Exploiting Dual Homing in Access Networks to Improve Resiliency in Core Networks

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***Abstract*—We propose a network architecture consisting of a long-reach passive optical network (LR-PON) based access and a transparent optical core network. The end users are connected to the remote node (RN), or the local exchange (LE), through an optical distribution network and the remote node is connected by disjoint feeder fiber links to the central offices located in two distinct metro/core (MC) nodes. This method of connecting a single remote node to two geographically separate MC nodes for dedicated protection in case of the feeder fiber failure, is referred to as dual homing.**

In this work, we explore the benefits of dual homing in the access to provide simultaneously, better resilience and load balancing in the core network, considering connections between local exchanges. While looking into the benefits of dual homing in terms of network resiliency, we also explore whether the path redundancies added by dual homing play a role in providing efficient distribution of load across the core network and thereby reduce the cost of provisioning capacity in terms of number of lightpaths, transponders etc.

Dual homing at both the source and destination LEs offers more options for paths between LEs through the core network. Our results show that dual-homed access proves to be advantageous over single-homed access in terms of enhancing both core network resiliency, and facilitating better load balancing.

***Index Terms*—Dual Homing, Long-Reach PON, Resiliency, Optimisation.**

I. Introduction

The Internet has become one of the basic amenities of the 21st century. The fast penetration of broadband to virtually every household and the demand for different high-bandwidth services are driving the network service providers to look for cost effective and reliable deployments. Furthermore, as more users get connected to the network with a plethora of heterogeneous services, the network complexity grows. Therefore, planning a network, keep it operational, and upgrade it to accommodate future traffic growth, become challenging for service providers, who need to operate within limited financial resources and power consumption constraints.

To reduce the network complexity and power consumption while accommodating seamless network upgrades, the FP7 DISCUS project envisages an architecture with a transparent or flat (i.e., without an underlaying electronic processing layer) optical core and a long-reach passive optical network (LR-PON) based access [1]. By having an integrated metro/core (MC) node (see Fig.1) that connects the core network directly to the remote nodes (RNs) of the long-reach access, the number of electronic switching stages are reduced. Note that, here the remote node can also be termed as a local exchange (LE) from where the optical distribution network (ODN) spans out. In the rest of the paper we would use the terms remote node and local exchange interchangeably and they both signify the same entity. With this simplified architecture, the end-users can connect to core network resources directly via their respective remote nodes and the network planner can optimize the resources by visualising the network as a single end-to-end entity[1] and the corresponding demands. Thus, the overall network becomes less complex and easy to manage.

As evident from Fig. 2, each LE connects to two MC nodes using *dual-homing*. The MC nodes form the backbone network. Therefore when we consider an end-to-end topology starting from one LE (i.e., RN) to another, both ingress and egress remote nodes will be dually homed. But if we consider primary path from one remote node to another remote node, that path will traverse through the primary MC nodes on both sides. The secondary paths for the same pair of remote nodes can use either the primary-homed MC node or the dual-homed MC node depending on the reliability requirements. In this paper, we address the benefits of dual-homing in the access to provide better resilience and load-balancing, where each connection spans from one local exchange to another through the core network. While looking into the LE-to-LE availabilities we also investigate whether the extra LE-to-LE paths that dual homing would provide, can benefit the network planning by efficiently distributing the load in the network and thereby reducing the cost of provisioning capacity in terms of number of lightpaths, transponders etc.

Wang et al.[2] explored the benefits of dual homing for core network survivability by proposing a coordinated protection scheme for dual-homing based IP-over-WDM networks where users (i.e., enterprises) connect to IP routers of different service providers. The authors consider dual homing at the source side only and attempt to establish working and backup paths to a common destination thereby minimising the protection cost at the core.

Wang et al., analyses the survivability of an IP-over-WDM network with dual-homing at the access. In our approach we intend to do a reliability analysis. The main difference

[1]By "end-to-end entity" we mean to consider the network as an aggregate of the paths from all possible source local exchanges (source-LEs) to destination local exchanges (dest-LEs) through the core network. In the rest of the paper, the term end-to-end is meant to be analogous with the term LE-to-LE and both the terms are used interchangeably.

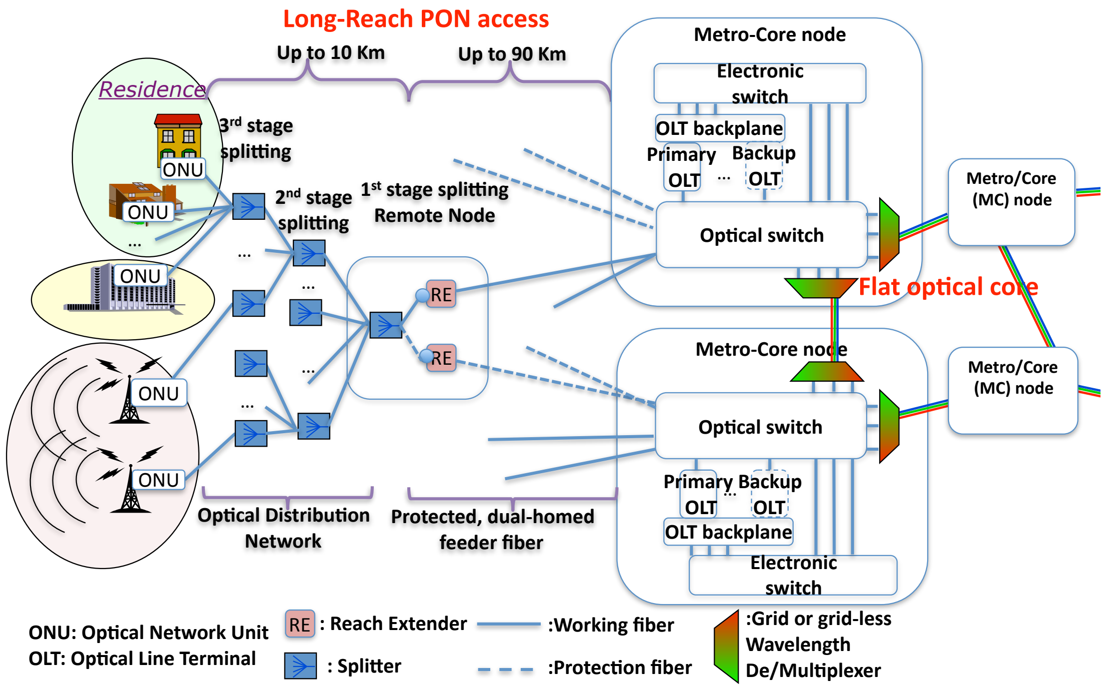

Fig. 1. DISCUS architecture.

between the two approaches is that, while the former assumes that failure in the system will implicitly occur and looks for alternatives to combat that failure. The latter, on the other hand focuses more on the statistical nature of the failures and tries to come up with a model which predicts how often on the average, the system might fail over a specific time window. Furthermore, we include the access links, i.e., the feeder fibres too in our reliability analyses which is not done by Wang et al. in their survivability analyses. So, the story that we intend to tell in our approach is that the presence of dual homing not only (1) enhances the survivability of the end-to-end network starting from the source access node to the destination access node with the core network in between; but also (2) makes the end-to-end network reliable even if the core network is not survivable. This is significantly different from what Wang et al. intends to portray, which is minimising the protection cost in the core network with dual homing in the access.

As Wang et al. does not consider the access network as the part of the network architecture for their analyses, they can envisage the demand model on a per-connection basis, i.e., the optical connections that originate and terminate from and into the core network nodes and hence they could propose a concise one-step mathematical model based on integer programming as well as heuristic. But in our case, demands are sub-wavelength in nature on the access side, and then they need to be aggregated at the metro/core (MC) nodes and efficiently mapped onto wavelengths on the core network side. Therefore, an end-to-end per-connection-based demand model is difficult to envisage in our approach and so we have split the problem into two stages. The first stage finds reliable routes that meet a target availability from one access node to the other via the core network. We also put a check on the used link capacities while we try to find these routes. The second stage then optimally finds a mapping of the sub-wavelength end-to-end demands on core network lightpaths given the routes are determined from the first stage.

While solving our envisaged problem in two stages we had to tailor our models that would find a reasonable solution for practical topologies with real datasets and therefore the problem size was always very large. So, we had to resort to heuristics. But, while doing the entire reliability analyses, we felt that the availability-aware route determination in the first stage is the most important stage and so we came up with a MILP formulation for the first stage to establish a proof-of-concept and the comparisons with the heuristic are shown (Tables I and II) and they are fairly comparable. For the second stage, we have completely relied on a heuristic model, the results of which are intuitively consistent. Our results show dual-homed access proves to be advantageous over single-homed [2] access by effectively utilising the end-to-end path alternatives.

The rest of the paper is organised as follows. In Section II, we present the formal problem statement and describe the methods used to solve it. In Section III we summarise our results and finally in Section IV, we conclude our studies.

II. Mathematical Formulation

The problem that we intend to solve is a multi-layer optimisation problem. The goal is to find a set of end-to-end (i.e., LE-to-LE) paths to satisfy a certain given target availability and also to minimise the network resources while providing

[2]By single-homed access, we mean that the local exchange is connected to a single metro/core node but the feeder fiber is assumed to be protected by another duplicated fiber of the same length vis-a-vis a dual homed access where the resource redundancy is provided by the feeder fiber that connects the dual home.

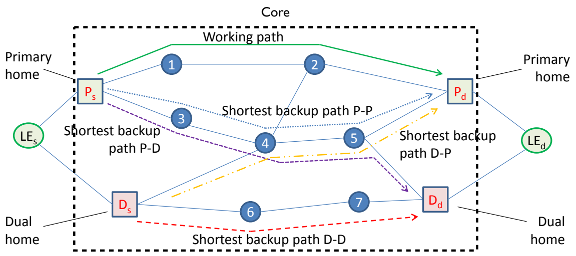

Fig. 2. Dual homing providing additional protection paths.

a certain degree of resilience. The principal inputs to this problem are the LE-to-LE topology with both the access and the core links as illustrated in Fig. 2, the LE-to-LE traffic flows (assumed to be known a priori), and the target availabilities. Once the routes meeting the target availabilities for each flow has been found, the routed flows are then mapped into the optical core network, i.e., lightpaths from MC nodes.

We split the problem into two steps for the sake of tractability. In the first step, we solve the LE-to-LE reliable route determination problem. For that, we use a modified version of the basic link-flow model described in [3]. From the first-step results, we obtain a set of reliable routes for each LE-to-LE connection together with a distribution of flows through the core network links. We utilise these results as input to the second step, which obtains a minimum-cost (in terms of number of wavelengths and lightpaths) logical topology design result. In the second step our focus is to design a transparent optical core network without any grooming or optical-to-electrical-to-optical (OEO) conversions at intermediate MC nodes. However, the transparency constraint can be relaxed to study variations of the current problem.

The variables and notations for the first-step mixed integer linear program (MILP) is described below:

- $\mathbf{b_e^n}$: Equals '1' if link e connects node (local exchange) n to its primary home.
- $\delta_{\mathbf{e,n}}$: Equals '1' if node n is an edge node of link e
- $\mathbf{x_{1,e}^{s,d}}$: Equals '1' if the working path $s-d$ uses link e
- $\mathbf{y_{1,n}^{s,d}}$: Equals '1' if working path of $s-d$ passes node n.
- $\mathbf{w_{e_1,e_2}^{s,d}}$: Equals '1' if the working path $s-d$ uses link e_1, while the backup path $s-d$ uses link e_2.
- $\mathbf{u^{s,d}}$,$\mathbf{u_e}$: The maximum allowed unavailability between source s and destination d and on link e respectively.
- $\mathbf{C}$: Total capacity in each link.
- $\mathbf{T^{s,d}}$: Traffic demand between local exchange s to local exchange d.
- $\mathbf{x_{2,e}^{s,d}}$: Equals '1' if the backup path $s-d$ uses link e.
- $\mathbf{y_{2,n}^{s,d}}$: Equals '1' if the backup path $s-d$ passes node n

The objective function is given by:

$$\mathbf{Minimize:} \sum_{\mathbf{s,d}} \sum_{\mathbf{e \in E}} \mathbf{x_{1,e}^{s,d} + x_{2,e}^{s,d}} \tag{1}$$

The constraints are given by:

$$\sum_{\mathbf{e \in E : \delta_{e,n}=1}} \mathbf{x_{1,e}^{s,d}} = \begin{cases} 1 & \text{if } n = s \text{ or } n = d \\ 2y_{1,n}^{s,d} & \text{otherwise} \end{cases} \tag{2}$$

$$\sum_{\mathbf{e \in E : \delta_{e,n}=1}} \mathbf{x_{2,e}^{s,d}} = \begin{cases} 1 & \text{if } n = s \text{ or } n = d \\ 2y_{2,n}^{s,d} & \text{otherwise} \end{cases} \tag{3}$$

$$\mathbf{x_{1,e}^{s,d} \leq 1 - b_e^s \quad \forall s, d \in V, e \in E} \tag{4}$$

$$\mathbf{x_{1,e}^{s,d} \leq 1 - b_e^d \quad \forall s, d \in V, e \in E} \tag{5}$$

$$\mathbf{x_{1,e}^{s,d} + x_{2,e}^{s,d} \leq 1 \quad \forall s, d \in V, e \in E} \tag{6}$$

$$\sum_{\mathbf{s,d \in V}} \mathbf{(x_{1,e}^{s,d} + x_{2,e}^{s,d}) \cdot T^{s,d} \leq C \quad \forall e \in E} \tag{7}$$

$$\sum_{\mathbf{e_1 \in E}} \sum_{\mathbf{e_2 \in E}} \mathbf{w_{e_1,e_2}^{s,d} \cdot u_{e_1} \cdot u_{e_2} \leq u^{s,d} \quad \forall s, d \in V} \tag{8}$$

The objective function in Eqn. (1) minimises the sum of the number of links traversed by each end-to-end connection. Equations (2) and (3) are flow conservation constraints that map the flow of links and the associated nodes. Equations (4) and (5) denote that working paths must use the primary homes on both source and destination sides, i.e., are not allowed to use feeder fiber which connects it to the dual home. Equation (6) accounts for link-disjointedness between primary and backup paths. Equation (7) enforces the capacity constraint whereas Eqn. (8) is the end-to-end availability constraint. The MILP provides us with the sequence of links that each end-to-end connection follows through the extended topology including both access and core.

Algorithm 1 Heuristic for Link-Flow Model

Input: End-to-end topology $G = (V, E)$, traffic matrix $T = [\Lambda_{sd}]$, set of connections S, link availabilities set A, core network link capacity upper limit C, target availability A_t

Output: Set of two disjoint paths between each connection in S meeting target availability A_t.

```
1:  Sort connections in descending orders of their demand and store in L.
2:  for each item ∈ L do
3:      Choose primary-home-to-primary-home path as working path.
4:      Reserve capacities for the working path on the intermediate links.
5:      Update residual capacities.
6:      Sort 4 backup paths in ascending hop counts and store them in BP.
7:      for each item ∈ BP do
8:          if availability of combination of working and backup path ≥ A_t then
9:              if residual capacities on the links of the chosen backup path can support
                the demand of the connection then
10:                 Assign the backup path.
11:                 Update the link capacities of each link in the backup path.
12:                 Update residual capacities.
13:             else
                    go to step 7
14:             end if
15:         else
16:             if availability of combination of working and backup path ≤ A_t then
17:                 go to step 7
18:             else
                    return "no solution".
19:             end if
20:         end if
21:     end for
22: end for
23: Calculate total path length for all working and backup paths.
```

The above MILP model is not scalable for practical network instances because the size of the problem is inherently large as we consider an end-to-end topology including the core network as well as thousands of local exchanges. Therefore, we propose a heuristic model described in Algorithm (1), to compute the availability-aware routes for each LE-to-LE traffic flows.

The algorithm takes the extended topology including the MC nodes as well as local exchanges and their associated connectivities as input. It also takes an end-to-end demand matrix (T) which contains the traffic flows for all possible LE-to-LE pairs, the set of connections (S), the link availability set (A), the core network link capacity limit (C), a set of two disjoint shortest paths between each MC node pair, and the target availability (A_t) as input.

The output of the algorithm returns a set of two disjoint paths between each connection in S meeting target availability A_t. The link flow model heuristic sorts the LE-to-LE connections in descending order and for each connection it sets the primary-home-to-primary-home path as the working path (as shown in Fig. 2). Out of the four possible choices for the backup path, the heuristic chooses the optimum path which meets both the link capacity requirement constrained by the capacity limit C and the target availability requirement i.e., the combined availability of the working and the backup path obtained by combining the intermediate link availabilities from set A, should be greater than the target availability A_t. Note that, if more than one backup path meet the above requirement, the heuristic chooses the first one.

Once we solve the link-flow model and find end-to-end routes for each LE-to-LE traffic flows, we proceed to the next step where we solve a lightpath topology design (LTD) problem. The LTD phase takes as input the entire set of LE-to-LE disjoint primary and secondary routes together with their aggregated traffic flows as a result of the link-flow model heuristic. Given this mapping of traffic flows in the core network links, the LTD phase assigns ligthpaths to support these demands and gives a distribution of transponders at each node.

The LTD heuristic is presented in Algorithm 2. It begins by sorting the demands in a descending order according to their path lengths. For demands whose amount of traffic $T^{s,d}$ exceeds the capacity of a single lightpath C, it will first set up $T^{s,d}/C$ lightpaths (rows 5 to 13) and then search for existing lightpaths which have sufficient free capacity to accommodate the remaining demand (rows 14 to 38)[3]. If such a lightpath is found and if its free capacity exactly matches the remaining amount of traffic of the current demand, it is denoted as exact fit (rows 19-21). If there is more than one lightpath with capacity greater than the remaining demand, the algorithm will select the lightpath with the largest free capacity, denoted as best fit (rows 23-25). Finally, the traffic flow of the demand will be added to the exact fit, or the best fit, if found, respectively. Otherwise, a new lightpath will be set up to carry the remaining demand of the current traffic flow. Note that the Algorithm 2 is run consecutively first for the traffic flows carrying working traffic, and then for the flow carrying backup traffic.

[3]Note that, when we say we accommodate remaining demand into the lightpath's free capacity, we do so only at the originating MC nodes. This should not be confused with grooming. As we have mentioned before, our architecture consists of a flat, transparent core and a long-reach PON access and grooming or aggregation of traffic is done only at the originating MC nodes where the access traffic is aggregated and packed into wavelength channels. There is no traffic grooming facilitated at intermediate core nodes (i.e., MC nodes) as any traffic passing through the intermediate core nodes is in optical domain unless they are add/drop traffic.

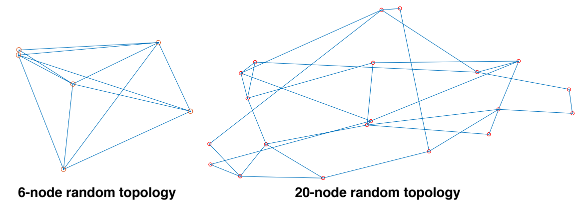

Fig. 3. Example topologies generated randomly using the Waxman Model [5].

Algorithm 2 Lightpath Topology Design

Input: Set of traffic flows routed over the physical topology, Link capacity C.
Output: Set of lightpaths L.

1: Sort the traffic flows in descending order
2: **for** each traffic flow F **do**
3: $Remaining\_demand \leftarrow F.demand$;
4: **while** $Remaining\_demand > 0$ **do**
5: **if** $Remaining\_demand \geq C$ **then**
6: Establish a new lightpath l over the physical route of F;
7: Add traffic flow F to lightpath l;
8: $l.residual\_capacity \leftarrow 0$
9: $Remaining\_demand - = C$
10: $L = L \cup l$
11: **end if**
12: **if** $Remaining\_demand > 0$ and $Remaining\_demand < C$ **then**
13: $Max\_free\_capacity \leftarrow 0$
14: $Exact\_fit = \varnothing$
15: $Best\_fit = \varnothing$
16: **for** $l = 1$ to $|L|$ **do**
17: **if** $l.get\_residual\_capacity == remaining\_demand$ **then**
18: $Exact\_fit \leftarrow l$
19: **else**
20: **if** $l.get\_residual\_capacity > remaining\_demandl.residual\_capacity > Max\_free\_capacity$ **then**
21: $Best\_fit \leftarrow l$
22: $Max\_free\_capacity \leftarrow l.residual\_capacity$
23: **end if**
24: **end if**
25: **end for**
26: **if** $exact\_fit! = \varnothing$ **then**
27: Add traffic flow F to lightpath $Exact\_fit$
28: $Remaining\_demand = 0$
29: $l.residual\_capacity \leftarrow 0$ $best\_fit! = \varnothing$
30: Add traffic flow F to lightpath $Best\_fit$
31: $l.residual\_capacity \leftarrow l.residual\_capacity - Remaining\_demand$
32: $Remaining\_demand = 0$
33: **else**
34: Establish a new lightpath l over the pyhsical route of F;
35: Add traffic flow F to lightpath l;
36: $l.residual\_capacity \leftarrow 0$
37: $Remaining\_demand = 0$
38: $L = L \cup l$
39: **end if**
40: **end if**
41: **end while**
42: **end for**

The results of the mathematical model and of the heuristic are presented in the next section.

III. Results and Discussion

For our analysis we consider four topologies as shown in Figs. 3 and 4. We test our mathematical formulation and the heuristic model on the small 6-node topology as shown in Fig. 3. The heuristic model is also applied to the

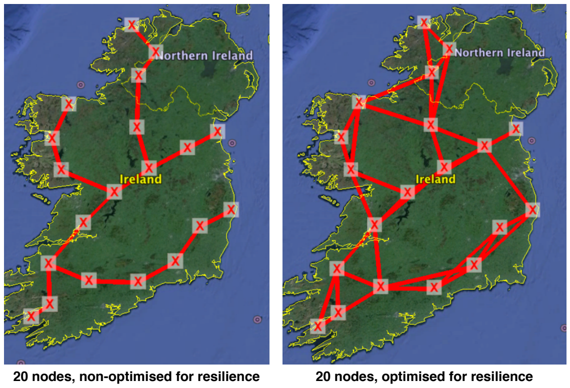

Fig. 4. Example topologies generated deterministically [9], [10].

large 20-node randomly generated topology (Fig. 3) and the deterministically generated topologies for Ireland (Fig. 4). It should be noted that the nodes in these topologies represent the consolidated MC nodes associated with the implementation of the optimized LR-PON-based DISCUS architecture[4] in those countries. These LR-PONs collect traffic from 1,840,479 users, distributed over 1121 remote nodes. The location of the MC nodes in these topologies are obtained through a placement algorithm as described in [4]. Each of these MC nodes serves several local exchanges. To a set of the local exchanges, say set A, a particular MC node serves as a primary home and to some other set of local exchanges completely orthogonal to set A, say set B, the same MC node serves as a secondary home. Therefore, the entire set of local exchanges are dually served by 20 MC nodes.

The topologies of the 6-node and the 20-node random networks are generated using the Waxman model [5], [6] with average nodal degree of 2.5 whereas the 20-node deterministic topologies are generated using the models in [9], [10], [11], and [12]. The 20-node deterministic topologies are generated for two cases namely, (1) optimized for resilience and (2) not optimized for resilience. In the topologies that are optimised for resilience, it is always ensured that there are at least two node-disjoint paths between all pairs of source-destination nodes and in the topologies that are not optimised for resilience, the above constraint is relaxed and only one path is ensured between each source-destination pair. In both the cases, optical network transparency constraints are enforced. The link lengths are generated multiplying the Euclidean distance between two nodes with the fiber routing factor of 1.4 [7].

The different parameters for the illustrative results on the 6-node topology are as follows: (1) the sustained data rate has been assumed to be 10 Mbps per user[5]; (2) the core network is assumed to have a capacity of 8 wavelengths per fiber with each wavelength carrying 100 Gbps of capacity; (3) the target availability is assumed to be 0.99995 (this is the maximum that is tested to be achieved on the 6-node topology); (4) the availability per kilometre of fiber is set to be 0.999979[6].

End-to-end traffic is calculated using the well-known gravity model [8]. The traffic T_{AB} between LEs A and B is calculated as: $T = (K \cdot R \cdot N_A \cdot N_B)/D^2$, where K is the traffic scaling factor, R is the sustained data rate provided per user, N_A and N_B represent the number of users served by LEs A and B respectively, and D is the Euclidean distance between the two LEs. The generated traffic is scaled using different scaling factors K to model different total network traffic intensities.

TABLE I
DUAL HOMING IN 6-NODE TOPOLOGY

Parameters	MILP	Heuristic
Total Link Usage	576	608
Availability Distribution	100% over 0.99995	75% over 0.99995; 25% $\in$ $[0.9999, 0.99995]$
Mean Availability	0.999996	0.99996
Mean Traffic per link [Gbps]	278.8	324.8
Computation time [s]	105	71

TABLE II
SINGLE HOMING IN 6-NODE TOPOLOGY

Parameters	MILP	Heuristic
Total Link Usage	588	696
Availability Distribution	100% over 0.99995	75% over 0.99995; 25% $\in$ $[0.9999, 0.99995]$
Mean Availability	0.999993	0.99995
Mean Traffic per link [Gbps]	354.4	415.2
Computation time [s]	90	67

The comparison between the MILP model and the heuristic model for the 6-node topology is presented in Tables I and II. It is evident from these tables that the MILP and the heuristic perform closely in terms of the objective function which is the total link usage for all end-to-end paths. A couple of more observations are also significant even for the small topology. Firstly, the total link usage for the single-homing case is slightly higher than the dual homing case both with the MILP and the heuristic. Secondly, the mean traffic per link which is the sum of the capacities of all the traffic flows that traverse a link averaged over the number of links[7], are also less in dual homing than in case of single homing. This suggests that dual homing provides better load balancing compared to single homing which will be also shown later in the paper with the studies involving the larger topologies. We further observe that the MILP provides overall best availabilities for the connections than the heuristic model while the heuristic performs slightly better in terms of computation time.

[4]The idea behind the DISCUS architecture is to aggregate and serve the traffic generated by the country-wide local exchanges through larger metro/core (MC) nodes. These MC nodes, typically span a geographical area of about 100 km radius and all local exchanges in that zone are served by the corresponding MC node. The MC nodes are optimally placed such that sum of the fiber cabling cost from the MC node to the local exchanges are minimised, and each local exchange is served by two MC nodes i.e., by dual homing. More details are provided in [1] and [4]

[5]Sustained data rate is defined as the maximum rate offered to all users in the network simultaneously.

[6]This is an average value we obtained from the availability figures of different types of fibers that come from the private communication with different industry partners of the DISCUS project.

[7]For the small topology we have 20 bidirectional links. So, if we lookup the flows that pass through each of these 20 links and add up the demands, we get a set of 20 total flows for 20 links. We then average the flow capacities over the 20 links and term them as mean traffic per link in Tables I and II.

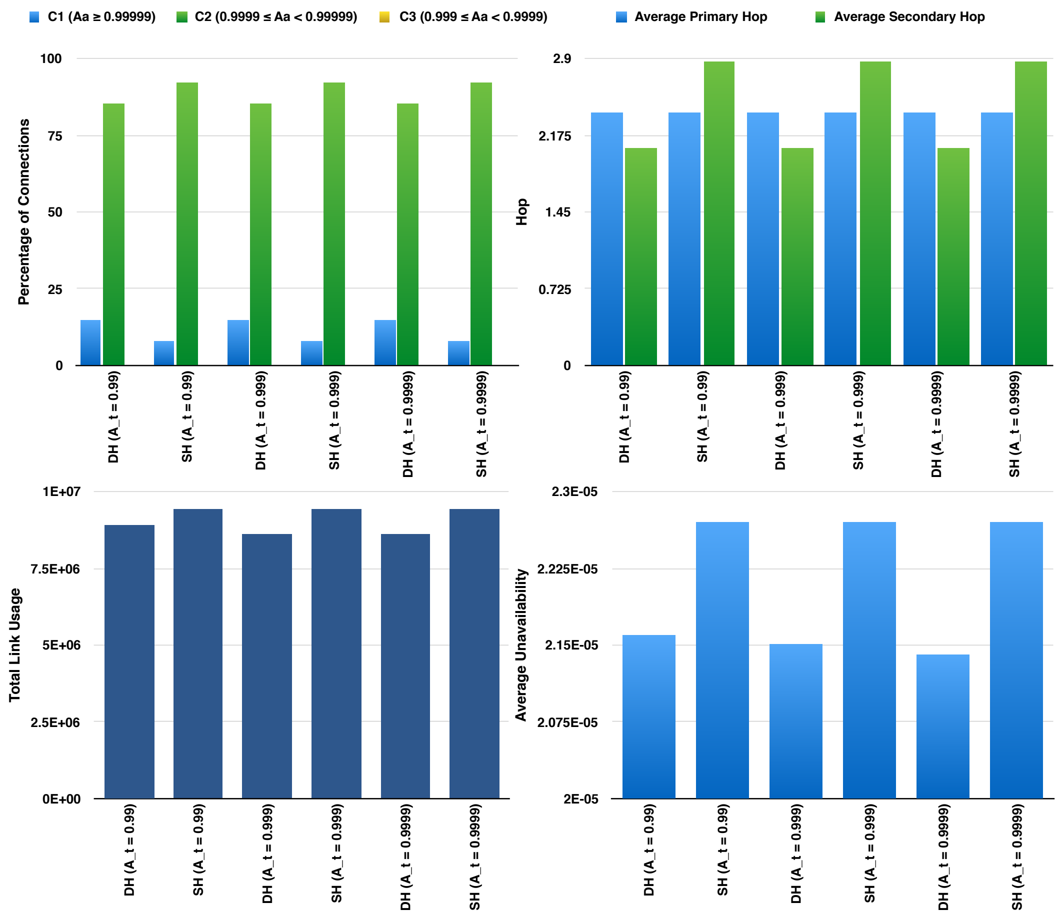

Fig. 5. Dual Homing vs. Single Homing in 20-Node Irish topology with connectivity generated randomly using Waxman's model.

Note that, for realistic network sizes, for example in case of the 20-node topology which serves 1121 local exchanges on the map of Ireland, we have about 1 million [8] end-to-end connections and it is impossible to solve the link flow model with an MILP. Thus, even for a relatively small network as the Irish network we need to resort to a proper heuristic model as we have devised here. From the results of Tables I and II, we also observe that a dual-homed access also provides better load balancing as we can see that both for the MILP and the heuristic we have less average traffic distribution per link.

Next we present our results for the 20-node topology using the heuristic as described in Algorithm 1 in Figs. 5 to 7. The simulation parameters remain the same as in the 6-node topology except that the number of wavelengths per link in the case of the large network is assumed to be 80. The different availability classes in these tables are defined as C1, C2, C3, and so on. These classes depict the percentage of connections that fall within a certain range of availabilities or the percentage of connections below or above a certain availability. Note that, the values of availabilities that are used to define the different classes are the actual connection availabilities achieved (A_a), whereas the availability values on the left-hand side of the tables where different scenarios are defined are the target availabilities (A_t) for which the experiments are performed. In Table 5, the results for different values of target availabilities on a dual-homed and a single-homed architecture are shown for the randomly generated 20-node reference network.

We observe that dual homing utilises the core network resources in a better way than the single homing case. The number of hops and the number of links used in the dual homing case is lower which is due to the fact that dual homing provides more options for end-to-end routing. Moreover, we also observe that the percentage of connections falling into the best availability class is higher in case of dual homing than single homing for the same target availabilities. This proves that dual homing also provides better end-to-end availability figures.

In Fig. 6 we present identical data as in Fig. 5 for the 20-node Irish reference network which is optimized for resilience. We see a similar trend as in the case of the randomly generated network. Single homing end up using more link capacity and also the average hops for the secondary routes are longer.

[8] We have considered bi-directionality which means that there will be $N \cdot (N-1)$ connections for N remote nodes. But then to reduce the problem size as well as to give more sense to the problem we were studying, we have omitted those connections which are between remote nodes served by the same MC node because they do not need to traverse through the core network to reach their destinations. Therefore connections originating and terminating from remote nodes served by the same MC node, do not necessarily get affected by the failures of resources in the core network. So, considering bidirectionally we would have 1,255,520 connections for 1121 remote nodes, but omitting the connections originating and terminating in the same MC node, we get 1,018,216 connections.

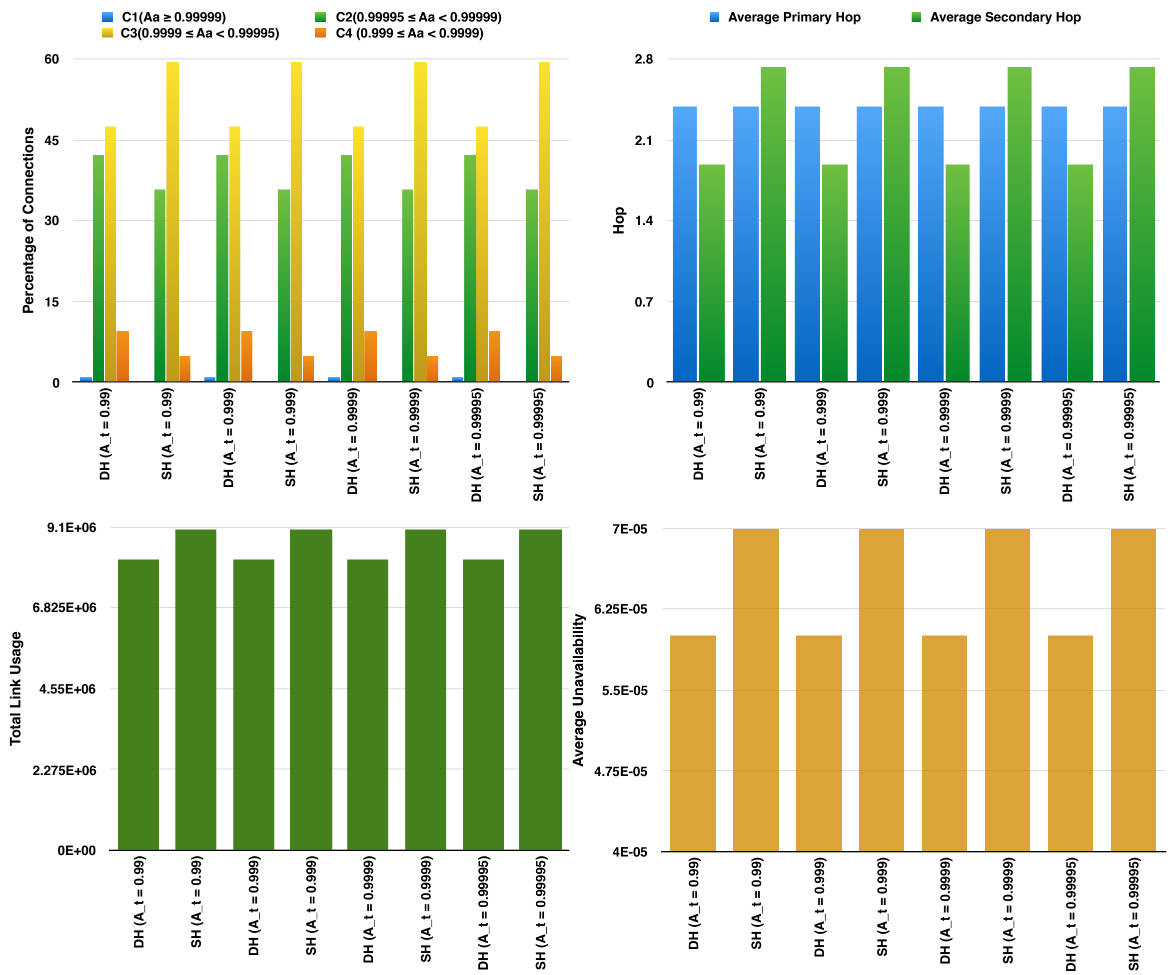

Fig. 6. Dual Homing vs. Single Homing in 20-Node Irish topology optimized for resilience.

Furthermore, the distribution of end-to-end connection availabilities are more dispersed in the case of the deterministically generated topology. We observe that about 43% of connections are in the second best availability class with dual homing compared to single homing where the corresponding figure is about 36%.

To further obtain a clearer picture of how dual homing provides better resiliency, we present results for the 20-node Irish topology that is not optimized for resilience (Fig. 7). As evident from Fig. 4, the topology that is not optimized for resilience is a mere minimum spanning tree and yet we can observe in Fig. 7 that dual homing provides a fair degree of resilience, i.e., an overall target availability of 0.9995 is met with dual homing whereas with single homing the maximum average availability that the topologies provide is 0.995. This is significant as it shows that dual homing not only protects the access but also plays a significant role in protecting the core network even when the core is not resilience-proof by its own.

Next we present our results for the LTD phase of our analyses in Table III. Here we have tabulated parameters such as mean number of lightpaths per link, total unused capacities on all established lightpaths, average working path length, average backup path length, and average lightpath length obtained from the LTD phase for the best possible target availability that can be achieved for the different scenarios mentioned in Table III.

In case of topologies that are optimized for resilience, we can observe that with dual homing in the access, the average lightpaths per link of the core network is lower compared to the single homing case. Furthermore, the total unused capacities over all established lightpaths are also higher in case of single homing compared to dual homing. These observations clearly indicate that dual homing, because of its path redundancies can be beneficial in efficiently distributing the traffic load across the network. Furthermore, the backup paths are about 42% shorter compared to the working paths if we use dual homing at the access for the resilience-optimized core network topology. This is again significant because shorter paths will use less overall resources.

In case of the non-resilience-optimized topology, there are no backup paths in the core and so the mean number of lightpaths per link is much less for single homing. In this case, single homing does not reserve any backup resources at all and that implies low overall end-to-end availability which has been captured in our results in Fig. 7. Secondly, the average backup path length is not reported for single homing as there are no backup paths at all for core network topology that is not optimized for resilience with single homing at the access.

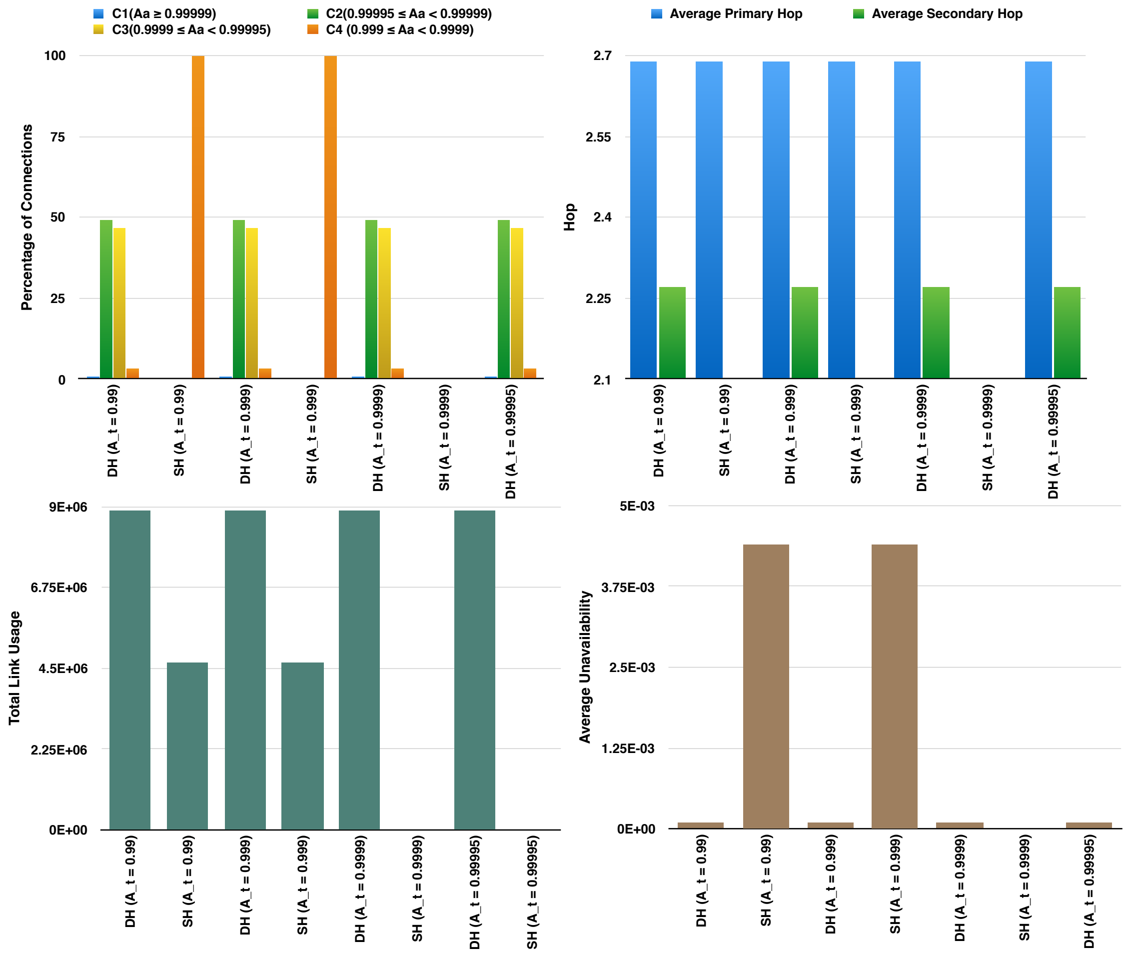

Fig. 7. Dual Homing vs. Single Homing in 20-Node Irish topology not optimized for resilience.

TABLE III
RESULTS FOR LIGHTPATH TOPOLOGY DESIGN

Metrics	Not optimized for Resilience, Dual Homing ($A_t = 0.995$)	Not optimized for Resilience, Single Homing ($A_t = 0.995$)	Optimized for Resilience, Dual Homing ($A_t = 0.9995$)	Optimized for Resilience, Single Homing ($A_t = 0.9995$)
Mean Number of Lightpaths per Link	2291.2	1159.8	982.7	1178.4
Total Unused Capacities [Gbps]	5899.88	6149.94	19799.9	23599.9
Average Working Path Length [km]	209.54	209.54	260.5	260.5
Average Backup Path Length [km]	210.05	-	160.8	276.3
Average Lightpath Length [km]	213.97	218	226.9	278.3

IV. CONCLUSION

We presented a framework to calculate end-to-end resilient routes for a network architecture that consists both of a core network and an extended topology including access local exchanges. We compared two access architectures namely, dual homing vs. single homing, and found that dual homing which has been an efficient resilience technique in the access can also provide better end-to-end resiliency and efficient load balancing in the core network.

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