Hierarchical Versus Flat Optical Metro/Core Networks: A Systematic Cost and Migration Study

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***Abstract*—Hierarchical metro and core network designs, which dominate today's networks, become increasingly cost-inefficient as traffic grows. In this paper we show that flat architectures are lower cost and we propose a migration strategy that ensures cost-efficiency throughout the migration process.**

I. Introduction

Metro- and core networks have historically been structured as hierarchical networks which consolidate traffic at gateway nodes. These hierarchical levels would typically be the backhaul network from Local Exchanges (LEs) to the first tier of outer core network nodes. The outer core nodes then connect to an inner tier of larger core nodes, often fully meshed.

When they were initially deployed, there were good reasons for hierarchical networks. They enabled efficient use of transmission capacity by multiplexing traffic onto more efficient high capacity links by adding and dropping traffic at intermediate nodes. In optical networks these transmission links would be wavelength channels or light-paths. However, as traffic grows the amount of traffic exchanged between any pair of core nodes increases to levels that also efficiently fill optical wavelength channels. When this occurs the alternative architectural option of a flat optical core network can perform better than the hierarchical network. A flat network is one where any two nodes are directly connected through a transparent wavelength channel. This reduces the need for intermediate traffic routing between the source and destination core nodes.

Using node-architecture and cost models developed within the EU FP7 DISCUS project [**?**], this paper carries out a techno-economic study of hierarchical versus flat core networks and shows that a threshold occurs beyond which flat networks are always lower cost than hierarchical networks. Morover, we introduce a migration strategy for passing from hierarchical to flat networks by progressively adding wavelength links, as they are required for capacity upgrade. Migration paths are indeed fundamental for any network upgrade strategy as any new architecture development needs to start from the current network infrastructure. The migration method we propose ensures cost-efficiency throughout the transition from hierarchical to flat optical core and turns out to be nearly cost optimal for all traffic levels.

Virtual topologies

Modern core networks are organized in layers, from service layers down to pure optical transport. For this paper we will roughly distinguish between a *physical layer*, which refers to the optical Layer 1 domain, and a *virtual layer*, which corresponds to the packet switching/routing domain (Layer 2/3). In the optical layer, dark fibers interconnect the core nodes and provide spectrum to realize high-speed optical circuits, the light-path channels. These channels transport bit-streams using optical modulation formats. Whenever a channel is terminated, optical-electrical-optical (OEO) conversion allows to aggregate and distribute, or to terminate the actual traffic in the electric domain, using for instance Ethernet, IP, or MPLS-TP protocols. The *virtual layer topology* comprises all (metro and core) nodes with OEO functionality as virtual nodes. We also speak of *active nodes*. A virtual link is a pair of active nodes directly interconnected by at least one optical channel.

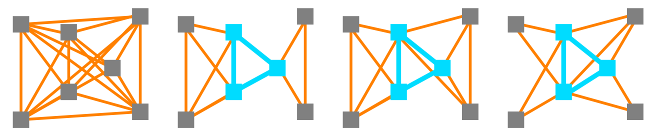


Fig. 1. Virtual network topologies, inner core and OEO grooming nodes in cyan: (a) single optical island flat core (b) multiple disjoint optical islands (c) multiple overlapping optical islands (d) hierarchical two-level network

A fully meshed virtual topology is called *optical island* or *flat network*, see Fig. 1(a). Such a network allows to get rid of intermediate OEO conversion. Every node can directly reach any other node and traffic is electronically switched only at the network edge. This architecture is cost-effective as long as the number of nodes is small (or the traffic is large). However, the number of necessary virtual links and corresponding interfaces (e.g. transponders) scales quadratically as $f(n) := n \cdot \frac{(n-1)}{2}$ where n is the number of nodes. This might result in a huge upfront cost for larger networks.

In such a case, it makes sense to introduce another aggregation tier with smaller outside metro/core nodes having connections only to a smaller (fully meshed) inner core of larger nodes, a *two-level* virtual topology, see Fig. 1(d). Data is transmitted from an outer core node to an inner core node, where it is packet switched, and from there to the destination outer core node, at times passing through at most a second OEO conversion at another inner core node. In two-level hierarchies the number of virtual links is proportional to $h(n,k) := 2 \cdot (n-k) + k \cdot \frac{(k-1)}{2}$ (assuming two connections to the inner core, where $k < n$ is the number of inner core nodes). It holds that $f(n) \gg h(n,k)$ as long as $n > k \gg 2$ which is why hierarchical networks have historically been the chosen design. However, the cost of the links is driven by its traffic capacity, that is, the transponders and packet processing required for each link given by the multiplicity of used wavelength channels. This multiplicity grows much faster for the hierarchical core than the flat core. We will see that a two-level topology saves interfaces as long as the traffic is small and that it becomes inefficient when the traffic increases.

Besides two-level and flat topologies, we will investigate a third alternative for virtual layers, namely topologies comprising multiple (smaller) optical islands, i.e., subsets of the network that are internally interconnected through a full mesh of wavelength channels. We will assume that these islands are interconnected using a small subset of the nodes, e.g. two nodes from each island. These designated aggregation nodes will form another inner flat core. Only traffic between different optical islands needs OEO conversion at the interconnecting nodes. We will distinguish between disjoint and overlapping (non-disjoint) optical islands with respect to the node sub-sets.

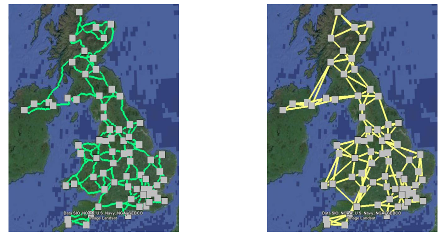
Fig. 1 summarizes the potential switching topologies. Fig. 1(a) and (d) show flat and (two-level) hierarchical topologies, respectively. In the topologies shown in Fig. 1(b) and (c) two fully meshed optical islands (disjoint and overlapping, respectively) are interconnected using 3 inner core nodes.

II. Model and solution methodology

For our study we assume a brown-field scenario. That is, the core networks are optimized assuming a given cable and fiber-network in the UK, see Fig. 2. To obtain this core fiber reference network, we did the following: In a first step, not described in this paper, we optimized the actual number and location of active nodes necessary for a long reach passive optical (LR-PON) access network with maximum reach of 125 km to connect all UK households to these active nodes, with some additional assumptions on survivability and the size of the resulting nodes. For details about this optimization, we refer the interested reader to [?], [?]. The optimisation results showed an optimum number of 73 core nodes selected from a subset of the LEs in the UK. Further, each LE in the UK can be connected to two different of the 73 core nodes via two disjoint fiber routes. The core node size has been limited to 1 million households. For the LEs we used anonymized data from British Telecom and for fiber/cable routes we used a metro cable reference network computed with street data from Open Street Maps [?], [?].

In a second step, we embedded the aforementioned core-fiber topology spanning the 73 core nodes into the same metro cable reference network. This has been done heuristically in such way that there are at least two (short) disjoint fiber-paths between any two core nodes (if possible). We obtain a network with 73 nodes and 159 fiber links, see Fig. 2 (a) and (b). We will assume all core links have sufficient spare fibers available.

Traffic scenarios are generated through a traffic modeling tool developed within DISCUS [?], [?], and released as open source in [?], which takes into consideration both residential



(a) (b)

Fig. 2. UK 73 MC node instance: (a) Physical cable layout (b) Topological cable layout

and business data requirements. The model generates traffic considering services that use data centers, Internet peering point, or other users as data sources. We selected 24 data center and 4 peering points among the biggest active nodes. To compute inter-core node peer-to-peer traffic not terminated at data-centers or peering-points, the traffic generator uses a simple gravity model, see for instance [?]. The model further adds inter data-center traffic as well as traffic from leased lines to the traffic matrix spanning the 73 nodes. In the default scenario this results in a total of 64Tbps (non-reflected peak) core traffic, which is close to the prediction for 2018 of Cisco [?]. However, to study the impact of traffic volume on cost-optimal topologies, we scaled the resulting traffic matrix and re-optimized the whole multi-layer core network for each individually scaled matrix.

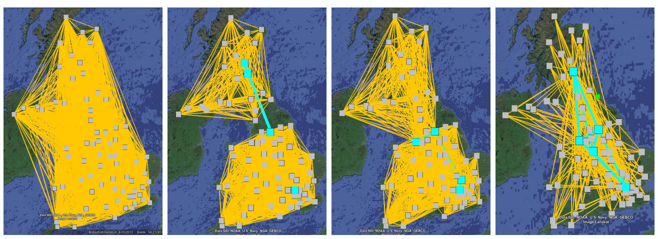
To compare different virtual topologies, shown in Fig. 3, we modeled the four types of network structures from Fig. 1. Clearly, the flat core from Fig. 3 (a) is simply a full virtual mesh of the 73 core nodes. For the two-level topologies consisting of an outer core and a fully meshed inner core we selected the k biggest nodes with $k \in \{5, 15, 25\}$ as the inner core. For the scenarios with several optical islands we first selected (disjoint and non-disjoint) subsets of active nodes based on geographical consideration constructing scenarios with 2 or 3 islands. We then fixed the interconnecting inner core by selecting the two biggest nodes in each of the islands. A traffic demand between two active nodes is realized by paths in the considered virtual switching topology. Paths with more than one hop involve OEO conversion at the designated nodes.

For switching we assume Mutliprotocol label switched transport-profile (MPLS-TP) switches with 400G-capable linecards and short reach line cards with grey interfaces of capacity 40G, 100G and 400G. Each MPLS-TP link is realized as an optical path in the given core fiber topology using appropriate transponders at both ends that connect to the grey switch interfaces with reaches of 2500 km (40G), 2000 km (100G), and 150 km (400G). The reach of a transponder can be doubled by introducing a regenerator for the respective optical channel at cost 1.6 times the cost of the corresponding transponder. A fiber may carry up to 120 channels, using 37.5 GHz spacing. Fibers need WDM terminals at both ends (including (de)multiplexers) as well as line amplifiers every 80 km. The preliminary cost model parameters used are shown in Table I.

For each core service, we provide 1+1 protection in such a

TABLE I
INITIAL COST MODEL PARAMETER.

Type		Provides	Cost in T EUR
Switch	16	400G Slots	192
400G slots	32	400G Slots	384
MPLS-TP	...	...	...
	112	400G Slots	1,344
	...	...	...
Line-card	10	40G ports	43.4
MPLS-TP	4	100G ports	54.2
	1	400G port	60.7
Transceiver	1	40G port	0.4
	1	100G port	1.6
	1	400G port	4.0
Transponder	1	40G port, 2500 km	24
	1	100G port, 2000 km	50
	1	400G port, 150 km	68
WDM Terminal	1	Fiber port	48
OLA	1	80 km EDFA amplifier	15



(a) (b) (c) (d)

Fig. 3. UK scenarios, Virtual topologies: (a) flat core (b) two disjoint optical islands (c) three overlapping optical islands (d) two-level topology with 5 inner core nodes. All virtual topologies will be embedded into the physical topology Fig. 2(b) ensuring end-to-end 1+1 protection for all services.

way that services are protected against single fiber and node failures. That is, for each service we provide a working and a dedicated backup path that are node-disjoint in the virtual domain and fiber-disjoint in the the physical domain.

Our optimization framework minimizes the cost for the required resources mentioned above. For all services it determines a near-optimal routing among a huge set of candidate paths using exact methods from Integer Programming. Both in the physical and virtual layer, we use adapted Dijkstra and Suurballe algorithms [?], [?] to compute short and disjoint path alternatives using different weight functions. Notice, however, that in all scenarios the designated switching topology already strongly restricts the solution space. The routing in the MPLS-TP domain is mainly fixed for each pair of active nodes by the given OEO locations and virtual channel topology (two-level, flat, or multiple optical islands). The optimizer is left to decide which OEO location has to be used for which service, and how channels should be realized in the fiber topology for 1+1 protection.

Starting from the topology $G = (M, E)$ of all potential fiber links (Fig. 2(b)) the mentioned set of candidate paths in the physical layer L forms a virtual topology $H = (M, L)$. Each of these paths can be seen as the realization of a virtual link, a potential channel connection. We restrict the set of paths in such a way that H represents the desired topology (two-level, flat, or multiple optical islands), see Fig. 3. The considered set of transponder types and modulation formats defines a set of signal types T, each signal in T having a certain bitrate and a certain reach in kilometer. In our study, the set T contains 6 signals: 40G, 100G, 400G, each either with or without the use of regenerators leading to a maximum signal reach of 5,000 kilometers, see Table I. We denote by T_ℓ the subset of signals that can be used on the path $l \in L$, that is, no optical channel will exceed the possible signal reach.

We further denote by $\mathcal{P}$ all (virtual) paths in the virtual network $H = (M, L)$. All paths corresponding to a particular service s are denoted by $\mathcal{P}_s$, that is, $\mathcal{P}_s$ contains all virtual paths that can be used to realize the service link.

We introduce the following three types of variables: Binary variable f_p will indicate whether virtual path $p \in \mathcal{P}$ is used or not. Integer variables y^t_ℓ counts how many optical channels with signal type $t \in T$ are active on the virtual link realization $l \in L$. Eventually, integer variables x_e count how many fibers are used on the fiber link e. Given these variables the following model (TLS) optimizes virtual and physical topology simultaneously, including routing and hardware realization:

$$\min \sum_{l \in L} \sum_{t \in T_\ell} \kappa^t y^t_\ell + \sum_{e \in E} \kappa_e x_e \tag{1}$$

$$(TLS) \qquad \sum_{p \in \mathcal{P}_s} f_p = 2, \qquad s \in S \tag{2}$$

$$\sum_{s \in S} \sum_{p \in \mathcal{P}_s} d_s f_p - \sum_{t \in T_\ell} c^t y^t_\ell \leq 0, \qquad l \in L \tag{3}$$

$$\sum_{l \in L : e \in \ell} \sum_{t \in T_\ell} y^t_\ell - 120 \cdot x_e \leq 0, \qquad e \in E \tag{4}$$

$$\sum_{p \in \mathcal{P}_s : e \in p} f_p \leq 1, \qquad s \in S, e \in E \tag{5}$$

$$f_p \in \{0, 1\}, \; y^t_\ell, x_e \in \mathbb{Z}_+$$

Constraints (2) guarantee that exactly two paths are chosen for each service (1+1 protection). The inequality system (3) ensures that enough optical channels are used on a virtual link to carry the (packet) flow (in Gbps) of all paths using the link. The term d_s denotes the traffic of the particular service coming from the (scaled) traffic matrix, while c^t is the bitrate capacity of the channel (40G, 100G, or 400G). Similarly, system (4) ensures enough fibers on all fiber links.

Objective (1) minimizes the cost of all required resources. The term κ^t denotes the cost of an optical channel of type $t \in T$. It includes the cost of two transponders, two transceivers, and, if necessary, the cost of a regenerator. The term κ_e denotes the cost of a fiber. In this case we include the cost for one WDM terminal on each side and the cost for amplification (OLA) every 80 kilometers, see Table I. It is possible to extend this model to also include cost for MPLS-TP switches and line-cards by introducing appropriate node capacity variables. For this study, we decided to heuristically include a certain share of line-card and switching cost into the link cost term κ^t. However, after applying model (TLS) we optimize and install the necessary equipment at each individual node. Network cost is evaluated with respect to these final installations.

Following the terminology from [?], [?], model (TLS) is a *path-flow over path-flow* model with *explicit light-paths* and *disaggregated flow*. That is, in both layers, the virtual channel layer and the physical fiber layer, we work with explicit set of paths. We only let the optimization model decide which of the paths to chose. This approach has the flexibility to work with different sets of preselected paths, easily integrating additional constraints on the path realizations such as distance or topology restrictions. Of course, since we do not work with column generation, we can speak of optimality only with respect to the chosen set of paths.

III. Results

In this section, we present our empirical findings using the optimization framework above. We will first establish a precise relation of traffic volume increase and cost evolution over time w.r.t the different switching topologies.

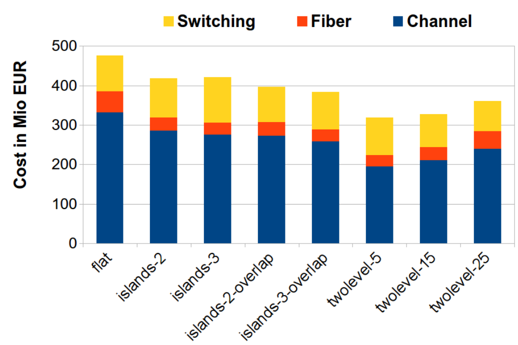


Fig. 4. Brown field core network cost in Mio EUR in 2018 for a traffic volume of 64Tbps, corresponding to an average busy hour user traffic of around 2.2Mbps: islands-k: k disjoint optical islands Fig. 1(b), islands-k-overlap: k overlapping optical islands Fig. 1(c), twolevel-k: two-level hierarchical network with k inner core nodes Fig. 1(d)

Fig. 4 provides figures for the total brown-field cost of the core network for the different topologies in year 2018. The cost values are categorized as MPLS-TP switches plus interface line cards (yellow), Fiber and WDM equipment (red), and optical transponders (blue). It turns out that for this traffic level the most expensive topologies are those with optical islands, while the most effective are two-level architectures. In fact, the sparser the topology, the lower the network cost.

However, these relations strongly dependent on user traffic growth. We considered a range of average busy hour customer traffic patterns down to 6.4Tbps and up to 6,400Tbps core traffic. As traffic grows we completely re-optimize all topologies to get the results in Fig. 5 which show the accumulated cost over time (upfront and upgrade cost) with user bandwidth growth. To cope with decreasing interface cost over time we we applied price learning curves to the cost values [?].

On the long run (Fig. 5(a)), the accumulated cost increases (almost) linearly with the traffic volume, which is because the required interface capacity increases linearly across the entire network and all layers. We note that as traffic increases flatter architectures become more cost effective. The flat core has the largest upfront cost but also the smallest slope and outperforms all other studied network topologies when the

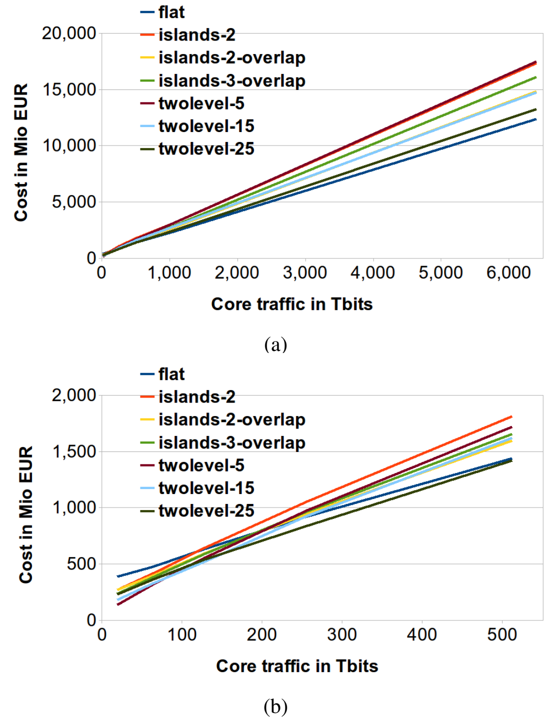


Fig. 5. Cumulative upgrade costs for different network topologies in Mio EUR. (a) Between 6 and 6500Tbps core traffic (b) Between 6 and 500Tbps core traffic

core traffic exceeds ~500Tbps for the model parameters used, which refers to ~17Mbps average user traffic (peak hour).

In fact, the existence of such a threshold can be proven mathematically with some simplifying assumptions: in the case of a single-layer network design problem (ignoring fiber resources and resiliency) with a single base capacity module (using a single circuit speed, e.g. 40G) it is known that in the moment the demand for all individual pairs of nodes exceeds the base capacity (40G), the cost-optimal topology is fully meshed, see [?] and others. We observe a similar law here in a more specific context. It clearly follows that this threshold mainly depends on the number of active nodes as well as the relation of traffic volumes with circuit speeds and not so much on the cost model [?], [?]. In general it holds, that if we increase the (smallest) interface capacity (going from 40G to 100G) or if we increase the number of active nodes, the threshold for 'flat being optimal' also increases.

It can be seen in Fig. 4 that with our cost-model the main cost driver is the cost for transponders. We also tested different cost-models with increased switching/routing cost which of course led to different total cost values but it gave similar results in terms of the cost evolution of the different topologies and it gave thresholds in the same order of magnitude.

Fig. 5 shows that given a particular virtual topology there is a specific (almost) linear cost evolution when traffic increases. To better understand both the cost offset (upfront cost) and the slope of the cost function for a given virtual topology, we have a look at the installed channel capacities for very small and very large traffic, respectively.

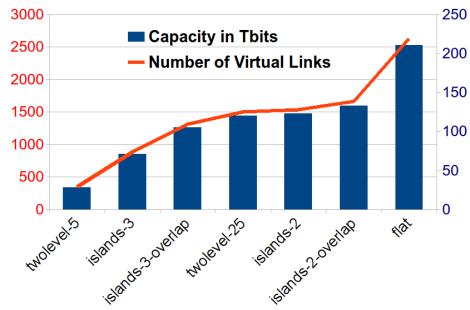


Fig. 6. Traffic volume 0.6415Tbps: Number of virtual links and total network capacity. Installed capacity depends on the sparsity of the virtual switching topology. This defines the cost offset.

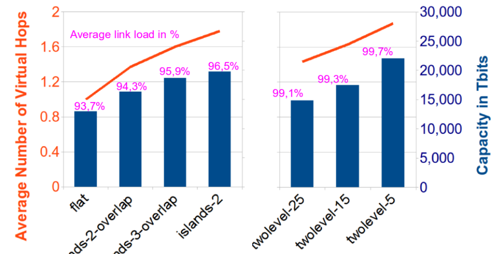


Fig. 7. Traffic volume 6,400Tbps: Average number of virtual hops (OEO conversions plus 1): Cost depends mainly on the average number of channel hops. This defines the slope of the cost function. However, the average link load, acts as a tie breaker.

Fig. 6 reports on installed capacity for the 2018 traffic matrix scaled with the factor 1/100 (0.64Tbps traffic). Topologies are sorted w.r.t increasing number of virtual links. It turns out that the upfront investment only depends on the number of virtual topology links, that is, the sparsity of the virtual topology, which results in a huge offset for the flat core. For small traffic we open exactly one channel for all connections.

In contrast, if the traffic is very large, then the main cost driver is the average number of virtual hops (OEO conversions) over all services, see Fig. 7 with a traffic of 100 times the 2018 matrix (6,400Tbps). Clearly, for given virtual topologies with fixed virtual routing, the average number of virtual hops can be pre-computed, e.g., for the flat core there is no OEO (one virtual hop), while for two-level architectures with very few grooming nodes, we need one OEO conversion for most of the services (mostly two virtual hops on average). It follows that once the node-pair traffic exceeds the interface threshold, the flat core needs less upgrade interfaces than two-level architectures or topologies with several optical islands.

We make one further observation in Fig. 7: comparing optical island topologies with two-level topologies having the same number of virtual hops, two-level architectures need less capacity. This is because the two-level architectures force small nodes to groom at large nodes which leads to relatively well exploited link capacities. In contrast, the multiple optical island architectures force direct communication also between smaller nodes, which leads to smaller link loads on average and a waste of resources, compare e.g. islands-2-overlap and twolevel-25 or island-3-overlap with twolevel-15 w.r.t. link loads, virtual hops, and network capacity. Summarizing, in general, two-level architectures perform better than topologies with multiple optical islands and the flat core is the most cost efficient above a certain threshold. Further, overlapping optical islands outperform disjoint optical islands, they have a similar number of virtual links if the islands are of the same size but the average number of virtual hops is smaller.

IV. Cost-efficient migration

We might clearly consider further virtual topologies, e.g. additional combinations of multiple optical islands or two-level architectures with more inner core nodes. This would introduce additional linear cost functions in Fig. 5 and might even change the threshold of 500Tbps. However, there is no virtual topology that is sparse (having a small cost offset) and provides a moderate cost evolution (small slope of the cost function) with increasing traffic volumes at the same time. That is, the general picture will not change: as user traffic increases the most cost-effective network solution moves from a hierarchical structure to a flat structure. In order to run cost-efficient core networks over a longer time period one needs to change both topology and routing.

Today we have hierarchical core networks and therefore need an effective and graceful evolution strategy that enables the continuation of the hierarchical core where it is most cost effective but transitions to the flat core architecture as traffic increases and inter-node traffic justifies direct optical interconnects.

In this context, we establish a migration strategy from hierarchical to flat core networks. Consider one of the optimized topologies at any given point in time. For a pair of nodes $(n_1, n_2) \in M$ that is not connected by a channel (and thus needs OEO at some intermediate grooming node), we define the *consolidated traffic* in Gbps for (n_1, n_2) as the sum of all service traffic across all services that sees OEO interfaces at one of the two nodes, either at the service end or for intermediate grooming. Now we suggest the following: (i) Start with a small inner core and provide (at least) two (disjoint) channel connections from outside nodes to that inner core. The inner core should consist of the largest traffic nodes. (ii) As network traffic grows the consolidated traffic between a pair of nodes will also grow. At specific points in time (e.g. every year) check for all (non-connected) pairs of nodes, whether the consolidated traffic exceeds the smallest channel capacity (e.g. 40G). If so, provide a direct channel connection and reroute all consolidated traffic accordingly, that is, all the consolidated traffic uses the new established link.

Notice that we do not expect the inner core to be fully meshed from the beginning. The defined consolidated traffic figure has the property that it is large if at least one of the two nodes is a grooming node. For two non-grooming nodes, the consolidated traffic is identical to the traffic demand. That is, the inner core becomes fully meshed first. Later all non-grooming nodes will be connected directly to all inner core nodes. Eventually, for very large traffic even pairs of small non-grooming nodes get a direct channel. This way we migrate slowly towards a flat core between all nodes. This process is illustrated in Fig. 8.

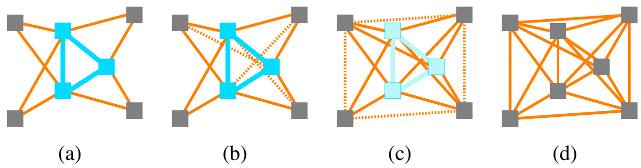


Fig. 8. Migration from two level hierarchy to flat optical core.

The efficiency of this migration strategy is illustrated in Fig. 9. We started with an inner core of the 5 largest nodes and optimized the network for a low user capacity utilization leading to a sparsely connected two level hierarchical topology as in Fig. 8(a). We then increased the user bandwidth and checked the consolidated traffic for all non-connected pairs. If the consolidated bandwidths exceeded the threshold (40G in this example) new direct channels were implemented between the node pairs and the routing changed as described above. Fig. 9 shows that this transition strategy outperforms the flat core at low bandwidths and the two level hierarchical topology at higher bandwidths providing an optimal solution for all traffic demands.

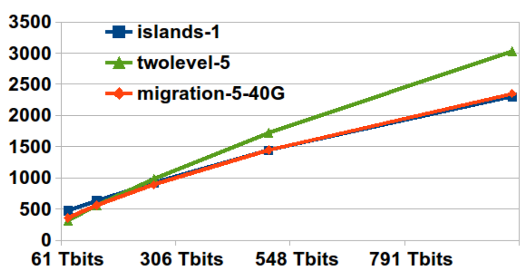


Fig. 9. Migration from two-level hierarchy to flat optical core: Accumulated upgrade costs in Mio EUR. Between 6 and 1,000Tbps core traffic

V. Conclusions

In this paper, we investigated the cost effectiveness of two core network architecture designs. On the one hand the hierarchical core, used in today's network, where data is transferred from source to destination edge core nodes through intermediate inner core nodes that carry out packet routing or switching functions. On the other hand the flat core architecture where all nodes are directly connected by at least one transparent wavelength link, so that data is transferred directly from source to destination edge core nodes without intermediate packet processing. The comparison is carried out as a techno-economic study for growing rates of sustained busy hour user traffic. We show that, while for low value of traffic the hierarchical core is more cost effective, justifying its widespread deployment today, as user traffic grows the flat core becomes increasingly more cost effective (and more power efficient, although those results are not shown in this paper). It turns out that a fully flat core incurs large upfront investment but a moderate cost increase over time. In contrast, sparse architectures involve small upfront investments but a steep slope in the cost function over time. Among the sparse topologies two-level architectures turn out to be the most flexible and most cost-effective compared to architectures comprising multiple optical islands.

After a threshold, which for our study on the UK network occurs for a sustained busy hour traffic of about 5 Mb/s, which we believe could be exceeded already in the short to medium term, the flat core architecture becomes more cost effective. The cost difference between the two architectures increases as the traffic grows, making the flat core already 25% more cost effective than the hierarchical core for a sustained rate of 35 Mb/s. In addition, since it is of paramount importance that any network upgrade is carried out through a sound migration strategy from the current architecture, we also showed a graceful migration strategy. Our results show that if such migration strategy is implemented today, the resulting network can achieve very similar cost to that of a clean slate flat core deployment, while pushing investment to the point in time when capacity upgrades are actually needed.

VI. Acknowledgements

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