Ref. Ares(2014)3625246 - 31/10/2014

D 7.4

Preliminary quantitative results for flat optical network

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Abstract:

The major objective of DISCUS is to produce an end-to-end design for a future network architecture that can deliver very high-speed broadband services to their users. The architectural design must meet this objective while remaining economically viable and scalable. The main objective of this deliverable is to optimise the core network based on architecture/ hardware specifications and reference data developed in this and other work packages. The results shall provide inputs and insights for the overall DISCUS network architecture discussion. In particular, this deliverable focus on the design and implementation of optimisation methods to determine optical island designs. In cases when a single transparent optical island is not feasible the application of Raman amplifiers is studied to obtain a transparent optical island. Resilient design strategies are also investigated in the context of core network.

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10	Polatis Ltd	POLATIS	United Kingdom
11	atesio GMBH	ATESIO	Germany
12	Kungliga Tekniska Hoegskolan	KTH	Sweden

Authors:

Name	Affiliation
Norbert Ascheuer	atesio
Andrea Di Giglio	TI
Marija Furdek	KTH
Deepak Mehta	UCC
Paolo Monti	KTH
Barry O'Sullivan	UCC
Cemalettin Ozturk	UCC
Luis Quesada	UCC
Christian Raack	atesio
Marco Schiano	TI
Roland Wessäly	atesio
Lena Wosinska	KTH

Internal reviewers:

Name	Affiliation
Marija Furdek	KTH
Farsheed Farjady	ASTON

Due date: 31.10.2014

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1 Introduction

The goal of the DISCUS project [15] is to produce an end-to-end design for a future network that can deliver a very high-speed broadband capability (of at least three orders of magnitude greater than today's networks to all users), reduce energy consumption by at least 95% and remain economically viable. The principle of the proposed architecture is to maximise the sharing of network infrastructure between customers by deploying a Long Reach Passive Optical Network (LR-PON) in the access part (which bypasses local exchange-sites, eliminating the electronic traffic processing in those nodes and the need for a separate metro transmission network) and a flat optical layer in the core network to interconnect a relatively small set of network nodes.

Figure 1 depicts the DISCUS architecture. It shows a dual-homed LR-PON bypassing existing local exchanges and terminating on the metro-core (MC) nodes, which are interconnected with an optical circuit switched wavelength layer.

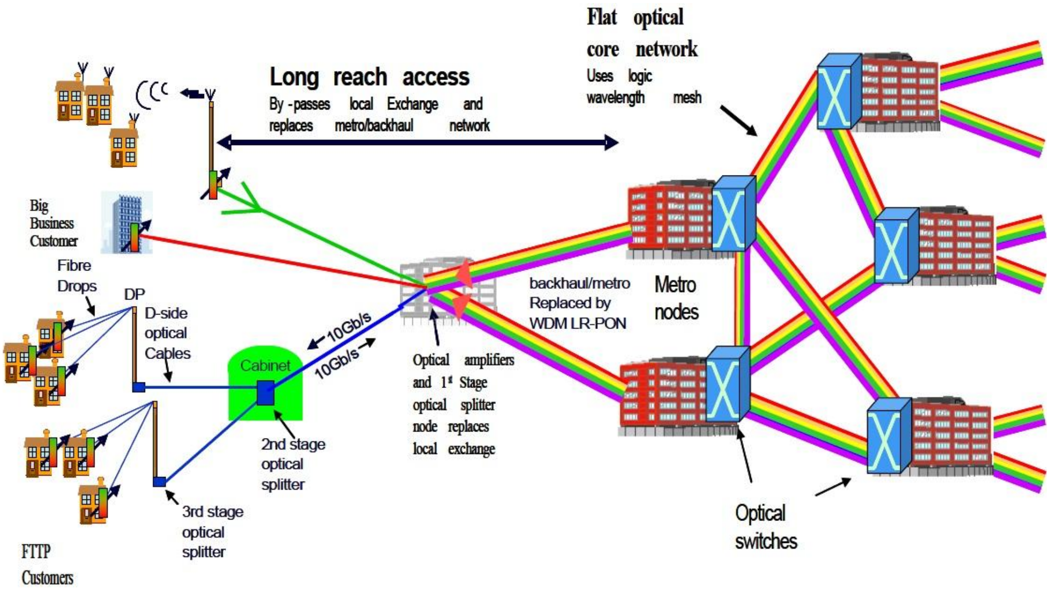


Figure 1: The end-to-end DISCUS architecture with LR-PON and flat optical core network

An optical island is defined as a set of MC nodes that are fully interconnected by transparent wavelength routes. Mathematically speaking, the corresponding channel topology is a complete graph, a fully meshed network. This assumption introduces a strong restriction on the number of possible core network solutions. However, the resulting planning and optimisation problem clearly remains extremely challenging:

Given (i) a nation-wide reference network, (ii) a set of MC nodes, (iii) an estimated traffic matrix, and (iv) a hardware/cost model for optical technologies, the task of the optimisation activities within WP7 is to decide about the fibre topology, that is, the embedding of fibre cables into the reference network, the routing of wavelength channels in this fibre topology, and a feasible placement of optical equipment for optical signal generation, optical switching, and optical amplification.

The problem complexity increases in case of assuming flexible grid technology with signals of different slot bandwidths and signal reach. First of all, channel contiguity has to be ensured, that is, an optical flexgrid signal has to use the same slot allocation on all used fibres in the fibre path routing. Secondly, the length of the chosen path should match the corresponding maximal reach of the signal. This results in a hard combinatorial optimisation problem, commonly known as *Routing and Spectrum Allocation* (RSA), which is clearly embedded in the optimisation problem for optical islands, as studied in WP7.

For many European countries it is envisaged that a single optical island may suffice for a core network, see deliverable D7.2 [6]. Depending on the MC node placement, in some cases it might be possible that the distance between a pair of MC nodes is even greater than the longest reach of an optical signal considered in the DISCUS project (greater than 2430 kilometre, see [6]). In principle, it is the task of the activities in WP4 and WP2 (access network and end-to-end optimisation) to avoid such a situation. However, if for bigger countries it turns out that this cannot be avoided or results in sub-optimal architectures, the DISCUS architecture proposes two alternative solutions. We may introduce multiple optical islands, which in turn are interconnected via a further higher layer optical island layer, which interconnects the lower optical islands, see deliverable D2.1 [1]. Alternatively, we extend the reach of the optical signals by regeneration and/or amplification.

In this deliverable, we study the use and placement of Raman amplifiers to extend the given optical signal reach of flexgrid signals. In order to differentiate between transparent optical islands with and without the application of Raman amplification we refer to the former as **Transparent Optical Island with Raman Amplification** (TIRA) and the latter as **Transparent Optical Island**.

We focus on the problem of designing a single transparent flexgrid optical island to route the traffic between pairs of metro-core nodes by allocating spectrum slots on the fibres that are running between the metro-core nodes, and determine the locations of Raman amplifiers if required. In particular, we focus on the decisions related to the core fibre network design, selection of optical channels for traffic demands, routing and spectrum allocation of optical channels.

A single node/link failure in an optical island can disrupt millions of applications and result in tremendous data and revenue loss to both end users and network operators. Therefore it is important to design resilient optical islands that can continue functioning correctly in the presence of failures of any node/link failure. There are two important issues that one faces when designing resilient networks: (1) providing alternate paths so that when a node or a link fails every other pair of core-nodes are still connected, and (2) provisioning the network with extra resources so that the demands can be satisfied by following the alternate routes. In this deliverable we focus on the resilience in the networks with dual homing. This last topic will further be explored in the future Deliverables 7.6 and 7.10.

2 Core Network

Following the trend to avoid electrical switching and electrical multiplexing in future core networks, the DISCUS architecture promotes a so-called “flat optical core”.

In a flat optical core (a.k.a. transparent optical island), Metro-Core (MC) nodes are directly connected with each other via circuit switched optical channels and a traffic demand from a MC-node to another MC-node can be sent directly through one or more optical channels without performing optical-electrical-optical (o-e-o) conversions. An example is shown in Figure 2. In Figure 2 the blue lines are meant to represent cable routes and the coloured lines are the logical optical wavelength routes, shown only from metro-core node 1 to all the other metro-core nodes. These paths traverse other metro-core nodes but do not carry traffic for those intermediate metro-core nodes and simply pass through. This means that no electrical switching is taking place. Nevertheless, to optically switch and multiplex individual optical channels it is assumed that optical cross-connect (OXC) device is installed.

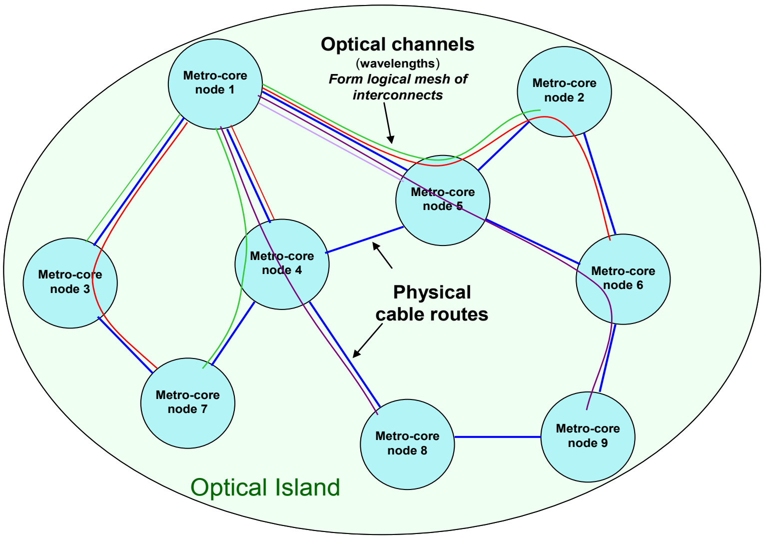


Figure 2: Optical island concept

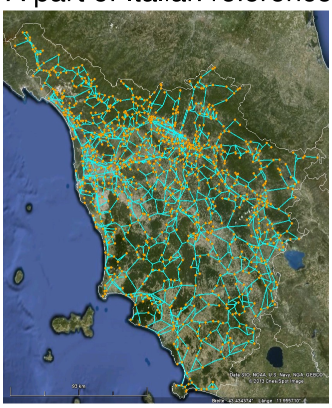
According to the architecture from deliverables 2.1 and 7.2, for most cases and most countries, it is envisaged to have a single nation-wide optical island connecting all the MC nodes. In case some traffic paths are longer than the maximum achievable reach, Raman amplifiers will be installed in appropriate locations for extending the reach.

In the following we describe the input for core network optimisation problems from other tasks of DISCUS project.

2.1 Reference Network

A nation-wide reference network (see e.g. Figure 3) is denoted by a graph $\langle V, R\rangle$. We assume that we are given this network as an input.

Figure 3: A part of Italian reference network



The nodes V of this network are given by existing MC sites or any additional equipment (optical line amplifier, etc.). We assume that any other special location such as an international peering point, a data-center, etc. is constructed at an existing MC site. Notice again that MC sites are just a subset of the nodes of the reference network. We denote them by $N \subseteq V$. The locations of MC sites are an output of Task 4.4 where they are selected in such a way that each exchange-site in the access network is covered by two MC-nodes. The objective is to satisfy one or more of the following criteria: (1) Minimise the number of MC nodes, (2) Minimise the distance based cost (e.g. length of cables/fibres) for connecting exchange-sites to their metro-core nodes (3) Minimise the total over-provisioning required for metro-core nodes for resiliency purpose, or (4) Maximise disjointness of the routes from each exchange-site to its two metro-core nodes.

We do not make any assumption on the links of the network $\langle V, R \rangle$. These links describe existing and potential fibre/cable/duct routes for the core-network Fibres are organised in bundles, which in turn are organised in cables. Cables lie in ducts, which in turn might be organised in super-duct systems. These duct systems typically have some spare capacity for future deployment of cables. In principle, there might also be empty ducts. By default we assume that enough cable and duct capacity is available for core connections and the cost function is linearly proportional to the length of the link.

2.2 Traffic Matrix

Another input for the core network optimisation problems we expect is a MC to MC traffic matrix which is dependent on the number of customers connected to the individual metro-core nodes and the traffic between pairs of metro-core nodes.

For every pair $\langle i, j \rangle$ of MC-nodes, we generate a non-negative traffic value $t(i, j) \in \mathbb{R}^+$ in Gbits/s using the following gravity model:

$$t_{ij} = pl_i \times \frac{pl_j / d_{ij}}{\sum_{k \in N, k \neq i} pl_k / d_{ik}}$$

- t_{ij} is the traffic going from MC-node i to MC-node j
- d_{ij} is the distance between MC-nodes i and j. If a reference network is given then this distance correspond to the shortest path in that network otherwise it is simply an Euclidean distance multiplied by a road-factor. The road-factor used for the results reported in this deliverable is 1.6.
- pl_i is the load of the MC-node $i \in N$ which is obtained by multiplying the number of customers associated with MC node i with the expected traffic for each customer.

2.3 Flexgrid Optical Signals

In rigidgrid systems, every optical signal uses a fixed bandwidth of exactly one slot in the grid. The total number of slots available in any fibre is denoted by ns. That is, if we use numbers $\{1, \ldots, ns\}$ for the available bandwidth slots, assigning spectrum to an optical channel reduces to selecting a number (spectrum slot) between 1 and ns.

Recently, flexgrid optical networks have received huge interest as they can facilitate very high traffic demands by operating on a flexible spectrum [4]. Spectrum allocation in flexgrid systems differs from traditional wavelength switched optical networks. In flexgrid, the channel width is not rigidly defined but can be tailored to the actual size of the transmitted signal and therefore one optical channel can be assigned to a number of contiguous spectrum slots. This new capability leads to an additional spectral contiguity constraint while the wavelength continuity constraint is referred to as spectrum continuity constraint. Flexgrid systems introduce the notion of superchannels (see deliverables D2.1 and D7.2). A signal may be composed of multiple sub-carriers and may use multiple consecutive bandwidth slots.

Table 1: Optical Signal Types: The Flexible WDM Grid

Signal	Net-Ser (GE)	No of 37.5 GHz Slots	G.652 reach (Km)	Modulation format	WDM spectral eff.	OCh/SCh
1	40	1	2430	DP-BPSK	2 bit/s/Hz	OCh
2	100	2	2430	DP-BPSK	2 bit/s/Hz	SCh dual carrier
3	100	1	1170	DP-QPSK	4 bit/s/Hz	OCh
4	100	1	500	DP-16QAM	8 bit/s/Hz	OCh (twin 100 GE client)
5	400	4	1170	DP-QPSK	4 bit/s/Hz	SCh quad carrier
6	400	2	500	DP-16QAM	8 bit/s/Hz	SCh dual carrier

We assume a finite set of signal types, denoted by Φ, where signal $\phi \in \Phi$ has a bitrate b_ϕ, uses ns_ϕ bandwidth slots, and has a maximum reach of l_ϕ. The total number of slots available in any fibre is denoted by ns. A set Φ proposed for the DISCUS core network in D7.2 is shown in Table 1.

Unless a Raman amplifier is used, it is assumed that the reach of a signal defines the maximum distance over which it can be carried. Every lightpath (also referred as channelpath) has to be routed in the fibre graph. Depending on the WDM system used, the total available bandwidth on a fibre is limited. We have to assign a bandwidth interval to every lightpath such that for all visited fibres there is no bandwidth overlap (interference) with other lightpaths.

2.4 Transparent Optical Island using Raman Amplifiers

In terrestrial optical networks, the optical amplification technology of choice is typically Erbium Doper Fibre Amplifier (EDFA). As shown in deliverable D7.2 [6], this amplification technology limits the transparency reach to approximately 2000 km for the transmission technology selected for DISCUS core network (32 Gbaud DP-BPSK optical channels, for other formats the reach is shorter). While this figure is abundant when referring to small or medium European countries, it may become insufficient for large European countries or for continent-wide networks. In latter cases the network is no more fully transparent in the sense that some traffic demands have to be regenerated and the network has to be designed as a translucent one [8]. However, a fully transparent backbone is highly preferable compared to a translucent one because of its advantages in terms of cost, design simplicity and facility of circuit provisioning and reconfiguration.

This subsection shows how to upgrade a translucent network with sparse Raman amplified links to ensure a transparent network operation. Raman amplification is a well-known optical amplification technology that uses the transmission fibre as the active medium. The pump power is injected into the transmission fibre either at the receiver side (counter-propagating pump) or at the transmitter side (co-propagating pump). Optical amplification is achieved by the energy transfer between the pump signal and the transmission signal that is typical for the Raman effect.

Raman amplification is typically used in combination with EDFAs in very long amplification sections of terrestrial or submarine links. Its major benefit is a strong reduction in equivalent noise figure of the EDFA and therefore in the amplification section equivalent Optical Signal to Noise Ratio ($OSNR_{eq}$, see [6] for the definition).

Considering that in an optical network the end-to-end $OSNR_{eq}$of a lightpath is a function of the traversed links individual $OSNR_{eq}$, it is clear that the end-to-end $OSNR_{eq}$ can be improved by including Raman amplification in some selected links. If the end-to-end $OSNR_{eq}$ of a regenerated lightpath is sufficiently increased, and it crosses the threshold of the selected transmission technology $OSNR_{eq,min}$, the lightpath becomes transparently feasible and the regenerator can be removed. This concept is shown in Figure 4, and expanded further in Section 5.2.2.

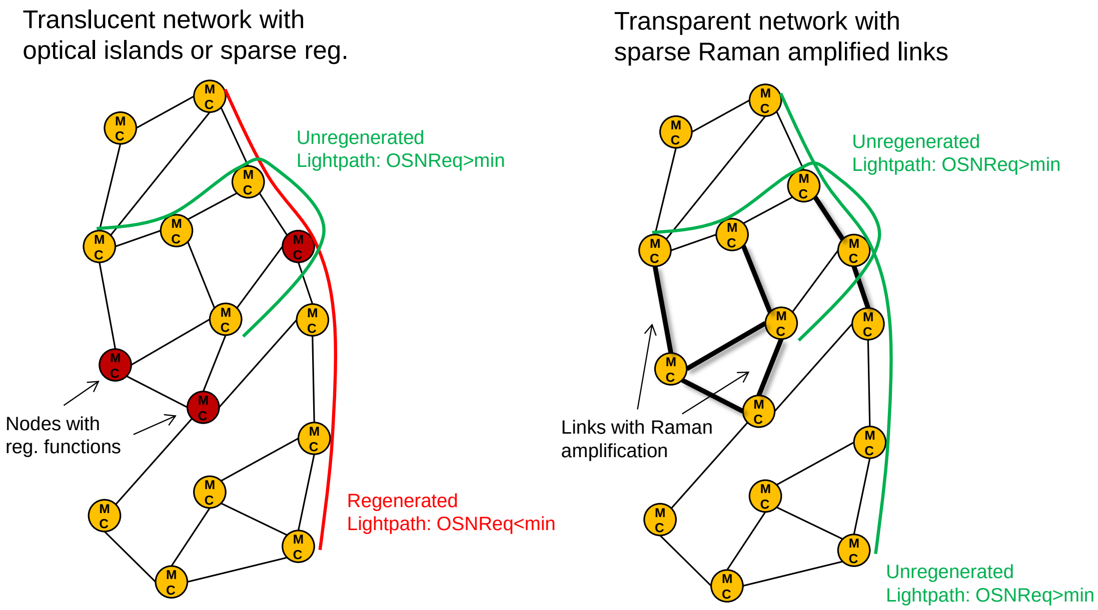


Figure 4: Illustration of the concepts of translucent network and transparent network with sparse Raman amplified links

Raman gain can be calculated from pump power and fibre characteristics but this is out of the paragraph scope. For calculation details see for instance [3]. The Raman gain profile of various types of fibres is shown in Figure 5.

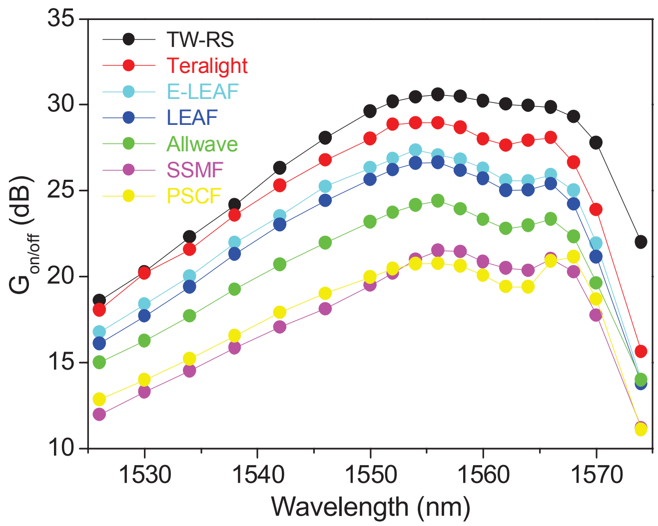


Figure 5: On/off Raman gain of various kinds of optical fibres. Fibre length is 100 km. Counter-propagating pump power and wavelength are 700 mW and 1455 nm respectively (from [9])

Raman amplifiers are relatively inexpensive; their cost is of the same order as EDFA and they are a very mature technology indeed. The only concern of Raman amplification technology is the high level of pump power that has to be launched into the fibre that may pose some operational problems (use of angled connectors on fibre terminations, connectors cleanness, etc.).

For the DISCUS core network, a reasonable trade-off between $OSNR_{eq}$ reduction and Raman amplification operational complexity is to set the Raman pump power and the related Raman gain so that to reduce the equivalent Noise Figure of the hybrid Raman-EDFA amplifiers by 3 dB using counter propagating pump only. This in turn produces a 3 dB reduction of the $OSNR_{eq}$. The Raman gain and the corresponding pump power to achieve this 3 dB $OSNR_{eq}$ reduction are shown in Table 2 for different fibre types and lengths.

Table 2: Calculation of Raman gain and pump power to attain a 3 dB reduction in the amplification section $OSNR_{eq}$, for different fibre types and lengths (G.655 LEAF fibre)

Fiber	Lspan [km]	Margin [dB]	Aspan [dB]	Raman Gain [dB]	Raman Pump [W]	EDFA gain [dB]
G.652	50	3,0	14,50	7,38	0,299	7,12
G.652	60	3,0	16,80	7,3	0,283	9,50
G.652	70	3,0	19,10	7,3	0,275	11,80
G.652	80	3,0	21,40	7,3	0,269	14,10
G.652	90	3,0	23,70	7,2	0,261	16,50
G.652	100	3,0	26,00	7,25	0,260	18,75
G.652	110	3,0	28,30	7,25	0,257	21,05
G.652	120	3,0	30,60	7,3	0,257	23,30
G.652	130	3,0	32,90	7,2	0,251	25,70
G.652	140	3,0	35,20	7,25	0,252	27,95
G.655	50	3,0	14,50	7,35	0,984	7,15
G.655	60	3,0	16,80	7,3	0,936	9,50
G.655	70	3,0	19,10	7,25	0,902	11,85
G.655	80	3,0	21,40	7,25	0,883	14,15
G.655	90	3,0	23,70	7,25	0,869	16,45
G.655	100	3,0	26,00	7,25	0,859	18,75
G.655	110	3,0	28,30	7,25	0,850	21,05
G.655	120	3,0	30,60	7,25	0,843	23,35
G.655	130	3,0	32,90	7,25	0,837	25,65
G.655	140	3,0	35,20	7,25	0,832	27,95

In terrestrial systems, Raman pump power of the order of 300-800 mW is typically enough for a 3 dB reduction of the equivalent noise figure. It is worthwhile to note that, if all network links were upgraded with Raman amplifiers with the characteristics of Table 2, all lightpaths' $OSNR_{eq}$ would be reduced by 3 dB. However, in most cases this is not necessary, and an optimisation procedure to minimise the number of Raman amplifiers can be implemented. An example of such procedure is shown below.

Algorithm 1 *Minimise the number of Raman links that makes the network transparent for a given modulation format on all shortest paths (i.e. the $OSNR_{eq}$ of all shortest paths is higher than $OSNR_{eq,min}$ of that format)*

for *each required modulation format (i.e different values of $OSNR_{eq,min}$)* **do**
  $OSNR_{eq}$ of all links is calculated by equations of D7.2
  $OSNR_{eq}$ of all shortest paths between any couple of nodes is calculated and the paths with $OSNR_{eq} < OSNR_{eq,min}$ are selected
  The links that are shared by the higher number of "non-transparent paths" are equipped with Raman amplifiers and the related $OSNR_{eq}$ is reduced by 3 dB
  Non transparent paths $OSNR_{eq}$ are checked and further Raman amplified links are added heuristically if required
  Repeat the procedure for the second shortest paths (physically disjoint from the working one) to guarantee protection and possibly to the third one for enhanced resilience
end for

Summarizing, the optical transparency can be adopted in all national European networks. For small networks (e.g. Ireland) the transparency is guaranteed by traditional EDFA links. For larger national networks, with 2000 km or larger diameter, the optical transparency is achieved by sparse Raman amplified links.

3 Main Optimisation Scenarios

In this section, we specify the optimisation problem associated with the interconnection of metro-core nodes in terms of its input, constraints and expected output for a single transparent optical island, single transparent optical island and a resilient optical island.

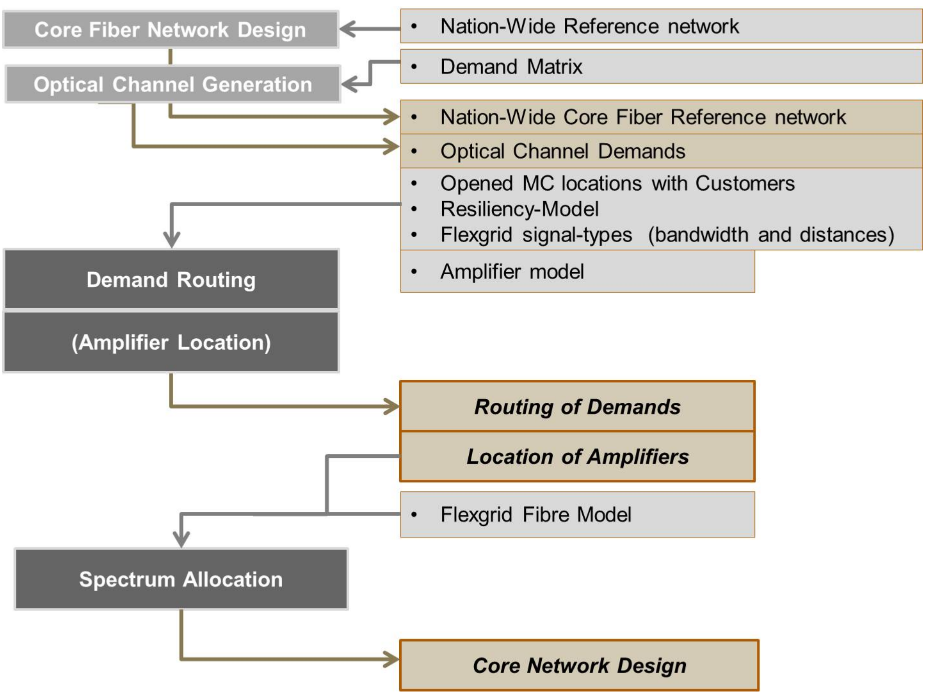


Figure 6: Core optimisation: Detailed view

In a transparent optical island it is desired that traffic stays in the optical domain between source and target of the traffic demand. Within a single optical island the structure of the virtual IP-layer is fixed, a full mesh. Also the virtual IP-routing is fixed, traffic is routed directly from source metro-core node to target metro-core node. It turns out that the overall problem for a single optical island reduces to a (single-layer) network design problem corresponding to the optical layer only. We briefly list out the outputs, constraints and objective involved in this problem. The following is the list of output for the core network:

- The physical links for connecting all pairs of metro-core nodes
- The selection of the number of optical channels and their types for each traffic request
- Routing path of each optical channel
- Slot and fibre allocation for each optical channel of each traffic request

Within an optical island the following constraints must hold:

- Each pair of metro-core nodes must be connected and the length of the shortest path can not exceed the maximum signal reach.
- The traffic request in Gbits/s between all pairs of metro-core nodes must be satisfied. That is, the signals established between the demand end-nodes should have a sufficient bitrate capacity in Gbits/s.
- The signal type and the assigned spectrum (bandwidth interval) must be consistent over its entire fibre route.
- The limit on the distance that each signal can travel must be respected.
- The capacity constraints of the node hardware (e.g. maximal number of connected fibres, maximal number of switched channels) must be respected if any.
- Raman amplification on fibres when signal reach is less than the length of the lightpath

The main objective is to minimise the capital expenditure by minimising the cost of physical links based on fibres/ducts/cables and amplifiers, and the cost for node hardware (OXC, Raman amplifiers, transponders etc.). Another objective could be to design the core network such that energy consumption is minimised.

The main solution process is described in Figure 6. We are given the potential nation-wide network topology (Italy, UK, Ireland) including a number of selected MC nodes and assumptions on the possible signal types as well as the resiliency. Moreover, we are given a demand matrix between these MC-nodes as explained in the previous section.

Before actually optimising the routing and spectrum allocation we have to consolidate the input. First we cannot start directly from the given fibre topology unless we believe that each of the links in this network may carry a core fibre, which is typically not the case. Instead we take the nation-wide street topology as input to a core fibre reference network design problem which results in a sub-network containing all potential core fibre links:

Core Fibre Network Design: In the network design subproblem we focus on minimising the total length of physical links required to connect metro-core nodes such that the length of the shortest path between any pair of metro-core nodes is less than the maximum signal reach. The reachability constraint ensures that the traffic can be sent between pairs of metro-core nodes without electronic-optical-electronic conversion. The objective is to minimise the cost of the physical links. Another objective could be to minimise the sum of the lengths of the paths between all pairs of nodes, and optionally each path could be multiplied with the value of the traffic. This in some sense tries to minimise the total length of fibres.

- Input: Reference network with MC locations, maximum signal reach constraint
- Output: A set of core network links required for connecting MC nodes

Secondly, the traffic demand between any two MC nodes is typically larger than the capacity of a signal channel. To come up with a set of channels between any two MC nodes we solve an Optical Channel Generation Problem:

Optical Channel Generation: Given the core fibre network and the traffic matrix the optical channel generation problem is to determine the partition of the traffic between a pair of MC nodes into a set of optical channels. The constraint is that there must exists a path between the pair of nodes such that its length does not exceed the reach of the signal. In this problem one can either minimise the number of channels or minimise the number of slots required for these demands.

- Input: Core network containing MC locations and links between them, traffic matrix, flex-grid signal types
- Output: A set of optical channels for each pair of MC nodes either based on minimising number of slots or number of channels, or cost of the transponders required for each channel.

At the center of the core optimisation is the Routing and Spectrum Allocation problem including the location of Raman amplifiers:

Routing. Given a network and a set of optical channels, the problem of routing is to find a route for each optical channel in the network from its source metro-core node to the target metro-core node such that the length of the path does not exceed the signal reach associated with the optical channel.

- Input: Network containing MC locations and links between them, flexgrid signal types, optical channels associated with each traffic request
- Output: Route for each optical channel subject to signal reach.

Spectrum Allocation. Given a network, a set of optical channels and a route for each channel, the spectrum allocation problem is to find assignment of slots to channels in a fibre subject to the continuity and contiguity constraints. The objective is to minimise the cost related with the number of fibres. Among many optimal solutions, we might wish to prefer those that use the spectrum in the most efficient way. In a certain sense we want a solution that leaves enough consecutive bandwidth slots for future capacity expansions.

- Input: Core network containing MC locations and links between them, flexgrid optical channels, association between channels and routes
- Output: Spectrum assignment for each channel.

Raman Amplification. A single transparent optical island might not be always be feasible for some large European countries because the distance between one or more pairs of metro-core nodes could be longer than the maximum optical signal reach. For such countries the goal would be to design a transparent optical island and use Raman amplifiers to increase the reach of the signals. For transparent optical island with Raman amplification one would also like to minimise the number of Raman amplifiers. Notice that one Raman amplifier is used for one fibre and the reachability of all the signals passing through that fibre is extended.

- Input: Core network containing MC locations and links between them, traffic matrix, flexgrid signal types, a set of optical channels for each traffic request, OSNR Tables, OSNR thresholds for different modulation techniques
- Output: Routing and Spectrum allocation for each channel and identifying fibres that require Raman amplification. The objective is to minimise the number of Raman amplifiers.

Resiliency. Survivability to metro-core node or link failure is very important for optical island as a single failure could disrupt the communication between millions of users. Therefore it is important to design resilient optical island that can survive in case of a failure of a node or a link. When designing resilient optical islands we want to provide node disjoint paths between all pairs of metro-core nodes so that each pair of nodes are connected when a failure occurs. We would also like to make sure enough spectrum is available so that all demands affected in case of a failure can be allocated slots in their alternate paths for transmission.

- Input: Reference network with MC locations and the links between them, flexgrid signal types, traffic matrix
- Output: Disjoint paths between each pair of MC-nodes and spectrum allocation for each traffic request. The spectrum will be allocated depending on the strategy used for protection paths.

4 Single Transparent Optical Island

In this section we focus on the design of transparent optical island. We assume that we are given a set of locations of metro-core nodes along with a potential fibre reference network, and a set of optical signals along with their reachability limits (i.e., Table 1) that could be used to transmit traffic between pairs of MC-nodes.

A link in a fibre reference network might already be ducted and might have fibres going through it or in some cases it might be just a potential link where fibre might be deployed in future. As this information is not available we assume that fibres need to be deployed in all links. Nevertheless, the models and the approach presented in the following sections can also be used when more precise information is given.

The main decisions for designing an optimal transparent optical island are *(*a) selecting a set of links where the fibres will be deployed, (b) determining a set of optical channels and (c) routing and allocating spectrum in fibres for each optical channel. The constraints are:

- All pairs of MC-nodes must be connected and there must exist at least one path between each pair of MC-nodes such that its length is less than the maximum signal reach of an optical channel.
- The total capacity associated with the optical channels must satisfy the traffic demand between a pair of MC-nodes. There exists at least one path for each optical channel such that its length is less than the reach of the optical channel.
- The length of every light-path in the network is consistent with the reach of the type of signal associated with the light-path. For spectrum allocation the contiguity constraint is enforced to ensure that if an optical channel requires k slots then k contiguous slots must be allocated to it. The continuity constraint is enforced so that the same k slots must be allocated on each link along the end-to-end path of an optical channel.

As the cost of different elements of the network is still being developed in the DISCUS project we analyse the cost of our solutions based on the total length of the links, the total length of the fibres, the maximum number of fibres in a link, and the number of optical channels.

It is unreasonable to attempt to solve the whole optimisation problem at once. Therefore we decompose the problem as shown in Figure 7.

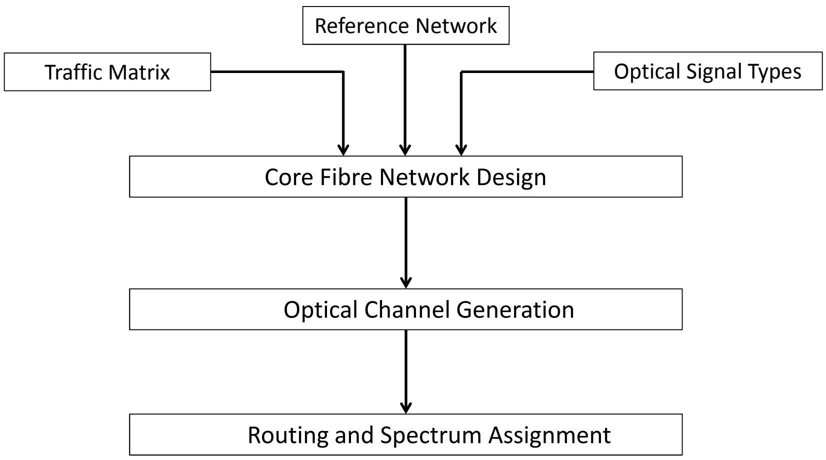


Figure 7: Solution approach

1. **Core Fibre Network Design**. In this phase we consolidate a given fibre reference network in to a smaller network. We select the pairs of nodes that we are going to interconnect. In this selection we make sure that all traffic requests can be satisfied using the selected links. That is, for each traffic request we make sure that the shortest path from the source to the destination (using the selected links) is shorter than the maximum signal reach in Table 1. When selecting the links we try to minimise the total length of the selected links followed by the total distances between all pairs of metro nodes. The intuition is that by having a smaller graph one might increase the sharing of resources and reduce the probability of failure of components.
2. **Optical Channel Generation**.

   Once the links have been selected, each traffic request is partitioned into a set of optical channels. In this phase the best reach feasible signal type for each light-path is selected with one of these objectives : (a) Minimise the number of slots (which helps in minimising total number of fibres), (b) Minimise the total number of optical channels which in turn minimises the total number of transponders (c) Minimise total cost of optical channels if the cost of transponders is known. Of course it is possible to generate optical channels with combination of these three criteria.

3. **Routing and Spectrum Assignment**. Given a set of optical channels per traffic request, the routing problem is to find a route for each optical channel. A mapping of an optical channel to a path is referred as a light-path. Thus, each light-path is associated with a set of links. Given a set of light-paths (denoted by $\mathcal{P}$), the spectrum allocation problem is to determine a set of slots for each light-path throughout the links in its route taking into account both the contiguity constraint (i.e., that the set of slots allocated to the light-paths need to be contiguous) and the continuity constraint (i.e., the same slots are used in all the links of the light-path). The objective is to minimise the total length of the fibres and reduce the maximum number of fibres in a link.

4.1 Network Design

In the context of the DISCUS project the premise is that when the number of core-nodes is sufficiently small (because of their long reach in the access part) they can be directly connected together via circuit-switched optical channels. Here the direct connection means that no traffic is dropped or added at the intermediate nodes that are physically traversed by the fibre route between a source and destination node. An optical island can be defined as a set of nodes that are fully interconnected by a set of transparent wavelength routes (lightpaths). The advantage is the absence of Optical-Electrical-Optical (OEO) conversions and the reduction in switching, routing and packet processing in the metro-core nodes. The disadvantage is that as the number of metro-core nodes, denoted by n, grows, the possible number of physical connections to interconnect metro-core nodes can grow quickly and in the worst-case it could be $n(n-1)$. Therefore, it is important to minimise the number of links while guaranteeing a full mesh of optical (wavelength) channels between metro-core nodes.

Let $\langle V, R\rangle$ be a given reference core network. Here V is a set of nodes subsuming MC nodes, junction nodes, local exchanges etc. and R is the set of available links between them. For the purpose of solving optimisation problems related with transparent optical island we compute metro-node reference network $\langle N, L\rangle$ where $N \subseteq V$ is the set of locations of metro-core nodes and L is the set of links between pairs of metro-core nodes that denote fibre routes between pairs of core-nodes. To be precise, if $\langle i, j\rangle \in L$ then there exists a path in the original reference network $\langle V, R\rangle$ when we exclude all the other metro nodes different to i and j, and we use the length of shortest path as the length of the link. This is done to ensure that a link connecting two metro nodes in the transformed core reference network does not refer to a path that involves another metro node. It is important to emphasise the need of removing the other metro nodes when computing the shortest path of a pair of metro nodes. Notice that if we do not remove the metro nodes this could lead to an under estimation of the capacity deployed in a given link. Note that links of L are actually paths in the original reference network which traverse multiple links of R. If two links in the metro node reference network share road links, those shared links will carry the fibre assigned to both metro core links. Ideally we would like the set of links in the core reference network to be mutually disjoint. The approach above is a first step towards that objective.

Checking the existence of an optical island for a given set of core nodes is a task that can be carried out in time polynomial in the size of the network. It can be verified by checking that the shortest path between each pair of core-nodes is within the maximum reach of at least one of the available optical signals. Notice that in the core fibre network design problem we are restricting our attention to computing a smallest physical network that allows to send traffic between any pair of nodes without OEO conversion. In general the problem of finding an optimal optical island is NP-hard. This can be shown by reducing the constrained-shortest path problem [16] to our problem. Nevertheless, if the diameter of the Minimum Spanning Tree (MST) of the graph corresponding to (N, L) is less than the maximum signal reach then the solution of the minimum spanning tree will be optimal with respect to the cost.

4.1.1 Mathematical Formulation

In this section, we present an Integer Programming (IP) formulation for designing an optical island for a given set of metro-core nodes, N, by selecting a subset of a given set of physical links L.

Notations. Let $\langle N, E\rangle$ be a directed metro core reference network. Each link $l \in L$ is associated with two directed edges in E for the corresponding pair of metro core nodes. The two edges $\langle i, j\rangle$ and $\langle j, i\rangle$ in E are associated with the same link $\{i, j\}$. We will say that a link is used if one of its edges is used. We enforce that the traffic going from metro node i to metro node j follows the same route as the traffic going from metro core node j to metro core i. That is, there is only one link between a pair of metro nodes but traffic flows in both direction. In the following model we refer to the elements of E as edges. The length of link $e \in E$, is denoted as $|e|$.

A traffic request τ, from the set of traffic requests $\dagger$, is directed from source $s(\tau)$ to target $t(\tau)$. We use the notation $\texttt{In}(n)$ ($\texttt{Out}(n)$) to denote all edges entering (leaving) node n.

Let λ denotes the maximum reach of any allowed optical signal, which is 2430km based on Table 1.

Variables. A binary variable $x_{\tau e}$ is true if and only if edge e is used for traffic request $\tau \in \dagger$. A binary variable y_l is true if and only if link $l \in L$ is included in the optical island.

Objective. The objective is to minimise the length of the links included in the optical island and the total distances between all pairs of metro-core nodes. To formulate this multi-criteria objective function, we use weighted-sum method [13] as in the following:

$$\min \alpha \times \sum_{l \in L} |l| \times y_l + \sum_{\tau \in \dagger} \sum_{e \in E} |e| \times x_{\tau e} \tag{1}$$

Here α is a carefully chosen value which is greater than the total distances between all pairs of metro-core nodes and give higher priority to the total cost of links.

Constraints. A link l between nodes i and j is selected if any corresponding directed edge between them is used by any traffic request:

$$\forall_{\tau \in \dagger} \forall_{l \equiv \{i,j\} \in L} \forall_{e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}} : y_l \geq x_{\tau e} \tag{2}$$

For each traffic request, no route should reach the source or leave the target and exactly one edge must leave (reach) from (to) the source (the target).

$$\forall_{\tau \in \dagger} : \sum_{e \in \texttt{In}(s(\tau))} x_{\tau e} = 0, \quad \sum_{e \in \texttt{Out}(s(\tau))} x_{\tau e} = 1 \tag{3}$$

$$\forall_{\tau \in \dagger} : \sum_{e \in \texttt{Out}(t(\tau))} x_{\tau e} = 0, \quad \sum_{e \in \texttt{In}(t(\tau))} x_{\tau e} = 1 \tag{4}$$

At each intermediate node the incoming degree should be equal to the outgoing degree:

$$\forall_{\tau \in \dagger} \forall_{i \in N \setminus \{s(\tau), t(\tau)\}} : \sum_{e \in \mathtt{In}(i)} x_{\tau e} = \sum_{e \in \mathtt{Out}(i)} x_{\tau e} \tag{5}$$

The length of the route from source to target cannot exceed the threshold:

$$\forall_{\tau \in \dagger} : \sum_{e \in E} |e| \times x_{\tau e} \leq \lambda \tag{6}$$

4.1.2 Solution Method: Large Neighbourhood Search

Even for the small instances, solving the IP model is intractable [16]. Hence, we propose a Large Neighbourhood Search (LNS) [12] approach for designing an optical island in the Core Network. LNS attempts to combine the power of systematic search with the scalability of local search. The overall solution method is shown in Figure 8. We first find the initial routes for all pairs of metro-nodes. We maintain a current solution, which is initialised with the initial solution. At each iteration we select a subset of the pairs of metro-nodes for recomputation of their routes and, accordingly, create the sub-problem. We solve the resulting sub-problem, and keep the best solution found as our new current assignment if it is improving. The search stops when the total elapsed time is greater than the given time threshold. Details of the procedure are shown in Algorithm 2. Other methods that are used in Algorithm 2 are described in Appendix.

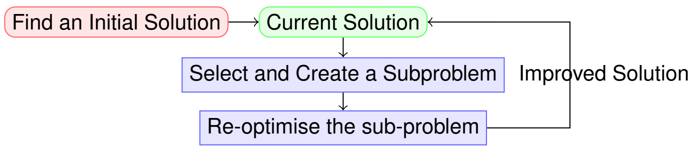


Figure 8: Principle of the LNS approach.

Algorithm 2 starts with finding a lower bound for evaluating the quality of the solution (line 4). This lower bound is computed based on the total length of the links in the minimum spanning tree (see Algorithm 8 in Appendix for details). A greedy approach is then used to find an initial solution (line 5). The greedy approach, Algorithm 3 in Appendix, is based on finding the cheapest (in terms of the total length of the links and the paths) links to connect source ($s(\tau)$) and target ($t(\tau)$) nodes of any traffic request (τ) starting from the closest ones. First, all traffic request are sorted in ascending order of the distances between the source and the target nodes. Thus, each traffic request is associated with a subproblem. The problem of constructing cheapest feasible paths for each traffic request is decomposed into a sequence of subproblems which are solved starting with the first pair in the sorted list. In each iteration of the decomposition scheme, the IP model given in Figure 23 is solved for only one traffic request (τ) and the cheapest (i.e., in terms of the total length of the links used) shortest path is found between $s(\tau)$ and $t(\tau)$. When the decomposition scheme starts to solve the next traffic request, the cost of links which are used by metro-core node pairs of previous iterations are reduced to zero. Hence, for the metro-core node pair $< s(\tau), t(\tau) >$ of any traffic request τ, using previously selected links will be cheaper than using a new link and therefore it reduces the number of links used overall. However, because of the myopic structure of the decomposition scheme, the resulting number of links and the total length of the links will be sub-optimal. For example, a link that is added to the network in the later iterations of the decomposition algorithm may enable to remove some links added in the previous iterations. Therefore, a refinement method is called (see Algorithm 4 in Appendix) to remove such redundant links.

Before starting to search for improving the initial solution, the algorithm checks the quality of the current solution (Line 6). If the size of the initial solution equals the size of the minimum spanning tree, then algorithm stops (Line 7). Note that optimality of a solution is measured by both the total length of the links and the total number of links (see Algorithm 9 in Appendix) . Else, searching for a better solution starts (Line 8) by assigning the initial refined solution as the best solution.

Neighbourhood search tries to improve the refined initial solution by repeatedly selecting and solving subproblems. Each traffic request τ is associated with a path, that is a set of edges, $path^b_\tau \subset E$. Search starts with sorting each link $l \in L^b$ in the best solution based on their support value in which refers to the number of links $l' \in L \setminus l$ that has at least one common metro-node pair path ${path^b}_\tau$ with l (line 9). Sorting method (Algorithm 10 in Appendix) which uses the number of paths relying on each link, $|relying_{l^b}|$, (Algorithm 5 in Appendix) also takes into account the usage frequency and the length of the links in case of a tie.

Then, search is triggered for each depth of neighborhood $d \in \{1, 2\}$ (line 10) where d refers to the number of links removed from the best solution to create a set of subproblems. Once the links are selected via selection method (Algorithm 12 in Appendix), set of subproblems are created by all paths relying on the selected links (Algorithm 13 in Appendix) as shown in lines 15 and 16. For solving the set of subproblems (line 18) we call another optimisation method (Algorithm 15 in Appendix) which is based on removing the path of traffic requests relying on the selected links and searching for better ones.

Re-optimisation is ensured by calling a decomposition scheme for every traffic request within the set of subproblems as in the initial solution method. After each iteration of the decomposition scheme, we update the set of used links and their costs are reduced to zero for the next iteration.

However, different then the decomposition scheme in the initial solution method, once a new path is constructed for the current traffic request, before going to the next traffic request in the set of subroblems, we compare the size of the current network and the best solution using Algorithm 15 in Appendix, line 38 to check whether the size of the current network becomes larger than the best one or not. If the size is less than the best solution, it points out that the current set of subproblems is promising (Algorithm 15, line 39) and re-optimisation continues for the remaining subproblems. Else, re-optimisation algorithm terminates and search continues with selecting a new set of links and new set of subproblems until stopping conditions (line 14) are met which are given in Algorithm 11 in Appendix.

Note that, if the current set of subproblems is promising, in the re-optimisation algorithm it is possible that links added in the last step of the decomposition method may also resolve some set of subproblems which will be considered in the next iterations. Hence, removing these already solved subproblems from the set of subproblems will speed up the re-optimisation process. Therefore, before the next iteration of the decomposition procedure, a refinement algorithm is executed (Algorithm 14) which removes some set of already solved subproblems (i.e. traffic requests) the set of subproblems (Algorithm 15 in Appendix, line 40).

If there is an improvement at the end of re-optimising the set of subproblems (line 27), then the updated solution is compared with the lower bound. Since some links are removed from the network and some others are included, even if the solution is not optimal, the set of paths relying on each link is re-computed (line 24) and it is recorded that there is an improvement. Links are not re-sorted until all selected links sorted at the beginning are tested. When all selected links are tested, if there is at least one improvement while searching with the current depth d, the search restarts with the same value of d by re-sorting links and initializing the link selection variables (line 28). Otherwise, next links are selected and search continues until all link selection combinations in depth d are tested without any improvement.

Algorithm 2 *Large Neighbourhood Search Algorithm for Designing an Optical Island in the Core Network*

Input: $n \in N$, $N^{source} \subset N$, $l \in L$, $e \in E$, $\tau \in \dagger$, $s(\tau)$, $t(\tau)$, c_l, $\texttt{In}(n)$, $\texttt{Out}(n)$, $E^b \subset E$, $L^b \subset L$, $L^c \subset L$, $L^* \subset L^b$, $E^c \subset E$ $l^b \in L^b$, $l^c \in L^c$, $l^* \in L^*$, $e^b \in E^b$ $path^b{}_\tau \subset E$, $path^c{}_\tau \subset E$, $relying_l \in \dagger$, $S \subset \dagger$, $TimeLimit$
Initialize all sets as empty sets
$minlength = 0$
LOWERBOUND(N,L)
Find an initial best solution $[L^b, path^b{}_\tau]$=INITIALSOLUTION(E,L)
if OPTIMAL(NETWORKSIZE(L^b),$|L^b|$) **then**
    return $[L^b, path^b{}_\tau]$
else
    Sort the set of links in the best solution SORT(L^b)
    for $d \in \{1, 2\}$ **do**
        $firstlinkindex_d = 0$
        $secondlinkindex_d = d - 1$
        $improve = false$
        while $\neg$ STOP() **do**
            Select a set of links, L^*=SELECT(L^b,$firstlinkindex_d$,$secondlinkindex_d$)
            Create a set of sub-problems, S=CREATE(L^*)
            $update = true$
            Re-optimise S, $[L^b, path^b{}_\tau]$=REOPTIMISE(S,L^*,L^b,$path^b{}_\tau$)
            if $update$ **then**
                if OPTIMAL(NETWORKSIZE(L^b),$|L^b|$) **then**
                    return $[L^b, path^b{}_\tau]$
                    break
                end if
                FREQUENCY(L^b)
                $improve = true$
            end if
            if $firstlinkindex_d = |L^b| - d \wedge secondlinkindex_d = |L^b| - 1$ **then**
                if $improve$ **then**
                    SORT(L^b)
                    $improve = false$
                    $firstlinkindex_d = 0$
                    $secondlinkindex_d = d - 1$
                end if
            else
                if $firstlinkindex_d < |L^b| - d \wedge secondlinkindex_d = |L^b| - 1$ **then**
                    $firstlinkindex_d + +$
                    $secondlinkindex_d = firstlinkindex_d + d - 1$
                else
                    $secondlinkindex_d + +$
                end if
            end if
        end while
    end for
end if
Output: $[L^b, path^b{}_\tau]$

4.2 Optical Channel Generation Problem

Given a traffic-request τ between a pair of MC-nodes, the Optical Channel Generation Problem (OCGP) is to generate optical channels that can satisfy the request. Given a traffic-request $\tau \in \dagger$, we use the notation $V(\tau)$ to denote the traffic that flows from metro-core node $s(\tau)$ to metro-core node $t(\tau)$. Given a signal type $\phi \in \Phi$, we use b_ϕ and ns_ϕ to refer to the capacity and the number of slots of a signal of that type. Let Φ_τ denote the set of signal types that could be used whose reach limitations can be respected for the traffic-demand τ in the core fibre network obtained in the previous section. Given the available signal types to minimise the interface cost (IP port-card, transponder on both ends) over the traffic requirement constraint

$$\sum_{\phi \in \Phi_\tau} b_\phi x_\phi \geq V(\tau), \quad x_\phi \in \mathbb{Z}^+ \tag{7}$$

where the decision variables $x_\phi \in \mathbb{Z}^+$ count the number of channels of type ϕ used traffic-request τ. The objective could be to minimise the total cost of transponders cost if the cost functions are given, otherwise it can be be approximated by

1. minimising the number of slots which could help in minimising the number of fibres

$$\min \sum_{\phi \in \Phi} ns_\phi x_\phi \tag{8}$$

2. minimising the number of optical channels which could help in minimising the number of transponders

$$\min \sum_{\phi \in \Phi} x_\phi \tag{9}$$

4.3 Routing and Spectrum Allocation

In our experiment we are routing optical channels via their shortest paths on the computed links obtained during the network design phase. We remark, though, that we are not forced to do so. In fact it could be sensible to

Given the core network and a set of optical channels, the problem now is to find a route for each optical channel in the core network and allocate spectrum. We use shortest path for each optical channel. In principle not all optical channels associated with a traffic request need to be routed through the same shortest path. However, when the selected links in the first phase form a spanning tree, routing optical channels via their shortest paths is the only way of transmitting the traffic request. Other routing strategies that lead to a more load-balanced fibre allocation to links would be considered in future.

After the routing phase we are left with a set of lightpaths (denoted by $\mathcal{P}$), where each lightpath $p \in \mathcal{P}$ is associated with the number of slots that we need to allocate (denoted by $\omega(p)$). Each lightpath p is also associated with a set of links (E_p). Our task is then to allocate slots to lightpaths taking into account both the contiguity constraint (i.e., that the set of slots allocated to the lightpaths need to be contiguous) and the continuity constraint (i.e., the same slots are used in all the links of the lightpath).

In what follows we use $\mathcal{S}$ to denote the set of slots available in a spectrum and $\mathcal{F}$ to denote the domain of fibres available at any link. Let us assume that both $\mathcal{S}$ and $\mathcal{F}$ are sets of continuous integers starting from 1 (i.e., $\mathcal{S} = \{1 \ldots |\mathcal{S}|\}$ and $\mathcal{F} = \{1 \ldots |\mathcal{F}|\}$). Our task is to take the following decisions for every lightpath p:

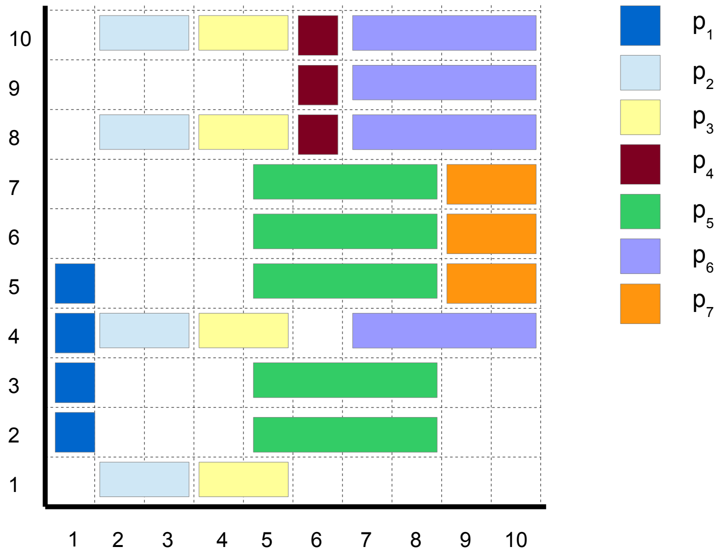


Figure 9: A visual representation of a solution of the the slot allocation problem where 7 paths are assigned to their slots. The network of 10 links contains one fibre per link and each fibre has a spectrum of 10 slots.

- where to place the path in the spectrum ($z_p \in \mathcal{S}$), i.e., $z_p = s$ means that p is using slots $s \ldots s + (\omega(p) - 1)$ across all links.
- which fibre to use at every link e ($f_p^e \in \mathcal{F}$), i.e., $f_p^e = f$ means that p is using fibre f at link e.

The aim is to minimise $|\mathcal{F}|$ such that the non-overlapping constraints between each pair of paths p_1 and p_2 sharing a link are maintained:

$$E_{p_1} \cap E_{p_2} \neq \emptyset \Rightarrow (z_{p_2} \geq z_{p_1} + \omega(p_1)) \vee (z_{p_1} \geq z_{p_2} + \omega(p_2))$$

Figure 9 shows a visual representation of an allocation of 7 paths to slots in a network of 10 links containing one fibre per link. In this example, each fibre has a spectrum of 10 slots. For instance, lightpath 1(p_1), which uses links 2, 3, 4 and 5, has been given slot 1 since it only requires one slot. p_2, which uses links 1, 4, 8 and 10 has been given slots 2 and 3 and so on.

As mentioned above the decision to be taken for each lightpath is where to place the wavelength in spectrum (z variables) and which fibre should be used at every link (f variables). In the example there is only one fibre per link so $f_{p_i}^j = 1$ for each path p_i where $1 \leq i \leq 7$, and for each link j where $1 \leq j \leq 10$. When it comes to the allocation of slots, we observe that $z_{p_1} = 1$, $z_{p_2} = 2$, $z_{p3} = 4$, $z_{p_4} = 6$, $z_{p_5} = 5$, $z_{p_6} = 7$ and $z_{p_7} = 9$.

In this simple example we only have one fibre per link, so assuming that we set z_{p_5} to 5, we could either assign z_{p_7} to 9 or to a value less than or equal to 3. However, if we had a second fibre available in the link the assignments $\{z_{p_7} = 5, f_{p_7}^5 = 2, f_{p_7}^6 = 2, f_{p_7}^7 = 2\}$ would be also consistent since p_7 would not be overlapping with p_5 in that case.

Approach. The optimisation problem is NP-Hard ([5]). We implemented a heuristic that provided us with solutions close to optimal with respect to the maximum number of fibres spent per link:

1. The links are weighted depending on the number of lightpaths using them.
2. The lightpaths are weighted depending on the weight of their links.
3. The lightpaths are allocated in decreasing order with respect to their weight.

When allocating a lightpath we place it in the first slot where the lightpath fits.

4.4 Empirical Results

To demonstrate the feasibility of having a single flexgrid transparent optical island and the effectiveness of approaches as presented in the previous sections, we study the networks corresponding to three countries: Ireland, UK and Italy. For each network we obtain optical islands for different number of metro-core nodes and analyse the corresponding optical channels and spectrum assignment solutions. For Ireland we use 18, 20, 22 and 24 as the numbers of metro-core nodes, for UK we use 74, 79, 84, 89, 94, 99 and Italy 132 and 189. For Italy atesio provided us the Italian reference network therefore actual road distances were used. For Ireland and UK we did not have the reference network and therefore we use the Euclidean distance multiplied by a routing factor value of 1.6[1]. The locations of metro-core nodes for each network were computed as a part of the work done in Task 4.4 by considering dual-homing coverage criterion.

4.4.1 Core Fibre Network Design

In the network design phase we take the initial reference network and consolidate the connections between pairs of MC nodes by reducing the initial network as much as possible. More precisely, we remove a set of links while maintaining connectivity (and reachability) between all pairs of nodes. On the one hand this could reduce the cost of deploying fibre but on the other hand it might reduce the application of flexgrid technology. The reason is that as the sum of the total length of all the links decreases the average length of the shortest path would increase in which case it might force to use optical channel associated with longest reach. Consequently, this might increase the number of optical channels and hence the cost of transponders. Thus, there is a trade-off between the total lengths of the links and the number of optical channels. We analyse this trade-off and present the results for both the initial reference network and the ones that we obtained after minimising the distance based cost. The former is denoted by **Initial Design** while the latter is denoted by **Minimum Distance Design**.

Table 3 shows the minimum, maximum and median lengths of links between pair of metro-core nodes in the initial design and the minimum distance design that is obtained with the large neighbourhood search Algorithm 2. Results show that, while LNS keeps the shortest links in the initial design, it is also successful in reducing the average link lengths. As the network grows, the benefits of minimum distance design network becomes more apparent.

In Table 4, the resulting size of each network in terms of the number of links, the total length of the links selected for optical island design, the total length of the paths between all pairs of MC nodes, and the diameter of the optical islands is presented. The lower bound (LB) is computed using minimum spanning tree and the upper bound (UB) is computed using LNS algorithm. Notice that when the diameter of the minimum spanning tree (i.e., the longest distance between any pair of metro-core nodes) is less than the maximum signal reach, optimal transparent island

[1] At the time of writing this deliverable both Irish and UK reference network were made available which we will use in our future work

Table 3: Link statistics in the initial and the minimum distance networks

Network	Number of Metro Nodes	Link Lengths (km)					
		Initial Design			Minimum Distance Design		
		Min	Max	Median	Min	Max	Median
Ireland	18	24.90	509.02	215.74	24.90	117.97	76.05
	20	38.22	557.52	222.18	38.22	103.90	74.08
	22	30.07	549.13	209.11	30.07	134.56	64.80
	24	27.46	576.32	232.77	27.46	125.60	73.87
UK	74	16.50	1747.41	514.33	16.50	193.96	75.55
	79	6.51	1751.29	514.85	6.51	193.96	77.23
	84	9.86	1761.31	504.28	9.86	196.61	70.54
	89	7.90	1751.29	496.55	7.90	193.96	70.29
	94	13.72	1754.03	482.02	13.72	196.61	60.50
	99	7.90	1748.13	500.87	7.90	193.96	67.49
Italy	132	2.10	1779.44	620.91	2.10	383.08	51.52
	189	8.26	1843.60	612.36	11.71	401.07	60.97

is found and there is no need to run LNS algorithm. This is the case in Ireland network with all metro-core nodes options. In contrast to Ireland network, diameters of the minimum spanning tree solutions for all metro-core node instances of UK and Italy network are greater than the maximum signal reach. Hence, the LNS algorithm is used for these instances, However, in Table 4, minimum spanning tree solution is used as a lower bound to compare the quality of the LNS solutions. Last column in Table 4 shows that duality gap is varying between 0.39% and 6.90% which means the resulting networks for UK and Italy are quite reasonable in terms of minimising the distance based objective function (see Equation 1). We remark that the network forms of all the transparent optical islands for Ireland, UK and Italy turned out to be spanning trees but this may not be true for other European countries.

Table 4: Transparent network results (LB:Lower Bound, UB: Upper Bound)

Network	Number of Metro Nodes	Total number of Metro-node Pairs	Solution	Number of Links	Total Length of the Links (km)	Total Length of the Paths (km)	Diameter (km)	Duality Gap (%)
Ireland	18	306	Optimal	17	1313.72	110310.00	782.76	-
	20	380	Optimal	19	1400.16	143010.00	917.91	-
	22	462	Optimal	21	1416.20	187277.00	897.39	-
	24	552	Optimal	23	1645.05	237596.00	1135.32	-
UK	74	5402	LB	73	5506.02	6446532.57	3442.84	-
			UB	73	5527.76	5298129.86	2417.94	0.39%
	79	6162	LB	78	6010.46	6838256.22	3091.49	-
			UB	78	6020.33	5810867.84	2407.32	0.16%
	84	6972	LB	83	5942.87	8000445.08	3176.15	-
			UB	83	5991.54	6722330.53	2426.57	0.81%
	89	7832	LB	88	6198.15	9088205.67	3128.95	-
			UB	88	6241.69	7535329.14	2414.74	0.69%
	94	8742	LB	93	5948.81	8531777.00	2739.60	-
			UB	93	6044.67	7792802.50	2427.20	1.58%
	99	9702	LB	98	6479.59	10087836.60	2918.00	-
			UB	98	6520.63	8475946.01	2428.48	0.62%
Italy	132	17292	LB	131	7124.02	19799333.80	2973.77	-
			UB	131	7273.75	17142407.12	2410.11	2.05%
	189	35532	LB	188	11299.70	42619208.21	3367.09	-
			UB	188	12137.00	35099869.79	2425.95	6.90%

Table 5: Signal Type Distributions for Initial and Min Distance Network Designs

Netwok	Number of Metro Nodes	Total Number of Metro-node Pairs	Diameter (km.)		Signal Reach (km) of each signal type and number of pair of metro-nodes that can be served with that signal in the best solution					
					2430 km		1170 km		500 km	
			Initial Design	Min. Dist. Design	Initial Design	Min. Dist. Design	Initial Design	Min. Dist. Design	Initial Design	Min. Dist. Design
Ireland	18	306	509.02	782.76	306	306	306	306	304	230
	20	380	557.52	917.91	380	380	380	380	374	286
	22	462	549.13	897.39	462	462	462	462	458	298
	24	552	576.32	1135.32	552	552	552	552	542	350
UK	74	5402	1747.41	2417.94	5402	5402	5070	3500	2580	1182
	79	6162	1751.29	2407.32	6162	6162	5800	4190	2922	1338
	84	6972	1761.31	2426.57	6972	6972	6588	4504	3406	1516
	89	7832	1751.29	2414.74	7832	7832	7412	5102	3902	1682
	94	8742	1754.03	2427.20	8742	8742	8328	6294	4490	2136
	99	9702	1748.13	2428.48	9702	9702	9164	7048	4792	2380
Italy	132	17292	1779.44	2410.11	17292	17292	15218	10976	6752	3432
	189	35532	1843.60	2425.95	35532	35532	31374	23380	13910	5770

We now focus on the impact of considering a minimum size optical island on the application of flexgrid technology. As mentioned before if we reduce the network size then on average the length of the paths between pairs of MC nodes will increase and this might inhibit or skew the distribution of applicability of signals associated with different reachability limits. We analyse this in Table 5 for Ireland, UK and Italy for both initial network design and minimum distance transparent networks. It is recalled that there are six signal types as shown in Table 1 and there are 3 different distance limits (in km): 2430, 1170 and 500. Results show that as the diameter of the network increases, the number of metro node pairs which can be served with shorter reach signal types reduces not only for the minimum distance design but also for the initial network design.

Detailed coverage percentages of signal types with 500 km and 1170 km signal reaches are presented in Figures 10, 11 and 12 for each network with both initial and minimum distance designs. The results for 2430 km signal reaches are not plotted because the network is designed as a transparent optical island and hence coverage is 100%. Note that, since the diameter of minimum distance design is less than 1170 km for each instance of Ireland, only 500 km signal reach is considered in Figure 10. It is interesting to observe that for minimum distance design Italy network with 189 metro-core nodes, as shown in Figure 12, only 16% of the pairs of MC nodes can be served with 500 km signal type.

Figure 10: Coverage percentages of 500 km signal reach in initial and min distance design of Ireland network

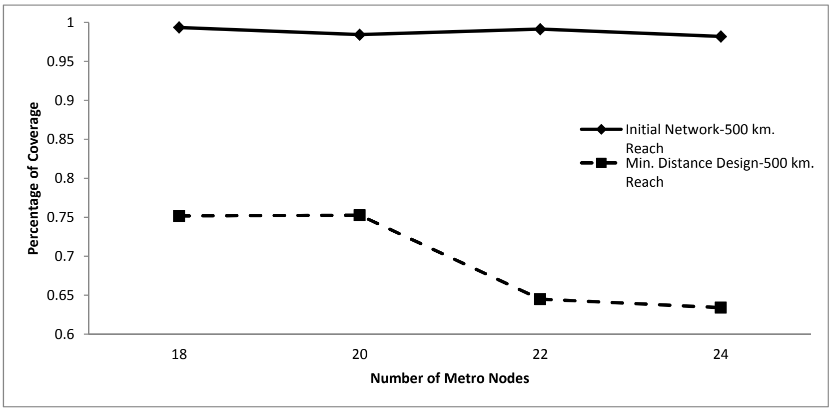


Figure 11: Coverage percentages of 500 km and 1170 km signal reach in initial and min distance design of UK network

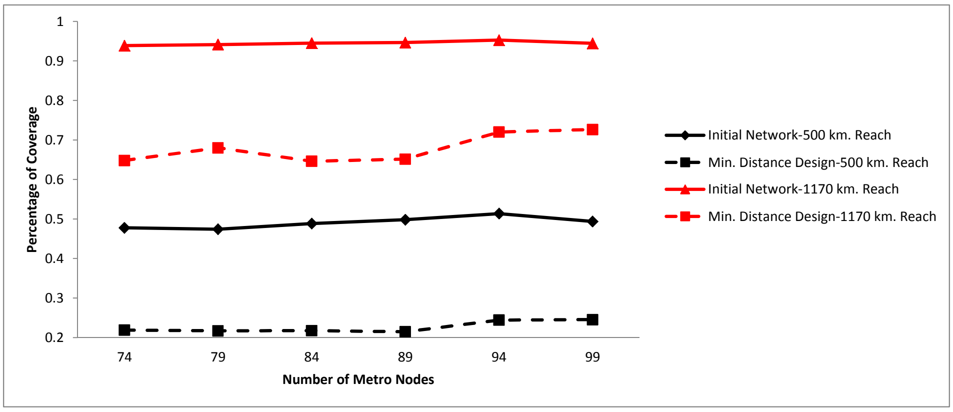
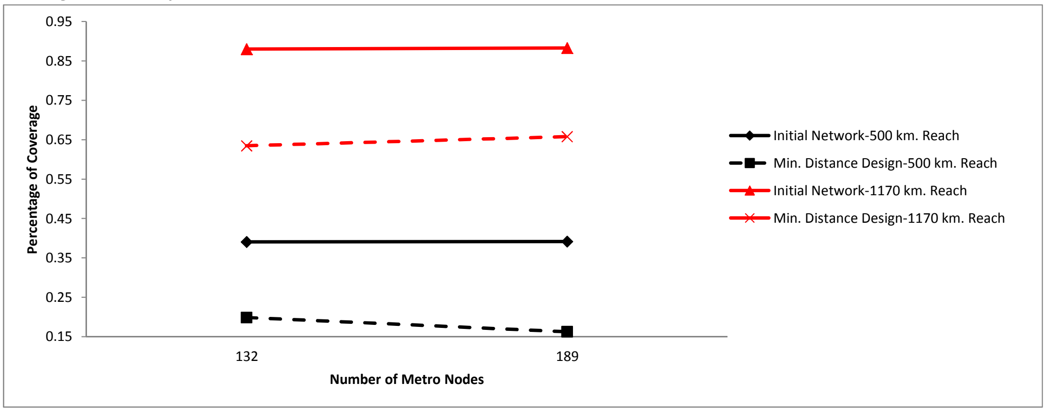


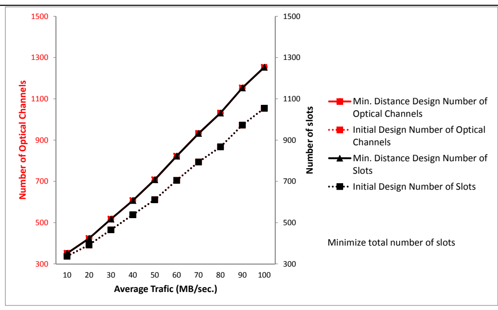
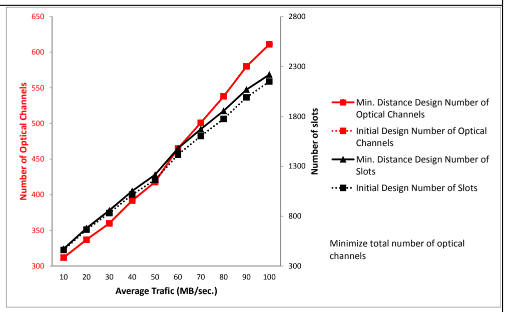
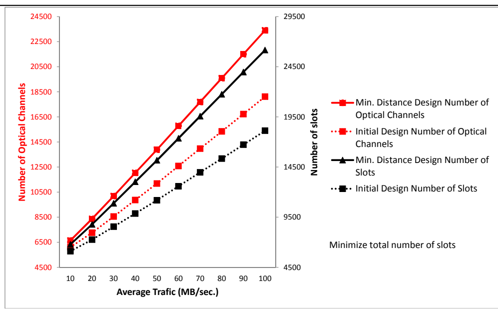
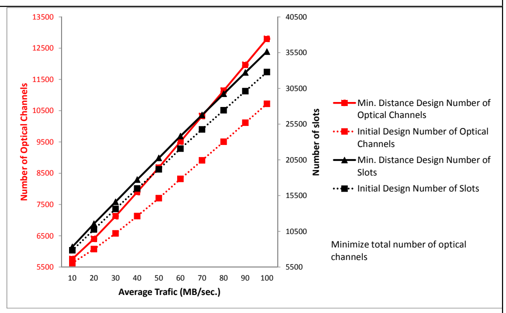
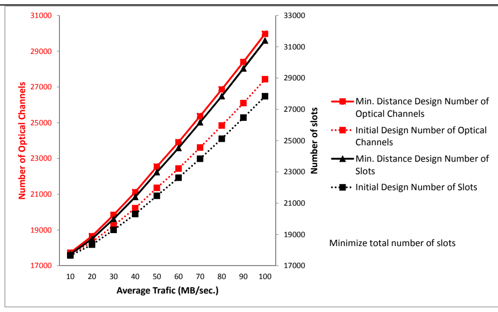
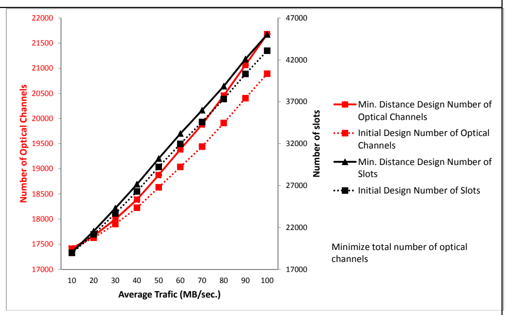
Figure 12: Coverage percentages of 500 km and 1170 km signal reach in initial and min distance design of Italy network



4.4.2 Optical Channels

Given a core network, we analyse the impact of increasing the average user traffic on the total number of optical channels and total spectrum requirement. Notice that optical channels are generated with two alternative objectives (1) minimising the number of slots and (2) minimising the number of optical channels (see Section 4.2). In each graph we plot both the number of optical channels and slots using two y-axis. All the results are depicted in Table 6 for both the initial and the minimum distance design of all networks. Note that we only present results for the smallest number of metro-core node designs that are considered for each network. Nevertheless, same pattern is observed for other numbers of metro-core nodes for different networks. First of all, results show the negative correlation between two criteria. However, regardless of the objective considered, increasing the average traffic will increase the number of optical channels generated and slots used which also means increasing the number of transponders and fibres. Another interesting insight from Table 6 is for Ireland both minimum distance and initial network designs require the same number of optical channels when the number of optical channels is minimized. The reason is that the network topology is too small as such the increasing the path length does not require increasing the number of optical channels thanks to capacity of 1170 km reach signals. While the number of optical channels with 500 km signal reach decreases in the minimum distance design, the number of optical channels with 1170 km signal reach increases the same amount. See Table 7 and Table 16 in Appendix for details.

Table 6: Total number of slots and optical channels generated for initial and minimum distance design of each network with different objectives and smallest number of metro-nodes

Network	Minimize Total Number of Slots	Minimize total Number of Optical Channels
Ireland (18)		
UK (74)		
Italy (132)		

The number of optical channels generated for each of the signal types in Table 1 are shown in Tables 7, 8 and 9 respectively. In these plots, it is observed that when the number of slots used is minimized, signal types with less slot requirements tend to be used. In contrast, when the number of optical channels is minimised, signal types with higher capacity are selected and slot requirements are not taken into account. Hence, another cost based optimisation criteria might yield more reasonable results and might combine these two objectives. However, the difference on the signal type assignments tends to be reduced as the network size increases.

Table 7: Analysis of signal type distribution for Ireland with each network design and optical channel generation method

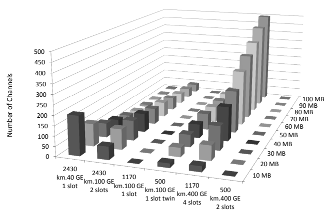
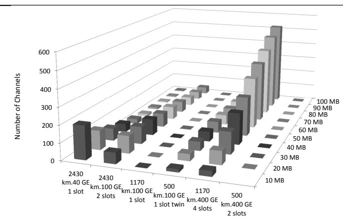
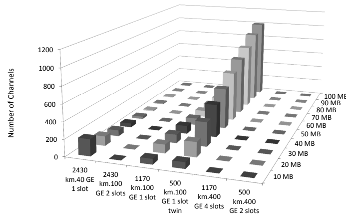
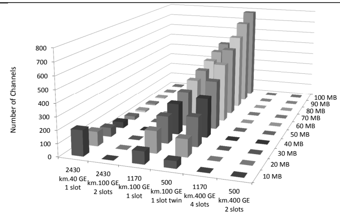
Minimize Total Number of	Initial Network	Min. Distance Network
Optical Channels		
Slots		

Table 8: Analysis of signal type distribution for UK with each network design and optical channel generation method

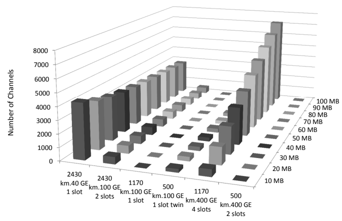
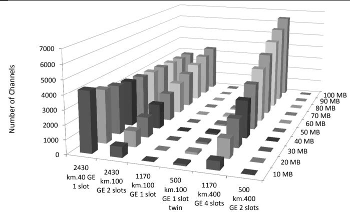
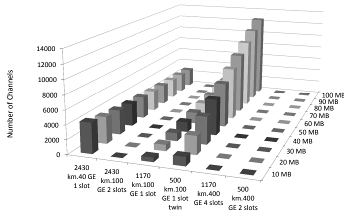
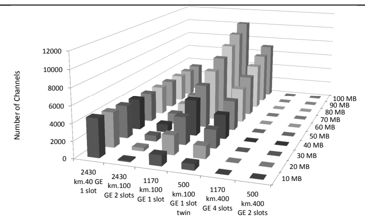
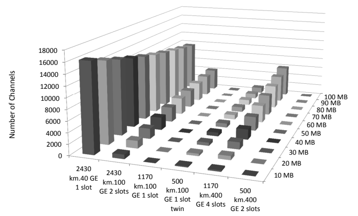
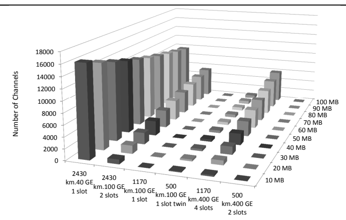
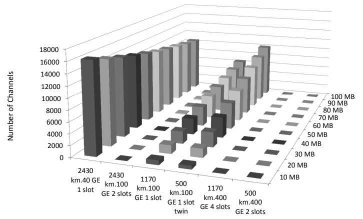
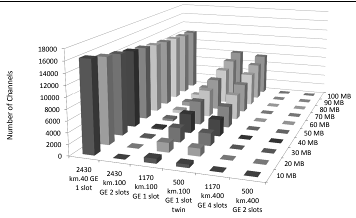
Minimize Total Number of	Initial Network	Min. Distance Network
Optical Channels		
Slots		

Table 9: Analysis of signal type distribution for Italy with each network design and optical channel generation method

Minimize Total Number of	Initial Network	Min. Distance Network
Optical Channels		
Slots		

Furthermore, despite increasing the average path length between pairs of MC nodes the distribution of different types of channels in minimum distance design network is very close to that of initial design network. This is mainly because (1) the length of the path is increased more between those pairs of metro-core nodes which have less traffic following the gravity model and (2) the length of the path between metro-core nodes which are closer is not increased enough to make any significant difference in the total number of optical channels. For a small size country like Ireland the usage of higher capacities channels associated with 1170KMs increases while the ones associated with 2430KMs decreases as the average user traffic grows. For a large size country like Italy, because of greater distances between pairs of nodes the distribution changes hardly, and the network relies more on the channels associated with longest reach.

4.4.3 Routing and Spectrum Allocation

In Table 10 we analyse the impact of increasing average traffic on the total length of the fibres when the optical channels are computed using minimum number of slots or minimum number of optical channels. Regardless of the size of the network, it is clear that minimum distance based network design requires much less fibre than the initial network design. Because in initial design, a fibre is employed in every link whereas only selected links in the minimum distance design are used for the fibre deployment. Furthermore, results in Table 10 also show that minimising total number of slots increases utilisation of fibres and hence minimises the length of the fibres used.

The maximum number of fibres in any link of a network is an important design factor to be used to decide cable capacities. If this number could be minimised, there would be more room for future expansion of the traffic and for resiliency. The maximum number of fibres in any link in the minimum distance design is analysed in Table 11 for each network. Results reveal that minimising the total number of slots used also minimises the maximum number of fibres in a link. Although the maximum number of fibres is not restricted in the transparent optical island studied in this deliverable, it is obvious that a single cable capacity of 120 would be enough for today's and future's expected traffic requirement. More numerical analysis and results can be found in Tables 16, 17 and 18 in Appendix.

Table 10: Total length of fibers used in the initial and min. distance network designs with both minimizing the total number of slots and the total number of optical channels objectives for optical channel generation method

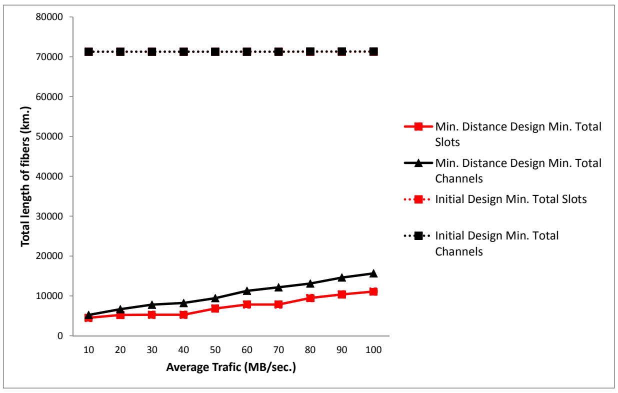
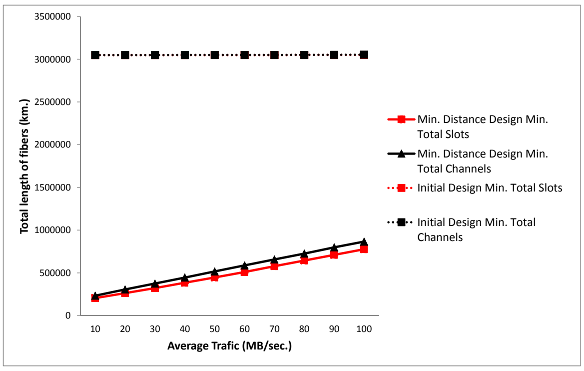
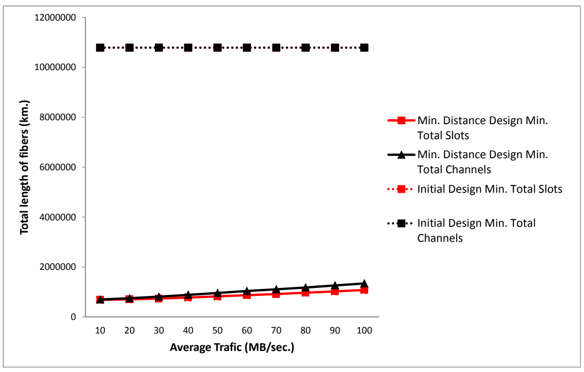
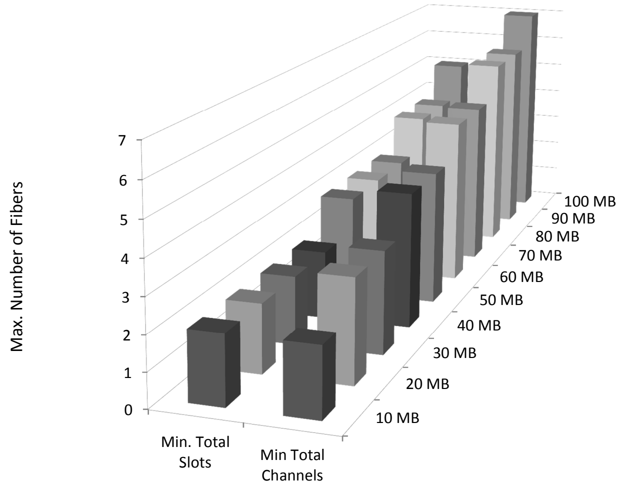
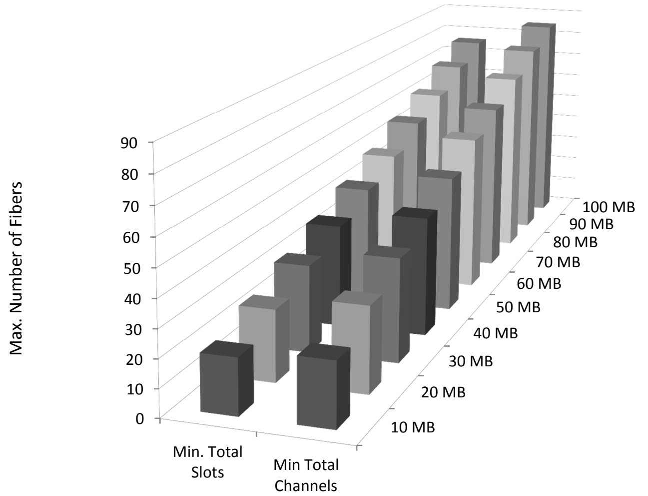
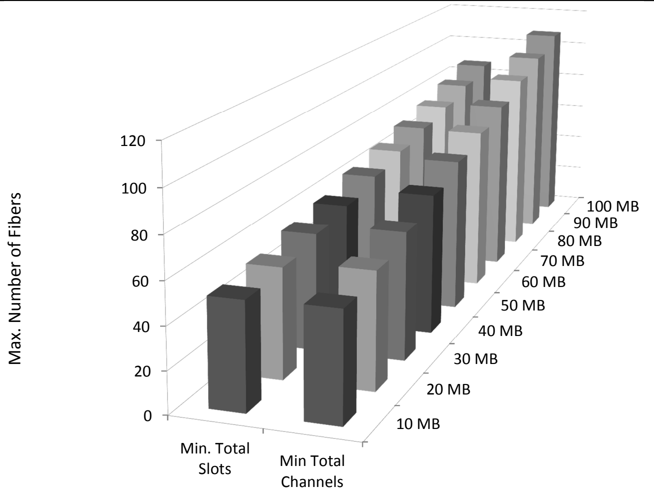
Network	Total length of fibers vs. average traffic
Ireland (18)	
UK (74)	
Italy (132)	

Table 11: Maximum number of fibers in the minimum distance network design with both minimizing the total number of slots and the total number of optical channels objectives for optical channel generation method

Network	Maximum number of fibers vs. average traffic
Ireland (18)	
UK (74)	
Italy (132)	

4.5 Summary

In this section we have focused on an end to end core network optimisation problem, in particular the focus was on transparent flexgrid optical island. We used a decomposition approach where a large neighbourhood search approach was used to solve the core fibre network design problem, a MIP based approach was used to solve the optical channel generation problem, and a greedy heuristic was used to solve the spectrum allocation problem. The results suggest that consolidation of network is important as it can significantly reduce the total length of fibres which might help in reducing the fibre-based cost. Furthermore, minimising the number of optical channels can significantly reduce the number of transponders. We noticed that as the size of an optical island increases in terms of both the number of metro-core nodes and total length of links, the average length of the paths also increases. Overall, we notice that as the size of the network increases, minimising the total length of fibres and the total number of optical channels heavily skewed the distribution of flexgrid optical signals towards the ones that have longer reach.

5 Transparent Optical Island with Raman Amplification

Transparent Optical Islands might be infeasible for big countries as the distance between a pair of metro-core nodes could be greater than the maximum signal reach. This is particularly true when a stronger notion of resiliency needs to be enforced at the level of connectivity of the core network as multiple disjoint paths would increase the length of the paths. In this section, we explore the possibility of extending the reach of the signal by placing Raman amplifiers in the links. After defining the problem formally, we will present our approach where, as before, we decompose the overall optimisation problem into network design (i.e. selection of links connecting metro core nodes), optical channel generation, routing and spectrum allocation problems.

5.1 Problem Definition

As mentioned before, in an optical island, MC nodes are directly connected with each other via circuit switched optical channels. In other words, an optical island can be defined as a set of core nodes that are fully interconnected and traffic from a core-node to another core-node can be sent directly through an optical channel without performing optical-electrical-optical (o-e-o) conversions. However, in some cases, traffic paths are longer than the maximum reach of an optical signal, so Raman amplifiers need to be placed in appropriate locations for extending the reach. Our objective is to design the network, generate the optical channels, find the routes and allocate slots in such a way that the number of required Raman amplifiers is minimised. Additionally, we want to minimise cable and fibre related expenditure as we did for transparent optical island.

5.1.1 Raman amplification

Assuming that we have connected the core network through a set of selected links, the task is to determine which locations of which links need to be equipped with Raman amplifiers in order to satisfy all the traffic between metro-core nodes. For the purpose of network design we assume the following:

- All traffic between a pair of metro-core nodes uses the same path. This assumption can be relaxed when solving routing and spectrum allocation problem.
- The Raman amplifiers can be placed at regular intervals of 30 to 80km in each link which defines a set of possible locations.
- When the distance between a pair of metro-nodes exceeds the maximum signal reach the traffic is sent using the optical signals associated with maximum signal reach.

The criteria to decide whether a Raman amplifier is needed at a particular location or not is based on the Optical Signal-to-Noise Ratio (OSNR) of the evaluated path. We say that the traffic can be sent through a path without violating reachability constraint if its corresponding OSNR is above a given threshold of the modulation format of the signal associated with maximum signal reach.

The different modulation formats considered in the DISCUS project are presented in Table 1. Each modulation format is associated with its spectrum efficiency. In Figure 13 we present an example of a lightpath. As mentioned before the feasibility of the lightpath depends on its

OSNR. The location of the metro-core nodes and amplifiers define the sections of the path. Each section contributes to the OSNR of the path. A section is a segment of the lightpath where each of the segment is limited either by a metro-core node or an amplifier. Similarly the transit metro-core nodes (in this case metro-core node B) and the two terminal metro-core nodes (metro-core nodes A and C) also contribute to the OSNR of the path.

In the following we distinguish two types of sections in a lighpath: (i) lightpaths limited by metro-core nodes only, that is, a section with no Raman amplification (e.g., the first section of Figure 14); (ii) lightpaths that are limited by at least one Raman amplifier (e.g., all sections of Figure 13).

Formally, the OSNR of a path can be expressed as follows:

$$OSNR_{\text{path}} = \frac{1}{\sum_{ns \in \text{nsect}} \frac{1}{OSNR_{ns}} + \sum_{rs \in \text{rsect}} \frac{1}{OSNR_{rs}} + \frac{|\text{trans}|}{OSNR_{\text{trans}}} + \frac{|\text{term}|}{OSNR_{\text{term}}}} \quad (10)$$

where:

- nsect refers to the sections with no Raman amplification,
- rsect refers to the sections with Raman amplification
- trans refers to the transit metro-core nodes
- term refers to the terminal metro-core nodes. Notitce that any path will have two terminals so |term| will always be 2.

5.1.1.1 Example: No Raman amplification is needed. In the example of Figure 13 there are 6 amplification sections. In each section we are assuming a distance of 20km. We also assume that the modulation format is DP-BPSK and the cable type is G652. In Table 12, we list the contributions of each metro-core node (be it terminal or transit), and each section depending on its length. When replacing these numbers in the equation above we get:

$$\begin{aligned} OSNR_{\text{path}} &= \frac{1}{\frac{6}{8373.56} + \frac{1}{1522,76} + \frac{2}{382,48}} \\ &= 151.46 \end{aligned}$$

which is clearly above the permitted threshold of 15.52, given in Table 13

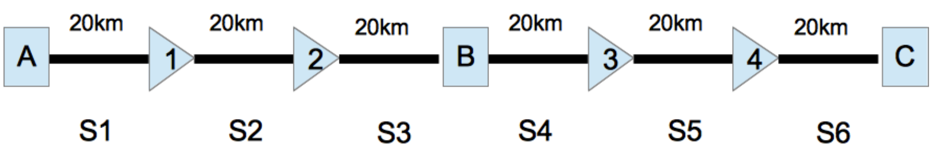


Figure 13: An example of an amplified lightpath. Squares represent metro-core nodes. Triangles represent Raman amplifiers

5.1.1.2 Example: Raman amplification is needed. Suppose now that we have:

- 10 100km Raman sections,

	OSNR
Terminal metro-core node	382.48
Transit metro-core node	1522.76
G652 20km section	8373.56
G652 100km section	417.60

Table 12: OSNR contribution

Modulation Format	OSNR min
DP-BPSK	15.52
DP-QPSK	31.05
DP-16QAM	131.22

Table 13: OSNRmin

- 5 100km Non Raman sections,
- 9 Transit metro-core nodes, and
- 2 Terminal metro-core nodes

as shown in Figure 14, where Raman sections are coloured red. Suppose now that our modulation format is DP-QPSK. The corresponding OSNR for the path is:

$$OSNR_{\text{path}} = \frac{1}{\frac{5}{417.6}+\frac{10}{417.6*2}+\frac{9}{1522,76}+\frac{2}{382,48}}$$
$$= 28.50$$

which is below the threshold (31.05) thus suggesting that Raman amplification is required.

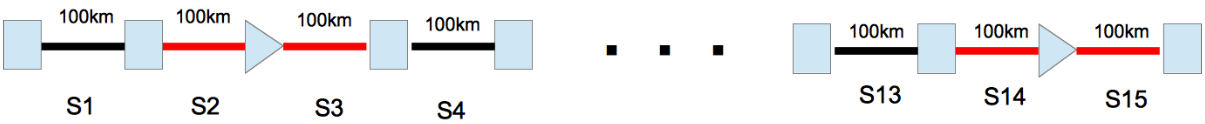


Figure 14: An example of a lightpath going through several Raman amplifiers and metro-core nodes

5.1.2 Mathematical formulation

In this section, we present an Integer Programming (IP) formulation for designing a transparent island with Raman amplification (TIRA) for a given set of metro-core nodes, N, by selecting a subset of a given set of physical links L. As before, each link $l \in L$ is associated with two directed edges in the (directed) transfer network $\langle N, E\rangle$. Let λ denote the maximum reach of any allowed optical signal, which is 2430 km based on Table 1. $\langle N, E\rangle$ constitutes an optical island if any pair of metro nodes in N can be connected via a path whose length is less than λ only using edges in E.

Variables. A binary variable $x_{\tau e}$ is true if and only if edge e is used for traffic request $\tau \in \mathcal{T}$. A binary variable y_l is true if and only if link $l \in L$ is included in the optical island. Each traffic

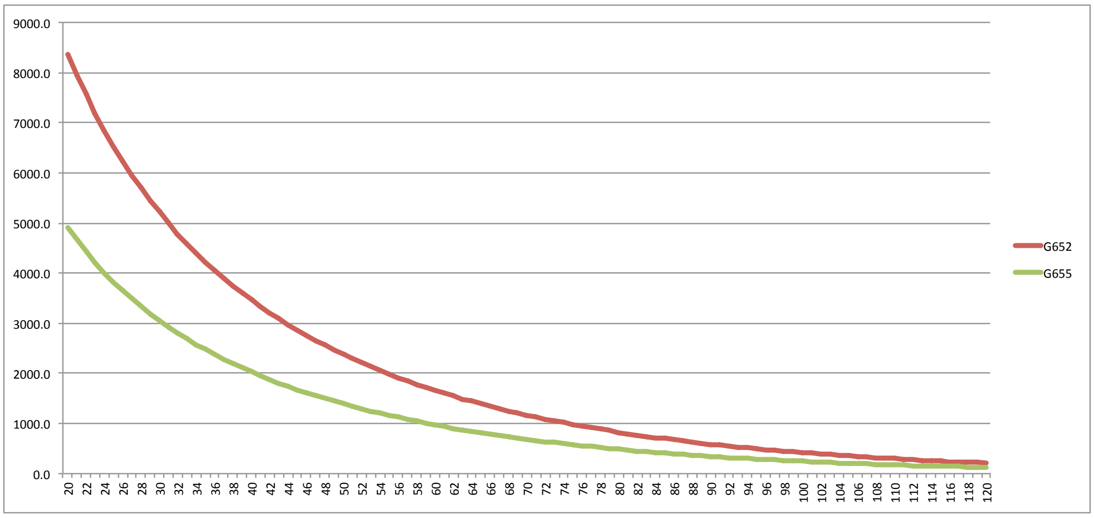


Figure 15: OSNR of the different modulation formats. X axis is the distance in km of the amplification section. Y axis is the OSNR of the signal

request is associated with a Boolean variable z_τ, which denotes whether traffic request τ is transparent (i.e., does not require amplification) or not. We also introduce variable w_e, which denotes whether we are amplifying link e.

Objective. We first minimise those pairs of metro nodes that require Raman amplification, and then minimise the cost of the links included in the optical island followed by minimising the total distances of used edges breaking ties with the weighted sum of Raman links [2]. α, β and γ are constants defined in such a way that the lexicographic composition of these four objectives is ensured.

$$\min \alpha \times \sum_{\tau \in \mathcal{T}} (1 - z_\tau) + \beta \times \sum_{l \in L} c_l \times y_l + \gamma \times \sum_{\tau \in \mathcal{T}} \sum_{e \in E} |e| \times x_{\tau e} + \sum_{e \in E} r_e \times w_e$$

r_e is a constant that can be precomputed for each link representing the inverse OSNR for the link when Raman amplifiers are in place. Similarly, nr_e represents the inverse OSNR for the link when Raman amplifiers are not in place.

Constraints. A link l between nodes i and j is selected if any corresponding directed edge between them is used by any traffic request:

$$\forall_{t \in \mathcal{T}} \forall_{l \equiv \{i,j\} \in L} \forall_{e \in \{\langle i,j \rangle \cup \langle j,i \rangle\}} : y_l \geq x_{\tau e}$$

For traffic request, no route should reach the source or leave the target and exactly one edge must leave (reach) from (to) the source (the target).

$$\forall_{t \in \mathcal{T}} : \sum_{e \in \mathtt{In}(s(\tau))} x_{\tau e} = 0, \sum_{e \in \mathtt{Out}(s(\tau))} x_{\tau e} = 1$$

$$\forall_{\tau \in \mathcal{T}} : \sum_{e \in \mathtt{Out}(t(\tau))} x_{\tau e} = 0, \sum_{e \in \mathtt{In}(t(\tau))} x_{\tau e} = 1$$

At each intermediate node the incoming degree should be equal to the outgoing degree:

$$\forall_{\tau \in \mathcal{T}} \forall_{i \in N \setminus \{s(\tau), t(\tau)\}} : \sum_{e \in \mathtt{In}(i)} x_{\tau e} = \sum_{e \in \mathtt{Out}(i)} x_{\tau e}$$

[2] In the future a more realistic cost function will be taken into account where we minimise the overall cost, which is fibre cost (link cost) and amplifier cost subject to demand and OSNR constraints.

The length of the route from source to target cannot exceed the threshold (i.e., the maximum signal reach) if the traffic request is not provided with Raman amplification:

$$\forall_{\tau \in \mathcal{T}} : z_\tau = 1 \Rightarrow \sum_{e \in E} |e| \times x_{\tau e} \leq \lambda$$

The OSNR of the optical channel should be above the threshold (or equivalently its inverse should be below the threshold). In the following equation we use x_τ to denote the vector of Boolean variables associated with traffic request τ.

$$\forall_{\tau \in \mathcal{T}} : \text{invRaman}(x_\tau) \leq \frac{1}{\pi}$$

In the previous model π is the most flexible OSNR in Table 13. That is, we take into account that, in the worst case it is always possible to use the signal with longest reach. invRaman(x_τ) is a function that returns the inverse of the OSNR of the path defined by the x_τ. We recall that $x_{\tau e}$ is 1 if edge e is in the path associated with traffic request τ. invRaman(x_τ) can be defined as follows:

$$\begin{aligned} \text{invRaman}(x_\tau) \quad \equiv \quad & \textstyle\sum_{e \in E} r_e \times x_{\tau e} \times w_e \\ + \quad & \textstyle\sum_{e \in E} nr_e \times x_{\tau e} \times (1 - w_e) \\ + \quad & \frac{1}{OSNR_{\text{trans}}} \times (\textstyle\sum_{e \in E} x_{\tau e} - 1) \\ + \quad & \frac{2}{OSNR_{\text{term}}} \end{aligned}$$

The above expression is certainly not linear but it can be made linear easily by introducing a new Boolean variable $u_{\tau e}$ that is equivalent to $x_{\tau e} \times w_e$. Notice that the previous equivalence can be expressed easily as follows:

$$\begin{aligned} x_{\tau e} + w_e - 2u_{\tau e} \quad & \geq \quad 0 \\ x_{\tau e} + w_e - u_{\tau e} \quad & \leq \quad 1 \end{aligned}$$

5.2 Solution Approach

5.2.1 Network Design problem

We remark that as reducing the number of traffic requests requiring Raman amplification is lexicographically more important, traffic requests for which the shortest path in the reference network is above the OSNR threshold are bound to be discarded for Raman amplification. This effectively means that those decisions can be taken in polynomial time, which leaves us pretty much with the optimisation problem of Section 4. Therefore, the large neighborhood search algorithm given in Algorithm 2 is also used for designing a minimum distance TIRA with a little modification.

In Section 4 it is shown that if there exists a transparent optical island, the maximum shortest path distance between pair of metro-nodes of any traffic request ($\tau \in \dagger$) in the initial network is less than the maximum signal reach λ. However, for TIRAs there are certain pairs of metro-nodes ($< s(\tau), t(\tau) >$) that have a shortest path length longer than λ even in the initial design. Hence, forcing those pair of metro nodes to have a path length shorter than λ in Algorithm 2 is meaningless. Therefore, before running Algorithm 2 we run a shortest path algorithm on the initial network design to identify the set of Raman traffic requests ($\tau \in \dagger^r$) (i.e., traffic requests that require Raman amplification). Then, for the Raman traffic requests, we remove Constraint (15) from the SOLVE(τ) decomposition model given in Figure 23 (see Appendix). Similarly, signal reach feasibility check for Raman traffic requests in Algorithm 6 and Algorithm 14 given in Appendix is not taken into account. With these modifications we design a TIRA which has minimum distance and ensures that there are no more than $| \dagger^r |$ Raman traffic requests.

5.2.2 Location of Raman Amplifiers

Solving the MIP model of Section 5.1.2 certainly leaves us with a set of links where a subset of those are selected for Raman amplification. While the addition of the extra variables and constraints for handling Raman amplification does not change the complexity of the size of the model, it may still slow down the performance.

Alternatively to solving the previous MIP mode, we can consider omitting Raman optimisation. That is, solving the same optimisation problem that we solved in Section 4. In this case, though, λ would be dependent on the traffic. For those traffic requests that do not require amplification, λ would be as before. For those demands that do require amplification, λ would be equal to the length of the shortest path for that demand in the reference network.

We are left then with a set of links and the objective is now to select a subset of those for Raman amplification. For each link l we can compute the number of traffic requests that require Raman amplification and whose shortest path uses l. We rank links according to this and select for amplification the link at the top of the ranking. If all traffic requests requiring amplification are satisfied after the amplification of l, we stop there. Otherwise, we recompute the ranking and repeat the process taking into account that the amplification of l may have reduced the set of traffic requests requiring amplification, and therefore it may have modified the ranking of the remaining links.

5.2.3 Optical channel generation

Optical channels for a pair of metro-nodes in a TIRA are generated using the mathematical models developed in Section 4.2. However, we assume that any pair Raman traffic request can be served with only the longest reach signal types in Table 1 which are the first two signal types with 2430 km reach. More formally, $\Phi_\tau \in \{1, 2\}\ \forall_{\tau \in \dagger^c}$.

5.2.4 Routing Spectrum allocation

As before we route optical channels through the shortest path. In order to deal with the minimisation of Raman amplifiers we extend the approach presented in the previous section as follows:

1. The links are weighted depending on the number of lightpaths using them.
2. For each lightpath we compute two weights:
    - one based on the weight of the links it has
    - another based on the number of Raman links that it has.

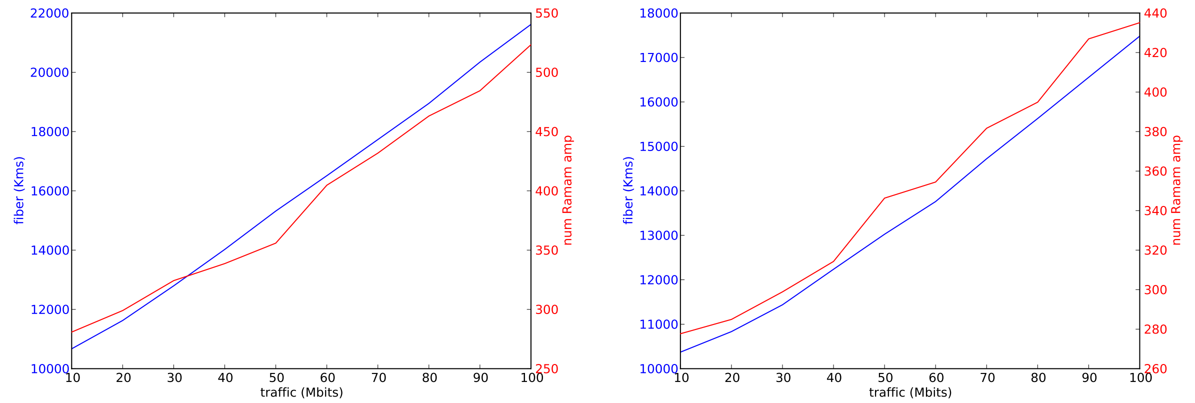
3. The lightpaths are allocated in decreasing order of the lexicographic composition of the two weights. That is we consider first those lightpaths invoking more Raman links, and we break ties using the weight coming from the frequency of the links.

When allocating a lightpath we place it in the first slot where the lightpath fits.

5.3 Results

We design 20 different TIRAs with varying number of metro-nodes and Raman traffic requests to show applicability of our methods for computing Raman locations. Input for these TIRAs are prepared by taking the same traffic matrices for corresponding Ireland, UK and Italy networks with 18, 74, 132 and 189 metro-nodes mentioned in Section 4. For each of these networks, we consider five different designs where the number of Raman traffic requests varies from 2 to 24. As an example, for the network with 18 metro-nodes, to generate 2 Raman traffic requests, we take two traffic requests (τ) with farthest source $(s(\tau))$ and target $(t(\tau))$ metro-node pairs in the reference network and iteratively increase the length of edges on the shortest path of those pairs until the length of these two paths goes above the transparent threshold. Similarly, this procedure is repeated to generate the remaining networks with different number of Raman traffic requests. Results of TIRA traffic requests are presented in Table 14. Since we do not enforce signal reach constraint for Raman traffic requests, diameter of the networks are longer than the maximum signal reach. Furthermore, the size of the network also increases both in terms of the number of links, the total length of the links and the total length of the paths comparing to results given in Table 4.

We also present some preliminary results where we evaluate our approach for computing Raman location on the biggest networks presented in Table 14 (i.e., the 132 nodes case and the 189 nodes case). In the evaluation we are also assuming that the length of the amplification section is 80kms. We have focussed on the cases associated with the highest number of metro-core pairs requiring Raman amplification (20 ordered pairs). In Figures 16 and 17 we show the situation for the network of 132 nodes and 189 nodes respectively. In each figure we show the situation obtained when considering the two different approaches for generating optical channels, i.e., minimising slots and minimising optical channels. In the four cases we observe that the evolution of fibre expenditure with respect to traffic is almost linear. We also observe that the number of Raman amplifiers required tend to follow the same trend. In order to compute the number of Raman amplifiers that are required in a link we take into account that we are placing amplifiers every 80kms in a link that has been selected for amplification, and that one amplifier only deals with one fibre.

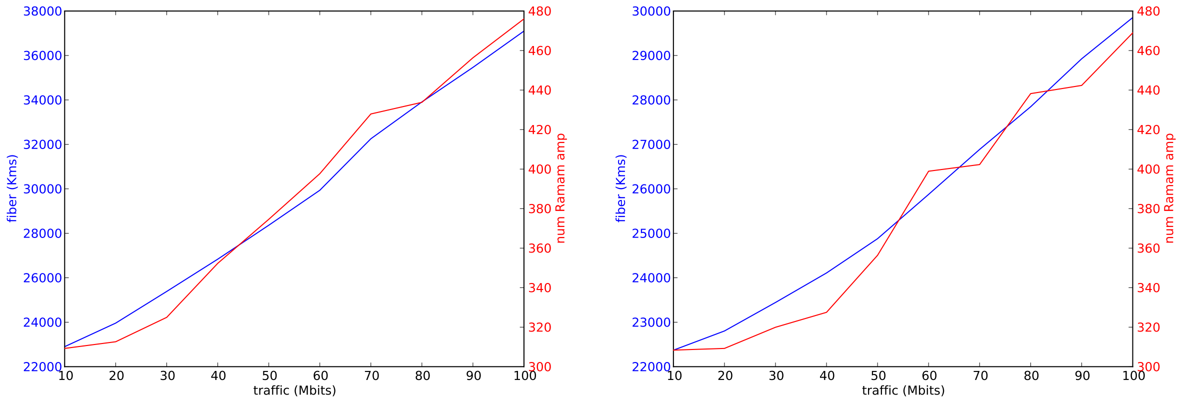


(a) Minimising demands. (b) Minimising slots.

Figure 16: Evaluation of the Network of 132 metro-core nodes .

Table 14: TIRA results

Metro-nodes	Number of Translucent Pairs	Number of Links	Total Length of the Links (km.)	Total Length of the Paths (km.)	Diameter (km)
	2	20	9841.12	429576.00	2531.55
	6	21	10422.10	435074.00	2757.45
18	10	22	10988.40	440175.00	2926.2
	14	22	10713.60	436879.00	3068.17
	20	23	12153.60	457265.00	3323.49
	2	73	6462.06	4811836.45	2704.77
	6	74	7633.53	5026859.78	3018.36
74	10	74	9807.67	5365936.68	3234.46
	14	74	10127.80	4812843.27	3382.67
	24	75	12465.70	6125869.58	3467.13
	2	131	8717.81	15130685.24	2692.17
	6	135	15120.90	16459461.09	2771.27
132	10	136	15672.30	16406206.64	2785.05
	14	134	14993.50	18052607.43	2833.32
	20	134	16975.60	16843564.53	2852.88
	2	188	14328.90	34471998.57	2607.73
	6	191	20223.00	37423853.94	2741.18
189	10	192	21322.70	37680340.46	2809.4
	16	194	23446.90	36031486.07	2806.78
	20	196	25892.00	33174212.49	2802.66



(a) Minimising demands.

(b) Minimising slots.

Figure 17: Evaluation of the Network of 189 metro-core nodes .

5.4 Summary

In this we introduced the optimisation problem that we face when we have pairs of metro-core nodes that cannot be connected with any of the signal types supported. We showed how Raman amplifiers can resolve this problem and presented an approach that aims at minimising the number of Raman amplifiers required while still ensuring connectivity between each pair of metro core nodes. We also showed that the slot allocation problem becomes more challenging when the minimisation of Raman amplifiers is also a concern. Even though our approach to slot allocation is a heuristic it proved to perform well in practice in the instances considered.

6 Resilient design strategies

Resilient design strategies are one of the key factors to ensure high connection availability in the network architecture envisioned by the DISCUS concept. These approaches need to be cost efficient and should also be able to ensure the desired level of end-to-end survivability, i.e., from local exchange to local exchange. In addition, resilient strategies should also be able to address scenarios in which the network might be the target of deliberate physical layer attacks.

This section presents two resilient approaches that address the aspects mentioned above. Section 6.1 investigates the advantages of designing survivability approaches which take into account the dual homing characteristic of the local exchanges in the DISCUS architecture. Section 6.2 provides a different take on network survivability by considering optical-layer security vulnerabilities and methods of protection from deliberate or unintentional insertion of jamming signals in the network.

In this section we assume that the network design has been carried out ensuring that enough fibre capacity is provided to make the survivability approaches of Section 6.1 and Section 6.2 feasible. That is, the decision of which pair of metro core nodes are directed connected and how much fibre is deployed in the corresponding links has been already taken. The task is then to decide how to route the lightpaths in such a way that the objectives in Section 6.1 and Section 6.2 are met satisfying the requested traffic.

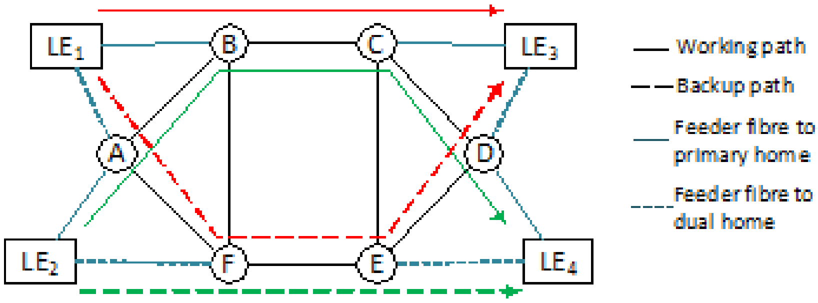


Figure 18: An illustrative example of protection strategy utilizing dual homing.

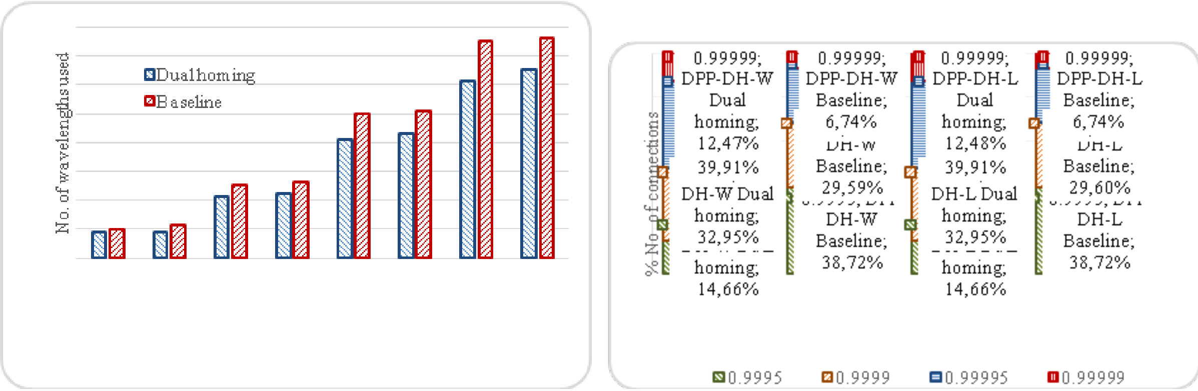
6.1 Resilience in networks with dual homing

The DISCUS architecture employs dual homing, where each Local Exchange (LE) is connected to two Metro/Core (M/C) nodes in order to protect the access network from feeder fibre and/or partial or whole M/C node failures. Moreover, since dual homing increases LE accessibility, it also allows for greater flexibility when planning resilience for the core part of the network. Taking dual homing into account when designing a scheme for protecting the core segment can lead to improvements in resource efficiency of the solution and the overall network availability [2].

Figure 18 shows an illustrative example of a dedicated path protection scheme that takes advantage of dual homing when finding the working and backup paths for the connection requests. In the example, there are six M/C nodes (denoted with letters A to F) and four LEs. The closest M/C node to each LE is selected as its primary home (denoted with a solid line) and the second closest as its dual home (denoted with a dashed line). The most likely scenario envisioned in the DISCUS architecture is that all LEs use their primary homes for communication when there are no failures in the network. Hence, the working path of each connection uses the primary home at the source and at the destination side. The backup paths, on the other hand, can benefit from a greater degree of freedom. Allowing each backup path to use the primary or dual home at both the source and the destination side can lead to a reduction in path lengths and an improvement of resource efficiency and network availability. In the example shown in Figure 18, this can be seen for the backup path between LE_2 and LE_4, where their selected backup path, i.e., the one which uses dual homes of both LEs (path F-E), is the shortest among all possible backup path candidates between all combinations of primary and dual homes at the source and destination side (i.e., paths A-F-E-D, A-F-E and F-E-D).

The described benefits can be fully exploited by designing a resource-efficient approach called Dedicated Path Protection with Dual Homing (DPP-DH) [2]. In order to investigate the trade-off between cost and availability of different solutions (i.e., with and without dual homing) the DPP-DH strategy is simulated on the DISCUS reference Irish optical communication network where traffic is generated using a gravity model that is scaled to have total network traffic intensities in the interval from 27 Tbit/s to 203 Tbit/s [2]. Two variants of the DPP-DH algorithm are designed with different optimisation objectives. The objective of the first variant, denoted as DPP-DH-W, is to minimize the number of wavelengths used in the network, while the second variant, denoted as DPP-DH-L, aims at minimizing the length of the established primary and backup paths allowing greater utilization of wavelengths. Both approaches are compared to a baseline case where there is no dual homing.

Figure 19 shows the average path length of the working and backup paths for the dual homing and baseline approaches when the total network load is 27 Tbit/s. The results show that utilizing dual homing for protection against fibre link failures reduces the length of backup paths by 45% in comparison to a baseline architecture with no dual homing. The number of wavelengths used



(a) The number of used wavelengths for different values of total network traffic load.

(b) The percentage of connections in different availability categories .

Figure 19: 27 Tbit/s total network traffic .

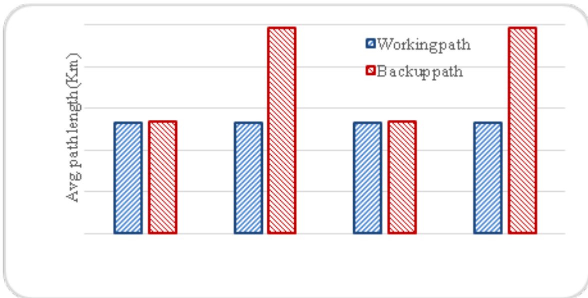


Figure 20: Average path lengths for dual-homed and baseline architecture using DPP-DH-W and DPP-DH-L for 27 Tbit/s total network traffic

for different traffic loads in the network is shown in Figure 20 (a). In all cases, using DPP-DH-W/-L in a network with dual homing results in a lower number of used wavelengths than in the baseline case. This is a very useful trend as it reduces the overall cost for network operators. Comparing the two variants of DPP-DH, it is evident that DPP-DH-W uses fewer wavelengths than DPP-DH-L. This advantage is particularly visible in the scenarios with higher traffic load. Figure 20 (b) shows the percentages of connections satisfying different availability categories for 27 Tbit/s total traffic load. Both variants of DPP-DH obtain significant improvements in the percentage of connections with high availability (99.999% and 99.995%), due to the path length reduction enabled by dual homing. Therefore, in general, DPP-DH achieves higher availability for connections whilst utilizing less network resources.

6.2 Physical layer security considerations

Aside from providing survivability from a variety of network component failures, a different view on resiliency strategies can be taken by considering deliberate attacks targeting the vulnerabilities of the optical layer. Optical networks are vulnerable to attack methods aimed at eavesdropping (e.g., fibre tapping), or at service disruption (e.g., taking advantage of high-power jamming, alien wavelengths or signal insertion) [14], [11]. Certain methods, such as high-power jamming, (i.e., a signal which is 5-10 dB stronger than the legitimate signals is inserted in the network to deteriorate the quality of co-propagating user signals) can also appear in the network due to unintentional component misconfiguration. As DISCUS aims at providing direct access to the core network for selected customers, the likelihood of inserting harmful signals in the network

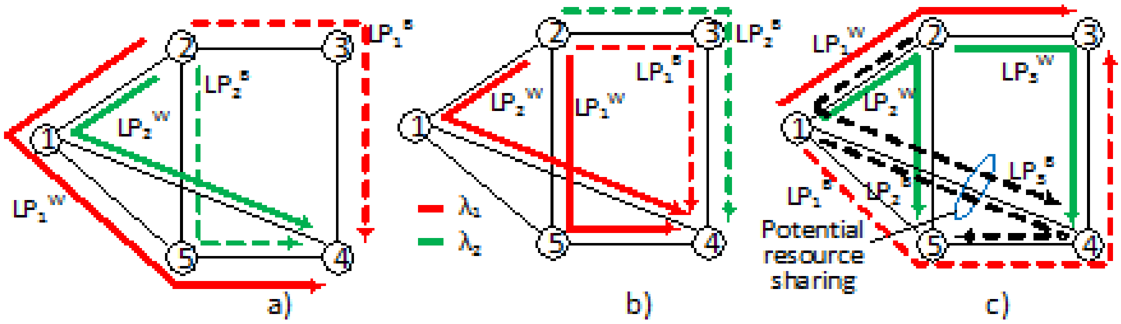


Figure 21: Illustrative examples of jamming-aware dedicated and shared path protection constraints.

by mistake increases, and related security issues can be further complicated by the envisaged lack of distinguishing between the access ports and core connection ports inside an optical switch in M/C nodes.

The extent of damage that can be inflicted by different attacks strongly depends on the characteristics of used network devices, as well as lightpath topology. To give an example for high-power jamming, optical switches used in DISCUS M/C are planned to provide power monitoring and optical attenuation per port, but their dynamic range can be exceeded by the high-power signal so certain harmful effects can be incurred to the co-propagating signals. The harmful effects include increased fibre non-linearities that may generate out-of-band crosstalk, gain competition in erbium-doped fibre amplifiers, and increased in-band crosstalk in switches.

Planning survivability from attacks requires consideration of mutual attacking possibilities between lightpaths and making sure that the working and protection path of each connection cannot both get affected by the same harmful signal. To provide protection from high-power jamming, we use a concept called Attack Groups (AGs)[10] , where the AG of a lightpath LPi encompasses all lightpaths that can affect LPi in case they carry a jamming signal (and vice versa). To guarantee a certain degree of protection from high-power jamming, when identifying the attack groups, we make an assumption that any user signal can become a source of jamming at any point along its physical path, and ensure that the working and backup path of each connection are mutually AG-disjoint.

Figure 21 shows an illustrative example of constraints introduced to dedicated and shared path protection by awareness of high-power jamming. In Figure 21 (a), there are two working and backup paths, i.e., LP_1^W, LP_2^W, LP_1^B and LP_2^B. LP_1^W and LP_1^B are assigned wavelength λ_1, while LP_2^W and LP_2^B use λ_2. If the power of LP_1^W becomes excessive, it can jam LP_2^W via out-of-band effects on their common physical link, causing the switching of transmission from LP_2^W to LP_2^B. However, LP_2^B also shares a common physical link with the jamming signal LP_1^W and can also be affected by the out-of-band effects. Therefore, to achieve protection in the presence of jamming, paths in the example should use different routes. Figure 21 (b) illustrates the potential hazard from jamming signals via in-band effects in optical switches. If, for example, a jamming signal is inserted along LP_2^W at wavelength λ_1, it can affect LP_1^W inside their common switches 2 or 4, and cause switching the transmission to LP_1^B. However, LP_1^B also shares a common switch with LP_2^W at λ_1, and can suffer from the same effects as LP_1^W. Therefore, to protect from jamming, LP_1^B should be assigned a wavelength other than λ_1.

Figure 21 (c) illustrates the impact of jamming in a resource sharing scenario for a shared path protection case for three working and backup paths. Lightpaths LP_1^W and LP_1^B are both assigned wavelength λ_1. LP_2^W and LP_3^W both share a link with LP_1^W, and must be assigned a

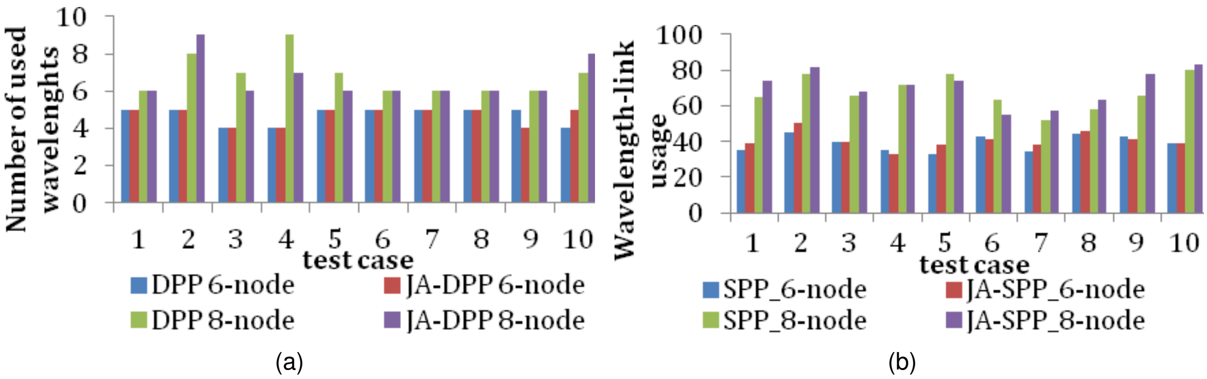


Figure 22: Wavelength usage of JA-DPP and JA-SPP approaches.

different wavelength, i.e., λ_2. Routes of backup paths $LP_2{}^B$ and $LP_3{}^B$ are shown with a dashed black line in the figure, as their wavelengths are not yet decided. Since $LP_2{}^W$ and $LP_3{}^W$ do not share common physical links, $LP_2{}^B$ and $LP_3{}^B$ could be assigned the same wavelength (either λ_1 or λ_2) which could be shared on link 1-4. However, $LP_2{}^W$ and $LP_3{}^W$ both share links with a potential jamming signal $LP_1{}^W$, which means that $LP_2{}^B$ and $LP_3{}^B$ might need to be activated at the same time to protect $LP_2{}^W$ and $LP_3{}^W$ from jamming on lightpath $LP_1{}^W$. Therefore, $LP_2{}^B$ and $LP_3{}^B$ are not allowed to share resources in order to provide protection from high-power jamming.

We modelled the jamming-aware dedicated and shared path protection (JA-DPP and JA-SPP) problems as Integer Linear Programs (ILPs) and tested on a 6-node and 8-node network [7]. The obtained results, together with the benchmarking DPP and SPP approaches (i.e., which do not consider jamming) are shown in Figure 22. For both networks, JA-DPP uses the same number of wavelengths as DPP. JA-SPP uses only 3.6% and 4.1% more wavelength links than its counterpart SPP for the 6-node and 8-node network, respectively, indicating that protection from jamming can be obtained without adding significant extra cost.

7 Summary

We have focused on an end to end core network optimisation problem. We used a decomposition approach for designing transparent flexgrid optical island where a large neighbourhood search approach was used to solve core fibre network design problem, a MIP based approach was used to solve optical channel generation problem, and a greedy heuristic was used to solve spectrum allocation problem. The results suggest that consolidation of network is important as it can significantly reduce the total length of fibres by increasing the number of optical channels marginally which can help in reducing the overall fibre-based cost. We noticed that as the size of the network increases minimising the total length of fibres and the total number of optical channels skewed the distribution of the types of flexgrid optical signals towards the ones that are associated with longer reach.

We also introduced the optimisation problem that we face when we have pairs of metro-core nodes that cannot be connected with any of the signal types supported. We showed how Raman amplifiers can resolve this problem and presented an approach that aims at minimising the number of Raman amplifiers required while still ensuring connectivity between each pair of metro core nodes. We showed that the heuristic implemented for computing location of Raman amplifiers works well in practice. In the future we may consider how the number of Raman amplifiers is affected by changes in the amplification section length and different maximum signal reach.

We also implemented an approach for slot allocation. This problem becomes more challenging when the minimisation of Raman amplifiers is also a concern. Although our approach is a heuristic, it performed well in practice. Other routing strategies that lead to a more load-balanced fibre allocation to links would be considered in the future. In the evaluation of our spectrum allocation approaches we were only focusing on the minimisation of fibre expenditure. However, it is also sensible to minimise the level of fragmentation of the spectrum of the fibre in order to end up with a slot allocation that is more suitable for the allocation of additional optical channels given a potential traffic increase. This is also another direction for future work.

Finally, we explored the advantages of designing survivability approaches which take into account the dual homing characteristic of the local exchanges in the DISCUS architecture. We also studied optical-layer security vulnerabilities and methods of protection from deliberate or unintentional insertion of jamming signals in the network.

A Abbreviations

Acronym	Explanation
AG	Attack Group
DPP-DH	Dedicated Path Protection with Dual Homing
EDFA	Erbium Doper Fibre Amplifier
IP	Integer Program
LB	Lower Bound
LE	Local Exchange
LNS	Large Neighbourhood Search
LR-PON	Long Reach PON
MC	Metro-core
MST	Minimum Spanning Tree
OCGP	Optical Channel Generation Problem
OEO	Optical-Electrical-Optical
OSNR	Optical Signal to Noise Ration
OXC	Optical Cross Connect
PON	Passive Optical Network
RSA	Routing and Spectrum Allocation
TIRA	Transparent Optical Island with Raman Amplification
UB	Upper Bound
UK	United Kingdom
WDM	Wavelength Division Multiplexing
WP2/WP4/WP7	DISCUS Work Package 2/4/7

B Notations

$n, i, j \in N$	a set of metro-core nodes
$N^{source} \subset N$	a set of source nodes
$l \in L$	set of all undirected links between nodes i and j in the reference network
$l^b, a, b \in L^b$	set of all undirected links between nodes i and j in the best solution
$l^c \in L^c$	set of all undirected links between nodes i and j in the current solution
$l^{mst} \in L^{mst}$	set of all undirected links in the minimum spanning tree
$l^* \in L^*$	set of all undirected links between nodes i and j to be removed from the current solution
$l^b_{[u]} \in L^b$	u.th element of the set of links in the best solution, $u \in \{0..\lvert L^b\rvert - 1\}$
$e \in E$	directed edges between any pair of metro-core nodes
$e^b \in E^b$	directed edges between any pair of metro-core nodes in the best solution
$e^c \in E^c$	directed edges between any pair of metro-core nodes in the current solution
$\tau \in \dagger$	the set of traffic requests between all directed pairs of metro-nodes. Each element τ is a tuple $< s(\tau), t(\tau), V(\tau) >$ where $s(\tau)$, $t(\tau)$ and $V(\tau)$ refer to the corresponding source node, target node and the size of the traffic request τ, respectively.
$path^b{}_\tau \subset E$	path between $s(\tau)$ and $t(\tau)$ in the best solution
$path^c{}_\tau \subset E$	path between $s(\tau)$ and $t(\tau)$ in the current solution
$relying_l \in \dagger$	set of pair of metro-nodes which path is relying on link l
$S \subset \dagger$	set of pair of metro-nodes (i.e., sub-problems)which to be re-optimise
$\dagger^c \subset \dagger$	subset of pairs of metro-core nodes in the current solution
$frequency_l$	number of pair of metro-nodes using link l
$support_l$	number of links $l' \in L \setminus l$ that has at least one common metro-node pair path $path^b{}_\tau$ with l
$improve$	boolean variable which indicates whether there is at least one improved solution during the search
$d \in \{1, 2\}$	refers to the number of links selected during the search
$firstlinkindex_d$	index of the first link selected in the search and refers to the $firstlinkindex_d$.th element of the set of links in the best solution $firstlinkindex_d \in \{0..\lvert L^b\rvert - 1\}$
$secondlinkindex_d$	index of the second link selected in the search and refers to the $secondlinkindex_d.th$ element of the set of links in the best solution, $secondlinkindex_d \in \{0..\lvert L^b\rvert - 1\}$
$update$	boolean variable which indicates whether there is an improvement during re-optimisation of the subproblems
$reachfeasible$	boolean variable which indicates whether the length of each path between pair of metro-core nodes are within the maximum signal reach
$networksize$	indicates the size of the network in terms of the total length of the links
$minlength$	indicates the total length of the links in the minimum spanning tree
$d \in D$	indicates the number of links to be selected (i.e., depth) during the search
$\lvert path_\tau\rvert$	length of the path between pair of metro-nodes $s(\tau)$ and $t(\tau)$
$SolutionTime$	time elapsed during the search
$TimeLimit$	time limit for the search
$terminate$	boolean variable which indicates the terminating condition
$k \in K$	set of disjoint path indices
$u \in U \subset L$	set of used links in the resilient network
c_l,c^b_l,c^c_l	cost of each link in the original, best and the current solution

c_e	cost of each directed edge $e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ which equals to the cost of the corresponding undirected link $l \equiv \{i,j\} \in L$
$\|e\|$	length of each edge
$\texttt{In}(i)$	all edges entering node i
$\texttt{Out}(i)$	all edges leaving node i
θ	a big number
μ	total fibre bandwidth spectrum
$\phi \in \Phi$	set of signal types
ns	number of slots
b_ϕ	bitrate of signal $\phi \in \Phi$
ns_ϕ	number of bandwidth slots required by a signal $\phi \in \Phi$
l_ϕ	maximum reach of each signal $\phi \in \Phi$
trc_ϕ	transponder cost of each signal $\phi \in \Phi$
nf_e	number of fibres in link e
α_e	Boolean value representing whether edge e is ducted
x_ϕ	Integer variable representing the number of optical channels of type ϕ
$p \in P$	set of lightpaths, to be routed and assigned to set of sectrums
$w(p)$	number of slots that we need to allocate to each lightpath
E_p	set of links that ligtpath p is associated
$s \in S$	available slots in a fiber
$f^e \in F$	available fibers in link e

C Detailed Methods for Large Neighborhood Search Algorithm

Algorithm 3 INITIALSOLUTION(E,L)

Sort $\tau \in \dagger$ *in ascending order of shortest path lengths in the reference network*
Initialize binary variables $x_{\tau e} = 0$ *for each* $\tau \in \dagger$, $e \in E$
for $\tau \in \dagger$ **do**
    SOLVE(τ)
    for $l \equiv \{i, j\} \in L$ **do**
        for $e \in \{\langle i, j\rangle \cup \langle j, i\rangle\}$ **do**
            if $x_{\tau e} = 1$ **then**
                $path^b{}_\tau \rightarrow path^b{}_\tau \cup e$
                for $e \in \{\langle i, j\rangle \cup \langle j, i\rangle\}$ **do**
                    $E^b \rightarrow E^b \cup e$
                    $L^b \rightarrow L^b \cup l$
                    $c_l^b = c_l$
                    $c_l = 0$
                    $|e^b| = |e|$
                    $c_e = 0$
                end for
            end if
        end for
    end for
end for
REFINEMENT(L^b)
return $[L^b, path^b{}_\tau]$

Algorithm 4 REFINEMENT(L^b)

FREQUENCY(L^b)
Sort $l^b \in L^b$ *in ascending order of* $frequency_{l^b}$
for $l^b \equiv \{i,j\} \in L^b$ **do**
    Sort $\tau \in relying_{l^b}$ *in ascending order of* $|path^b{}_\tau|$
    $L^c \to L^c \cup l^b$
    $relying_{l^c} \to relying_{l^c} \cup relying_{l^b}$
    for $e^b \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ **do**
        $E^c \to E^c \cup e^b$
    end for
end for
for $l^c \equiv \{i,j\} \in L^c$ **do**
    $path^c{}_\tau = \emptyset$
    $L^b \to L^b \setminus l^c$
    for $e^c \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ **do**
        $E^b \to E^b \setminus e^c$
    end for
    if PATHFEASIBLE($relying_{l^c}$,E^b) **then**
        $path^b{}_\tau = \emptyset$
        $path^b{}_\tau = path^b{}_\tau \cup path^c{}_\tau$
    else
        $L^b \to L^b \cup l^c$
        for $e^c \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ **do**
            $E^b \to E^b \cup e^c$
        end for
    end if
    if $|L^b| = |N| - 1$ **then**
        break
    end if
end for

Algorithm 5 FREQUENCY(L^b)

for $l^b \in L^b$ **do**
    $frequency_{l^b} = 0$
    $relying_{l^b} = \emptyset$
end for
for $\tau \in \dagger$ **do**
    for $l^b \equiv \{i,j\} \in L^b$ **do**
        for $e^b \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ **do**
            if $e^b \in path^b{}_\tau$ **then**
                $frequency_{l^b} + +$
                $relying_{l^b} \to relying_{l^b} \cup \tau$
            end if
        end for
    end for
end for

Algorithm 6 PATHFEASIBLE($\dagger^c$, E^b)

$reachfeasible = true$
$N^{source} \subset N$
for $\tau^c \in \dagger^c$ **do**
  $path^c{}_\tau = \emptyset$
  $N^{source} \rightarrow N^{source} \cup s(\tau^c)$
end for
for $\tau^c \in \dagger^c$ **do**
  $path^c{}_\tau$ =SHORTESTPATH(N^{source},N,E^b)
  if $|path^c{}_\tau| > \lambda$ **then**
    $reachfeasible = false$
    break
  end if
end for
return $reachfeasible$

Algorithm 7 NETWORKSIZE(L)

$networksize = 0$
for $l \in L$ **do**
  $networksize = networksize + c_l$
end for
return $networksize$

Algorithm 8 LOWERBOUND(N,L)

$L^{mst} = \emptyset$
for $l \in L$ **do**
  if $l \in$ MINIMUMSPANNINGTREE(N,L) **then**
    $L^{mst} \rightarrow L^{mst} \cup l$
  end if
end for
$minlength =$ NETWORKSIZE(L^{mst})

Algorithm 9 OPTIMAL(NETWORKSIZE(L^b),$|L^b|$)

$optimum = false$
if [NETWORKSIZE(L^b),$|L^b|$]=[$minlength$, $|N| - 1$] **then**
  $optimum = true$
end if
return $optimum$

Algorithm 10 SORT(L^b)

FREQUENCY(L^b)
for $a \in L^b$ **do**
  for $b \in L^b \setminus a$ **do**
    for $\tau \in relying_a$ **do**
      if $\tau \in relying_b$ **then**
        $support_a$++
      end if
    end for
  end for
end for
Sort $l^b \in L^b$ *in ascending order of* $support_l^b$. *In case of tie, use* $|relying_{l^b}|$ *and* c_{l^b}

Algorithm 11 STOP()

$terminate = false$
if $firstlinkindex_d = |L^b| - d \wedge secondlinkindex_d = |L^b| - 1 \wedge improve = false$ **then**
  $terminate = true$
else
  if $SolutionTime \geq TimeLimit$ **then**
    $terminate = true$
  end if
end if
return $terminate$

$$\min \sum_{e \in E} (\alpha \times c_e + |e|) \times x_{\tau e} \tag{11}$$

$$\sum_{e \in \texttt{In}(s(\tau))} x_{\tau e} = 0, \quad \sum_{e \in \texttt{Out}(s(\tau))} x_{\tau e} = 1 \tag{12}$$

$$\sum_{e \in \texttt{Out}(t(\tau))} x_{\tau e} = 0, \quad \sum_{e \in \texttt{In}(t(\tau))} x_{\tau e} = 1 \tag{13}$$

$$\forall_{i \in N \setminus \{s(\tau), t(\tau)\}} : \sum_{e \in \texttt{In}(i)} x_{\tau e} = \sum_{e \in \texttt{Out}(i)} x_{\tau e} \tag{14}$$

$$\sum_{e \in E} |e| \times x_{\tau e} \leq \lambda \tag{15}$$

Figure 23: SOLVE(τ)

Algorithm 12 SELECT(L^b,$firstlinkindex_d$,$secondlinkindex_d$)

$L^* = \emptyset$
$L^* \rightarrow L^* \cup l^b_{[firstlinkindex_d]} \cup l^b_{[secondlinkindex_d]}$
return L^*

Algorithm 13 CREATE(L^*)

```
S = ∅
for l* ∈ L* do
    for τ* ∈ relying_{l*} do
        S → S ∪ τ*
    end for
end for
Sort τ* ∈ S in descending order of |path_{τ*}|
return S
```

Algorithm 14 REFINESUBPROBLEMS(S, E)

```
N^source = ∅ ⊂ N
for τ ∈ S do
    path^c_τ = ∅
    N^source → N^source ∪ s(τ)
end for
for τ ∈ S do
    path^c_τ = SHORTESTPATH(N^source, N, E)
    if |path^c_τ| ≤ λ then
        resolved → resolved ∪ τ
    end if
end for
return resolved
```

Algorithm 15 REOPTIMISE(S,L^*,L^b,$path^b{}_\tau$)

```
$L^c = \emptyset$
for $l^b \equiv \{i,j\} \in L^b$ do
    $L^c \to L^c \cup l^b$
    $c^c_l = c^b_l$
    for $e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ do
        $E^c \to E^c \cup e$ and $|e^c| = |e^b|$
    end for
end for
for $\tau \in \dagger$ do
    $path^c{}_\tau = \emptyset$
    $path^c{}_\tau \to path^c{}_\tau \cup path^b{}_\tau$
end for
for $l^* \in L^*$ do
    $L^c \to L^c \setminus l^*$
end for
for $\tau^* \in S$ do
    $path^c{}_{\tau^*} = \emptyset$
end for
for $l^c \equiv \{i,j\} \in L^c$ do
    $c^c_l = 0$
    for $e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ do
        $c^c_e = 0$
    end for
end for
while $|S| > 0 \wedge update$ do
    SOLVE($\tau^*_{[0]}$)
    for $l \equiv \{i,j\} \in L$ do
        for $e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ do
            if $x_{\tau^*_{[0]}e} = 1$ then
                $path^c{}_{\tau^*_{[0]}} \to path^c{}_{\tau^*_{[0]}} \cup e$
                for $e \in \{\langle i,j\rangle \cup \langle j,i\rangle\}$ do
                    $E^c \to E^c \cup e$ and $L^c \to L^c \cup l$
                    $c^c_l = 0$ and $c^c_e = 0$
                end for
            end if
        end for
    end for
    if [NETWORKSIZE($L^c$),$|L^c|$] $<_{lex}$ [NETWORKSIZE($L^b$),$|L^b|$] then
        $update = true$ and $resolved = \emptyset$
        $resolved =$ REFINESUBPROBLEMS($S, E^c$) and $S \to S \setminus resolved$
    else$update = false$
    end if
end while
if update then
    return $[L^c, path^c{}_\tau]$
else
    return $[L^b, path^b{}_\tau]$
end if
```

D Detailed Results for Fiber Consumption of Different Networks

Table 16: Fiber consumption in Ireland network

Average traffic (MB/sec)	Optical Channel Generation Objective	Designed Network	Total Number of Optical Channels	Total Number of Slots	Slot/ Lightpath	Fiber Consumption				
						Total number of Fibers	Minimum number of Fibers	Maximum Number of Fibers	Average Number of Fibers	Average Fiber Length (km)
10	Min. Total Slot	Initial	337	337	1.00	306	1	1	1	232.91
		Min. Distance	351	351	1.00	57	1	2	1.68	78.66
	Min. Total Channels	Initial	312	461	1.48	306	1	1	1	232.91
		Min. Distance	312	473	1.52	67	1	2	1.97	77.77
20	Min. Total Slot	Initial	392	392	1.00	306	1	1	1	232.91
		Min. Distance	423	423	1.00	67	1	2	1.97	77.77
	Min. Total Channels	Initial	337	665	1.97	306	1	1	1	232.91
		Min. Distance	337	680	2.02	85	2	3	2.5	78.26
30	Min. Total Slot	Initial	465	465	1.00	306	1	1	1	232.91
		Min. Distance	517	517	1.00	68	2	2	2	77.28
	Min. Total Channels	Initial	360	831	2.31	306	1	1	1	232.91
		Min. Distance	360	858	2.38	100	2	3	2.94	77.9
40	Min. Total Slot	Initial	538	538	1.00	306	1	1	1	232.91
		Min. Distance	607	607	1.00	68	2	2	2	77.28
	Min. Total Channels	Initial	392	1016	2.59	306	1	1	1	232.91
		Min. Distance	392	1052	2.68	106	3	4	3.12	77.49
50	Min. Total Slot	Initial	611	611	1.00	306	1	1	1	232.91
		Min. Distance	708	708	1.00	88	2	3	2.59	77.66
	Min. Total Channels	Initial	418	1164	2.78	306	1	1	1	232.91
		Min. Distance	418	1215	2.91	122	3	4	3.59	77.22
60	Min. Total Slot	Initial	705	705	1.00	306	1	1	1	232.91
		Min. Distance	822	822	1.00	101	2	3	2.97	77.6
	Min. Total Channels	Initial	465	1416	3.05	306	1	1	1	232.91
		Min. Distance	465	1479	3.18	145	3	5	4.26	77.64
70	Min. Total Slot	Initial	794	794	1.00	306	1	1	1	232.91
		Min. Distance	932	932	1.00	101	2	3	2.97	77.6
	Min. Total Channels	Initial	501	1603	3.20	306	1	1	1	232.91
		Min. Distance	501	1672	3.34	157	4	5	4.62	77.43
80	Min. Total Slot	Initial	867	867	1.00	306	1	1	1	232.91
		Min. Distance	1031	1031	1.00	122	3	4	3.59	77.55
	Min. Total Channels	Initial	538	1774	3.30	307	1	2	1	232.31
		Min. Distance	538	1855	3.45	169	4	6	4.97	77.47
90	Min. Total Slot	Initial	973	973	1.00	306	1	1	1	232.91
		Min. Distance	1153	1153	1.00	133	3	4	3.91	77.93
	Min. Total Channels	Initial	580	1990	3.43	307	1	2	1	232.31
		Min. Distance	580	2068	3.57	188	5	6	5.53	77.67
100	Min. Total Slot	Initial	1054	1054	1.00	306	1	1	1	232.91
		Min. Distance	1253	1253	1.00	143	3	5	4.21	77.49
	Min. Total Channels	Initial	611	2149	3.52	307	1	2	1	232.31
		Min. Distance	611	2218	3.63	202	5	7	5.94	77.45

Table 17: Fiber consumption in UK network

Average traffic (MB/sec)	Optical Channel Generation Objective	Designed Network	Total Number of Optical Channels	Total Number of Slots	Slot/ Lightpath	Fiber Consumption: Total number of Fibers	Minimum number of Fibers	Maximum Number of Fibers	Average Number of Fibers	Average Fiber Length (km)
10	Min. Total Slot	Initial	6107	6107	1.00	5278	1	1	1	577.63
		Min. Distance	6639	6790	1.02	2697	9	20	18.47	75.9
	Min. Total Channels	Initial	5625	7840	1.39	5278	1	1	1	577.63
		Min. Distance	5756	8319	1.45	3071	13	23	21.03	75.76
20	Min. Total Slot	Initial	7261	7261	1.00	5278	1	1	1	577.63
		Min. Distance	8371	8779	1.05	3466	13	26	23.74	75.87
	Min. Total Channels	Initial	6074	10751	1.77	5279	1	2	1	577.53
		Min. Distance	6402	11554	1.80	4036	19	31	27.64	75.86
30	Min. Total Slot	Initial	8554	8554	1.00	5278	1	1	1	577.63
		Min. Distance	10183	10884	1.07	4245	20	32	29.08	75.85
	Min. Total Channels	Initial	6575	13629	2.07	5282	1	2	1	577.25
		Min. Distance	7126	14629	2.05	4945	24	38	33.87	75.79
40	Min. Total Slot	Initial	9867	9867	1.00	5279	1	2	1	577.53
		Min. Distance	12042	13025	1.08	5064	26	38	34.68	75.87
	Min. Total Channels	Initial	7129	16485	2.31	5287	1	3	1	576.74
		Min. Distance	7898	17740	2.25	5879	30	44	40.27	75.76
50	Min. Total Slot	Initial	11187	11187	1.00	5280	1	2	1	577.43
		Min. Distance	13879	15170	1.09	5878	31	44	40.26	75.85
	Min. Total Channels	Initial	7701	19173	2.49	5294	1	3	1	576.08
		Min. Distance	8683	20761	2.39	6814	36	51	46.67	75.79
60	Min. Total Slot	Initial	12584	12584	1.00	5282	1	2	1	577.25
		Min. Distance	15788	17366	1.10	6719	36	50	46.02	75.89
	Min. Total Channels	Initial	8318	22068	2.65	5299	1	4	1	575.61
		Min. Distance	9513	23826	2.50	7751	39	59	53.09	75.81
70	Min. Total Slot	Initial	13970	13970	1.00	5285	1	3	1	576.94
		Min. Distance	17686	19568	1.11	7617	40	57	52.17	75.86
	Min. Total Channels	Initial	8913	24762	2.78	5303	1	5	1	575.21
		Min. Distance	10328	26776	2.59	8671	45	65	59.39	75.8
80	Min. Total Slot	Initial	15346	15346	1.00	5286	1	3	1	576.85
		Min. Distance	19588	21754	1.11	8510	45	63	58.29	75.72
	Min. Total Channels	Initial	9506	27436	2.89	5308	1	5	1.01	574.76
		Min. Distance	11145	29736	2.67	9579	51	72	65.61	75.76
90	Min. Total Slot	Initial	16725	16726	1.00	5289	1	3	1	576.55
		Min. Distance	21502	23969	1.11	9383	49	70	64.27	75.72
	Min. Total Channels	Initial	10115	30109	2.98	5317	1	6	1.01	573.92
		Min. Distance	11970	32711	2.73	10546	58	79	72.23	75.78
100	Min. Total Slot	Initial	18119	18120	1.00	5294	1	3	1	576.08
		Min. Distance	23408	26166	1.12	10259	54	76	70.27	75.72
	Min. Total Channels	Initial	10720	32781	3.06	5329	1	6	1.01	572.88
		Min. Distance	12797	35649	2.79	11443	62	85	78.38	75.7

Table 18: Fiber consumption in Italy network

Average traffic (MB/sec)	Optical Channel Generation Objective	Designed Network	Total Number of Optical Channels	Total Number of Slots	Slot/ Lightpath	Fiber Consumption: Total number of Fibers	Fiber Consumption: Minimum number of Fibers	Fiber Consumption: Maximum Number of Fibers	Fiber Consumption: Average Number of Fibers	Fiber Consumption: Average Fiber Length (km)
10	Min. Total Slot	Initial	17653	17654	1.00	16131	1	2	1	668.8
		Min. Distance	17732	17740	1.00	12147	21	51	46.36	56.07
	Min. Total Channels	Initial	17408	18953	1.09	16132	1	2	1	668.76
		Min. Distance	17416	19024	1.09	12423	17	52	47.42	56.07
20	Min. Total Slot	Initial	18330	18348	1.00	16132	1	2	1	668.76
		Min. Distance	18655	18719	1.00	12541	21	53	47.87	56.05
	Min. Total Channels	Initial	17627	21163	1.20	16137	1	3	1	668.56
		Min. Distance	17663	21542	1.22	13368	20	56	51.02	55.96
30	Min. Total Slot	Initial	19251	19295	1.00	16133	1	2	1	668.72
		Min. Distance	19845	19995	1.01	13131	21	57	50.12	56.05
	Min. Total Channels	Initial	17900	23684	1.32	16141	1	4	1	668.39
		Min. Distance	17998	24294	1.35	14493	24	62	55.32	55.9
40	Min. Total Slot	Initial	20223	20308	1.00	16136	1	3	1	668.6
		Min. Distance	21121	21406	1.01	13841	16	60	52.83	56.01
	Min. Total Channels	Initial	18225	26304	1.44	16145	1	5	1	668.23
		Min. Distance	18388	27155	1.48	15852	28	69	60.5	55.78
50	Min. Total Slot	Initial	21359	21475	1.01	16138	1	3	1	668.51
		Min. Distance	22547	22982	1.02	14668	22	65	55.98	56.01
	Min. Total Channels	Initial	18630	29226	1.57	16150	1	6	1	668.03
		Min. Distance	18877	30224	1.60	17214	33	76	65.7	55.71
60	Min. Total Slot	Initial	22436	22629	1.01	16141	1	4	1	668.39
		Min. Distance	23912	24530	1.03	15602	24	69	59.55	55.86
	Min. Total Channels	Initial	19037	31981	1.68	16155	1	7	1	667.82
		Min. Distance	19388	33198	1.71	18624	37	82	71.08	55.67
70	Min. Total Slot	Initial	23615	23842	1.01	16143	1	4	1	668.31
		Min. Distance	25374	26173	1.03	16406	25	73	62.62	55.83
	Min. Total Channels	Initial	19442	34588	1.78	16160	1	8	1	667.62
		Min. Distance	19881	35992	1.81	19894	41	88	75.93	55.64
80	Min. Total Slot	Initial	24844	25120	1.01	16145	1	5	1	668.23
		Min. Distance	26867	27843	1.04	17364	27	77	66.27	55.83
	Min. Total Channels	Initial	19910	37334	1.88	16164	1	9	1	667.46
		Min. Distance	20457	38862	1.90	21195	46	95	80.9	55.6
90	Min. Total Slot	Initial	26101	26468	1.01	16147	1	5	1	668.15
		Min. Distance	28397	29615	1.04	18329	29	82	69.96	55.82
	Min. Total Channels	Initial	20404	40321	1.98	16170	1	10	1	667.23
		Min. Distance	21068	42098	2.00	22676	50	101	86.55	55.58
100	Min. Total Slot	Initial	27430	27833	1.01	16150	1	6	1	668.03
		Min. Distance	29978	31401	1.05	19336	32	87	73.8	55.82
	Min. Total Channels	Initial	20892	43093	2.06	16177	1	11	1	666.95
		Min. Distance	21678	45030	2.08	24101	56	108	91.99	55.55

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