Failure Survivability Strategies for Optical Transport Networks

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***Abstract*—The significant growth in telecommunication traffic, allied with the development of unpredictable new technology and client services leads to uncertainty when predicting future traffic in optical transport networks, which motivates the network operators to adopt planning and traffic prediction tools. Network resources must be planned carefully to reduce the network's cost while guaranteeing the quality of service levels and availability agreed with the clients. A failure in a network may lead to the disruption of communication services, enforcing the need for implementation of survivability techniques to assure resilience in these scenarios. Throughout this thesis, several heuristic routing strategies were studied, developed and simulated for different cost metrics and different networks. The results and impacts of these strategies were then compared and analyzed under the same traffic scenario. Various survivability methods in both optical and electrical layers using several routing algorithms were studied and implemented in an optical transport network simulation tool (programmed in MatLab language) for incremental traffic scenarios and different multiperiod planning strategies. For the same simulation tool, several analytic methods were developed and implemented to determine the traffic demand availability in every simulation scenario. At last, a comparison between the different survivability strategies, routing strategies, and multiperiod planning was performed, considering the number of line interfaces, link occupation, total traffic blocked and traffic demand availability for different networks and traffic scenarios.**

I. Introduction

Transport networks are technological platforms that assure a transparent and reliable transfer of information at a significant distance while providing support to different services [1]. Nowadays, transport networks operate with Optical Transport Network (OTN) technology, an ITU-T G-872 recommendation, created to provide transport, aggregation, routing, supervision and resilience to the client traffic signals, processed in the electrical domain and transported in the optical domain, using Dense Wavelength Division Multiplexing (DWDM).

The OTN network planning consists of optimizing the aggregation of client signals in lightpaths (bidirectional channels with an established route and a single wavelength), network resource allocation, and lightpath routing. To minimize the network's Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) while assuring the signal quality, performance and availability agreed with the clients.

A failure in a network element may collapse entire communication services and lead to significant data loss [21].

These failures impact network availability. With the development of new communication services, the need for higher availability grows, which demands improvements on the network's capacity to adapt and survive faulty scenarios [24].

With the needs previously imposed, it becomes critical to use traffic prediction and network planning tools, to compare and evaluate different strategies and their performance in different scenarios, facilitating the usage of the most adequate methods that benefit the network overall.

II. Aspects and Considerations of OTN Technology

In this chapter, a general and summarized description regarding the state of the art of OTN technology. The following subsections contain an overview of the OTN physical and logical topology, the description of OTN optical and electrical domain and respective layer models as well as the OTN network elements.

A. *Physical and logical topologies for OTN networks*

The physical topology of an OTN network is composed of its optical links and its nodes. Each optical link is characterized by its cost, defined by the cost metric. Usually, the cost metric is considerers parameters such as physical link distance, number of hops, signal degradation, delay, etc.

The logical topology of an OTN network is the traffic flux routed through the network that guarantees the connection between the network nodes. The network traffic that circulates the network can be categorized as static traffic, incremental traffic and dynamic traffic [7]. For static traffic, an initial study is performed for all the requests that will be routed throughout the network. The incremental traffic arrives sequentially, by time intervals and remain for an indefinite time in the network. At last, the dynamic traffic requests arrive one at a time in the network and last for a variable time.

B. *OTN optical and electrical domains*

In a layer model, OTN networks can be divided into two domains: electrical and optical domain [4].

The optical domain uses DWDM technology and is responsible to generate, multiplex, switch and manage lightpaths that operate with different wavelengths.

The electrical domain oversees mapping and aggregation of the client signals into fixed-length frames and assures the addition of appropriate overhead for monitoring and other purposes [3].

The optical domain can be divided into three layers (Fig. 1): Optical Channel (OCh), Optical Multiplex Section (OMS) and Optical Transmission Section (OTS). The Optical Channel is the physical implementation of the lightpath, this layer allows signal identification, integrity verification, and connectivity management. Each Optical Channel forms an Optical Multiplex Unit (OMU) in the OMS layer, which is responsible for wavelength attribution and conversion and multiplexing. The OTS layer defines the optical parameters associated with the physical interfaces and is responsible for their management and monitoring [5].

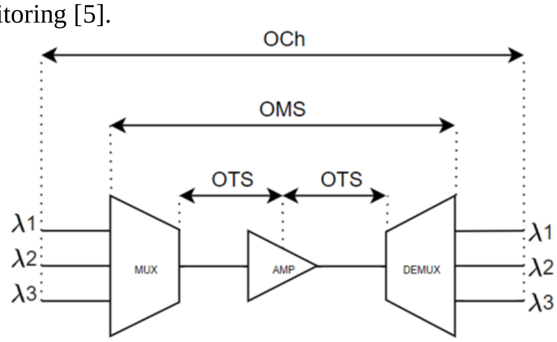

Fig. 1. Optical domain's layers [5]

In the electrical domain, the client signal is introduced in the Optical Data Unit's (ODU) payload. The payload is then added to an ODU-k frame along with overheads for monitorization, fault detection and location, and Automatic Protection Switching (APS) among others [5]. ODU-k frames can be then mapped into a higher-order ODU-k frame, allowing the encapsulation of lower-order ODU frames.

The ODU-k frame is then introduced in an Optical Transport Unit k (OTU-k) frame with overheads to allow communication between network nodes, monitoring, fault detection, maintenance, protection, and control plane communication. The bridge between the optical and electrical domain is crossed when the OTU frames are mapped into OCh frames. Fig. 2 illustrates OTN frame architecture by layers.

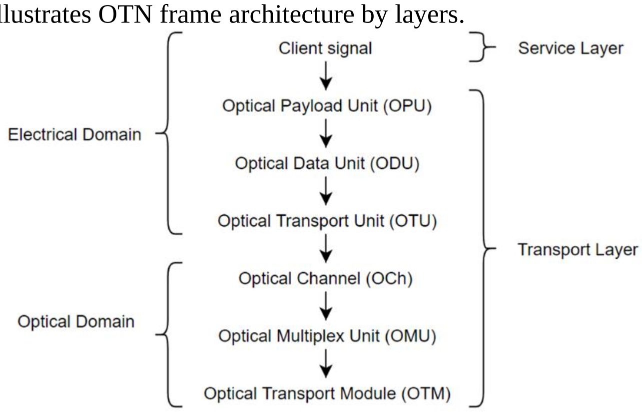

Fig. 2. Optical Transport Hierarchy (OTH) [5]

C. *OTN network elements*

Optical networks can be characterized as transparent, opaque or translucid networks. In transparent optical networks, the optical signal is transported from source to destination without any conversion to the electrical domain. On the other end, opaque optical networks perform optical to electrical and electrical to optical (OEO) conversion in every intermediate node. OTN networks are defined as translucid networks, these networks allow the transparent routing of the optical signal while enabling the OEO conversion to regenerate the signal whenever required.

The OTN network nodes use Reconfigurable Optical Add-Drop Multiplexers (ROADMs) to add and remove wavelengths from the network and include multiplexers to allow aggregation and separation of wavelengths. ROADMs can be classified as Contentionless (allows wavelengths to converge to the same wavelength selective switch module input), Colorless (allows automated assignment of wavelengths to any add/drop port) and Directionless (able to rout any wavelength to any add/drop port [16].

ROADMs are also connected to line interfaces; these interfaces perform the conversion of OTU frames into OCh signals. ODU Switches receive the client signal from Client Cards (CC), encapsulate it in ODU-k frames and generate OTU signals at their outputs which are connected to line interfaces. Fig.3 illustrates a typical translucid node architecture for OTN networks.

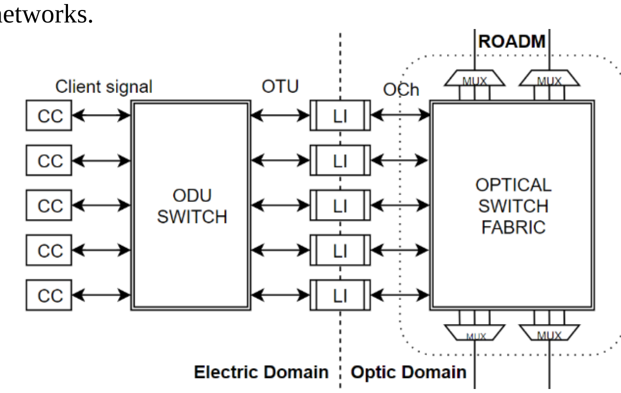

Fig. 3. Translucid node architecture – OTN network [4]

Optical fiber signal transmission as some limitations, which can be classified as linear (for example attenuation and optical noise) and nonlinear (for example cross-phase modulation and crosstalk) [6]. These limitations impose maximum distance traveled by the lightpath, defined as maximum transmission distance. To work around this issue, regenerators and optical amplifiers (OA) can be placed in key points of the network to allow signal amplification (typically in the optical links) and regeneration (typically in the network nodes).

III. Routing and Wavelength Assignment and traffic grooming

One of the challenges in optical network planning is the development of algorithms and protocols to efficiently establish lightpaths in the network, using a minimal number of resources and maximizing the number of connections established.

The process of path attribution and wavelength selection for a lightpath is designated as routing and wavelength assignment, this process can be divided on these two subproblems.

A. Routing

The simplest way to define a path between the source and destination nodes is to assign a static route, this method is designated as fixed routing. Differing from the previous definition, the fixed-alternate routing consists of the attribution of a finite number of paths between each node pair which are stored in the routing table of each node. At last, the adaptative routing allows the path established between the source and destination node to be determined dynamically depending on the state of the network [7].

For scenarios where multiple traffic requests are examined simultaneously, traffic demand ordering is required. The most common ordering methods are the shortest path first (priority given to the lowest path cost demand), longest path first (priority given to the highest path cost demand), largest first (priority given to the highest traffic unit demand) and random [1].

B. Wavelength Assignment

After the routing process, the attribution of a wavelength to transport the lightpath from end to end is required. The selection of a wavelength must guarantee that no wavelength is used by different lightpaths in the same optical link simultaneously while guaranteeing the usage of the minimum number of wavelengths possible.

The wavelength assignment process requires wavelength ordering methods, the most common methods are the first fit (wavelengths are numbered, the search for a wavelength starts from the lowest number to the highest, first wavelength available is used), least used (selects the least used wavelength available in the network), most used (selects the most used wavelength available in the network) and random wavelength assignment [7].

C. Traffic Grooming

OTN networks allow the lowest bit rate traffic demand aggregation to a single optical signal to provide better efficiency of network resources [8].

In translucid networks, such as the OTN networks, traffic demands can only be aggregated at the source node of the lightpath or at any intermediate node where the lightpath is regenerated [9].

IV. Multiperiod Planning Strategies

Traffic predictions are based on assumptions and estimations from traffic evolution studies and similar projects and should attend the life expectancy of the network.

Technological evolution should also be considered for network planning, equipment innovations tend to reduce costs and improve performance, which motivates a close look over new technology and investment delays to reduce uncertainty [11].

The equipment administration and network resource allocation can be accomplished by adopting multiperiod strategies. These strategies consist of dividing the network's life expectancy into several periods, allowing a progressive development of the network and initial CAPEX reduction. At each period, new client demands are implemented and (if necessary) more network resources are implemented. This work analyzes the following planning methods:

- All Periods Planning (APP);
- Incremental Planning (INC);
- End-of-life Planning (EOL);

With all periods planning method, at each iteration, the traffic matrix is discarded, and the network is reconfigured considering every traffic request until the period of the iteration. While this method may lead to a perfect solution, it requires complete knowledge of the network's traffic matrix and requires network reconfiguration [12].

Incremental planning consists of optimizing each period individually and sequentially at each iteration. At each iteration, the traffic predicted for the current period is added to the existing traffic matrix [10]. Although this process is optimized for each period individually and only requires knowledge of the current period at each iteration, it may lead to less ideal traffic scenarios for the overall network life expectancy [12].

The end-of-life planning goal is to optimize the last period of the network's expected lifetime. On the first iteration, the final network's composition is determined, for the following iterations, traffic requests from future periods are removed to obtain the network resource allocation for previous periods. This method requires complete knowledge of the traffic matrix until the last period [13].

Every iteration of each multiperiod strategy for a three-period scenario is exemplified in Fig. 4.

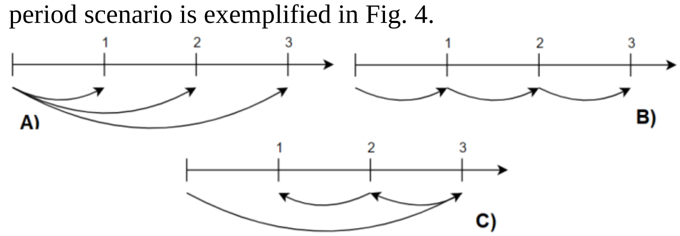

Fig. 4. (A) All Periods Planning (B) Incremental Planning (C) End-of-life Planning;

V. Survivability Methods for OTN Networks

In OTN networks, a faulty network element may lead to the disruption of communication services, and consequentially, lead to loss of a significant amount of data [21]. Resilience, survivability, and resistance to failures are synonyms that refer to the network's capacity to provide communication services after the occurrence of failures [23].

Resilience mechanisms require a significant over-provisioning of network resources. Increasing network resources implies the use of more network elements or implementation of specific elements to support survivability actions, which impacts the network's CAPEX directly [17].

A communication channel is defined by the service and backup paths transporting a traffic request. The unavailability of a communication channel is defined as the probability of that channel is out of service at any given instant. Mean Time Between Failures (MTBF) is defined as the average time between two consecutive failures in the same network element. Mean Time to Repair (MTTR) is defined as the average time needed to repair failures in a specific network element. Cable

Cut (CC) is defined as the average optical fiber cable length in which occurs one failure per year [15].

A. Protection Schemes

Protection schemes are one of the two most common survivability methods. They may be implemented in both optical and electrical domains.

Starting with the optical domain, protection strategies can be applied to the OMS layer. Using this layer enables each link to be protected individually, in a link failure scenario, every service lightpath is rerouted to avoid the faulty link. This protection is often designated as link protection [21].

Protection procedures can also be applied to the OCh layer. In this layer, the service lightpath is a protected entity. This protection can be defined as dedicated path protection and can be defined as dedicated path protection 1:1 or 1+1.

In dedicated path protection 1:1, for each service lightpath, dedicated protection lightpath resources are allocated and idle in absence of failures.

For dedicated path protection 1+1, each service lightpath is protected by one protection lightpath, the signal is sent by a single line interface and then duplicated by an Optical Switch (OS) and routed through disjoint paths until the destination node (example illustrated in Fig. 5), this protection requires contentionless ROADMs to allow wavelengths to converge to the same wavelength selective switch input. Fault recovery in this protection scheme is usually below 100ms [22].

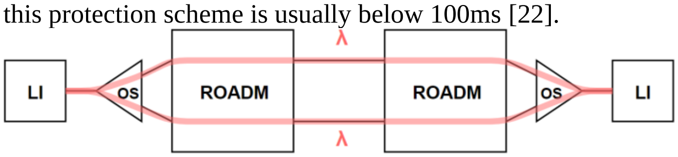

Fig. 5. Dedicated path protection 1+1 (OCh layer) example

The most common protection scheme in the electrical layer is the linear protection, described by ITU-T G.873.1 recommendation which defines the APS protocol and linear protection operations in ODU frames. Using this architecture, the protection mode is activated after a failure is detected. Linear protection schemes can also be defined as 1+1 or 1: N [20].

For 1: N linear protection, one or more traffic signals are protected by a single protection entity that is not established until the protection mode is activated.

In a 1+1 linear protection scheme, each traffic signal is protected by a single dedicated protection. Both service and protection entities are simultaneously forwarded in the network through disjoint paths. Upon failure detection, ODU Switch blocks the service signal and starts operating with the protection signal provided by the protection line interface (example shown in Fig. 6). As both service ODU frame and protection ODU frame are sent simultaneously, ODU Switching at the end node is the only procedure required to activate protection mode, the failure recovery time is around 10ms [18].

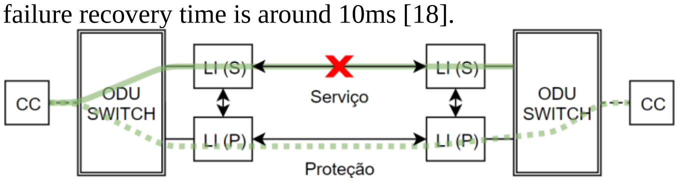

Fig. 6. Linear path protection 1+1 (ODU layer) example

B. Shared Restoration Schemes

Shared restoration schemes can be introduced in the optical domain (OCh layer) or electrical domain (ODU layer).

After a failure is detected, the control plane is responsible for switching the service signal into the restoration signal. These schemes assume that no more than one failure occurs in the network simultaneously, which allows different restoration signals to share resources if their service paths are disjoint. (one failure can't affect both disjoint service paths).

Resource allocation can either be preplanned, all the restoration paths are calculated offline, or dynamic, where the restoration paths are determined after the failure is detected and depending on the network's resources. Dynamic allocation allows more adaptability to failures and more versatility, while the preplanned allocation allows a faster failure recovery time as it does not require available resource analysis or path discovery procedures after the failure is detected [21].

The preplanned shared restoration (PSR) at the ODU layer is only activated upon failure detection and the control plane switches the traffic towards the restoration ODU resources using ODU Switches. Restoration ODU resources may be considered capacity within a lightpath that is idle in the absence of failures. Typically, failure recovery times for this scheme are below 100ms [19].

In the network illustrated in Fig. 7, there are six nodes connected by optical fiber links. Two demands are routed over S1 and S2 working paths. S1 and S2 are disjoint, R1 and R2 have common sub-path between node C and D. This sub-path can only be shared by both R1 and R2 restoration paths if there are optical channels terminated at these two nodes, to provide resource sharing, in this scenario, two line interfaces need to be allocated at node C and other two line interfaces need to be allocated at node D.

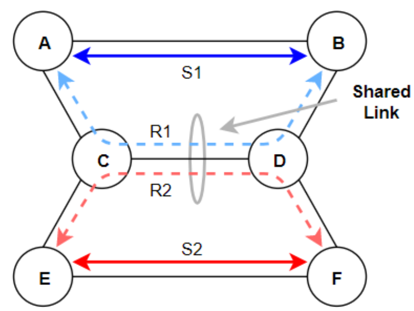

Fig. 7. Network exemplifying PSR scheme [19]

The PSR at the OCh layer is only activated upon failure detection and the control plane switches the signal to be forwarded to a different input/output fiber, this process may also require retuning of the line interfaces and ROADMs to a different wavelength, for the previous reasons this scheme requires colorless and directionless ROADMs and tunable line interfaces. These processes demand more time when compared to preplanned shared protection in the ODU layer, having failure recovery times that can range from hundreds of milliseconds to seconds [19].

Differing from PSR at the ODU layer, PSR at the OCh layer is no longer constrained to using the same lightpaths (and line interfaces) in the restoration path. Considering Fig. 7 again, R1 and R2 can be used as end-to-end paths in the same wavelength without the need for intermediate line interface allocation (this is only possible because PSR assumes both restoration paths will never be activated simultaneously).

C. Routing algorithms for disjoint paths

Protection and restoration schemes can also be classified for their ability to guarantee link failure survival or both link and node failure survival. Specific routing algorithms are necessary to assure and provide disjoint routes to service and backup paths.

This work considers three different routing algorithms for disjoint paths, Two-Step Dijkstra with disjoint links [22], Two-Step Dijkstra with disjoint nodes [22] and Suurballe and Tarjan's algorithm [24].

Two-Step Dijkstra with disjoint links [22] and Two-Step Dijkstra with disjoint nodes [22] are very similar algorithms, both provide the closest path between source and destination nodes (service path) and the disjoint (link disjoint or link and node disjoint) shortest path (backup path). Although these solutions provide the shortest service path, the overall distance of both paths may not be minimal. To avoid this problem, Suurballe and Tarjan's algorithm [24] provides the pair of link disjoint paths that minimize the overall distance and traffic in the network.

VI. Routing Algorithms for OTN Networks

In this chapter, several routing algorithms are analyzed, using different physical topologies and two different cost metrics, distance and number of hops, for an incremental traffic scenario and uniform for the whole network (one ODU4 traffic request between each node pair) without survivability schemes.

The different physical topologies studied in this chapter are COST239 [14], NSFNET [14], UBN [14], and three regular physical topologies with same node degree for every node (equal to 3), unitary link cost, and different number of nodes (8, 12 and 20).

A. Fixed routing algorithms

In this section, Dijkstra's shortest path algorithm [14] and Yen's K-shortest paths algorithm [14] were simulated for the previously mentioned scenarios (using K=2 and 3 for Yen's algorithm), taking into consideration the average and maximum distance traveled by lightpaths, average number of hops and traffic load for most and least loaded links in the network.

As expected, the best results were obtained using Dijkstra's shortest path algorithm, using both distance and number of hops as the cost metric. Dijkstra's shortest path minimizes average and maximum distance in the network when applied with distance cost metric and minimizes the average number of hops and traffic load of the most loaded links in the network when applied with the number of hops as cost metric. This scenario was verified for every physical topology studied.

B. Traffic balancing algorithms

Network traffic balancing refers to the uniformization of traffic load distribution through all network links, reducing the traffic load on the most loaded links in the network. The performance of the balancing algorithms may be measured by their capacity to reduce the traffic load in the most loaded links of the network and their impact on the maximum and average distances traveled by lightpaths.

In this section, three different traffic load balancing algorithms are analyzed, the Non-Iterative algorithm [26], the Iterative algorithm and the K-shortest path balanced algorithm.

Non-Iterative algorithm is a fixed-alternate algorithm that calculates the shortest route between every node pair in the network and then attempts to reduce the traffic load of the most loaded links in the network by rerouting lightpaths that use these links to their second shortest routes.

Iterative algorithm is categorized as an adaptative routing algorithm, this algorithm calculates the shortest route between every node pair in the network, then it selectively increases link costs to reduce traffic load of network links with above-average load (multiplies most loaded link by constant X1 and other above-average load links by constant X2) and recalculates every route with the new costs, this process is repeated for as long as network balancing is verified.

K-shortest paths balanced algorithm is defined as a fixed-alternate algorithm that selects the shortest path (if there are multiple shortest paths) that provides lower traffic load to the most traffic loaded links in the network.

Table 1 includes Dijkstra's shortest path algorithm and the balancing algorithm that provided better traffic load balancing results (Iterative Algorithm with X1=2 and X2=1.25) for irregular topologies (COST239, NSFNET, UBN) using distance cost metric. D_{MAX} and D_{AVG} correspond to the maximum and average distance traveled by the lightpath, H_{AVG} corresponds to the average number of hops of each lightpath and T_{MAX} and T_{MIN} correspond to the traffic load of the most and least loaded network links.

		COST239	NSFNET	UBN
DIJKSTRA	D_{MAX}	1386	4444	7200
	D_{AVG}	679	2263	3015
	H_{AVG}	1,8	2,4	3,2
	T_{MAX}	11	24	64
	T_{MIN}	0	2	0
ITERATIVE X1=2 X2=1,25	D_{MAX}	1511	4879	7200
	D_{AVG}	699	2319	3094
	H_{AVG}	1,6	2,3	3,1
	T_{MAX}	6	17	50
	T_{MIN}	1	2	0

Table 1. Traffic load balancing algorithm (distance as cost metric)

Table 2 includes Dijkstra's shortest path algorithm and the balancing algorithm that provided better traffic load balancing results (Iterative Algorithm with X1=1.10 and X2=1) for irregular topologies using the number of hops cost metric.

		COST239	NSFNET	UBN
DIJKSTRA	D_{MAX}	1971	5727	8850
	D_{AVG}	779	2520	3263
	H_{AVG}	1,6	2,1	3
	T_{MAX}	7	17	42
	T_{MIN}	1	3	2
ITERATIVE X1=1,10 X2=1	D_{MAX}	1594	5727	8850
	D_{AVG}	728	2551	3259
	H_{AVG}	1,6	2,1	3
	T_{MAX}	6	15	39
	T_{MIN}	1	3	2

Table 2. Traffic load balancing algorithm (number of hops as cost metric)

As previously mentioned for the fixed routing algorithms, the number of hops cost metric proves to be more effective performing traffic load balance, the same is verified for the traffic balancing algorithms that provide more balanced links when used with the number of hops cost metric. In both scenarios the Iterative algorithm proves to be more effective in reducing traffic load of the most loaded links in the networks, however, using different X1 and X2 values. For this algorithm, when using the number of hops cost metric, X1 and X2 values closer to 1 lead to better traffic load balancing results. In practice, the number of hops metric defines every network link with unitary cost, thus the network is more volatile to cost changes which are detrimental to the algorithm's performance.

Table 3 includes Dijkstra's shortest path algorithm and the balancing algorithm that provided better traffic load balancing results (K-Shortest Path balanced) for regular topologies using the number of hops cost metric.

		8 Nodes	12 Nodes	20 Nodes
DIJKSTRA	H_{AVG}	1,7	2,1	2,6
	T_{MAX}	9	12	23
	T_{MIN}	1	5	11
K-SHORTEST PATH BALANCED	H_{AVG}	1,7	2,1	2,6
	T_{MAX}	5	10	18
	T_{MIN}	3	6	15

Table 3. Traffic load balancing algorithm on regular topologies (number of hops as cost metric)

Opposite to the irregular networks, better results were obtained using the K-shortest path balanced algorithm. These regular networks feature a higher number of tied shortest paths, leading to more traffic load balancing possibilities.

C. *Link capacitated problem*

As previously defined, network optical fibers are limited to a maximum capacity. This capacity limits the traffic load that each network link supports at any given time.

In this section, a study is performed using Dijkstra's shortest path algorithm for capacitated link networks. When a link's capacity is reached, the cost of this link is changed to infinity. For each scenario, the maximum link capacity is limited to the minimum value that allows the routing of every traffic demand (zero traffic demands blocked) and defined as M_{CAP} shown in Tables 4, 5 and 6.

Tables 4, 5 and 6 include Dijkstra's shortest path algorithm scenarios with incapacitated links and with capacitated links (equal to M_{CAP}) for irregular topologies (Table 4 and 5) and regular topologies (Table 6) with distance cost metric (Table 4) and number of hops cost metric (Table 5 and 6).

		COST239	NSFNET	UBN
DIJKSTRA (Incapacitated)	D_{MAX}	1386	4444	7200
	D_{AVG}	679	2263	3015
	H_{AVG}	1,8	2,4	3,2
	T_{MAX}	11	24	64
	T_{MIN}	0	2	0
DIJKSTRA (C = M_{CAP})	D_{MAX}	1386	8811	7350
	D_{AVG}	716	2667	3259
	H_{AVG}	1,7	2,5	3,3
	T_{MAX}	5	17	35
	T_{MIN}	1	3	0
	M_{CAP}	5	17	35

Table 4. Limited capacity links (distance as cost metric)

		COST239	NSFNET	UBN
DIJKSTRA (Incapacitated)	D_{MAX}	1971	5727	8850
	D_{AVG}	779	2520	3263
	H_{AVG}	1,6	2,1	3
	T_{MAX}	7	17	42
	T_{MIN}	1	3	2
DIJKSTRA (C = M_{CAP})	D_{MAX}	1971	5727	8850
	D_{AVG}	787	2571	3272
	H_{AVG}	1,6	2,2	3,1
	T_{MAX}	4	14	35
	T_{MIN}	2	4	2
	M_{CAP}	4	14	35

Table 5. Limited capacity links (number of hops as cost metric)

		8 Nodes	8 Nodes	8 Nodes
DIJKSTRA (Incapacitated)	H_{AVG}	1,7	2,1	2,6
	T_{MAX}	9	12	23
	T_{MIN}	1	5	11
DIJKSTRA (C = M_{CAP})	H_{AVG}	1,7	2,1	2,6
	T_{MAX}	6	11	19
	T_{MIN}	2	6	13
	M_{CAP}	6	11	19

Table 6. Limited capacity links on regular topologies (number of hops as cost metric)

Limiting the maximum link capacity proves to be a helpful tool to perform network traffic balancing, however, for some cases this method may increase drastically the distances traveled by the lightpaths causing undesirable results, NSFNET in Table 4 is a perfect example of this case, the maximum distance traveled by a lightpath almost doubled for the capacitated scenario.

VII. OTN SOFTWARE DESCRIPTION

In this chapter, the reader is introduced to the OTN simulation tool adapted from [16] and developed throughout this work. This software is divided into two main modules, topology demand generation, and OTN simulator.

A. *Topology Demand Generation*

The topology demand generation module allows the user to select a physical topology, number of wavelengths per optic fiber, the bit rate per wavelength (OTU rate), number of simulation periods, number of demands for each ODU rate selected, among other parameters. This first module generates the network resources such as line interfaces (depending on the number of wavelengths selected) and a list of ODU incremental traffic, randomly distributed throughout network nodes for each simulation period.

B. *OTN Simulator*

The second module, OTN Simulator, processes the output information received from the topology demand generation module and performs a multiperiod simulation and forwards the previously generated traffic through the OTN network.

For this multiperiod simulation, the user may select the multiperiod planning strategy (APP, INC or EOL), routing cost metric (number of hops, distance or optical signal degradation), network resilience methods, routing strategy, among other parameters.

VIII. OTN Simulator Module Architecture

In this chapter, the OTN Simulator module architecture and algorithms are described.

A. *Traffic Mapping*

Fig. 8 illustrates a simplified fluxogram for the OTN simulator module, after importing the network and traffic from the previous module, user inputs are selected, then the system performs the path routing for every node pair and the multiperiod planned simulation is started. For multiperiod iteration, traffic demands are ordered, and every traffic demand is either mapped in the network or blocked (if no resources are available).

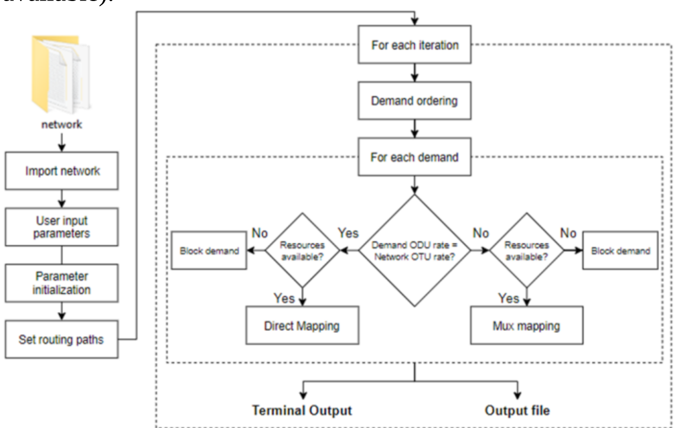

Fig. 8. OTN Simulator fluxogram

OTN simulator supports lower-order traffic aggregation. For each traffic demand, the throughput (ODU rate) of this demand is compared to an optical channel's capacity (OTU rate), if the traffic demand's throughput is equal to the OTU rate, the demand uses the whole capacity of an optical channel and aggregation is not possible, the lightpath capacity is fully occupied by the single traffic demand (referred as Direct Mapping). For scenarios where lightpath capacity is greater than the traffic demand's throughput, several traffic demands may be aggregated in a single lightpath (referred to as Mux Mapping).

Traffic demand blocking corresponds to the decision of not establishing a requested connection. Traffic blocking occurs when there are not enough resources in the network to support a traffic demand. It may occur due to the unavailability of wavelength, line interfaces or absence of physical connection between the source and destination nodes.

For resilient networks, the lack of resources to support any of the signals (service or backup) leads to a traffic demand block, and none of the signals is mapped.

B. *Available Network resilience methods*

The developed simulation tool includes the following resilience schemes for protected networks:

- ODU dedicated protection 1+1 (ODU P);
- ODU preplanned shared restoration (ODU R);
- ODU dedicated protection 1+1 and preplanned shared restoration (ODU P&R);
- OCh dedicated protection 1+1 (OCH P);
- OCh preplanned shared restoration (OCH R);
- OCh dedicated protection 1+1 and preplanned shared restoration (OCH P&R);

The ODU P&R and OCH P&R schemes consist on the implementation of both protection and restoration scheme simultaneously, promoting a second backup signal.

C. *Available Routing algorithms*

The OTN simulator proposes different routing solutions depending on the network's survivability strategy. Networks without resilience can either use Dijkstra's shortest path [14] or Yen K-shortest path's routing algorithms [14].

For resilient networks, the user can select the Two-Step Dijkstra link or node disjoint algorithms [22] or Suurballe and Tarjan's algorithm [24]. For Two-Step Dijkstra solutions, users may also select Shortest Path Routing (SPR) with the shortest path and respective disjoint path, or Fixed-Alternate Routing (FAR) for a solution with K shortest paths and their respective disjoint paths.

D. *Network unavailability determination*

After the multiperiod simulation is finished, the software calculates every network element's availability and determines the highest and lowest communication channel's unavailability.

The availability methods use the following assumptions [25]:

- Each network element can only be either in service or in failure state;
- A failure in a network element is independent of other failures in the network;
- Only single, double and triple simultaneous failures are taken into consideration;
- MTTR and MTBF are independent and memoryless processes;

The programmed calculation methods take into consideration the availability of the following elements: Line interfaces (LI), optical amplifiers (OA), ROADMs and optical fiber cable.

The availability of each element is calculated based on the MTBF and MTTR of each element, selected by the user. Availability is approximately given by MTTR divided by MTBF.

Communication channel unavailability is determined based on the availability of every network element used by its lightpath(s) and using probability models developed throughout this work. An example of a network element disposition is shown in Fig. 9.

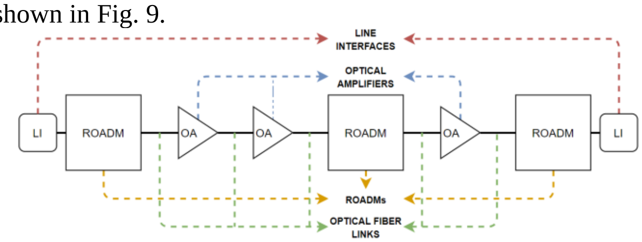

Fig. 9. Network elements considered for unavailability calculation (example)

IX. OTN Software Simulations

In this chapter, several simulations are performed for COST239 [14] and UBN [14] physical topologies using different multiperiod strategies, resilience schemes and routing algorithms for 1000 ODU-2, 200 ODU-3, and 20 ODU-4 traffic demands divided in a three-period simulation (using Colorless, Directionless and Contentionless ROADMs).

A. *Resilience schemes result analysis*

For this analysis a total of 120 bidirectional wavelengths per fiber are available, using APP multiperiod strategy, traffic routing is based on the Two-Step Dijkstra link disjoint algorithm with FAR (K=3).

Fig. 10, 11 and 12 feature the total number of line interfaces, the average number of wavelengths allocated per network link and the total number of traffic demands blocked respectively, for each resilience scheme using COST239 [14] physical topology.

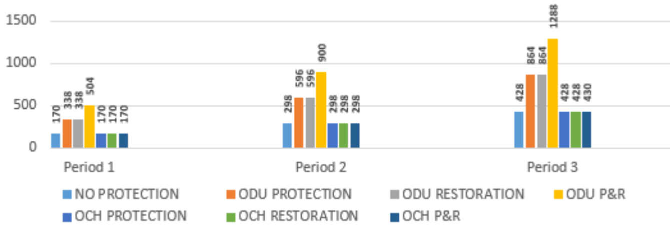

Fig. 10. Total number of line interfaces for each resilience scheme (COST239)

As shown in Fig. 10 the number of line interfaces is significantly higher for ODU resilience schemes, while OCh resilience schemes require the same number of line interfaces as the solution without resilience. As illustrated in Fig. 5, OCh protection does not require the allocation of more line interfaces (because the optical signal is cloned at the Optical Switch) and The OCh restoration scheme reuses the service line interface for restoration resources. The ODU protection requires line interfaces for both restoration and protection paths (As illustrated in Fig. 6), and even though ODU restoration signal is only activated after a failure occurs the idle ODU capacity for this scheme's restoration signal requires the permanent allocation of optical elements and line interfaces.

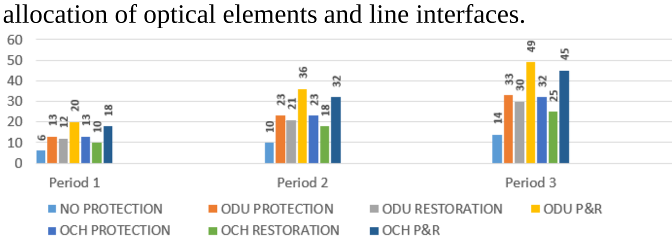

Fig. 11. Average number of wavelengths allocated per network link (COST239)

The average number of wavelengths allocated in the network can quantify the network's degree of occupation, as expected, resilience schemes require the allocation of more wavelengths. Some wavelength savings were verified when comparing protection to restoration schemes, this difference was less accentuated for protection and restoration at the ODU layer because in this layer, to allow restoration sub-path sharing, this sub-path must be an end to end optical channel (thus making resource sharing more restrictive when compared to the OCh restoration).

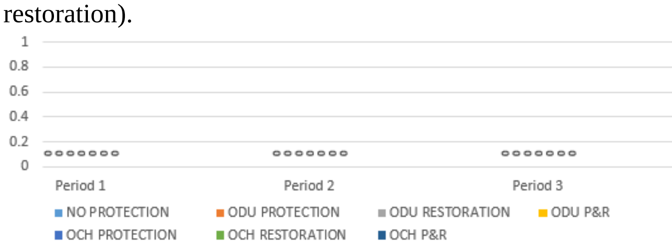

Fig. 12. Total number of traffic demands blocked (COST239)

As shown in Fig. 12 no traffic demands are blocked, verifying a total of 382, 796 and 1220 traffic demands mapped for first, second and third periods respectively.

Fig. 13, 14 and 15 feature the total number of line interfaces, the average number of wavelengths allocated per network link and the total number of traffic demands blocked respectively, for each resilience scheme using UBN [14] physical topology.

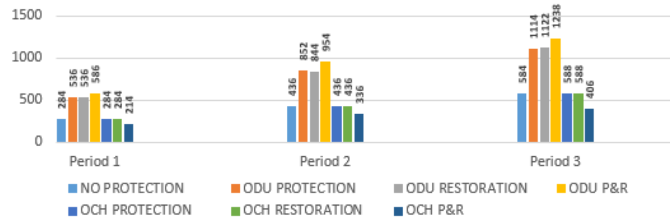

Fig. 13. Total number of line interfaces for each resilience scheme (UBN)

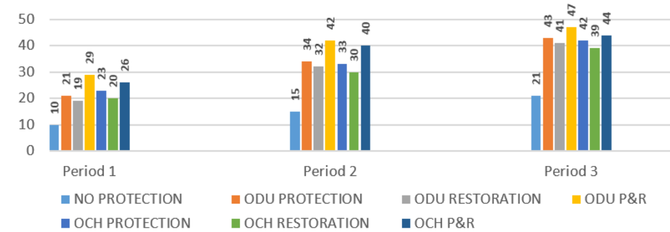

Fig. 14. Average number of wavelengths allocated per network link (UBN)

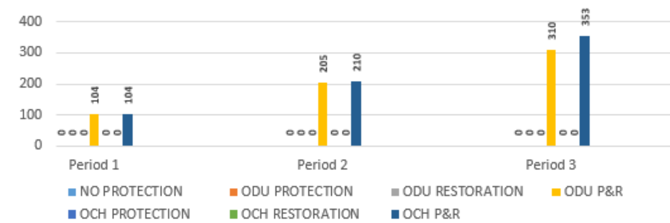

Fig. 15. Total number of traffic demands blocked (UBN)

As shown in Fig. 15, for UBN physical topology, some traffic blocking is verified for the ODU P&R and OCh P & R schemes, these traffic blocking is caused by the reduced node degree of this topology, some nodes are only connected by two different links which make them incapable of routing three link disjoint paths (required by ODU P&R and OCH P&R schemes).

In general, having in mind the differences between the two physical topologies, the different resilience schemes show very similar variations between each other for COST239 and UBN physical topology.

B. *Traffic blocking analysis*

Tables 7 and 8 contain the number of traffic demands blocked per simulation period for each resilience scheme, for COST239 [14] and UBN [14] physical topologies respectively.

COST239						
Resilience Schemes	**SPR**			**FAR (K=3)**		
	Per. 1	Per. 2	Per. 3	Per. 1	Per. 2	Per. 3
No Resilience	0	0	0	0	0	0
ODU P	0	26	370	0	26	289
ODU R	0	18	298	0	18	204
ODU P&R	0	107	503	0	92	430
OCh P	0	22	116	0	0	22
OCh R	0	0	100	0	0	23
OCh P&R	6	156	335	1	31	141

Table 7. Number of traffic demands blocked per simulation period (COST239)

UBN						
Resilience Schemes	SPR			FAR (K=3)		
	Per. 1	Per. 2	Per. 3	Per. 1	Per. 2	Per. 3
No Resilience	3	70	262	4	53	117
ODU P	15	201	543	16	162	492
ODU R	7	168	451	6	132	366
ODU P&R	165	487	914	117	415	824
OCh P	47	192	444	42	208	328
OCh R	28	177	485	21	117	337
OCh P&R	177	456	842	167	413	748

Table 8. Number of traffic demands blocked per simulation period (UBN)

For both physical topologies, a significant reduction of total demands blocked was verified when using the FAR routing strategy, this can be expected as this strategy offers more routing possibilities for every node pair, traffic demands without available resources for the shortest path may use the second or third shortest paths (K=3).

C. Multiperiod result analysis

Fig. 16 and 17 feature the total number of line interfaces and the total number of traffic demands blocked respectively, for each multiperiod strategy, with ODU dedicated protection 1+1 and using COST239 [14] physical topology.

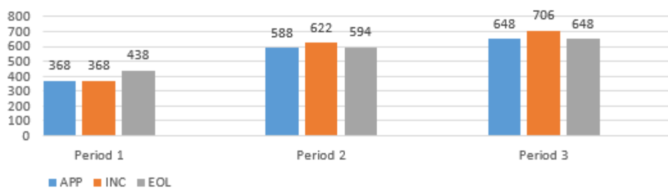

Fig. 16. Total number of line interfaces for each multiperiod strategy (ODU dedicated protection 1+1 – COST239)

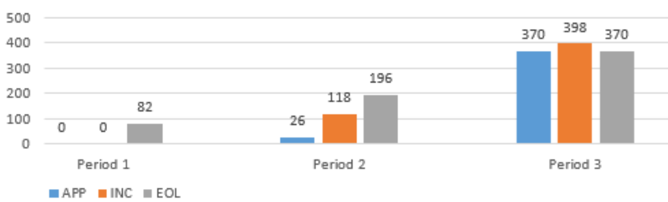

Fig. 17. Total number of traffic demands blocked (ODU dedicated protection 1+1 – COST239)

The multiperiod strategy that presents better results (minimizes line interfaces and total traffic blocked) is the APP, this can be expected as this strategy requires reconfiguration of the entire network at each iteration thus leading to the perfect solution for each period (however traffic reconfiguration should be avoided in real scenarios, which is a huge disadvantage for this strategy). INC strategy allows the optimization of the first simulation period; however, it is the solution that presents the worst results for the third period (more line interfaces allocated, and more traffic demands blocked). As an alternative EOL provides an optimized solution for the third period, however, to converge to this result, this strategy requires traffic demand blocking since the first simulation period and leads to a very unoptimized solution for the first simulation period.

D. Availability result analysis

Table 9 includes the MTBF and MTTR values used for every network element in these simulations (based on reference [27]).

Element	MTBF [h]	MTTR [h]	CC [km]	A [%]
LI	298043	2	-	99.99932896
OA	236682	2	-	99.99915499
ROADM	508427	2	-	99.99960663
Optical Fiber	-	12	537	-

Table 9. MTBF, MTTR, CC and corresponding Availability for each network element [27];

Table 10 features the highest communication channel unavailability for each resilience scheme for COST239 [14] and UBN [14] physical topologies.

Resilience Schemes	Highest Unavailability	
	COST239	UBN
No Resilience	33 h & 22 min/year	156 h & 1 min/year
ODU P	8 min/year	3 h & 25 min/year
ODU R	13 min/year	4 h &10 min/year
ODU P&R	4 min/year	6 min/year
OCh P	14 min/year	3 h & 31 min/year
OCh R	20 min/year	4 h & 13 min/year
OCh P&R	11 min/year	13 min/year

Table 10. Highest communication channel unavailability (COST239 and UBN)

Results obtained in Table 10 enforce the need for the implementation of resilience schemes, there's a very significant unavailability difference between non-resilient and resilient schemes for both physical topologies. Overall ODU resilience methods show lower unavailability time when compared to their OCh counterpart, this is the result of the allocation of backup line interfaces for the electric domain backup signals.

When comparing protection and restoration schemes from the same layer, it's noticeable that the protection scheme allows lower unavailability, this is due to the resource sharing promoted by PSR schemes that do not foresee double failure scenarios.

The ODU P&R and OCh P&R schemes present the lowest unavailability, this is a consequence of the second allocated backup path after both service and protection path fails, the traffic demand may still be routed through the restoration path.

Communication channel's unavailability is directly affected by the physical topology (the longer the distance traveled by a lightpath the higher is the failure probability and the higher is the unavailability), this consequence can be verified by comparing both COST239 and UBN unavailability results, noting that UBN's net diameter is 6 and the average link distance is 977 km while COST239's net diameter is 3 and the average link distance is 461.

X. Conclusion

Studies performed in chapter VI conclude that the traffic load balancing of an algorithm capacity varies with the cost metric and physical topology used. The ideal solution consists of improving traffic load balancing without increasing lightpath distances significantly.

Simulations performed in chapter IX emphasize the importance of simulation tools, the physical topology affects the communication channel's unavailability directly. Different scenarios may require different resilience mechanisms to achieve the desired availability.

Although OCh layer resilience mechanisms allow a significant reduction of allocated line interfaces, more complex and expensive network devices are required for these schemes and may not benefit the overall network CAPEX.

Future work includes studies of simultaneous protection and restoration schemes in different layers and hybrid resilience networks (different resilience schemes for different traffic demands) for similar simulation environments.

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