and so on, we get to reduce the total number of backup OLTs in all MC nodes, for a single MC-node failure. Therefore, for a static design problem, given the locations of all the MC nodes, and the number of primary OLTs they require to connect their respective PONs, we can find out using an appropriate formulation, what will be the minimum number of backup OLTs at each MC node that can handle all possible single MC node failures.

We formulate the above problem into a two-step mixed integer linear program (MILP). In the first step, we solve the MC-node-placement problem *to minimise the overall fiber distances* from each MC node to its respective primary and backup exchange sites. The constraints imposed here are: (1) each exchange site should be connected to *two unique* MC nodes, one primary and one backup, and (2) the distance of a MC node from its primary or secondary 1st stage splitter sites (which correspond to local exchanges in our Irish network dataset) should be within a 100 km radius i.e., the maximum distance for the feeder fiber. The variables and constants for the MC-node-placement model are given below:

- $\mathbf{E}$: set of exchange sites.
- $\mathbf{D} = \left[d_{ij}\right]$: Euclidean distance matrix, where each element d_{ij} is the Euclidean distance between the nodes i and j.
- $\mathbf{M}$: Maximum number of MC nodes.
- $\mathbf{D_{max}}$: Maximum distance of an MC node from its corresponding exchange site.
- $\mathbf{M_i}$: binary variable which takes value 1 if there is a MC node at the i^{th} exchange site location.
- $\mathbf{P_{ie}}$: binary variable that takes value 1 if MC node at site i is primary to exchange site e.
- $\mathbf{S_{ie}}$: binary variable that takes value 1 if MC node at site i is secondary to exchange site e.

The objective function for MC-node-placement is given by:

$$\mathbf{Minimize} : \sum_{\mathbf{i}} \sum_{\mathbf{e}} (\mathbf{d_{ie} P_{ie} + d_{ie} S_{ie}}) \qquad (1)$$

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The constraints are given by:

$$\mathbf{P_{ie} + S_{ie} \leq 1} \quad \underline{\mathbf{\forall i, e \in E}} \qquad (2)$$

$$\sum_{\mathbf{i}} \mathbf{P_{ie} = 1} \quad \underline{\mathbf{\forall e \in E}} \qquad (3)$$

$$\sum_{\mathbf{i}} \mathbf{S_{ie} = 1} \quad \underline{\mathbf{\forall e \in E}} \qquad (4)$$

$$|\mathbf{E}| \cdot \mathbf{M_i} \geq \sum_{\mathbf{e}} (\mathbf{P_{ie} + S_{ie}}) \quad \underline{\mathbf{\forall i, e \in E}} \qquad (5)$$

$$\mathbf{M} \geq \sum_{\mathbf{i}} \mathbf{M_i} \quad \underline{\mathbf{\forall i \in E}} \qquad (6)$$

$$\sum_{\mathbf{i}} \sum_{\mathbf{e}} (\mathbf{d_{ie} P_{ie} + d_{ie} S_{ie}}) \leq \mathbf{D_{max}} \cdot \mathbf{M} \cdot |\mathbf{E}| \qquad (7)$$

Equation (2) ensures that the the primary and secondary MC nodes of an exchange site e are different. Equations (3) and (4) enforces that a local exchange is served by an unique primary and an unique secondary MC node. Equation (5) ensures if there is at least one primary line OR a secondary line from a node i, there exists a MC node at i. Here, $|\mathbf{E}|$ refers to the cardinality of the set $\mathbf{E}$. So, if at least one of the $\mathbf{P_{ie}}$-s or $\mathbf{S_{ie}}$-s take value '1', it sets the binary variable $\mathbf{M_i}$ to take value '1'. Equation (6) upper bounds the total number of MC nodes and Eqn. (7) constrains that all local exchanges served by an MC node fall within the maximum allowable distance.

The above model is solvable in reasonable time for small geo-types like Ireland but for larger geo-types like UK where the number of local exchanges are more than five thousand, the problem becomes intractable. Therefore, to solve the MC- node-placement problem for large instances we have used methods of partitioning the problem and solving it as described in [9].

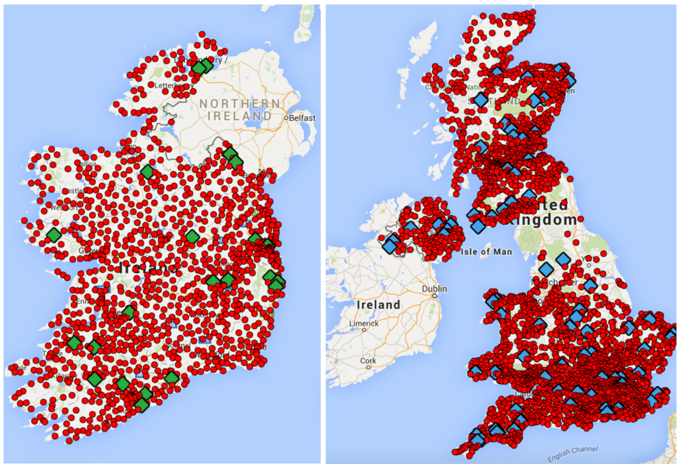

Fig. 4. Example location of local exchange sites for Ireland and UK and their corresponding coverage with 22 MC nodes and 73 MC nodes respectively.

Once we get the location of the MC nodes from the placement model (see example placement for Ireland and UK in Fig. 4, where local exchanges are marked in red dots and MC nodes are marked in green and blue diamonds respectively for Ireland and UK), we optimise the number of backup OLTs by load spreading as formulated below.

Note that, at this stage, i.e., after solving the first-stage dual-coverage placement problem we have the number of primary OLTs at each MC node. If we had gone for a simple 1+1 protection scheme, the number of backup OLTs would be exactly equal to the number of primary OLTs. But as explained before using Figs. 2 and 3, on the occasion of a complete MC node failure if we allow offloading of the load of the failed MC node other neighbouring MC nodes we end up with less backup resources on the average.

The various variables and parameters for the load spreading model are:

- $\mathbf{P_{ie}}$: Parameter, equals '1' if MC node i is primary to exchange site e.
- $\mathbf{S_{je}}$: Parameter, equals '1' if MC node j is secondary to exchange site e.
- $\mathbf{V}$: Set of optimal MC nodes' location.
- $\mathbf{L}$: Set of edges connecting two adjacent MC nodes.
- $\mathbf{h}$: Maximum hop distance from the failed node.
- $\mathbf{l_e}$: Number of users served by exchange site e as obtained from a real dataset.
- $\mathbf{SP_{ik}}$: Shortest path (expressed in number of hops) between any MC nodes i and k.
- $\mathbf{Q_i} = \sum_{\mathbf{P_{ie}=1}} \lceil \mathbf{l_e/512} \rceil$: Initial active OLTs at MC node i assuming each OLT serves 512 users.
- $\mathbf{U_{ij}} = \sum_{\mathbf{P_{ie}=1} \wedge \mathbf{S_{je}=1}} \lceil \mathbf{l_e/512} \rceil$: Maximum OLTs that node i can pass to neighbour node j.
- $\mathbf{T_{ijk}}$: OLTs passed from node i to j when node k fails.
- $\mathbf{F_{ik}}$: Final number of OLTs at i that includes the over-provision capacity that is required when k fails.
- $\mathbf{I_{ik}}$: Sum of incoming OLTs that i receives from its neighbours when k fails.
- $\mathbf{O_{ik}}$: Sum of outgoing OLTs that i passes to its neighbours when k fails.
- $\mathbf{L_p^i}$: Number of primary OLTs at MC node i.
- $\mathbf{L_o^i}$: Number of protection OLTs at MC node i.

The objective function is given by:

$$\mathbf{Minimize:} \quad \alpha \sum_{\mathbf{i}} \mathbf{L_o^i} + \sum_{\forall \mathbf{i,j,k} \in \mathbf{V}} \mathbf{T_{ijk}} \tag{8}$$

where α is a constant chosen such that $\alpha \geq \sum_{\forall \mathbf{i,j,k} \in \mathbf{V}} \mathbf{T_{ijk}}$. Note that, the role of the factor α is to weight appropriately the two objectives that we have in our minimisation problem. Our most important objective is to minimise the number of protection OLTs in an MC node and then our relatively less important objective is to also minimise the number of working OLTs disrupted in the form of $\mathbf{T_{ijk}}$ while we try to spread the load. These two objectives are mutually conflicting as more and more disruptions can help in more spreading of the load and thereby minimising the number of protection OLTs more. By choosing $\alpha \geq \sum_{\forall \mathbf{i,j,k} \in \mathbf{V}} \mathbf{T_{ijk}}$ we address this tradeoff between the minimum number of protection OLTs and the minimum amount of working OLT disruption in an efficient way.

The constraints for the load spreading model are as follows:

$$\mathbf{I_{ik}} = \sum_{\langle \mathbf{j,i} \rangle \in \mathbf{L}} \mathbf{T_{ijk}} \quad \underline{\forall \mathbf{i}, \mathbf{k} \in \mathbf{V}} \tag{9}$$

$$\mathbf{O_{ik}} = \sum_{\langle \mathbf{i,j} \rangle \in \mathbf{L}} \mathbf{T_{ijk}} \quad \underline{\forall \mathbf{i}, \mathbf{k} \in \mathbf{V}} \tag{10}$$

$$\mathbf{I_{kk}} = \mathbf{0} \tag{11}$$

$$\mathbf{O_{kk}} = \mathbf{Q_k} \tag{12}$$

$$\mathbf{F_{ik}} = \mathbf{Q_i} + \mathbf{I_{ik}} - \mathbf{O_{ik}} \quad \underline{\forall \mathbf{i}, \mathbf{k} \in \mathbf{V}} \tag{13}$$

$$\mathbf{SP_{ik}} > \mathbf{h}, \mathbf{I_{ik}} = \mathbf{0} \quad \underline{\forall \mathbf{i}, \mathbf{k} \in \mathbf{V}} \tag{14}$$

$$\mathbf{U_{ij}} \geq \mathbf{T_{ijk}} \quad \underline{\forall \mathbf{i}, \mathbf{j}, \mathbf{k} \in \mathbf{V}} \tag{15}$$

$$\mathbf{L_p^i} \geq \mathbf{Q_i} \quad \underline{\forall \mathbf{i} \in \mathbf{V}} \tag{16}$$

$$\mathbf{F_{ik}} \leq (\mathbf{L_p^i} + \mathbf{L_o^i}) \quad \underline{\forall \mathbf{i}, \mathbf{k} \in \mathbf{V}} \tag{17}$$

Equation (9), ensures that the incoming OLT load at MC node i, when MC node k fails, equals the sum of the load of OLTs passed from each node j. Similarly, for outgoing OLT load, Eqn. (10) must be satisfied. Note that, the load from node i to node j is thus passed along the edge $< i, j >$ which is not a real edge but rather a conceptual edge which exists if node i is within 100 km radius of node j. Similarly, the load from node j to node i will be passed along the edge $< j, i >$. Equation (11) enforces that no OLT load is incoming to the failed MC node, rather the failed MC node should pass all its initial load to other nodes as enforced by Eqn. (12). Equation (13) ensures that if MC node k fails, the final number of OLTs at MC node i is the sum of its initial OLTs and the required over-provisioning capacity. Equation (14) limits the OLT sharing to nodes that are maximum h hops away from the failed node k. Equation (15) upper bounds the number OLTs whose load can be transferred from a node i to another node j. In Eqn. (16), total number of primary OLTs at node i upper bounds the total number of primary lines from i and finally in Eqn. (17), it is enforced that the final number of OLTs at node i due to failure of node k cannot exceed the total resources at node i.

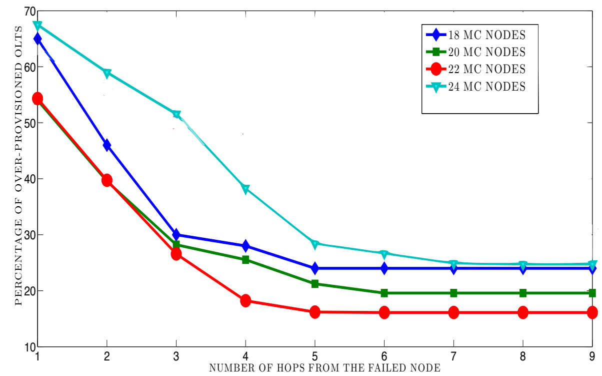

Fig. 5. Percentage of backup OLTs as a function of hop count for Ireland.

III. Results and Discussion

The results for Ireland are presented with 1204 locations for first stage amplified splitters (taken from a real dataset). For UK the number of local exchanges is 5449. The total number of lines served in the Ireland case is 1,840,479 and for UK the number of lines is 29,373,914. The overall PON split ratio is 512 and the different numbers of MC nodes that we use as an input to the placement problem are 18, 20, 22, and 24 for Ireland and 53, 73, and 106 for UK. These numbers of MC nodes have come up from different scenarios that we have finalised by discussing with our industrial colleagues. The number of metro/core nodes represent extreme but sensible cases that are worth investigating. For example, in case of UK, 53 is the minimum number of MC nodes that would cover the 5449 local exchanges in the entire country with dual homing and similarly for Ireland the corresponding number is 18. Basically, the number of MC nodes are also decided by two factors viz., different maximum distances of the local exchanges from their corresponding MC node (between 100 km to 115 km) and the number of users served per MC node. Furthermore, as UK is geographically larger than Ireland, the number of MC nodes are also relatively large compared to the numbers that are used as input for Ireland.

Figure 5 reports the results of our MILP model for Ireland, showing the reduction in the overall number of OLTs, compared to a 1+1 case, where each active OLT is directly protected by one backup OLT (representing 100% OLT over-provisioning). The x-axis represents the number of hops away from the failed node. A value of one denotes MC nodes directly protecting the failed nodes, so that no active

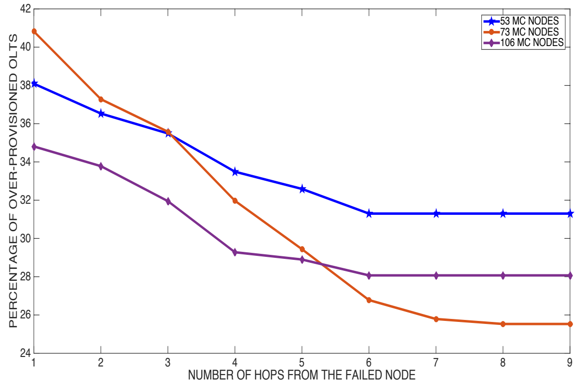

Fig. 6. Percentage of backup OLTs as a function of hop count for UK.

OLT is re-directed, as in Fig. 2. A value of two means that the operation can be extended up to two nodes away from the failure, and implies the redirection of active OLTs, as seen in Fig. 3, and so on. The percentage of over-provisioned OLTs is calculated by taking the average of the over-provisioned capacity over all nodes having non-zero over-provisioning for all possible single MC-node failures. The different curves show results for a different number of MC nodes used to cover the country. We have shown curves starting with 18 MC nodes which is the smallest number that can cover the whole country, followed by 20, 22, and 24 MC nodes.

The observations from these plots are as follows. First, our OLT-sharing mechanism can reduce the percentage of backup OLTs down by 84% (i.e., to 16%) of the total active OLTs. Secondly, as the number of hops from the failed node increase, the number of backup OLTs decrease and then saturates after a certain number of hops. Note that, this saturation takes place earlier, i.e., after a few number of hops for lesser number of MC nodes (e.g., 5 hops for 18 MC nodes and 7 hops for 24 MC nodes). In addition, increasing the number of MC nodes above the smallest value of 18, reduces the minimum over-provisioning from 24% to 16% and then it goes up with higher number of MC nodes. This is because the optimum location of MC nodes governs the distribution of primary OLTs per MC node significantly. Therefore, for higher number of MC nodes (20 nodes) than the minimum 18-node case, the minimum over-provisioning is reduced as the OLTs get more spread because of more overlap. But with further increase in MC node number, there is a tendency of higher clustering of MC nodes at some parts of the network than the other to minimise their distance from their splitters. This results in skewed number of spreadable OLTs between overlapping MC nodes. This manifests in higher values for the minimum over-provisioning.

In Fig. 6, we present the results for UK. The trends for UK is also similar to that of Ireland. In this case, we observe that the highest reduction of 74% in over-provisioning (i.e., requiring net provisioning of 26%) occurs in the 73 MC nodes case. The explanation also remains same as in case of Ireland, i.e., the distribution of customers and hence the distribution of spreadable OLTs across one MC node to another remains skewed because of the actual demographies.

To establish this justification, we have plotted the histograms (Figs. 7) for the number of local exchanges for each MC node for the four cases that we have considered for Ireland in Fig. 5. Similarly, the histograms for the UK cases are presented in Fig. 8. We observe that in case of 73 MC nodes for UK and for 22 MC nodes in case of Ireland, the number of local exchanges are more uniformly spread over a compact range of values than in the other cases. This suggests that the density of local exchanges for these two cases are relatively uniform and the concept of load spreading works better. Therefore the 73-MC-node case for UK and the 22-MC-node case for Ireland obtain the lowest over-provisioning in terms of OLTs.

The drawbacks of this method are two. First, it requires an optical fibre switch in order to allow N:1 OLT protection. However, its cost per port is much smaller compared to that of an OLT port. In addition, fibre switches are very reliable, with typical mean time between failures of hundreds of years [10]. Secondly, using active OLT to protect for failures could disrupt services to users in PONs which were not originally affected by a failure, if the switching time is too long. We have however shown in [11], [12] that OLTs can reactivate ONUs after failures in a couple of milliseconds. Although these mechanisms were initially based on 1+1 protection, recent tests on N:1 protection show that switchover can be achieved in less than 50 milliseconds [13].

IV. Conclusion

In this paper we proposed optimisation frameworks to minimise the number of OLTs in a resilient dual-homed LRPON architecture where the

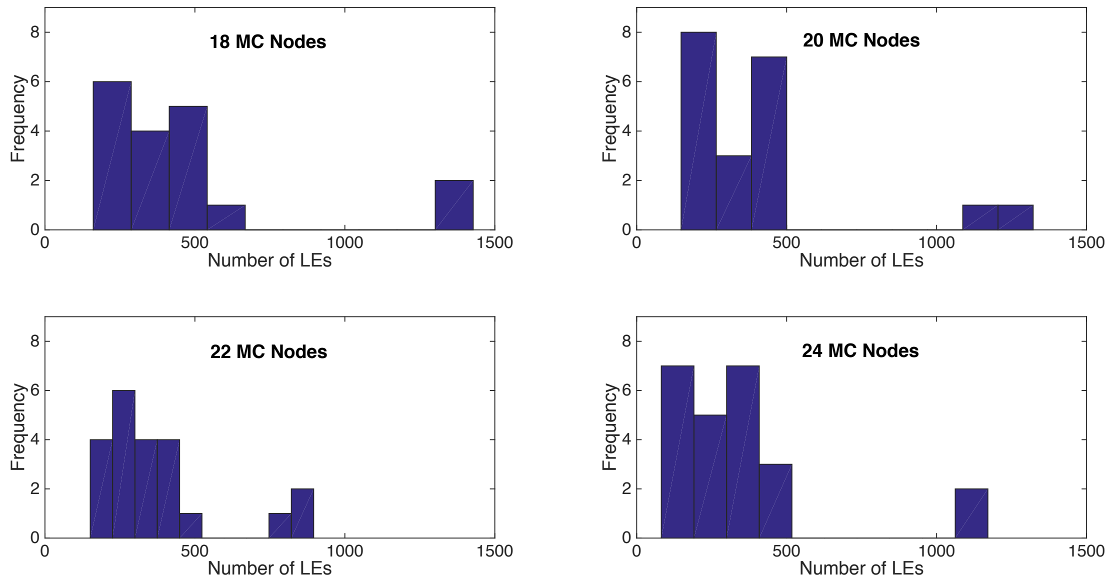

Fig. 7. Histogram of number of local exchanges in each metro/core node for Ireland.

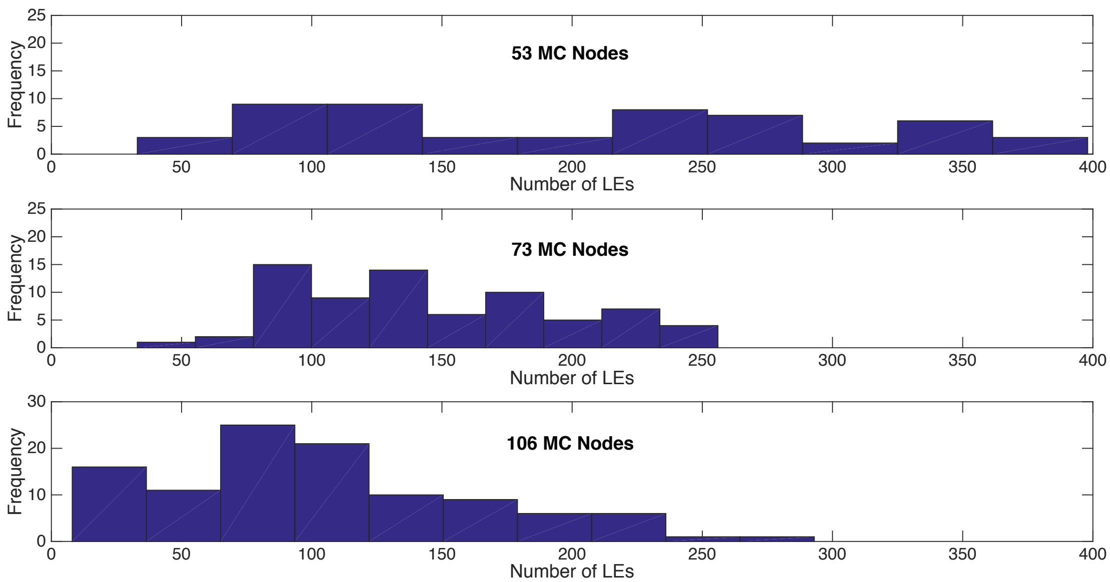

Fig. 8. Histogram of number of local exchanges in each metro/core node for UK.

LRPONs are connected directly to two metro/core (MC) nodes. We proposed an N:1 protection mechanism for OLT protection. Our scheme showed that in case of a complete MC node failure, by effectively spreading the load of active OLTs in an MC node to the backup OLTs of neighbouring MC nodes we can reduce the number of backup OLTs in the network by a significant margin. We could obtain a reduction in the number of backup OLTs of up to 84% (i.e., only 16% over-provisioning vis-a-vis 100% over-provisioning for 1+1 protection) for an Irish network deployment and up to 74% reduction (i.e., only 26% over-provisioning compared to 1+1 protection) for a UK deployment.

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