TZAR – TIME ZONE BASED APPROXIMATION TO RING: AN AUTONOMOUS PROTECTION SWITCHING ALGORITHM FOR GLOBALLY RESILIENT OPTICAL TRANSPORT NETWORKS

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AN AUTONOMOUS PROTECTION SWITCHING ALGORITHM
FOR GLOBALLY RESILIENT OPTICAL TRANSPORT NETWORKS**

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ABSTRACT

TZAR – TIME ZONE BASED APPROXIMATION TO RING: AN AUTONOMOUS PROTECTION SWITCHING ALGORTIHM FOR GLOBALLY RESILIENT OPTICAL TRANSPORT NETWORKS

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Widespread deployment of new generation high-speed networks, developments in large capacity DWDM technologies, and continuous demand for increasingly resilient global Internet services necessitates a revision on optical transport networks. Considered to be one of the most promising recent phenomena in that sense, OTN is evolving to become a major core switching platform.

In this thesis, we briefly present the progress in optical transport networking from hardware architecture and software hierarchy points of views. Then, trends in protection switching are pointed out through a peculiar taxonomy on computational, topological, and efficiency aspects. Finally, an autonomous, low complexity and inter-disciplinary (incorporating automatic protection switching of optical networks with distance vector routing of mobile ad-hoc networks) lightpath recovery algorithm is offered based on time-zone awareness of OTN nodes to fulfill the basic requirements expected from mesh optical networks. The proposed algorithm is evaluated with simulation in comparison to two well-known algorithms.

Keywords: optical transport networks, protection switching, global resilience

ÖZ

TZAR – ZAMAN DİLİMİ TEMELLİ HALKA YAKLAŞIMI: OPTİK İLETİM AĞLARININ KÜRESEL DAYANIKLILIĞI İÇİN ÖZERK KORUMA ANAHTARLAMASI ALGORİTMASI

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Yeni nesil hızlı ağların yaygınlaşması, yüksek kapasiteli DWDM teknolojilerindeki gelişmeler, küresel Internet servislerinin dayanıklılığını artırmaya yönelik süregelen talepler optik iletim ağlarını yeniden gözden geçirmeyi gerektiriyor. Bu bağlamda, güncel olguların en gelecek vadedenlerinden biri olarak değerlendirilen OTN, temel omurga anahtarlama platformu olarak evrilmektedir.

Tezimizde, optik iletim ağlarının donanımsal mimari ve yazılımsal hiyerarşi açılarından geldikleri nokta özetlendi. Koruma anahtarlama yöntemlerine ilişkin hesaplama, topoloji ve verimlilik bakımından özgün bir sınıflandırma yapıldı. Örgün optik iletim ağlarının temel gereksinimlerine cevap verebilecek nitelikte, OTN nodlarının zaman dilimi farkındalığına dayandırılan, özerk, hesaplama karmaşıklığı düşük ve disiplinlerarası (optik ağların otomatik koruma anahtarlaması ile geçici mobil ağların vektörel mesafe yönlendirmesini birleştiren) bir ışıkyolu onarım algoritması önerildi. Önerilen yöntem iki iyi bilinen algoritma ile benzetim yoluyla karşılaştırmalı olarak değerlendirildi.

Anahtar Kelimeler: optik iletim ağları, koruma anahtarlaması, küresel dayanıklılık

To my dear wife, Esra

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ABBREVIATIONS

AODV	Ad-hoc On-demand Distance Vector
AON	All Optical Networks
APS	Automatic Protection Switching
AS	Autonomous System
ASE	Amplified Spontaneous Emission
ASON	Automatically Switched Optical Networks
ATM	Asynchronous Transfer Mode
BLSR	Bidirectional Line-Switched Rings
BGP	Border Gateway Protocol
CD	Chromatic Dispersion
CDN	Content Delivery Network
CWDM	Coarse Wavelength Division Multiplexing
DBPP	Dedicated Backup Path Protection
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
FC	Fibre Channel
FCAPS	Fault, Configuration, Accounting, Performance, and Security
FTTX	Fiber to the X, where x can be home, building or curb
GbE	Gigabit Ethernet
GMPLS	Generalized MPLS
GPS	Global Positioning System
HAMP	Hamiltonian p-Cycle
ICT	Information and Communications Technologies
IP	Internet Protocol
ISP	Internet Services Provider
IT	Information Technologies

ITU	International Telecommunication Union
ITU-T	Telecommunication Standardization Sector of ITU
IXP	Internet Exchange Point
KSPF	k-Shortest Path First
MAN	Metropolitan Area Network
MANET	Mobile Ad-hoc Networks
MPLS	Multiprotocol Label Switching
MTTF	Mean Time To Failure
NTP	Network Time Protocol
OAM	Operations, Administration, and Maintenance
OCC	Optical Carrier Channel
OCh	Optical Channel
ODU	OCh Data Unit
OEO	Optical-Electrical-Optical
OH	Overhead
OMS	Optical Multiplex Section
OOS	OTM Overhead Signal
OPU	OCh Payload Unit
OSNR	Optical Signal to Noise Ratio
OTN	Optical Transport Network
OTM	Optical Transport Module
OTS	Optical Transmission Section
OTU	OCh Transport Unit
OXC	Optical Cross Connect
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
POP	Point Of Presence
PXC	Photonic Cross Connect
PXT	Pre-Cross-Connected Trails
ROADM	Reconfigurable Optical Add-Drop Multiplexer
ROW	Right Of Way
RR	Reverse Request

RWA	Routing and Wavelength Assignment
SBPP	Shared Backup Path Protection
SD	Signal Degrade
SDH	Synchronous Digital Hierarchy
SF	Signal Fail
SLA	Service Level Agreement
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SRG	Shared Risk Group
SRLG	Shared Risk Link Group
SRNG	Shared Risk Node Group
TZAR	Time Zone based Approximation to Ring
UPSR	Unidirectional Path-Switched Rings
UTC	Coordinated Universal Time
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch

CHAPTER 1

INTRODUCTION

Almost all the fundamental computer network books start the story by telling about a race condition among transportation and telecommunications. For quite a short while it might have worth comparing speeds of delivering gigabytes of data inside removable media with that of transmitting through 56 Kbps modem connections. But nowadays the game seems to be over in that respect, since optical networks are becoming a more and more practical reality.

With the latest advances in laser and semiconductor technologies it has already been possible to transmit 200Gbps on a single channel (lightpath). What is more, Dense Wavelength Division Multiplexing (DWDM) makes it possible to carry 160 such channels over a single fiber link. Optical line cards supporting 88 DWDM channels at speeds of 100Gbps and 200Gbps are commercially available to support resultant capacities of 8.8 Tbps and 17.6 Tbps, respectively [1].

Other than adding on the transmission speeds, improving distances to be covered without regeneration of optical signals (light waves) is under investigation. Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) appreciates efforts on longitudinally compatible intra-domain DWDM applications [2] as well as repeaterless optical submarine systems [3], which is important for extending coverage areas overseas in an economical fashion. One of the longest trans-Pacific runs has already demonstrated a 9,500 km traversal at 100 Gbps, and promising for 500 Gbps soon [4].

1.1. Thesis Objective and Motivation

Networks are being constructed in a hierarchy to comply with the demand characteristics of varying scopes. Access networks provide last mile connectivity to clients for up to tens of km. Metropolitan Area Networks (MAN) serve as a distribution layer within specific countries typically in a sub-1000 km range. Transport networks constitute the core international/intercontinental Wide Area Network (WAN) to provide global reach through interconnectivity among Tier1 and Tier2 ISP domains.

During 1990s fiber optic systems started to dominate long-haul transmission for WAN linear trails. Then in 2000s Synchronous Digital Hierarchy (SDH) and Synchronous Optical Network (SONET) infrastructure matured the services for MAN rings. And recently by 2010s Passive Optical Networks (PON) are being deployed to provide full wavelength access through star or bus FTTX (Fiber to the x, where x can be home, office, building or curb) topologies.

Hence, optical networking has eventually become a much more visible instrument of our era. As Internet continues to evolve with many new bandwidth-hungry applications (such as video on demand, cloud computing and social media) and clients (such as smart phones/TVs and tablets) on top of it, huge traffic consumption is expected to bounce back from access (PON) to distribution (MAN) and core (WAN) networks [5].

To cope with such an aggressive demand, transport protocols will have to adapt to efficient use of DWDM links for higher levels of throughput and reliability. That is why core players of global Internet industry are concentrating and investing more on optical networking both in terms of active equipment [6], and cabling infrastructure [7]. Electronic router market leaders tend to merge with smaller-size pure optical technology developers, while best circuit switching implementers change their strategies to provide routed packets a new media [8].

Nevertheless, whatever developments will be done to increase performance on active equipment, 70% of network downtime will continue to be related to physical layer [9]. There are three major categories of physical failure sources, examples of which are detailed in [10]:

I. Unfortunate natural disasters – floods, earthquakes, etc. (An earthquake with aftershocks continuing for the next two days took place in 26 December 2006 near Taiwan. Submarine cables connecting Asia to North America were damaged. Internet capacity of China was reduced to 26 %.)
II. Unintentional accidents – construction digging faults, human errors in cord patching, etc. (A train derailed into a tunnel in 18 July 2001 in Baltimore, which is one of the most critical ports for transoceanic fiber optic cabling infrastructure in the Northeast United States. Resulting fire caused backbone link failures for 7 major ISPs.)
III. Intentional cyber-attacks – well planned cable cuts approaching to or emanating from a targeted victim (In January 2008 Internet connectivity of most of Arabian Peninsula countries were tested via a series of cable cuts in the Mediterranean Sea and Indian Ocean. More than 20 million clients were suffered.)

Whenever such catastrophic events happen in physical layer, switching and routing layers in sequence try to recover whole network services from the failed state. However, uncorrelated nature and the random behavior of such failures make it quite difficult to handle them at upper layers. For the above mentioned examples;

- Taiwan 2006 – Although BGP was able to recover some part of the network, traffic between Taiwan and China had to traverse Pacific Ocean twice until manual traffic engineering was done.
- Baltimore 2001 – Although most of the traffic was rerouted on alternative links, overall network slowdown and the congestion could only be avoided within 36 hours after new cables were laid to restore the failed physical capacity.

As a result, highly realistic protection switching mechanisms should be deployed in optical transport networks to recover from any scenario in an immediate manner. This thesis offers a new approach, which we call "Time-Zone based Approximation to Ring" (TZAR), to improve autonomous resilience of globally distributed OTN over mesh topologies. Time zone parameter not only acts as a cross-layer carrier of geo-location information, but also a diversity guarantee among primary and protection (backup) lightpaths.

1.2. Focal Terminology

While focusing on resilience in OTN throughout this thesis, we will be using special terms, some of which are necessary to clarify from the very beginning:

- **Resilience**; is the ability of a network to provide accepted level of services even after physical failures or operational faults. When used in the context of networking, "survivability" has the same meaning.
- **Protection**; is a resilience mechanism, in which backup resources are provisioned with the primary services during initial network setup, i.e. before any failures or faults happen.
- **Restoration**; is a resilience mechanism, in which backup resources for the affected traffic patterns are computed and configured dynamically right after the detection of any failure or faults.
- **Lightpath**; is a two-tuple (P,λ), where P represents a path (a sequence of links connecting neighboring nodes) from a source to a destination and λ represents the wavelength(s) associated with each link along that P.
- **Diversity**; is a feature of at least two lightpaths. The less network resources these lightpaths share, the more diverse they are. Ideal diversity of primary and backup lightpaths for a specific connection is achieved, when they do not share any links or nodes other than the communicating end points.
- **Protection Switching**; is the operation performed at Data Link Layer (Layer-2) to recover failed services via switching on to a pre-computed, pre-configured, and/or pre-established connection.

- **Route Restoration**; is the operation performed at Network Layer (Layer-3) to recover failed services either via rerouting through a backup route, or by invoking a new routing process.

Although there may be different understandings in literature, we believe that the above descriptions are in line with the philosophy of ones given in relevant ITU-T standards. Technical details and inter-relations of all these terms will be studied in the following chapters as outlined below.

1.3. Organization of the Thesis

Starting with a brief introduction on Optical Transport Networks (OTN), we first summarize state of the art components of All Optical Networks (AONs), physical details of Wavelength Division Multiplexing (WDM), and principles of Routing and Wavelength Assignment (RWA) techniques.

In the third chapter a critical discussion on the Protection Switching algorithms offered and the performance metrics evaluated so far is presented. Then in the fourth chapter, we introduce a new approach (TZAR) based on Time-Zone parameter along with the assumptions made and benefits expected.

In the fifth chapter, after a description of simulation environment and data collection tools used in our analysis, simulation scenarios and results collected are detailed to evaluate the performance of TZAR in terms of optical path resiliency and service restoration times.

At the end of the thesis, we will conclude with a summary of our major contributions and suggestions for a couple of future works to be investigated further. Appendix A is also provided as a benchmark to check for the applicability of our new protection switching protocol.

CHAPTER 2

OPTICAL TRANSPORT NETWORKS

Optical Transport Network (OTN) is one of the most promising recent phenomena in networking industry. Regardless of the applications and appliances pushed into the Internet access market, OTN is expected to present the necessary core transport services in an efficient and granular manner.

Though OTN has to be considered in numerous dimensions, for the sake of simplicity we will be squeezing our scope to the standards published, key hardware components, physical state of optical communications, and the software restrictions on service provisioning.

2.1. Optical Transport Network

For decades voice-centric circuit switching networks and data-centric packet routing networks were operated by service providers in parallel. By the beginning of third millennium, sophistication of cloud computing, mobile applications, and multimedia services introduced a new transport network optimization demand to handle modern traffic patterns and content on a unified platform.

Thanks to the availability of Wavelength Division Multiplexing (WDM) technologies, OTN is then defined as a payload-transparent lightpath management infrastructure by Telecommunications Standardization Sector of International Telecommunications Union (ITU-T) with a series of recommendations, such as [11], [12], and [13].

2.1.1 OTN Architecture

As illustrated in Figure 1, OTN is designed to function as a digital wrapper. It takes optical signals generated by any upper layer services, and bundle them on specific wavelengths in a DWDM system. This feature not only provides backward compatibility with all the existing WAN protocols and equipment running them, but also utilizes each wavelength with as many services as the line rate allows asynchronously for achieving the best possible spectral efficiency. Details of how OTN interfaces with upper layer services and how client signals are mapped on to the OTN framing structure are given in [11].

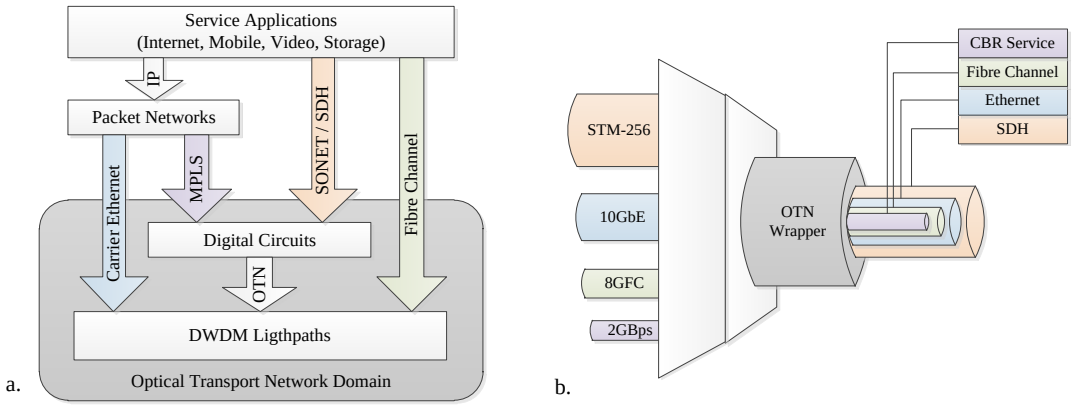


Figure 1 – OTN Functional Architecture: a. Protocol Stack, b. Digital Wrapper

Once OTN is populated with critical amount of services and data; operations, administration, and maintenance (OAM) of the network as well as fault, configuration, accounting, performance, and security (FCAPS) features of client payload have to be satisfied. A generic architecture in that respect is recommended in [12].

Figure 2 demonstrates a brief operational architecture applicable to OTN. Switching and multiplexing sort of optical functionalities take place in the transport plane on dedicated line cards. Connectivity between OTN nodes are provided through ports on these line cards. But the switching decisions are made by electronic processing units, which are located in the same chassis and communicate with the line cards through a high-speed backplane.

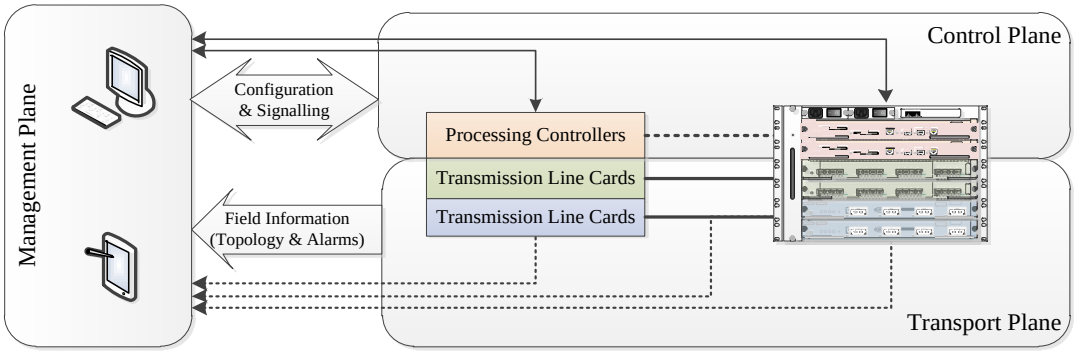


Figure 2 – OTN Operational Architecture

Processing controllers, which constitute the control plane, can either perform decisions autonomously via probing local transmission line cards and collecting information from neighboring nodes, or receive commands from a set of management hosts. Both of these communications are performed through a supervisory channel available in the encapsulation hierarchy (to be discussed in the next sub-section) of OTN.

Being responsible for the OAM and FCAPS features, management plane has to coordinate fixed hosts and mobile engineers. Harmonizing the signaling and alarms on fixed hosts with the field information regarding environmental situation and physical layout (such as equipment placement within cabinets and cable installation along the path) received from mobile engineers, control plane is configured by management plane.

2.1.2 Encapsulation Hierarchy

Optical Transport Module (OTM) is the entity carried across OTN. Fundamentally it can be decomposed into two parts; a digital wrapper section and an analog transmission section [14]. Although encoding speeds of each section and bit level decomposition of all headers and trailers within data units are out of the scope of this thesis, it is important to understand the basic building blocks for the rest of the study. Internal hierarchy of OTM and corresponding logical functionalities are illustrated in Figure 3.

- Optical channel Payload Unit (OPU) presents the client services, such as ATM, GbE, FC, and SDH. OPU overhead (OH) defines the payload type.
- Optical channel Data Unit (ODU) provides end-to-end path supervision in terms of switching and multiplexing control. ODU OH includes Path Monitoring (PM) field to check for the multiplex section performance and six Tandem Connection Monitoring (TCM) fields to let path monitoring functionalities managed by different ISP domains in nested, overlapping, and cascaded topologies as demonstrated in Figure 5.b.
- Optical channel Transport Unit (OTU) conditions the signal transmitted via 3R – retiming, reshaping, and regeneration. Section Monitoring (SM) field in OTU OH is basically used for alignment between OTN hops. General Communication Channel (GCC) bytes are used as a supporter to protection switching, service-level reporting, and control plane communications signaling. Another critical functionality, which is a distinction of OTN when compared to SDH, is provided by Forward Error Control (FEC) trailer in OTU. Reed-Solomon RS(255,239) code, where 16 bytes of overhead data is added to each 239 bytes of payload data, is used to detect 16 symbol errors or to correct 8 symbol errors in any code word [15].

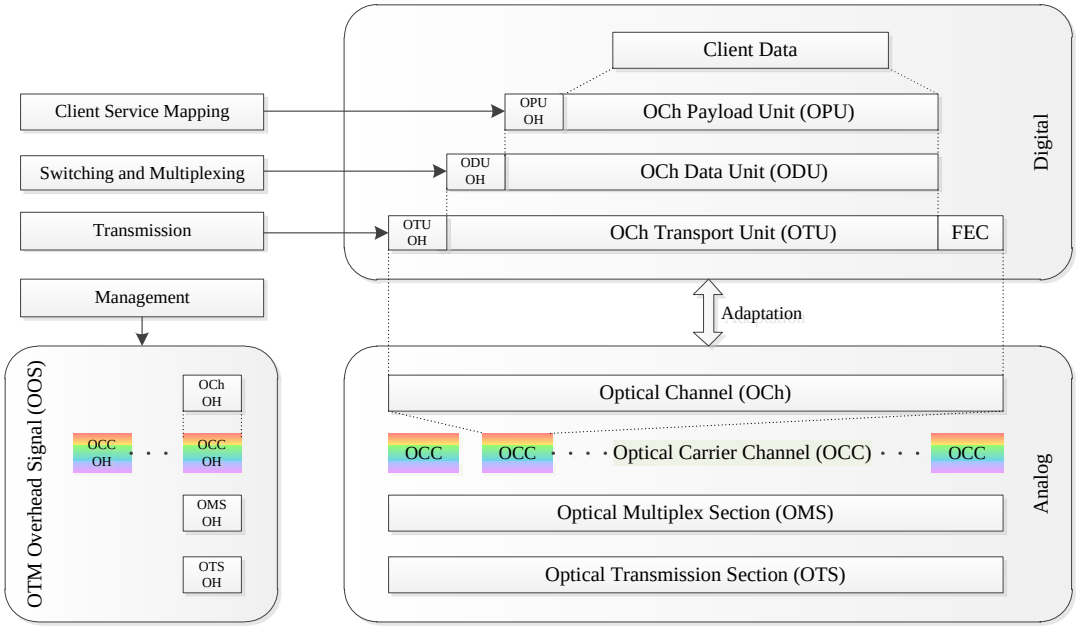


Figure 3 – Optical Transport Module (OTM) [14]

Each OTU envelope is adapted to an associated Optical Channel (OCh). Optical Carrier Channel (OCC) can carry as many OCh as the system permits on different wavelengths. By the way, client service rates are decoupled from the underlying line rates. OCC add-drop functionalities are provided on WDM-capable OTN nodes, which constitute the Optical Multiplex Section (OMS). Optical Transmission Section (OTS) identifies the fiber links in between any active optical element. A typical optical line breakdown pinning out these OTN sections is given in Figure 4. Further details of connection, termination, adaptation, and sub-layer functions of all these sections and layers are available in [13].

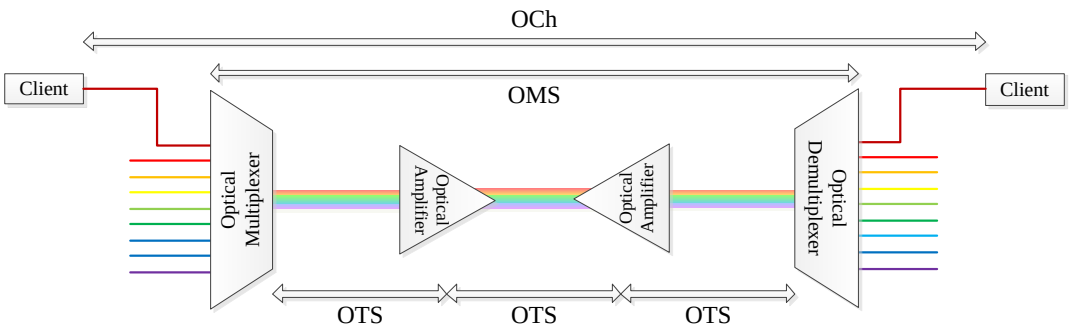


Figure 4 – Optical Line Structure Breakdown [14]

OTM Overhead Signal (OOS) is carried on a supervisory channel to include OCh, OCC, OMS, and OTS overheads. Especially OCh OH and OMS OH can be used to coordinate protection switching triggered by OCC OH and OTS OH, respectively. In addition to the protection mechanisms for existing point-to-point links, subnetwork trails, and ring topologies, available reserved fields in OOS makes research for mesh topologies necessary and meaningful. In the next chapter we will delve into further details of protection switching framework, and our proposal to improve resilience of OTN on a global scale will be based on signaling within OOS.

To conclude with the encapsulation hierarchy of OTM; sample ODU clients, their mapping on to OTU signals, and the associated transmission rates are merged from [12], [14] and [15] in Table 1. TDM-like mapping of client payload into server layer and closely matching line rates are not ordinary coincidences – OTN is just evolving as a successor to SDH.

Table 1 – Set of ODU clients and serving OTU rates

ODU Clients	ODU Server	OTU	Signal Rate
1GbE, STM-1, STM-4, FC-100	ODU0	-	-
ODU0, STS-48/STM-16, FC-200	ODU1	OTU1	2.666 Gbps
ODU0, ODU1, ODUflex, STS-192/STM-64	ODU2	OTU2	10.709 Gbps
10GBase-R, FC-1200	ODU2e	-	-
ODU0, ODU1, ODU2, ODU2e, ODUflex, 40GbE, STS-768/STM-256	ODU3	OTU3	43.018 Gbps
ODU0, ODU1, ODU2, ODU2e, ODU3, ODUflex, 100GbE	ODU4	OTU4	111.809 Gbps
Constant Bit Rare (CBR) signals, Generic Framing Procedure (GFP) frames, Asynchronous Transfer Mode (ATM) cells, InfiniBand (IB) data rates	ODUflex	-	-

2.1.3 OTN as a successor to SDH

With its comprehensive OAM features SDH has been the de facto transport network for at least last two decades. Its robust performance and ease of management gained enough popularity to result in a dense deployment base. But that popularity and the investment protection mood of ISP world cannot resist to the highly beneficial proposals of OTN anymore. [15]

Although encapsulation hierarchy of OTN presents similarities with that of SDH, there are some significant differences as listed in Table 2. OTN is designed to relax strict timing restrictions across the network, while still supporting both synchronous and asynchronous payloads. A much wider scalability is provided with OTN, which is currently offering 100 Gbps and ready for the beyond. Enabling transmission of optical signals over longer distances through fewer repeaters, FEC is also a milestone for lower OAM costs. [14]

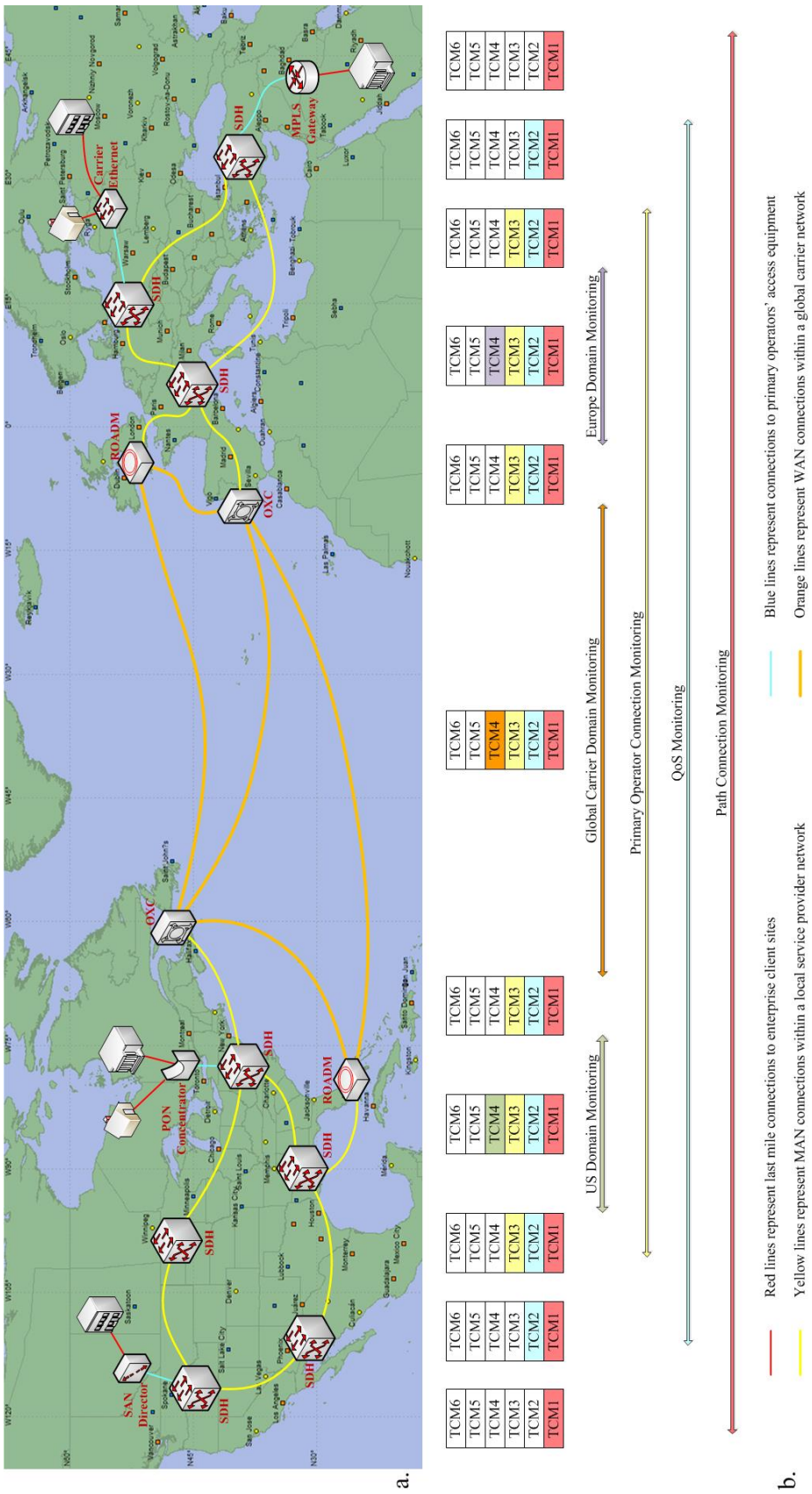


Figure 5 – Global Internetworking Topology: a. Network elements in various domains, b. Tandem Connection Monitoring in OTN

Table 2 – OTN versus SDH

	SDH	OTN
Timing	Synchronous	Asynchronous
Payload	Up to 40 Gbps (STM-256)	Scales to 100 Gbps (OTU4), and ready for beyond
Framing	Fixed frame rate or virtual concatenation of multiple frames	Variable frame size dynamically adapts to any client rates
Coverage	Limited inter-node distance and ring size	Extended distances through Forward Error Correction (FEC)
Enhanced Features	~50 ms protection switching	Inherent transparency, wire-speed encryption, virtual private networks

Due to these benefits, it has already become reasonable for service providers to switch to the OTN infrastructure. Recent surveys show a great tendency among leading global service providers to deploy OTN switching on their networks [6]. On the other hand, smooth migration scenarios, where tightly integrated SDH and OTN equipment can co-exist, are defined in [13] and [14]. Figure 5.a illustrates how such optical network elements are positioned on a global internetworking scale.

2.2 Optical Network Components

Philosophical background of the efforts on all-optical networking can go back to 1990s, when “Switch where you can, route where you must!” was used as a motto to highlight the importance of handling traffic in the lowest possible layers of Internet protocol stack. At those days Layer-3 routing functions were performed mostly on software, but Layer-2 switching functions were performed mostly on hardware. After that gap has just been disappeared with so-called unified platforms in electrical domain, there appears to be a new trend to handle as many networking functions as possible within optical domain. Occasionally referred to as a virtual layer (Layer-0), widespread implementation of DWDM accompanied some Physical Layer (Layer-1) and Layer-2 all optical network components.

2.2.1 Optical Fiber

Optical fiber is the medium, in which light waves propagate over distances. Fiber is a cylindrical composition of two-layer glass. Core is the inner part carrying light. Cladding is surrounding the core with a lower refractive index. As a result of "Total Internal Reflection" light waves are confined to the core. There are basically two types of fibers, properties of which are tabulated in Table 3. [16]

Table 3 – Types of Optical Fiber

	Multi-Mode Fiber	**Single-Mode Fiber**
Core / Cladding Diameter	50-62.5 / 125 μm	8-10 / 125 μm
Operating Wavelength	850 - 1300 nm	1310 – 1550 nm
Covered Distance	Hundreds m	Thousands km <
Transceiver Optics	LED-based	LASER-based

Non-Zero Dispersion Shifted Fiber (NZ-DSF) is the type of single-mode fiber addressed for DWDM deployment. Fiber optic cables are constructed by properly shielding the thin glass (i.e. core and cladding) via special buffer and jacket materials along the path. Various fiber optic cables for different purposes are manufactured as described in [3].

2.2.2 Optical Transceivers

Optical transceivers can be called as gates in between electrical and optical domains. Semiconductor Lasers are used as transmitters to convert electrical signals into optical rays. Vertical-Cavity Surface-Emitting Laser (VCSEL) suits some low bit rate – short distance applications, while Multi-Section Distributed Feedback (DFB) lasers are proper for high bit rate – long distance DWDM links. On the other hand, Avalanche Photodiode (APD) is the most responsive and widely used receiver to convert optical power to electrical current. These transmitter/receiver pairs are packed in small form factor transceiver modules (i.e. SFP+, XFP, CFP4) to be plugged into transmission line cards. [3]

2.2.3 Optical Amplifiers

When it comes to traversing terrestrial and submarine links, amplification of the carrier signal in optical domain without any OEO (optical to electronic and from electronic back to optical) conversions has become a must. On transmitter side, sending the data with maximum available power so as to reach the farthest next hop has no any detrimental effects. On receiver side though, a rather attenuated signal would be much safer [16]. However, too much attenuation would result in unacceptable bit error rates (BER) because of the noise introduced on the way. To provide more or less reasonable signal levels throughout the transmission link following optical amplifiers are developed:

- **Erbium Doped Fiber Amplifier (EDFA);** utilizes quantum properties of rare-earth Erbium ions (Er3+), which perfectly matches the low loss region of conventional (C band) and long wavelength (L band) telecom bands. EDFA operates via a pump laser, which is mixed with the input signal through a coupler. In the active medium Erbium ions are excited to higher energy levels. Some of the signal photons collide with these excited ions and cause stimulated emission. This action is the main source of signal amplification, since signal photons are doubled with each such collision. Gains on the order of 40 dB (10,000 photons out per photon in!) or more can be achieved with such EDFA architectures. [17]
- **Semiconductor Optical Amplifier (SOA)**; uses electrons in the active medium, which are excited electrically by a pump (if it is correct to say so) current. Since upper-state life-time is rather short, lower energy can be stored. And amplifier responds to pump power much more quickly (on the order of hundred picoseconds). [18]
- **Raman Amplifiers**; are also known as distributed amplifiers because of their intrinsic behavior, which can take place on installed single-mode fiber base. The principle behind their operation is stimulated Raman scattering. They best perform with counter-propagating pump light on the receiver side, and by the way they can be perfect complementary for EDFA. [3]

Table 4 – Comparison of Optical Amplifiers

	EDFA	SOA	Raman
Gain (dB)	>40	>30	>25
Waveband (nm)	1530-1560	1280-1650	1280-1650
Polarization	No	No	Yes
Dispersion	No	Yes	Yes
Size	Rack-mount	Chip-scale	Moderate
Cost Factor	Moderate	Low	High

Table 4 provides a comparative summary of available optical amplifier types. EDFA is suitable to be used as a booster amplifier right after a transmitting end or as a line amplifier in the middle of long haul multiplex sections. Raman is a natural pre-amplifier to be positioned just before a receiving end. With its low cost and small size SOA is an option to be considered within transceiver modules circuitry.

2.2.4 Reconfigurable Optical Add-Drop Multiplexers

Multiplexing is to combine multiple colors of light waves into a single fiber. Demultiplexing is to split a light wave back into multiple colors. Shortly referred as MUX/DMUX, multiplexer and demultiplexer modules are simple prism-like units. Based on MUX/DMUX units, Reconfigurable Optical Add-Drop Multiplexer (ROADM) selectively adds and drops certain wavelengths within a DWDM channel. Not to disturb wavelengths passing through, following internal components are used while doing these add-drop operations: [16]

- **Fiber Bragg Grating (FBG)**; is an optical bandpass filter used to reflect selected wavelengths.
- **Circulator**; is a 3-port fiber, where light coming from ports 1 and 2 goes out from 2 and 3, respectively.
- **Splitter**; is a tap to split optical signal into two. 50/50 splitter is used for protection switching, while 99/1 is used for optical performance monitoring.

2.2.5 Optical Cross Connects

Deployment of OTN in mesh WAN topologies depends on progress in Optical Cross Connect (OXC) (or Photonic Cross Connects (PXC)) capabilities. OXC is a device to provide optical switching among input and output ports on wavelength granularity. Optical Wavelength Selective Switches (WSS) are built with array of tiny mirrors, which can be moved electrically or magnetically within Micro Electro-Mechanical Systems (MEMS). [3]

Figure 6 emulates the internal structure of a sample 3-port OXC, which is quite similar to a ROADM. 2 Input/Output port pairs represent connection to WAN. Add/Drop port pair represents a client access to OTN. Port-wise much scalable and switching-wise more capable OXC systems are under development.

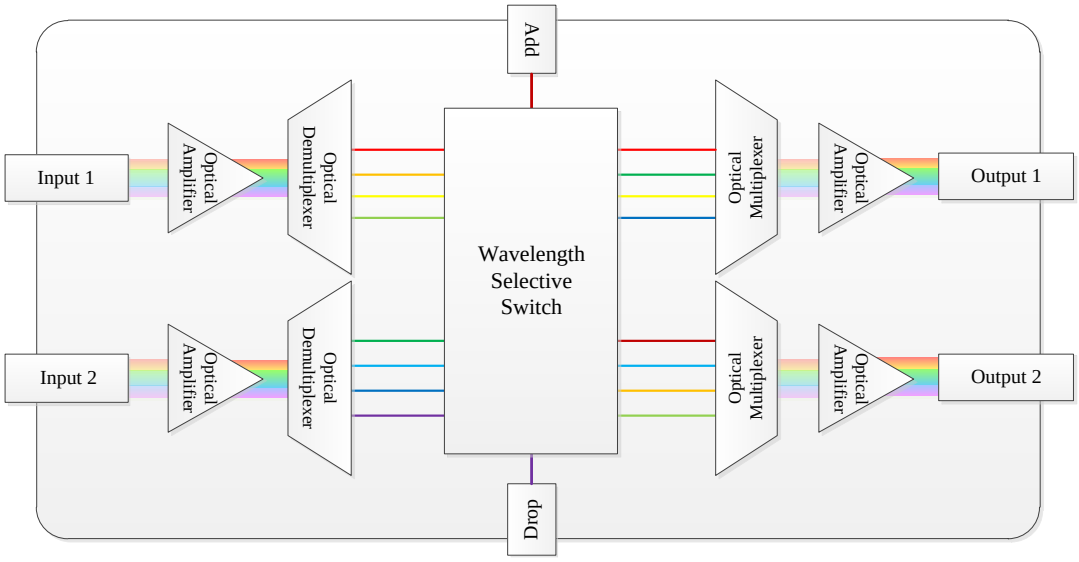


Figure 6 – A sample Optical Cross Connect

2.3 Wavelength Division Multiplexing

Wavelength Division Multiplexing (WDM) is indeed a kind of Frequency Division Multiplexing (FDM) to increase optical channel utilization. Instead of radio frequency signals, light waves are carried over different colors.

There are basically two types of WDM applications – Coarse WDM (CWDM) and Dense WDM (DWDM), spectral properties of which are given in [19] and [20], respectively. Although underlying physical principles are the same for both CWDM and DWDM, they have different implementations as outlined in Table 5.

Table 5 – CWDM versus DWDM

	CWDM	**DWDM**
Spectral Band	1271 – 1611 nm	1530 – 1625 nm
Channel Spacing	20 nm <	12.5 / 25 / 50 / 100 GHz 0.1 / 0.2 / 0.4 / 0.8 nm
Number of Channels	8 Channels are possible in 160 nm of spectrum	160 Channels are possible in 32 nm of spectrum
Implementation	Cheaper uncooled lasers, Telecom band multiplexing on to a single-strand fiber	Stays in C and L telecom bands, Works with EDFA in long haul systems

2.4 Routing and Wavelength Assignment

In optical domain connections refer to lightpaths, and corresponding connection requests can be handled not only by finding a physical path from source to destination, but also by assigning an appropriate wavelength. This is the most primitive definition of Routing and Wavelength Assignment (RWA). As the definition inspires, problem can be decomposed into two steps [21]:

i. **Routing**; to identify an appropriate path between source (S) and destination (D) nodes. In accordance with the protection mechanism deployed, there can be two or more paths – one primary path, and at least one backup path.
ii. **Wavelength Assignment**; to convert paths found in the routing step into lightpaths by assigning an available wavelength to each request. In case there are no any available wavelengths, the connection request is said to be blocked.

Both of these steps have their own metrics and implementation difficulties, which make exact solution for the problem unlikely to exist. Yet, the target of RWA algorithms is to minimize blocking probability (maximize the number of lightpaths set up successfully) [22] or to maximize mean time to failure (MTTF) [23] in handling new connection requests while making use of least number of wavelengths and traversing least number of hops [24].

Blocking probability and MTTF are sort of alarm triggers for service providers to upgrade their capacities. That is why, all serious service providers have to solve RWA problem in a continuous manner with their own methodology and cost/budget estimations. Meanwhile two basic constraints have to be considered:

- **Wavelength Continuity**: In case there is a lack of wavelength converters (a pair of embedded transceivers) within the optical network, each lightpath needs to use the same wavelength along the route (on each hop) from S to D. When this constraint is relaxed via dynamic wavelength converters, RWA problem simply turns into a version of circuit switching [25].
- **Wavelength Clash**: On each link any wavelength can only be used once. As a consequence, if two connections share a common link, they have to be assigned different wavelengths. This constraint can also be somewhat relaxed via installing parallel links (trunks) in between adjacent nodes [10].

As proved in [26] static RWA can be map-reduced to graph coloring problem. Bad news; the problem is NP-Complete. Good news; some greedy heuristic algorithms can be offered to achieve reasonable solutions within polynomial time.

Let N be the set of nodes (OXCs), L be the set of physical bidirectional links (a pair of unidirectional fiber links in opposite directions) connecting neighboring nodes, and W be the set of wavelengths that can be assigned on each link in an optical network. Lightpath setup demand is an N x N matrix P, where P[S,D] represent the number of lightpaths to be established from S (source node) to D (destination node) subject to the below equations.

$$\tau_{sd}^{wl}=\begin{cases}1, if\ wavelength\ w\ on\ link\ l\ is\ used\ for\ a\ demand\ in\ P[S,D]\\ 0, otherwise\end{cases} \quad (2.1)$$

Objectives:

$$maximize \sum_{w\in W}\sum_{l\in L}\tau_{sd}^{wl} \quad (2.2)$$

$$minimize \sum_{s,d\in N}\sum_{l\in L}\tau_{sd}^{wl} \quad (2.3)$$

Subject to:

$$\sum_{w\in W}\tau_{sd}^{wl} \leq 1, \forall l \in L, \forall s \in N, \forall d \in N, s \neq d \quad (2.4)$$

$$\sum_{w\in W}\sum_{s,d\in N}\tau_{sd}^{wl} \leq |W|, \forall l \in L \quad (2.5)$$

Objective (2.2) corresponds to maximal wavelength utilization on optical links for the efficient use of resources, while (2.3) represents shortest path routing for the overall network. Equation (2.4) restricts a lightpath through a link to a single wavelength, and (2.5) introduces the link capacities.

Then the RWA problem can be expressed as follows: Given a connected graph G(N,L,W) and a lightpath setup demand P, is it possible to establish lightpaths for all the demanded setup requests?

Be P[S,D] a static or a dynamic demand, connection requests in OTN are not so similar to that of the ones at access (PON) or distribution (MAN) layer networks. Poisson arrival rates and exponential holding times for any specific connection might still be valid with a significant relaxation – there happens to be very few lightpath setup requests, and once set up such lightpaths are almost never torn down under normal circumstances. [27]

What is more, each lightpath has to be protected against failures. Since such lightpaths in the optical core are used to transmit traffic related to thousands (if not millions) of second level customers (customers' customers), any service outage has very dramatic effects. While 99.97% availability (~ 3 minutes of downtime per week) might be enough for ordinary accounts [28], even six nines (99.9999% ~ 31.5 seconds of downtime per year) may be unacceptable for some highly critical core layer ISP accounts [14]. Therefore, RWA problem has to be solved in conjunction with the protection switching scenarios, so as to provide highest levels of resilience and availability in OTN.

CHAPTER 3

PROTECTION SWITCHING IN OTN

Since optical cross connects (OXCs) and DWDM links, which do lie at the very heart of international/intercontinental OTN, are responsible for delivery of the most critical amount of traffic, proper route restoration mechanisms have to be deployed to recover from any link and/or node failure. Main objective of recovery techniques that are employed in any network architecture should be to autonomously, rapidly, adaptively, and without great additional cost in terms of redundant capacity reroute the affected traffic, so as to minimize the information lost during outages.

Taking into consideration that simultaneous multiple failures occur very infrequently, major interest in literature is on recovery from a single link and/or node failure. Especially for dense mesh topologies, it is enough safe to assume that the next failure will likely to happen after all the previously affected traffic (lightpaths) has been restored. With such an assumption, amount of redundant capacity required to design a self-protecting network is significantly reduced.

In typical WAN, route restoration is a functionality offered at Layer-3. Whenever a timer expires or an alarm is triggered routing process is invoked and new routes are computed. Depending on the routing algorithm used and the complexity of network topology convergence time may increase up to the order of minutes. However due to the above-mentioned SLA reasons, in optical domain much tighter timing targets have to be set for fast lightpath recovery. Because in case recovery cannot be accomplished in a short period of time, upper layer route restoration mechanisms take place. [29]

Protection switching is the set of tools and algorithms developed to replace any failed network resource with a pre-assigned backup. Pre-assignment, which constitutes the basic distinction from route restoration, avoids additional lightpath setup/teardown events at intermediate nodes. As described in [30], protection switching approaches should;

- Run in a scalable manner to be able to recover numerous lightpath services concurrently,
- Be independent from upper layer protocols to support any client type (such as SDH, ATM, GbE, FC, etc.),
- Utilize a robust signaling methodology to circumvent any additional failures, and
- Not rely on non-time-critical functions (for example, fault localization should not be a part of protection switching) for the most immediate behavior.

After an extensive research and development, generic protection switching tools and methodologies are more or less standardized for linear trails [31], ring topologies [32], and mesh networks [33]. However due to the multi-dimensional heterogeneity of transport networks and commercial ISP business practices, there is still much to do for mesh optical core networks. Appendix A lists the principle objectives of further investigations.

There are several metrics that may be used to evaluate the performance of a protection switching technique/algorithm. Among these; recovery success ratio and speed of recovery are the most vital ones, which do bother the OTN clients. Capacity efficiency and implementation complexity are the two metrics, which refer mostly to the operational costs of ISPs. The number of signaling messages exchanged is already outdated with the out-of-band OOS in OTN encapsulation hierarchy presented in 2.1.2. In the following sections we introduce the taxonomy of protection switching in optical networks with a major focus on recovery success ratio, speed of recovery, and resource efficiency.

3.1. Computational Concerns

Two questions to be addressed for evaluating protection switching computation techniques in optical networks are;

I. When and in how much time backup lightpaths are assigned?
II. How backup lightpaths are computed and the decision is coordinated?

Answers to the first question can be either before failure happens, or right after any link/node failure. Considering the fact that protection switching has to take place as soon as possible, preplanned lightpath creation seems to be the best choice. In literature the other approach is even called route restoration rather than protection switching. [30, 34]

To catch up with the route restoration timers, switching from (originally working) failed lightpath to (associated backup) protection lightpath has to complete in the order of tens of milliseconds. Temporal model of protection switching given in Figure 7 identifies the following happenings within that time; [31]

- T_1: Network impairment should be detected either through sophisticated alarm indicators, or simply via Signal Failure/Degradation (SF/SD),
- T_2: Hold-off time (sometimes referred to as waiting time) should pass to make sure that it was not a false alarm,
- T_3: Protection path to be switched on to should be selected,
- T_4: Decision should be propagated to both communicating end nodes,
- T_5: Recovery time should elapse for data link frames to be synchronized.
- Confirmation (protection switching is required) Time: $T_c = T_1 + T_2$
- Transfer (protection switching is carried out) Time: $T_t = T_3 + T_4$
- Traffic Restoration (lightpath services are up and running again) Time: $T_r = T_1 + T_2 + T_3 + T_4 + T_5 = T_c + T_t + T_5$

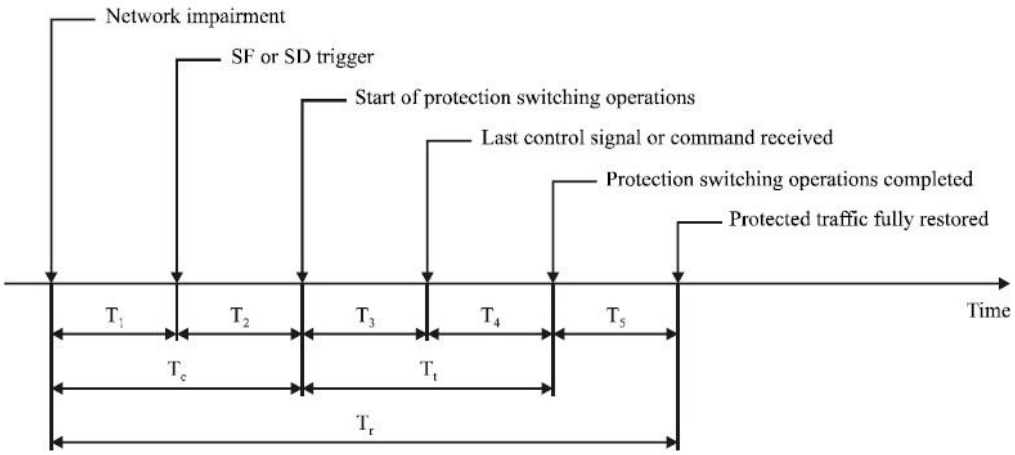


Figure 7 – Protection Switching Temporal Model [21]

Actual durations of T_5, T_c, and T_t in high-speed OTN turn out to be on the order of ns (nanoseconds), μs (microseconds), and ms (milliseconds), respectively. Since $T_5 \ll T_c \ll T_t$, the dominant factor for traffic restoration time via protection switching is T_t. When we check the components of T_t; T_3 corresponds to a few clock cycles within a kind of GHz processing unit, but T_4 corresponds to multiple propagation delays along the path.

Propagation delay is the time spent by any single bit on the way (in cables) from its source node to destination. Since optical signals carrying data in terms of bits are tapped into a fiber cable, laws of physics are in place for the propagation of these signals. Signal speed on any healthy link approaches to 70% of speed of light. So, propagation delay is only related to the distance (4.8ms per 1000km) to be covered on the path. Therefore, other than assigning the shortest primary and backup lightpaths for any traffic demand, appropriate signaling mechanisms have to be defined to accelerate protection switching.

Automatic Protection Switching (APS) protocol described in [31] offers a suit of such signaling efforts. Depending on the deployed network architecture, 1-phase, 2-phase or 3-phase handshake algorithms can be used as illustrated in Figures 8.a, 8.b, and 8.c, respectively. These algorithms basically differ in the number of one-way propagation delays required for traffic restoration on backup paths.

- **1-Phase APS**; is a destination-based approach to eliminate any confirmations from the source node.
- **2-Phase APS**; is also a destination-based approach with a required confirmation from source node.
- **3-Phase APS**; is a source-based approach, which prevents misconnections under all circumstances, and is suitable for any architecture type.

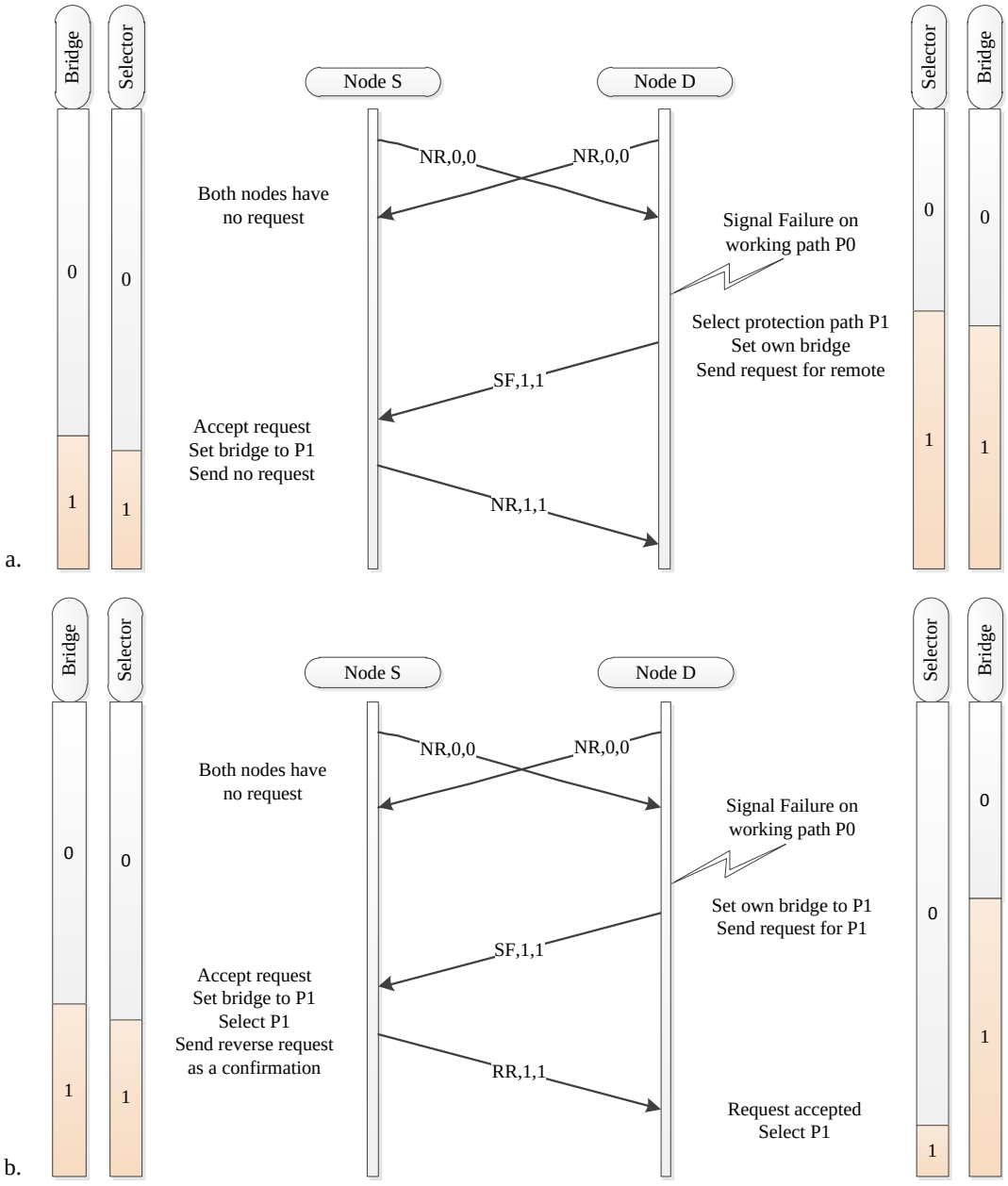


Figure 8 – APS Signaling Alternatives: a. 1-Phase APS, b. 2-Phase APS, c. 3-Phase APS

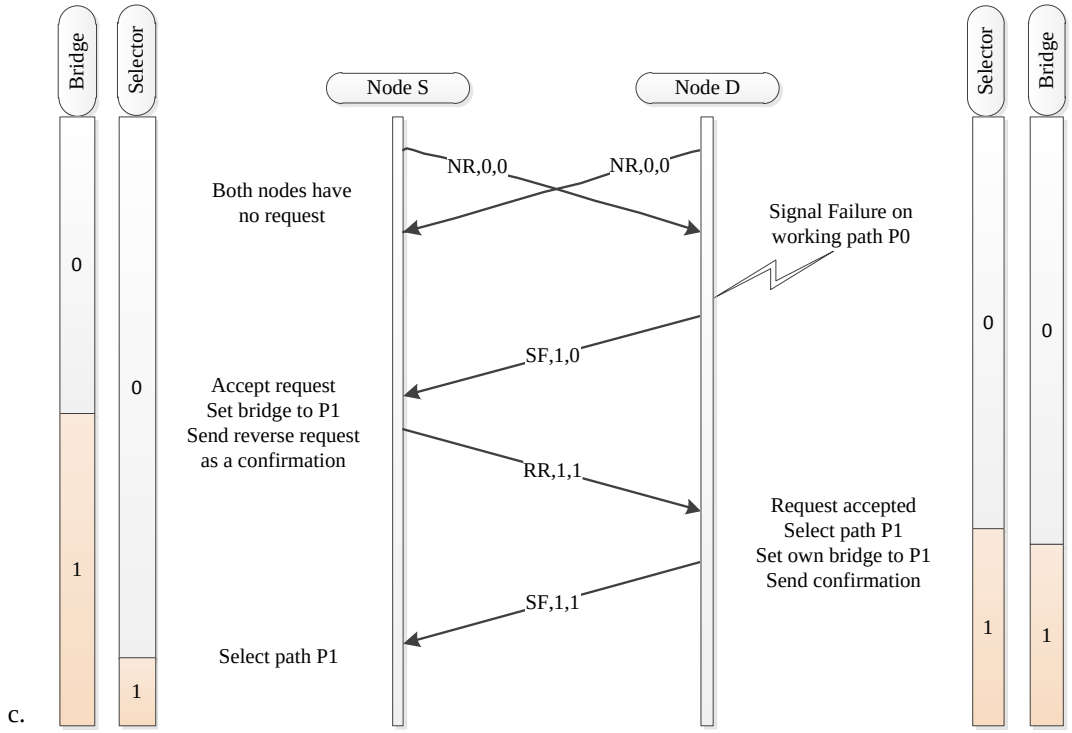


Figure 8 – APS Signaling Alternatives (continued)

(XX,y,z notation is used for the exchanged APS signals, where XX corresponds to the Request/State type, y is the requested signal, and z is the bridged signal)

Due to the nature of optical networking any impairment may trigger unpredictable interactions on core OXCs and customer equipment. Especially when SDH is used at customer premises, lightpaths provided by OTN works as a virtual channel, and within confirmation time (T_c) protection switching is also triggered in customer network. Thus protection redundancy and escalation coordination have to be handled through proper setting of protection switching timers. [35]

How this coordination is handled indeed answers the second question. As described in 2.1.1, it can be either centrally through a management plane, or autonomously on a control plane. Since centralized approaches make use of the complete network information, they definitely result in less computational overhead in the control plane and higher efficiency in terms of resource usage on the transport plane. On the other hand, relying on exchanged signaling messages on the fly, distributed approaches do scale well in large networks and react more resiliently against multiple link/node failures.

Nevertheless, centralized control might not be that possible within the multi-domain nature of real carriers. Limited (better to say summarized) information is available on border nodes, and inter-domain links cannot guarantee to provide backup lightpaths for all neighboring carriers [36]. Therefore, a broad set of network topologies have to run distributed and/or hierarchical protection switching algorithms by forming trust relationships and securely sharing any required monitoring or billing information via peering mechanisms [37].

3.2. Resource Efficiency

The more a network is utilized the more efficient turns out to be the investment made. While trying to provide the best protection switching performance in terms of time, we cannot underestimate the cost of laying new optical cables or installing more active devices. Therefore, equilibrium has to be reached between network redundancy and efficiency. Computation of primary and backup lightpaths has to be carried out in a manner to optimize resource utilization via sharing as many links as possible. APS architectures in point-to-point systems could be a nice starter to define the levels of efficiency in optical networks: [30, 38]

- **(1+1) Protection**: In this approach, practically, there are two working lightpaths. Transmitter-receiver pairs on both sides of a communication channel select among the two incoming signals on a quality basis. And there is no need for any signaling overhead in case of a failure. However, the required split up at the transmitter result in 3dB optical signal loss.
- **(1:1) Protection**: In this approach, there is one pre-computed backup path (DBPP – Dedicated Backup Path Protection) for each working lightpath. Advantage against (1+1) protection is backup paths can be utilized with low-priority traffic when associated working lightpaths are functional. But in case of failures, a low signaling overhead (either 1-phase or 2-phase APS) takes place. And depending on the defined priorities, suspended traffic is switched on to the backup path.

- **(M:N) Protection**: This approach is an extension and generalization of (1:1) protection. The only difference is there are M backup paths for N working lightpaths. Since N is typically greater than M, resources are shared (SBPP – Shared Backup Path Protection) with improved efficiency. Obviously, signaling overhead in case of a failure is expected to be higher (3-phase APS) for this implementation. For the most optimistic scenarios it may be possible for a lightpath to survive even after up to M link faults, but when failures effect all N working lightpaths only M of them can survive in this scheme.

With proper sharing in a mesh network, protection capacity may be well below 60% of the working capacity [39]. Though a value-based approach on service provider reliability costs (capital investments and operational expenses) and beneficial savings (reduced revenue loss and decreased SLA penalties) in [28] has shown that shared mesh network design posts an 8% saving over the dedicated protection.

One of the main issues while trying to increase efficiency is to deal with the Shared Risk Groups (SRG). Risk groups can be defined as a set $R = \{r_i \mid 1 < i < |R|\}$, where r_i is a set of links (Shared Risk Link Group (SRLG)) and nodes (Shared Risk Node Group (SRNG)), or both. Given any two network elements e_j and e_k, if there exists no any SRG r_i, such that both $e_j \in r_i$ and $e_k \in r_i$, then e_j and e_k are said to be SRG-independent. Given a path $P = \{N_0, L_{01}, N_1, L_{12}, N_2, \dots, L_{(j-1)j}, N_j\}$ and a network element e, if there exists no any SRG r_i, such that both $e \in r_i$ and either $N_j \in r_i$ or $L_j \in r_i$, then e and P are said to be SRG-independent. Given a pair of paths P_1 and P_2, if each link and each node in P_1 is SRG-independent with P_2 and vice versa, then P_1 and P_2 are said to be SRG-disjoint.

SRG is an important network design parameter especially when assigning protection lightpaths. Nevertheless, construction and deployment of optical cables introduce additional complexities, which can only be dealt with by human interaction. As described in [3] there may be tens of fiber cores within an optical cable. Lightpaths (i.e. wavelengths) on a fiber core can be distinguished on a node,

to which that specific core is connected. But there are no any means to understand whether fibers connected to different ports of an active device are assembled in the same ribbon with each other, or not. So, deployment procedures for optical cables underground not only have to follow the technical guidelines, but also obey standard documentation principles.

Fiber cables in optical transport systems are buried in a sequence of right of way (ROW) structures, which are frequently obtained from railway or pipeline companies. The economics of such ROW leasing in long-haul runs often necessitates several carriers share the costs. However, this collaboration may turn out to be a kind of fate sharing as well, since numerous carrier cables lay in close proximity to each other. What is worse, physical layout of the network may nullify the efforts on logical topology. As demonstrated in Figure 9 a single physical conduit failure may affect several logically diverse links. That's why, places where fiber cables enter/leave a ROW or cross each other have to be considered as critical SRG arguments in OTN design. [40]

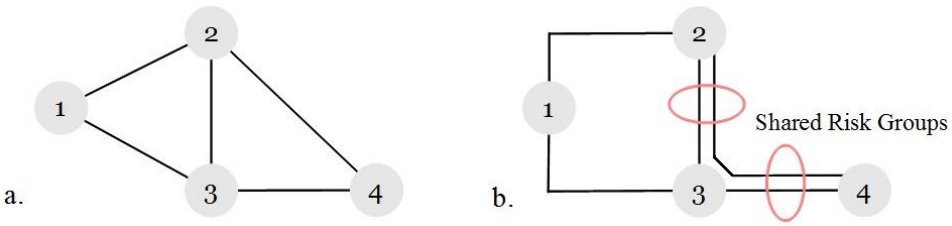


Figure 9 - Shared Risk Groups: a. Logical Topology, b. Physical Layout

Duct-layer constraints are used to optimize network survivability in [41]. Backup lightpaths are rerouted so as to maximize resource sharing, and then primary lightpaths are rearranged accordingly. But such rearrangements on working connections might cause service deteriorations in real life.

A probabilistic approach instead is offered in [42] to override the SRG paradigm. Link availabilities are used to calculate the most reliable paths (MRP), and some highly available links are used both on primary and backup lightpaths. However, this method does not provide link or node disjoint backup paths.

Two aspects have to be considered while trying to improve efficiency in OTN:

I. Load Balancing: Computing primary and backup lightpaths as diverse as possible would utilize most of the network resources in a homogenous fashion, and leave available wavelengths for further traffic demand.
II. Shared Risk Groups: Applying (M:N) protection techniques (SBPP) for those primary lightpaths that do not have any SRG would avoid contention in case of a failure, and reduce the blocking probability.

3.3. Topological Facts

There are two dimensions of topological discussions in lightpath protection:

I. Diversity of the primary and backup paths
II. Overall topology of the network

The main purpose of computing a backup lightpath is to be able to switch smoothly in case primary lightpath fails. However depending on; the type of failure, the number of affected lightpaths, and the density of network topology, it may be difficult to switch all the failed traffic to their associated backup lightpaths. To overcome such difficult scenarios different backup lightpath detouring alternatives are offered. Major three of these alternatives are link based protection, path based protection, and segment based protection, which are illustrated in Figures 10.b, 10.c, and 10.d, respectively. [34]

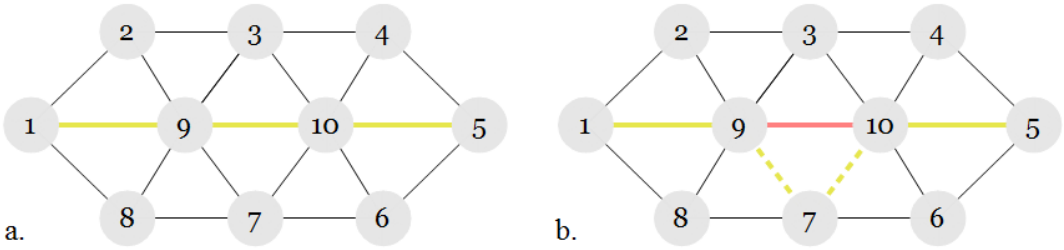


Figure 10 – Alternative Protection Schemes: a. Non-protected primary path, b. Link based protection, c. Path based protection, d. Segment based protection

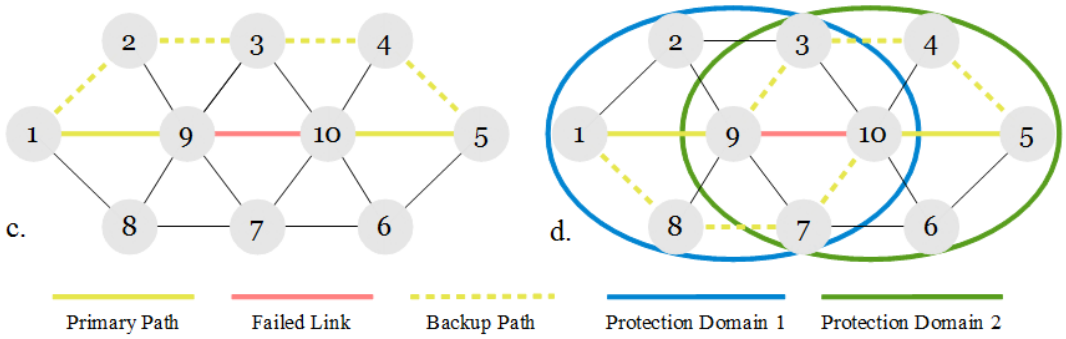


Figure 10 – Alternative Protection Schemes (continued)

- **Link Based Protection**: Only the nodes that bookend the failed link (nodes 9 and 10 in our case) initiate the protection switching. Faults are easily detected either by a low-threshold hit in optical signal quality, or simply by a loss of light. For each link L_{ij} connecting nodes N_i and N_j, a backup path in between nodes N_i and N_j is computed, such that protection switching can occur for all the lightpaths passing through link L_{ij}. However, link based protection requires lots of redundant capacity, and it is not suitable to provide recovery from node failures.
- **Path Based Protection**: Be it a link or a node, not using any common resources on primary and backup lightpaths is the basic rule. For each lightpath setup demand P_{sd} from a source node N_s to a destination node N_d one primary path P_{sd}^p consisting of a series of non-repetitive nodes and links $\left\{N_s^p, L_{01}^p, N_1^p, L_{12}^p, N_2^p, \dots, L_{(i-1)i}^p, N_i^p, \dots, N_d^p\right\}$ and a corresponding backup path P_{sd}^b $\left\{N_s^b, L_{01}^b, N_1^b, L_{12}^b, N_2^b, \dots, L_{(j-1)j}^b, N_j^b, \dots, N_d^b\right\}$ are computed, where $N_i^p \neq N_j^b \cap L_{(i-1)i}^p \neq L_{(j-1)j}^b \; for \; \forall i,j$. Given that such diversity in the network topology exists, protection quality would be much better and network would definitely survive under all sorts of single failure scenarios. Also there is a significant capacity utilization improvement, which becomes more promising with effective resource sharing. However, it is not easy to compute such protection switching paths, and in case of a failure signaling overhead in between nodes N_s and N_d (nodes 1 and 5 in our case) becomes unacceptable with growing topologies (i.e. longer propagation delays).

- **Segment Based Protection**: This can be considered as a middleware solution, which tries to combine advantages of link and path based approaches. Network is partitioned into segments, and path based protection switching techniques are applied on a reasonable scale. In our sample topology there are two protection domains 1 and 2, which compute backup lightpaths {1-8-7-10} for {1-9-10} portion of the primary path and {9-3-4-5} for {9-10-5} portion of the primary path, respectively. Depending on whether the failure on link $L_{9,10}$ is first signaled by node 9 or 10, protection domains 1 or 2 recovers the communication, respectively. By the way, efficiency can be increased without paying for protection time. What is more, this approach provides an adjustable scalability as well as an autonomous system support among service providers.

Though these link, path, and segment based protection schemes have their own advantages and disadvantages, they cannot be applied directly on all networks. Overall network topology also has an important bias on the decision of right protection switching algorithm.

Ring is the simplest topology to run path based protection switching. Because, as illustrated in Figure 11, routing primary and backup lightpaths on inverse (also referred to as clockwise/counter-clockwise and east/west with respect to each other) directions automatically gives us the solution. Three ring architectures have already become popular in real-life optical networks – two-fiber unidirectional path-switched rings (UPSR), two-fiber bidirectional line-switched rings (BLSR/2), and four-fiber bidirectional line-switched rings (BLSR/4). [43]

UPSR is an alternative for low-speed local exchange or point to multipoint access networks. On the other hand, with their spatial reuse capabilities and additional protection mechanisms BLSR provide a very resilient alternative for MAN. The only drawback of these ring topologies is their dependency on coverage area, since propagation delay becomes dominant as the distance to be covered increases.

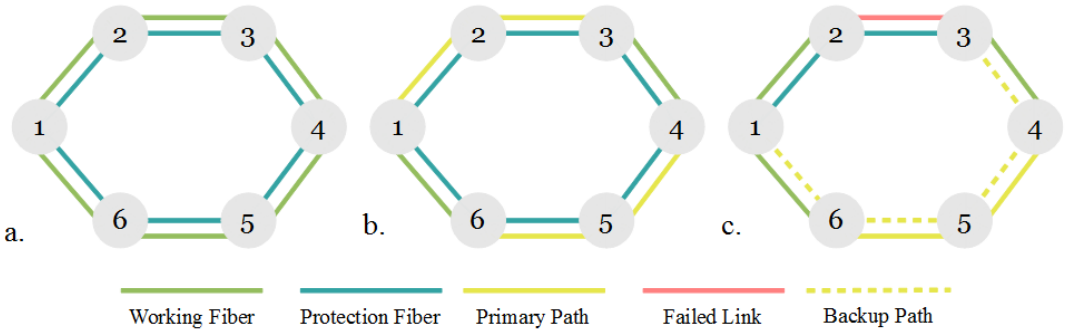


Figure 11 – Protection Switching in Ring Topologies: a. Working and protection fibers, b. Two independent lightpaths are setup between nodes 1-3 and 4-6 on working fiber, c. After a failure on link (2-3), lightpath (1-3) switches to the backup path, which traverses the ring in reverse direction. Since this backup path is established on protection fiber, lightpath 4-6 on working fiber is not affected from that operation.

Mesh is the natural topology of worldwide Internet. But practically, such large-scale networks are far away from the full mesh architecture, where all nodes are connected to each other via a link. Consequently, lightpath protection in sparse and long-haul mesh networks is quite a big headache for intercontinental carriers. As discussed in [34, 44], k-shortest paths (K-SP) and protection cycles (p-cycles) are the two mainstream methods to solve routing part of RWA, common purposes of which are to maximize load-balancing and to minimize shared risks.

K-SP are lists of K paths for any given S-D pairs. Yen's algorithm [45] to find loopless paths and Suurballe's algorithm [46] to find edge-disjoint paths were the two milestones for K-SP approaches. Basic principle is to run Dijkstra's algorithm iteratively by excluding the paths found in the next iteration and to enumerate the first K paths found. In K-penalty algorithm [47] protection against multiple failures is investigated by not excluding the links (via setting their costs to infinity) in found paths, but using transit nodes to adjust link costs. Another interesting algorithm is offered in [48], where all source nodes are allowed to compute at least two best first hop distinct paths to their corresponding destinations. For all these K-SP algorithms to be operational within OTN protection switching framework, they have to either introduce a proper fast rerouting of failed lightpaths or adapt themselves to some existing signaling protocol.

Especially after the applicability of APS signaling was proposed in [49] for p-cycles, protection switching in WDM networks has started to evolve around the following fundamental techniques as outlined below and illustrated in Figure 12. That evolution not only enjoys the maturity levels of APS functionality in already deployed node elements, but also offers a variety of survivability methods for mesh optical networks as summarized in [50] and [51], respectively.

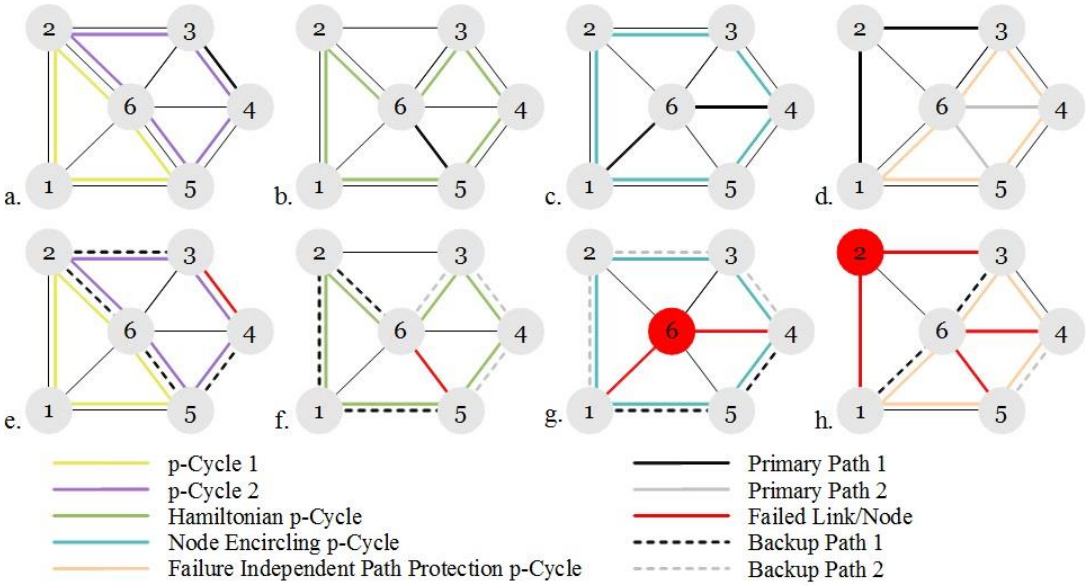


Figure 12 – Alternative p-Cycle Structures: a. Simple Protection Cycles, b. Hamiltonian p-Cycle, c. Node Encircling p-Cycle, d. Failure Independent Path Protecting p-Cycle, e. Recovery with Simple p-Cycles, f. Recovery with Hamiltonian p-Cycle, g. Recovery with NEPC, h. Recovery with FIPP p-Cycle

- **Simple p-Cycles**; are the ring structures found in mesh topologies to emulate BLSR behavior for protection switching. The idea was initially developed as a pre-failure cross-connection strategy in [52]. Distributed Cycle PreConfiguration (DCPC) protocol was defined via loading "Cycler" and "Tandem" roles to the nodes in a network. Two candidate p-cycles are highlighted with purple and yellow rings in Figure 11.a. These candidate p-cycles can realize protection switching for all the lightpaths passing through a failed link as shown in Figure 11.e. In addition to protecting such on-cycle links, p-cycle approach introduces a very interesting alternative for straddling links, which can better be explained on a Hamiltonian p-cycle as will be discussed next.

- **Hamiltonian p-Cycle** (introduced as Hamiltonian Cycle Protection in [53]); is the longest possible p-cycle for a network, since it traverses all the nodes once. What is more, all links in a network topology can be protected with a single Hamiltonian p-cycle, because any link would be either an on-cycle link, or a straddling link. Any link (edge), whose end-points are connected to nodes (vertices) on a p-cycle, but the link itself is not a part of the p-cycle, is called a straddling link. Existence (link (5-6)) and two diversely routed protection path alternatives (paths {5-1-2-6} and {5-4-3-6}) of such straddling links are illustrated in Figures 11.b and 11.f, respectively. Though Hamiltonian cycles do not exist for all topologies, this can and should be mitigated by service providers as a network design issue. Other than acting as an option for protection switching, presence of a Hamiltonian cycle makes resolution of graph coloring problem for spectrum allocation much simpler, since the auxiliary graph would have only two nodes.
- **Node Encircling p-Cycle (NEPC)**; is developed to protect the traffic passing through a particular node in [54]. Since there are no any means to deal with the originated or terminated lightpaths on that specific node, only the transit lightpaths are of concern. Beautiful thing is; each failed node emulates a straddling link for all passing by lightpaths, so that two distinct backup paths can be found on the p-cycle as illustrated in Figure 11.g. But it is not always possible to allocate as simple p-cycles (i.e. traversing links and nodes just once) as given in Figure 11.c to encircle each node. When it comes to finding and configuring non-simple p-cycles, computation complexity increases and management flexibility diminishes.
- **Failure Independent Path Protection (FIPP) p-Cycles**; are structures for defining compatible route sets to share the pre-cross-connected protection resources. Figures 11.d and 11.h demonstrate how such a FIPP p-cycle can be formed for 2 mutually disjoint paths and how lightpaths can be recovered independent of the failure (i.e. node or link), respectively. Nevertheless, since enumeration of compatible route groups for a given demand has combinatorial complexity, a reverse engineering solution for a candidate FIPP p-cycle is offered in [55], which is quite not practical in real networks.

Though all those projections of ring topologies on mesh networks sound impressive, their implementation still needs to follow hybrid methodologies. At initial network setup a central processing might be helpful to compute the most efficient primary and backup lightpath provisioning. Whenever failures start to occur in runtime, next backup lightpaths have to be addressed continuously in a distributed manner.

CHAPTER 4

PROBLEM DEFINITION AND PROPOSED SOLUTION

In this study we primarily focus on cases, which do replicate the real life experiences regarding protection switching. Our main aim is to provide a new protection switching framework in OTN.

We have several assumptions, and based on these assumptions we propose quasi-ring decomposition for mesh networks. We call our approach TZAR – Time Zone based Approximation to Ring. Currently we assume APS signaling described in 3.1 is used, however we believe that it is also possible to use GMPLS control plane.

4.1. Assumptions

I. If the maximum ring length can be relaxed from 1200 km (~6 ms propagation delay) to 48000 km (~240 ms propagation delay), then resulting worst-case service restoration time target can also be relaxed from 60 ms (up to 10 ms for failure detection and 50 ms for switch time) to the order of 300 ms. Four justifications for the possibility of that relaxation are:
   a. "Switch time" network objective has already been applied as 300 ms for transoceanic Multiplex Section shared protection rings in [56]. This is also applicable to situations, where distances between the nodes of a ring exceed 1500 km.
   b. A "Hold-off timer" of up to 10 seconds in steps of 100 ms is suggested across cascaded Ethernet linear protection switching groups to give chance for an upstream ring to fix the encountered problem. [57]

c. “Loss-of-sync timer” is increased to 100 ms, so that inter-switch links (ISL) between distant FC (Fibre Channel) switches remain online during a protection switching event in underneath OTN. For long distance E_Ports, it is possible to extend FC speeds over 1000 km via adjusting “BB (buffer-to-buffer) credits” accordingly. [58]
d. For most of the routing protocols like MPLS and BGP “hold down timers” are set as at least 3 missing “keepalives”, which are typically on the order of tens of seconds. A mechanism to improve that behavior is Bidirectional Forwarding Detection (BFD), for which 300 to 900 ms are accepted to be safe performance values on most equipment. [59]

II. Any OXC is capable of building a kind of routing table to keep track of specific information regarding communicating parties of each lightpath originating from or terminating in its own clients.
III. Typical number of conduits emanating a site can be on the order of 1 to 4 for buildings and up to 6 for campus networks. That is an important factor in SRG estimations.
IV. Due to the climatic conditions within the neighborhood of north and south poles, optical cables cannot be laid down there. They are either broken in winter time, or it is not feasible to operate on those links at all.
V. We do not consider physical-layer impairments in this work. In all-optical DWDM systems noise accumulates from physical-layer impairments, such as crosstalk, amplified spontaneous emission (ASE) noise, and nonlinear impairments such as four-wave mixing, cross-phase modulation, and stimulated Brillouin/Raman scattering. But we underestimate all those side effects just to concentrate on protection switching performance under perfect circumstances.

4.2. TZAR – Time Zone based Approximation to Ring

Time zone is one of the basic settings for any network equipment. Almost all those devices take time information from central NTP (Network Time Protocol) servers,

which provide accurate time from authoritative sources, such as a radio or atomic clock or a GPS (Global Positioning System) time source. Then time zone is used to offset from the UTC (Universal Coordinated Time) and adjust the local time. These usual configuration items are well documented best practices for systems management and troubleshooting.

Once time zone information is already available in OXCs, why not to use that in our protection switching algorithms! Even if it may sound like a kind of cross-layer approach, such a static info on fixed (optical routers/switches are definitely not mobile) equipment could not be more valuable than ever. As illustrated in Figure 13 time zone parameter gives us quite a precise hint on the real location of network elements. If we can pass this geographical hint into the header of protection switching layer packets or frames, we can achieve a very high performance regarding efficient lightpath computation.

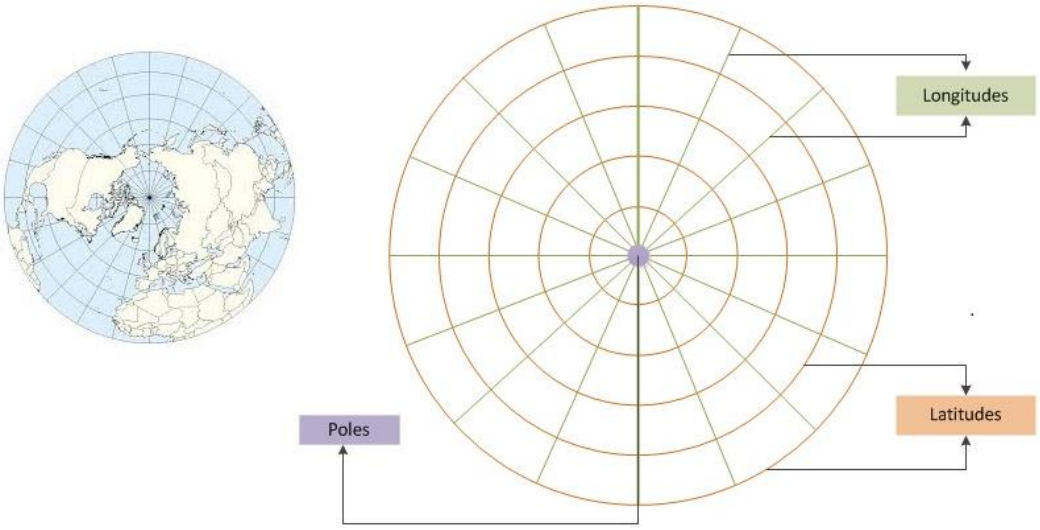


Figure 13 – Geographical correspondence of time zone parameter with longitudes

On the other hand, in almost all literature about wide area networking either North American or European network topologies are used to run simulations on. To the best of our knowledge, world-scale network topologies have never been discussed before. Because there are still several reasons for not being able to step further on the network boundaries [36, 37]:

- Governmental bodies enforce legal control on the cables laid underground. So, it is not possible for any ISP to install its own optical cables in all countries.
- Spatial distribution of customer base economically restricts any ISP to operate in a limited geographical coverage and number of POPs (Point Of Presence).
- When it comes to cooperation among neighboring ISPs, following facts introduce additional complexity on multiple management domains: [60]
  - Implementation differences in heterogeneous active network elements
  - Administrative restrictions on sharing topology and route information
  - Suboptimal SLA policies, which cause reluctance at the earning side

However, we believe that globalization trends in ICT industry are about to hit the OTN. Emerging business justifications to support this belief are two-fold:

i. **Internet Exchange Points:** Starting with Finland and Norway (probably our Assumption IV made it necessary) in 1993, Internet Exchange Points (IXP) are being established around the world to provide service providers a means to exchange Internet traffic. Colocation at an IXP not only gives relevant ISPs an opportunity to reach each other in a fast and cheap manner, but also results in a high-bandwidth and low-latency performance for the exchanged traffic. [61]

   Internet traffic is exchanged through Border Gateway Protocol (BGP), in which all communicating networks are represented with corresponding Autonomous System (AS) numbers. Routes among different AS are announced through peering links on a policy basis. Since there is an abundance of ISPs within most of IXP sites, it is a strategic decision of each AS to select with whom to peer. But as discussed in [62] rather immediate traffic recovery from emergency situations can be accomplished just inside the IXPs. Figure 14 lay out the physical (solid lines) and logical (dashed peering links) topologies relating IXP and AS domains.

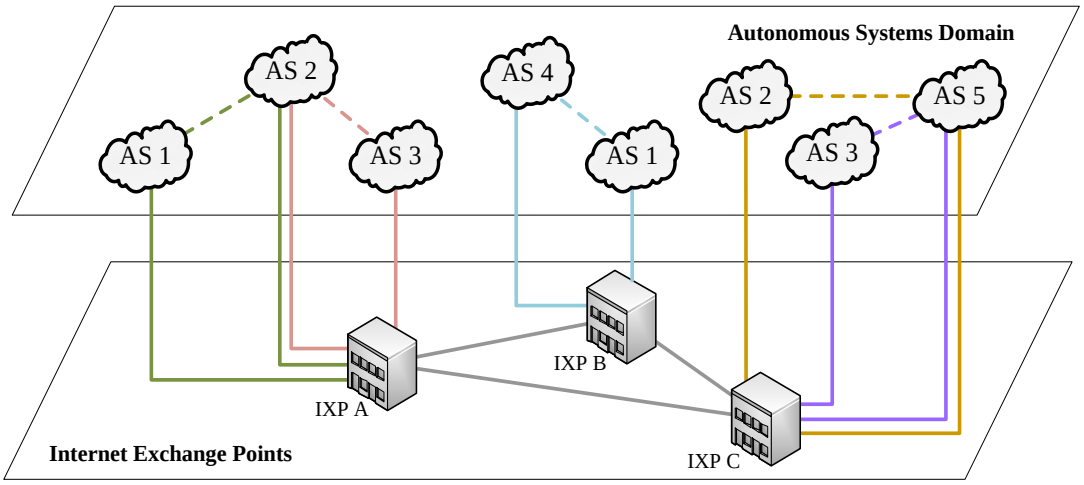


Figure 14 – Autonomous Systems peering at Internet Exchange Points

Leading IXPs, such as the ones located in Frankfurt (DE-CIX), Amsterdam (AMS-IX), and London (LINX) have already made 100Gbps ports available on their switching fabrics and passed the Tbps throughput thresholds [63]. But the most exciting business strategy is developed by Equinix, which operates as a network of IXPs around the globe (having presence in Paris, New York, Tokyo, Sydney, etc.). Any two AS on distant IXPs may soon peer via Ethernet over DWDM tunneling.

ii. **Content Delivery Networks:** Cloud computing era is driven by large software companies, which launch their products on Software as a Service (SaaS) platforms, such as Microsoft Azure and Amazon CloudFront. Targeting to provide the best performance and to excel in the user experience, those platforms started to reside on Content Delivery Networks (CDN), which are distributed data centers across the Internet.

CDN nodes are either operated individually, or collocated on an ISP site. In any case the interconnectivity (dashed links) is provided preferentially by dark fibers (solid lines) leased from two or more Tier-1 ISPs as shown in Figure 15. Many application delivery switching functionalities, such as web caching for lower latency, encryption for improved security, compression for efficient bandwidth consumption, and load-balancing for scalability and

fault-tolerance are provided within CDN architecture. As all these functionalities introduce new levels of excellence each day, more and more customers are engaged to CDNs. Therefore, global traffic management and real-time failover for any CDN cloud becomes one of the primary challenges to control and assure the provisioned SLAs [64].

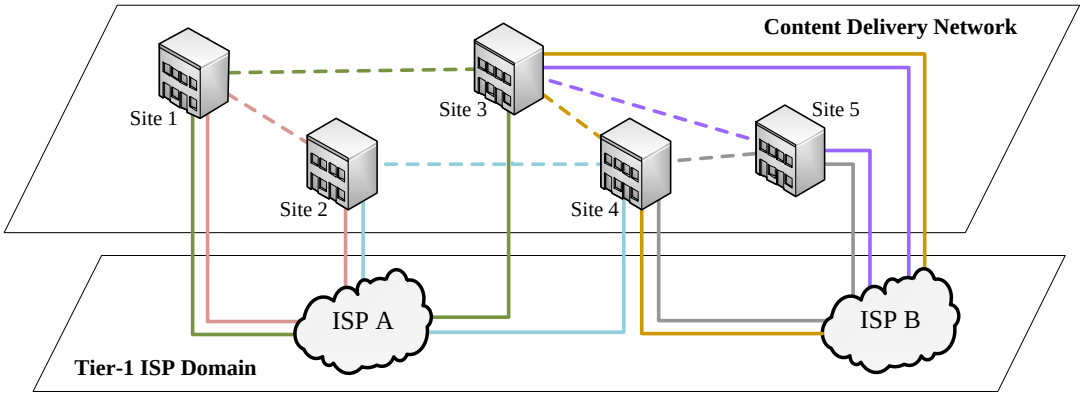


Figure 15 – Content Delivery Network leasing dark fibers of Tier-1 ISPs

Recently, Ericsson has announced to integrate Akamai's CDN technology in its network equipment to allow more intelligent traffic-routing and to introduce edge-caching capabilities into mobile networks [65]. On the other hand, Telco CDNs, who own the last mile connections closest to the customers, are evolving to a federated structure to co-exist in that new dimension of market space. So, it is not a dream to expect some control plane enhancements in optical domain to provide route resilience on mesh DWDM networks.

Blending the recent facts regarding long-haul test runs of DWDM links mentioned in "Introduction" with our assumptions above and the newly defined cross-layer parameter, i.e. Time Zone, we can concentrate on global topologies representing IXP networks and next generation CDN as demonstrated in Figure 16.

That is definitely an exciting mesh topology, which can utilize quasi-BLSR structures via calculating primary and backup light-paths through positive and negative directions of time zone. The intrinsic advantages of that global mesh are as follows:

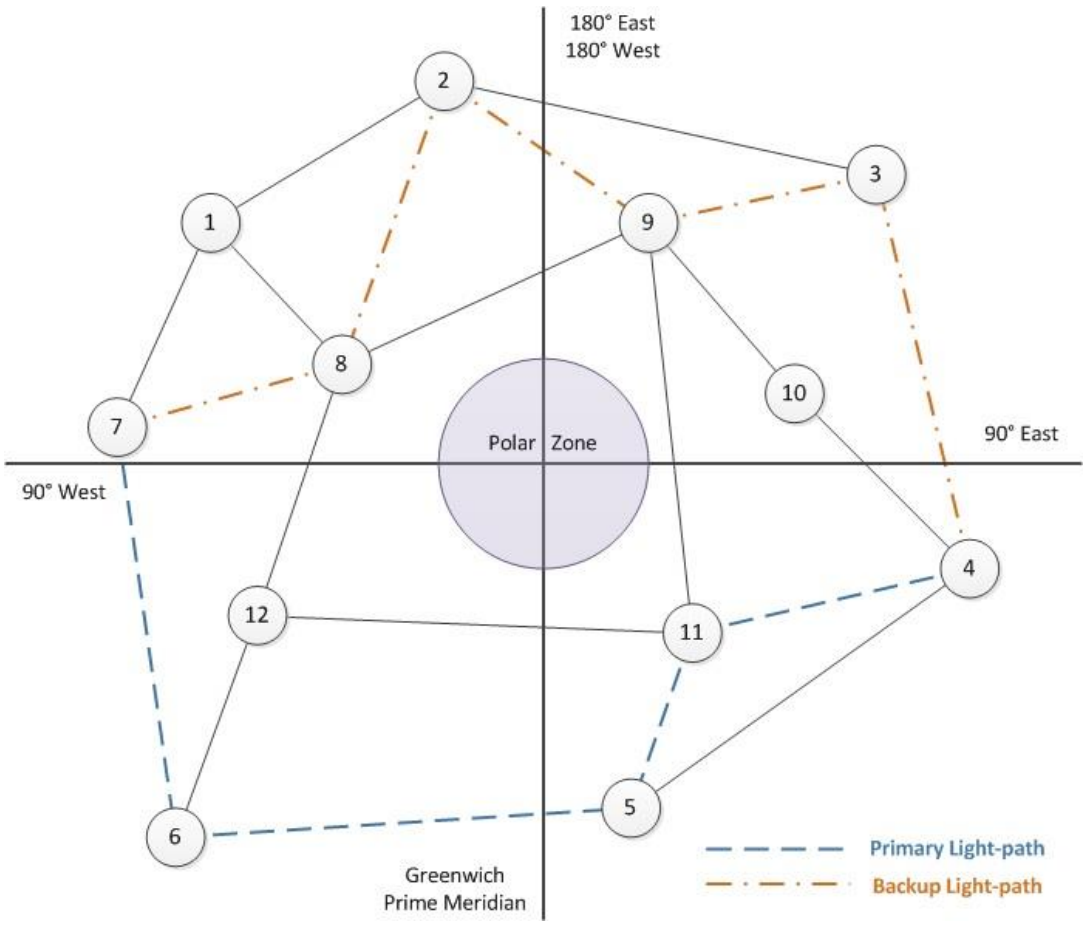


Figure 16 – Time Zone based Approximation to Ring for a global mesh network

- Longitudes, which designate the time zones, act as sort of cut-sets. Using cut-sets in RWA algorithms was proven to result in less run-time when compared to ILP or greedy variants [66].
- Once each lightpath end-point and each OXC on the path knows about its peers' and its neighbors' time zones, respectively (Assumption II), protection switching can be reduced to selecting just the reverse direction of primary lightpath in terms of time zone.
- Traversing the globe in clockwise and counter-clockwise directions provide the best possible diversity to minimize SRG. No any single link/node failure or a conduit cut can affect primary and backup light-paths simultaneously.
- Considering the fact that Internet traffic utilizations depend on the time of day for any specific country on the lightpaths, TZAR may also contribute to load-balancing on active sessions in case of failures.

- The utmost performance is expected for any S-D pair located 135° to 225° apart from each other. When the magnitude of time zone difference is 12 ∓3 hours, setting up the backup light-path in reverse direction makes the most sense.

4.3. Heuristics

We introduce our heuristics making an analogy from Ad-hoc On-demand Distance Vector (AODV) routing [67] offered for Mobile Ad-hoc Networks (MANET), so that large instances of TZAR can be solved with minimal computational overhead. Table 6 gives a summary of how we relate AODV with backup lightpath creation in TZAR.

Table 6 – Relation of AODV with TZAR

	AODV	**TZAR**
Path Setup Initiator	Route Request (RREQ) Route Error (RERR)	Signal Fail (SF) Signal Degrade (SD)
Confirmation	Route Reply (RREP)	Reverse Request (RR)
Working Path Identifier	Sequence Number	Connection ID
Distance Identifier	Hop Count	Time Zone (TZ)
Topology Controller	NET_DIAMETER is used to control maximum number of hops between any S-D pair	TZ_DIFFERENCE is used to control propagation of SD/SF messages along the path
Timing Controllers	PATH_DISCOVERY_TIME NET_TRAVERSAL_TIME	Hold-off Timers Wait-to-Restore (WTR)
Message Propagation	Broadcast / Unicast	Many_Cast / Unicast

Based on that analogy, APS signaling mechanism introduced in section 3.1 is modified as illustrated in Figure 17. By the way, intermediate nodes are also participating in our protection switching algorithm via making a kind of 1-phase handshake on ingress ports and 2-phase handshake on egress ports.

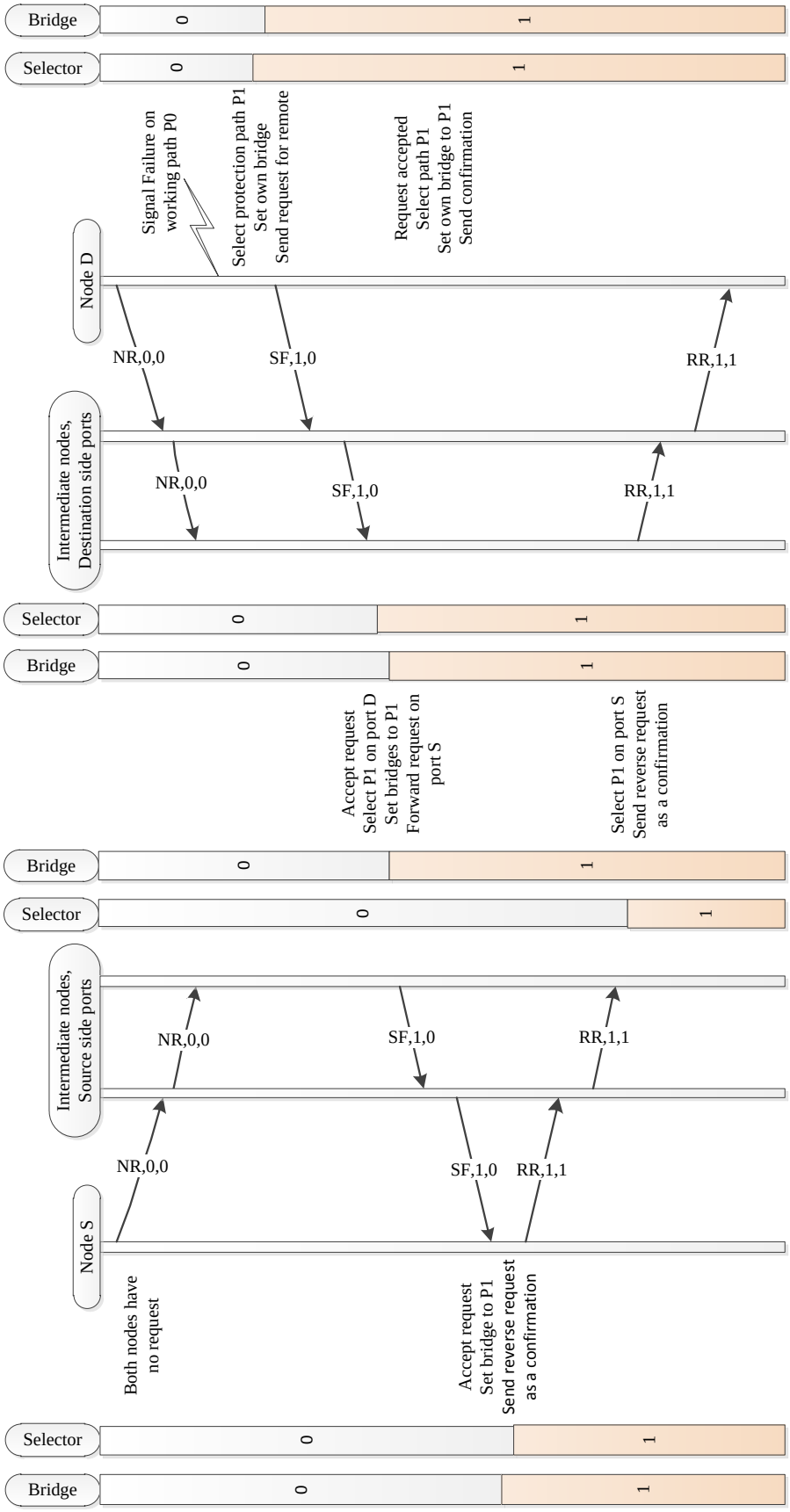


Figure 17 – APS Signaling scheme for TZAR

Although it is not apparent in Figure 17, we also assume that bridging to multiple links on each node is possible. As it will be explained in the heuristic below, forwarding backup lightpath setup requests on multiple non-overlapping links is expected to reduce blocking probability.

Table 7 – TZAR Heuristics

Protection Switching initiated by a source node

1. While (Max_Try_Count is not reached) Do
2. Set (TTL = Minimum (15, Number of Nodes)) and (Many_Cast = 0)
3. Send a lightpath setup request (SF) through a local interface, such that;
   i. If (Destination_TZ > Source_TZ) then (Neighbor_TZ < Source_TZ)
   ii. Else if (Destination_TZ < Source_TZ) then (Neighbor_TZ > Source_TZ)
   iii. Else select a random interface other than the one, on which connection was failed
   iv. Initialize RWA_Accumulated with source node/link info, and selected wavelength

SF/RR is processed at intermediate nodes

4. If (Destination_Address = Own_Address) then go to Step.8
   i. Else if (TTL is expired) then drop the SF
   ii. Else if (Conn_ID is cached within Hold_SF) then check RWA_Accumulated
   iii. Else decrement TTL, and compute new Many_Cast
5. Check Source_TZ to adjust forwarding interface candidates
6. Update RWA_Accumulated in accordance with selected candidate interfaces
7. For Many_Cast times forward SF through altering next-hop interfaces

Response of destination node

8. If (accumulated wavelengths list is empty) then do nothing
   i. Else select the accumulated wavelength on received link
   ii. Update RWA_Accumulated for RR
9. Bridge to the protection lightpath
10. Send a unicast reverse request (RR) on the new route

11. If (RR is not received within Hold_RR) then drop Conn_ID from cache
    i. Else assign wavelength and select the new lightpath
    ii. Update RWA_Accumulated for RR
12. Bridge to the protection lightpath
13. Forward RR along the path in reverse direction

14. If (RR is not received within Hold_RR) then increment Max_Try_Count and go to step 2
    i. Else assign wavelength, select and bridge on to the new lightpath
15. If (Max_Try_Count is exceeded) then backup lightpath setup request is blocked and protection switching is failed

Heuristics given in Table 7 figure out the additional features embedded in TZAR. These add-ons provide suboptimal solutions for protection switching in OTN within reasonable run times for realistic problem instances.

Protection switching starts with a selection in the source node at step 3. Pre-assignment, which makes us call our algorithm a protection rather than a restoration, is based on the TZ parameters of destination and neighboring nodes. Although first attempt is to switch away from the notified failure, that will not result in a global ring in every case. Steps 3.iii, 5, 6, and 7 inherently give chances for shorter backup lightpath creation.

Many_Cast functionality avoids contention in the vicinity of a failure, and reduces blocking probability for long paths. When compared to broadcast nature of AODV protocol, a dynamic many_cast operation is much more suitable for effective wavelength allocation in TZAR. Starting with 0, many_cast counter is adjusted up to 3 on each hop in accordance with the TTL value. Sort of load balancing is also provided with steps 2, 4.iii, 6and 7 via randomly selecting the forwarding interfaces among candidates. As a fruitful side effect of this behavior, protection switching against multiple failures is also provided. How all these heuristics are implemented will be explained in the next chapter.

A list of correlations between our heuristics and shared mesh network protection switching requirements (Appendix A) can be emphasized before proceeding with the modeling framework and simulation results:

- Utilization of existing OOS channel for signaling and OTM hierarchy for encapsulation per se is a solution to provide backward compatibility (A.1), to co-exist with APS specifications (A.2), to apply on cascaded or nested deployments (A.3), to communicate protection switching information (A.10), to fine-tune counter and timeout variables so as to comply with the network size and traffic demand (A.20), and to support external commands (A.24).

- Keeping track of candidate interfaces and featuring Many_Cast operation allows consideration of multiple links between nodes as a scalability option (A.16), and well-bounded wavelength resources per link as a constrained allocation for protection switching (A.19).
- Operation beyond inter-domain boundaries (A4) and bidirectional switching types (A23) are supported by employing carrier and domain independent Time_Zone parameter as a cross-layer information.
- Protection for multiple ingress and egress lightpaths (A.5), independence of shared resources on communicating end nodes (A.6), status monitoring and switching triggers (A.7), concurrent or multiple failures (A.25), and capability to initiate protection switching on either end or both ends (A.26) by using SF, RR messages on a granular basis on the levels of both lightpath clients and traversed nodes.
- Managed timers like Hold_RR and counters like Max_Try_Count provide deterministic recovery times (A.11), protocol failure detection (A.12), and protection switching activity coordination (A.14).

CHAPTER 5

COMPARATIVE PERFORMANCE EVALUATION

We have used OPNET Modeler [68] (a component of Riverbed SteelCentral product portfolio as of 2012) to create our network object models and to run simulations for different optical protection switching scenarios. Our simulator runs in conjunction with Microsoft Visual Studio 2008 on a virtual machine of Intel Core i7-3770 CPU @ 3.40GHz, 2,00 GB RAM, and Microsoft Windows XP Professional Version 2002 SP3 operating system. In the following sub-sections our methodology will be summarized in a little OPNET Modeler terminology.

5.1. Definition of Packet Formats

In our OTN network model we need to define three new packet formats to be able to simulate TZAR through SF and RR messages. The rest of the message types (packet formats) and payload data to traverse the network are out of the scope of our TZAR simulations.

- **OTN_Setup**; packets are used to create a baseline lightpath load in the network. We do not use any "Teardown" packets considering the fact that lightpaths in our OTN simulations will be permanent connections.
- **OTN_Signal_Fail** (SF); packets are used to indicate a failure recovery process has been started for a specific lightpath.
- **OTN_Reverse_Request** (RR); packets are used to respond to SF messages in case of successful attempts.

Figure 18 illustrates the fields used in our, SF, RR, and Setup packet formats. Brief explanations for the functions of those fields are as follows:

- *conn_id*; identifies the primary lightpath, i.e. the service to be recovered, for which protection switching is performed. Since we use growing number of lightpath connections to represent network load, we have kept the size of that field open (0 bits) for simulation purposes.
- *dest_addr*; identifies the address of peer node on the other side of the lightpath to be protected. Since we have decided to run our simulations for topologies of at most 30 nodes, size of that field is set as 5 bits.
- *source_tz*; identifies the time zone of source node, which triggers the protection switching action via sending SF packets. Since there are 24 time zones around the globe, 5 bits are required to represent each TZ.
- *ttl*; counts down the number of hops traversed. We use 4 bits to initialize that field to the minimum of 15 and the number of nodes in the topology during packet creation at source node. TTL is then decremented until 0 at each node along the route. Packets with TTL value set to 0 are destroyed to clean up the network from malfunctioning packets and useless interrupts.
- *many_cast*; adjusts the contention avoidance and load balancing metric. It is initialized to 0 at the source node, which creates the SF packet. Considering the TTL value and the number of available outgoing physical links on each hop, Many_Cast value may go up to 3.
- *rwa_accum*; keeps track of nodes, links, and available wavelengths associated with the accumulating backup lightpaths. In contrast to the other fields, we use OPNET Modeler's structures for RWA_Accum in our packets.

a.

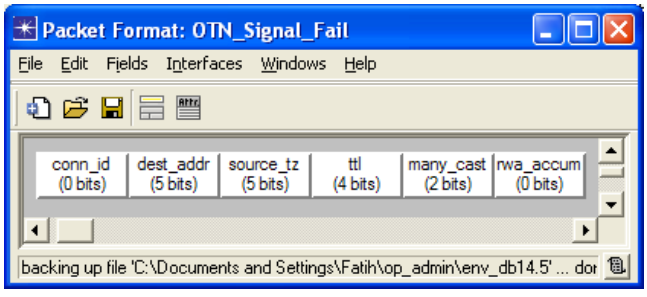
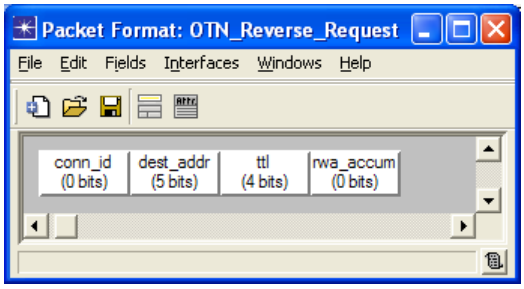


Figure 18 – TZAR Packet Formats: a. OTN_Signal_Fail, b. OTN_Reverse_Request, c. OTN_Setup

b. 

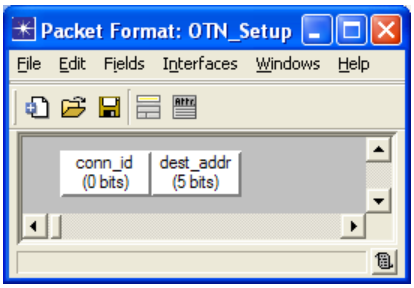
c. 

Figure 18 – TZAR Packet Formats (continued)

A dedicated field to represent "Source Address" does not appear in our packet formats, because we prefer to use one of OPNET Modeler kernel procedures (*op_pk_creation_mod_get (pkptr)*) to get that information.

5.2. Optical Link Model

Once packet formats are defined, we need a new link model as shown in Figure 19 to accommodate such packets at supported speed, duplex, delay, and error rate conditions. Again for simplicity we decided to use clear error-free links. And since we are interested in evaluating the impact of catastrophic events such as fiber cuts or earthquakes, only point-to-point full-duplex (*ptdup*) operation is supported.

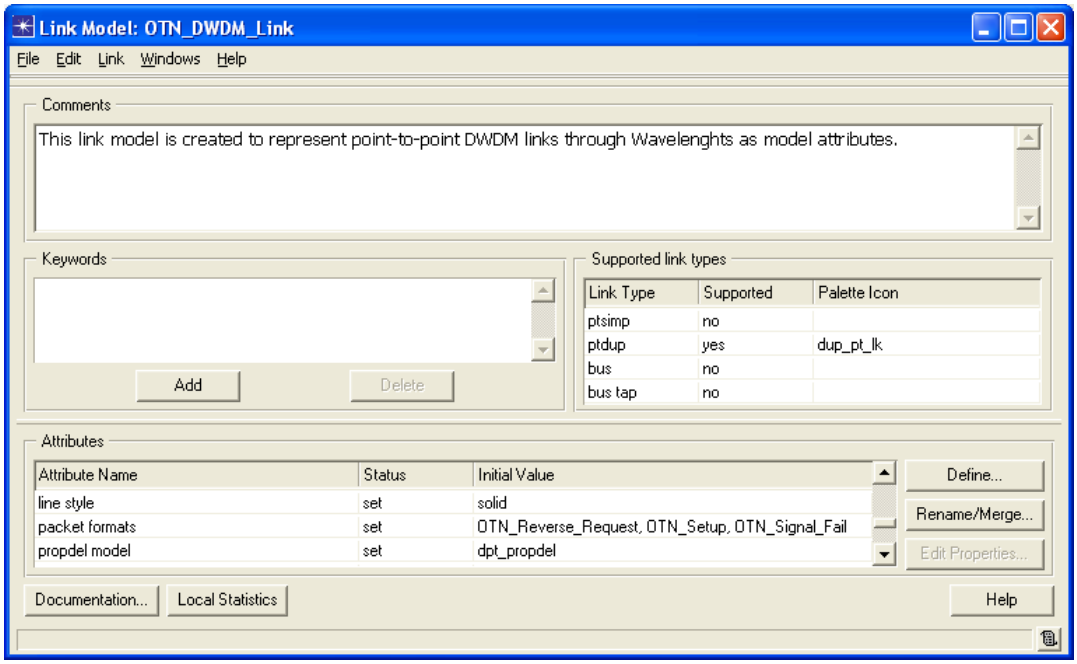


Figure 19 – DWDM Link Model

Although we use the primary channel with an associated propagation delay model (*dpt_probdel*) as a medium for OOS, we have defined a new link model attribute of type "Compound" to assign configurable number of wavelengths for each link. Figure 20 demonstrates that "*Wavelength*" attribute properties. Such a configuration works fine for us, since we are just interested in the availability of free wavelengths for lightpaths to be established through those links.

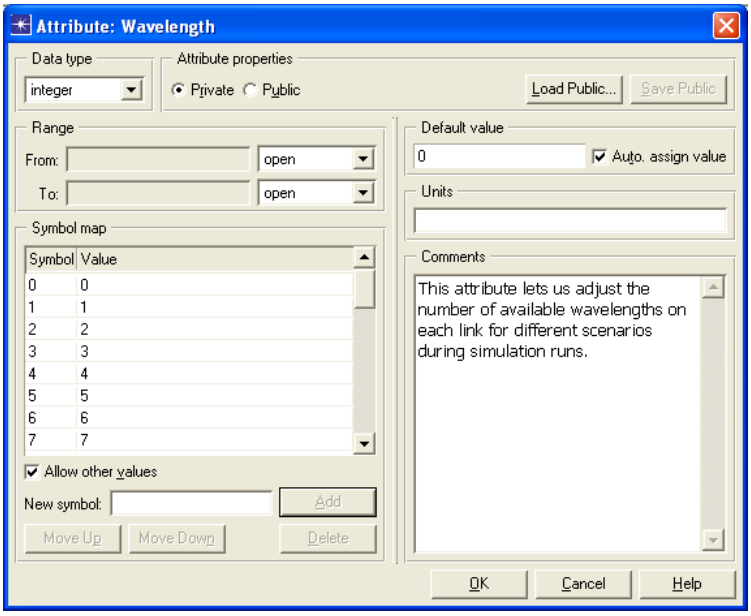


Figure 20 – Wavelength Attribute of DWDM Links

5.3. Processing Node Model

Geographical realities impose some restrictions on the number of conduits, in which fiber-optic cables can be laid down. When we speak about a building as a network center, there can be at most 4 approximations from different directions of the building. This number may go up to 6 in case of a campus network. So, in our simulations we have decided to model just 1 type of processing node with 6 ports.

In OPNET Modeler there are two major steps to create a new processing node. In the first step a node model should be created using the relevant building blocks. In the second step, process models should be created for the processor modules used in the node model.

5.3.1. Node Model

In our node model given in Figure 21 we have used three processing modules, and six transmitter-receiver pairs. Two of the processing modules, i.e. *otn_source* and *otn_sink*, are representing add and drop facilities, respectively. The third processing module, *oxc*, acts as the switching core. It basically checks for all the relevant information regarding any incoming packet to either forward it to its destination through an appropriate transmitter, or destroy it to clean up the network.

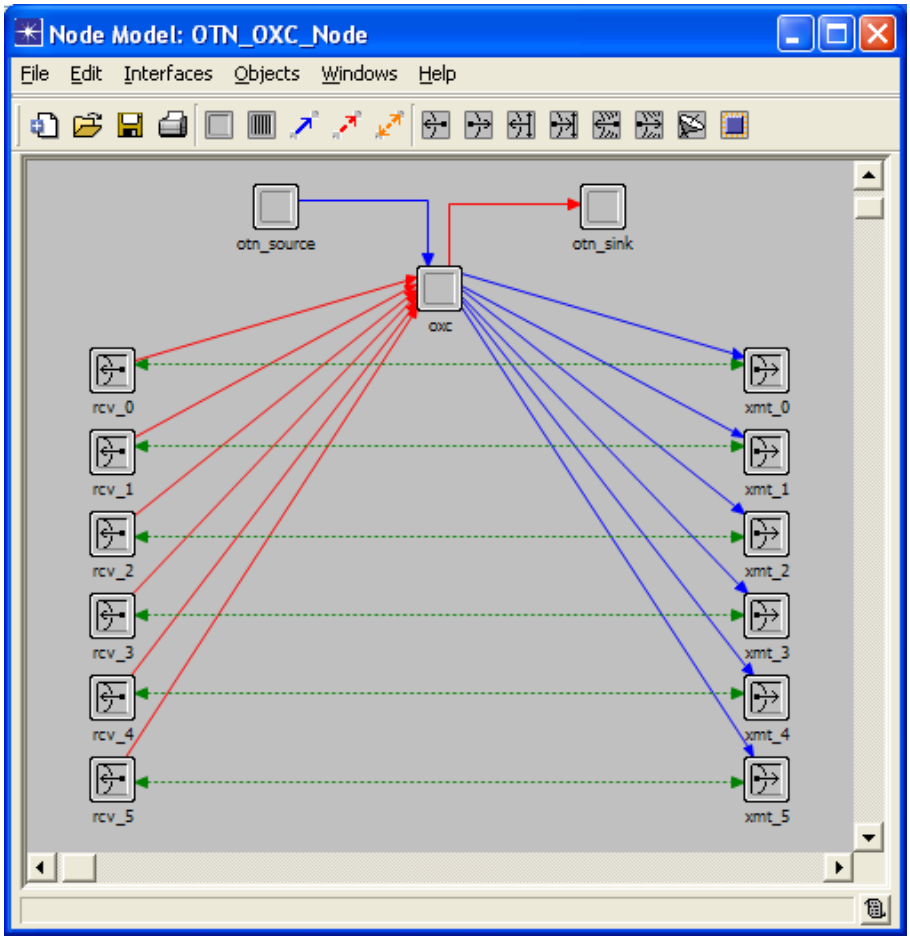


Figure 21 – Optical Cross Connect with 6 ports

All the transmitter receiver pairs are connected to each other with logical association wires (dotted green lines in the figure) to assemble a full-duplex optical port. And 6 such pairs are more than enough to provide Many_Cast of up to 3 SF packets for any lightpath setup request in our heuristic design.

While creating the node models it is rather important to place stream wires in a strategic sequence. Other than using logical associations among ingress and egress port pairs, matching stream indexes with respect to the *oxc* processor module is also very handy when making packet forwarding decisions. Output of "Show Connectivity" on *oxc* module given in Figure 22 illustrates how our *xmt* and *rcv* indexes are closely related to the central *oxc*.

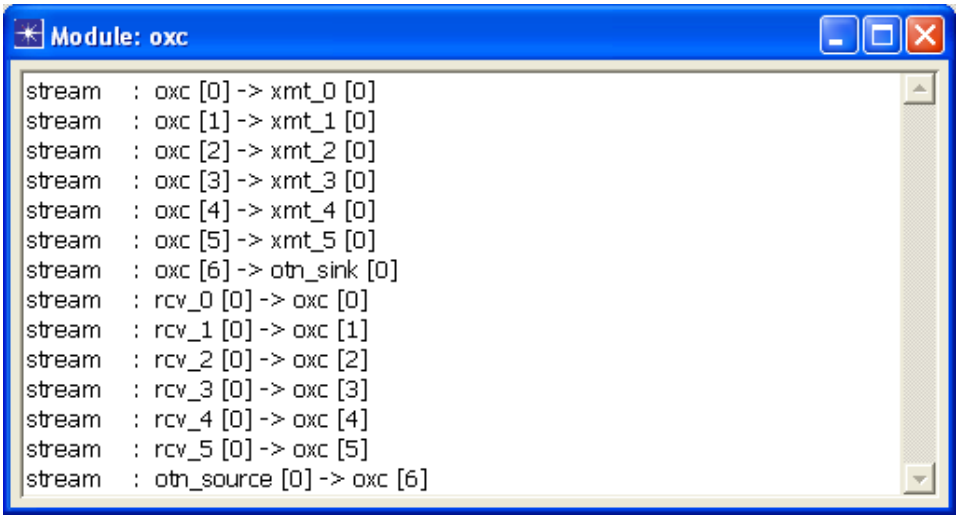


Figure 22 – Verify Connectivity for OXC Module

One last item to be clarified in a node model is again the data rate and packet formats supported on each *xmt/rcv* pairs. This is important due to the fact that previously created link models should suit well on all those transceivers for normal network behavior. A sample channel attribute configuration is given in Figure 23. Data rate of 10 Gbps is chosen throughout the network to set up a realistic OOS channel.

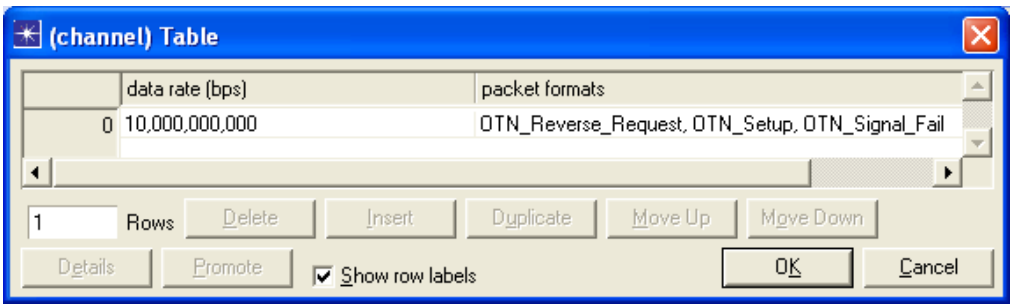


Figure 23 – Channel Table for Transmitter and Receiver Modules

5.3.2. Process Model

"A process model is represented by a state transition diagram (STD) that describes the behavior of a node module in terms of states and transitions. [68]" Process models are the objects, where software (C/C++) codes and algorithms are embedded in to relevant network node models. Some of the variables/statistics configured here are promoted to be defined/accessed/measured on higher levels during the simulation runtime.

For each of the processing modules in our node model, we may use different process models. Nevertheless, within the scope of this thesis we are just interested in *oxc* module. (*otn_source* and *otn_sink* modules are presented above for the sake of completeness; to show the compliance of our model with the OXC architecture introduced in subsection 2.2.5, and to provide a vision for further studies.) We have created the following three process models to describe the underlying logic of TZAR in OTN.

- **OXC_WSS_Parent**; is our root process, which is invoked by the beginning of simulation via a *begsim* interrupt. As illustrated in Figure 24, it has 6 states and 9 transitions, only 4 of which are conditional. Brief explanations regarding the tasks performed at each of those states are as follows:
  - *Init*: Global variables are initialized by an OTN_OXC_Node that takes the first turn from the simulation kernel. Then each node registers itself and the associated links to the network topology, obtains an *Address*, and sets a self-interrupt to proceed with *Wait* state.
  - *Wait*: Each node normally waits in that *unforced* state for an event to happen. Depending on the type of network event different interrupts may be received. Decoded interrupts result in conditional transitions.
  - *Setup_LP*: Each OTN_OXC_Node sets up lightpaths in that forced state. After attempting to establish as many baseline lightpaths as indicated by the "*Load Factor*" attribute, an unconditional transition to *Wait* state takes place.

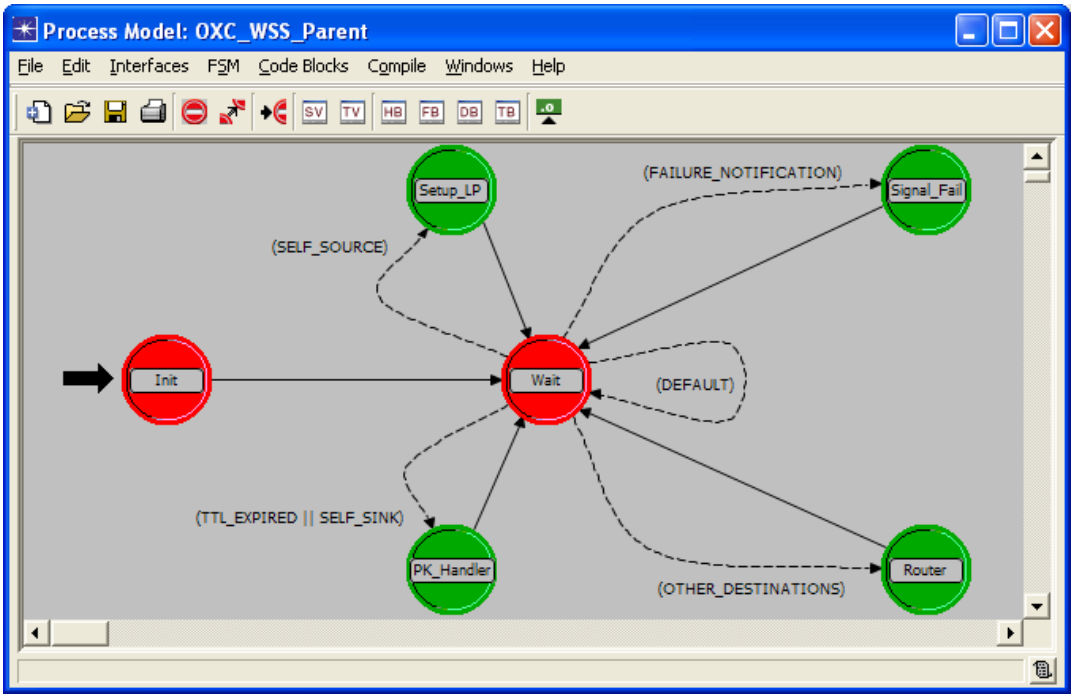


Figure 24 – OXC Root Process Model

- *Signal_Fail*: OPC_INTRPT_FAIL event takes the root process to that state. If the failed node or link causing that interrupt is an element of any lightpaths sourced from this node, protection switching is initiated for all the affected lightpaths. OTN_Client_Child processes are invoked, if the simulation choice is TZAR.
- *Router*: OPC_INTRPT_STRM event is generated by the simulation kernel whenever a packet arrives to a node processing model. If the received packet is not destined to that parent node, then it is routed to its destination in this state. OTN_Gateway_Child process is invoked, if the simulation choice is TZAR.
- *PK_Handler*: If the received packet is destined to that parent node or if the *ttl* is expired, it is processed locally. In case TZAR is the choice of simulation, tasks mentioned in steps 4.i, 8, 9, and 10 are performed.

- **OTN_Client_Child**; is our child process, which handles SF/RR messages with respect to the client side, i.e. on communicating parties of each failed lightpath. As illustrated in Figure 25, it has 4 states and 4 transitions, only 2 of which are conditional. Brief explanations regarding the tasks performed at each of those states are as follows:

- *Init*: State variables are initialized, counters and timers are set, and an OTN_Signal_Fail packet is sent. (Steps 1, 2, and 3 in TZAR)
- *Wait*: OTN_Reverse_Packet is expected. Depending on the counter or timer status and the information in received packets conditional transitions to the relevant states occur.
- *Resend_SF*: If RR is not received within the expected duration and Max_Try_Count is not reached, another SF is sent with an updated *rwa_accum* field values. (Steps 14, 2, and 3 in TZAR)
- *End*: If RR is received, new lightpath is established and protection switching is done. (Step 14.i in TZAR) If the Max_Try_Count is expired, process is given up. (Step 15 in TZAR) After updating the statistics each child process kills itself and releases memory resources.

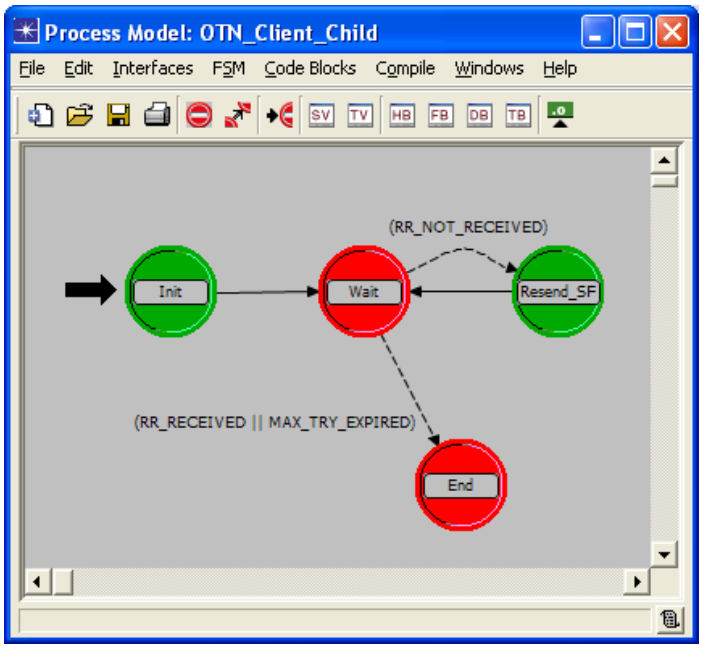


Figure 25 – Child Process Model for OTN Clients

- **OTN_Gateway_Child**; is our child process, which handles SF/RR messages with respect to the gateway nodes, i.e. on nodes participating in TZAR along the path. As illustrated in Figure 26, it has 4 states and 4 transitions, only 2 of which are conditional. Brief explanations regarding the tasks performed at each of those states are as follows:

- *Init*: State variables are initialized, counters and timers are set, and the first SF packet for the specified *conn_id* is forwarded. Forwarding decision is based on *dest_addr*, *source_tz*, *ttl*, and *many_cast* values. (Steps 4, 5, 6 and 7 in TZAR)
- *Wait*: RR for the cached *conn_id* is expected. Depending on the timer status and the information in received packets conditional transitions to the relevant states occur.
- *Forward_RR*: If RR is received within the expected duration, forward RR back to the associated SF source via a unicast operation and switch selector bridges on for the new lightpath. (Steps 11.i, 11.ii, 12 and 13 in TZAR)
- *End*: After updating the statistics child process kills itself and releases allocated resources.

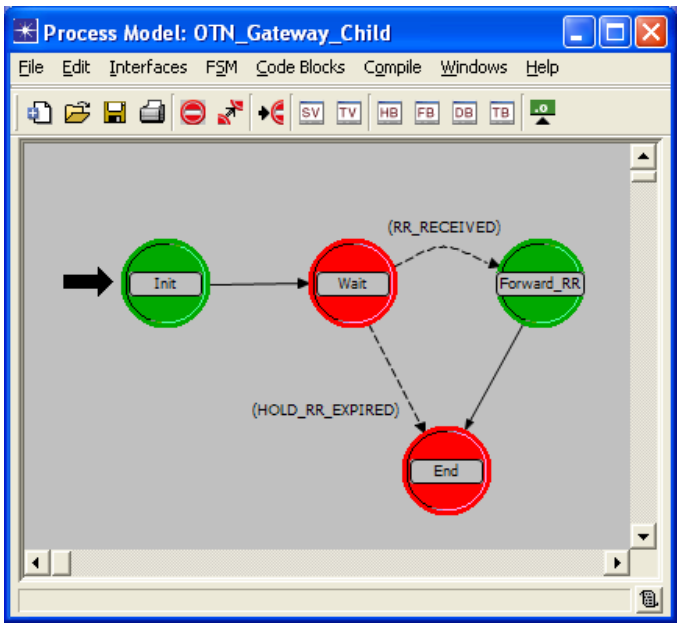
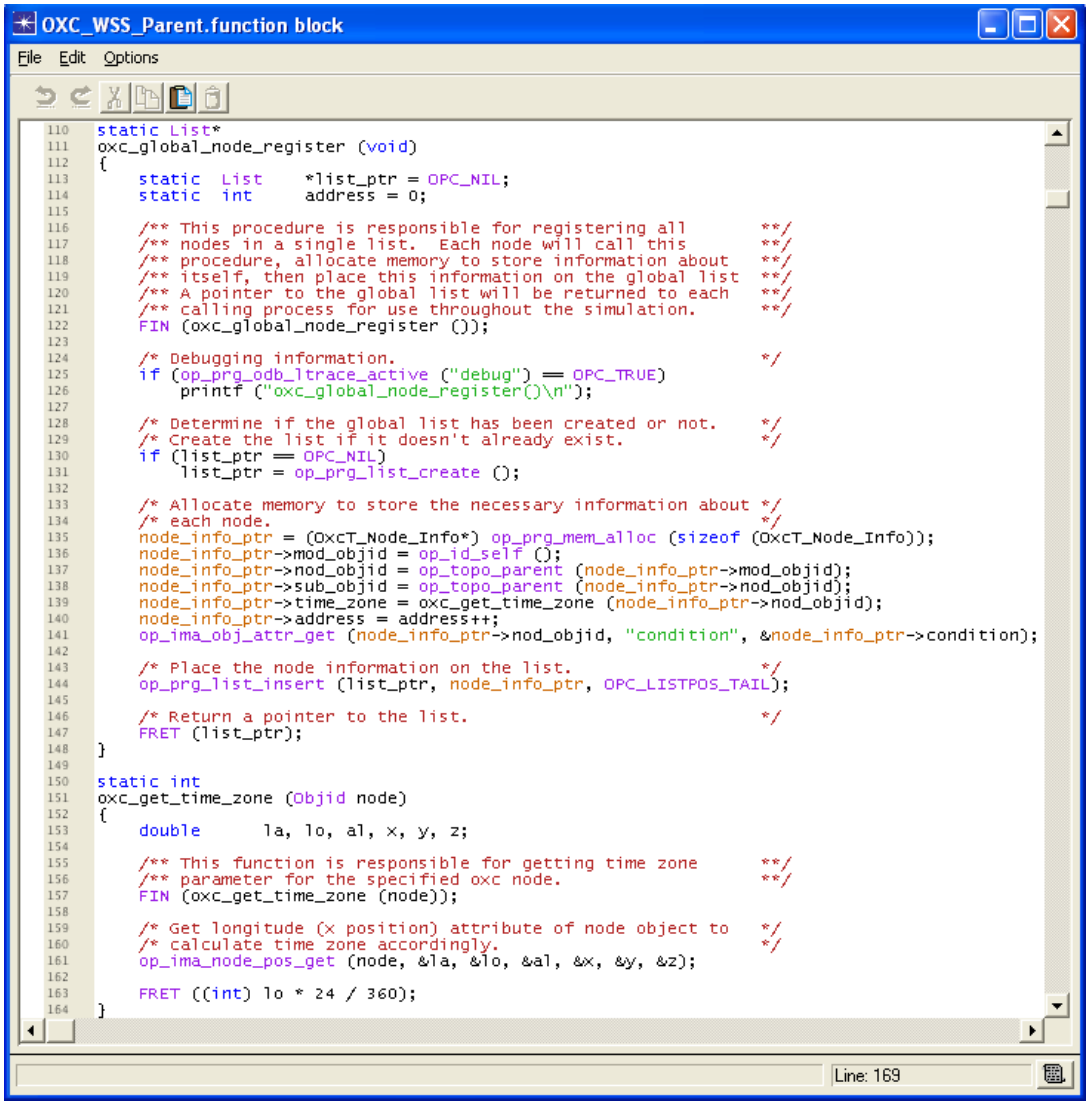


Figure 26 – Child Process Model for OTN Gateways

Once high level process models are created, State Variables are used to record the accumulated information, which might be necessary to access at next invocations. Temporary Variables, such as loop indexes or packet pointers, are used to perform complex computational expressions within a single invocation. Header Block is used to include files, define constants/macros/structures, and declare functions.

Detailed protocols and specific functional behavior are implemented through coding within Enter/Exit Executives of relevant states, Transition Executives of relevant transitions, and Function Block of the process model. Figure 27 shows a portion of Function Block of OXC_WSS_Parent process model. We have purposefully selected that part to demonstrate how our OXC nodes are registered to a global list together with their *time_zone* values and uniquely assigned *address* attributes.




```
static List*
oxc_global_node_register (void)
{
    static  List    *list_ptr = OPC_NIL;
    static  int     address = 0;

    /** This procedure is responsible for registering all       **/
    /** nodes in a single list.  Each node will call this       **/
    /** procedure, allocate memory to store information about   **/
    /** itself, then place this information on the global list  **/
    /** A pointer to the global list will be returned to each   **/
    /** calling process for use throughout the simulation.      **/
    FIN (oxc_global_node_register ());

    /* Debugging information.                                   */
    if (op_prg_odb_ltrace_active ("debug") == OPC_TRUE)
        printf ("oxc_global_node_register()\n");

    /* Determine if the global list has been created or not.    */
    /* Create the list if it doesn't already exist.             */
    if (list_ptr == OPC_NIL)
        list_ptr = op_prg_list_create ();

    /* Allocate memory to store the necessary information about */
    /* each node.                                               */
    node_info_ptr = (OxcT_Node_Info*) op_prg_mem_alloc (sizeof (OxcT_Node_Info));
    node_info_ptr->mod_objid = op_id_self ();
    node_info_ptr->nod_objid = op_topo_parent (node_info_ptr->mod_objid);
    node_info_ptr->sub_objid = op_topo_parent (node_info_ptr->nod_objid);
    node_info_ptr->time_zone = oxc_get_time_zone (node_info_ptr->nod_objid);
    node_info_ptr->address = address++;
    op_ima_obj_attr_get (node_info_ptr->nod_objid, "condition", &node_info_ptr->condition);

    /* Place the node information on the list.                  */
    op_prg_list_insert (list_ptr, node_info_ptr, OPC_LISTPOS_TAIL);

    /* Return a pointer to the list.                            */
    FRET (list_ptr);
}

static int
oxc_get_time_zone (Objid node)
{
    double      la, lo, al, x, y, z;

    /** This function is responsible for getting time zone      **/
    /** parameter for the specified oxc node.                   **/
    FIN (oxc_get_time_zone (node));

    /* Get longitude (x position) attribute of node object to   */
    /* calculate time zone accordingly.                         */
    op_ima_node_pos_get (node, &la, &lo, &al, &x, &y, &z);

    FRET ((int) lo * 24 / 360);
}
```

Figure 27 – Part of OXC_WSS_Parent Function Block

Essential kernel procedures from Distribution, Identification, Internal Model Access, Interrupt, Packet, Programming, Process, Simulation, Statistic, and Topology packages of OPNET Modeler are extensively used in our OTN models.

5.4. Simulation Scenarios

As mentioned throughout this report, the focus of our thesis studies is to study the behavior of optical transport networks on global topologies. For simulation purposes we have created a large number of different scenarios to test the performance of OTN node, OXC process, and DWDM link models described in the previous sections.

The scenarios cover 5 set of OTN node densities over the topology, 2 variants of failure types, 8 set of wavelength capacities on the DWDM links, 8 set of lightpath setup demand offered in the network, and 4 set of protection switching algorithms implemented within the OXC process models; adding up to 2560 different scenarios. The following subsections give further details regarding the simulation scenarios categorization.

5.4.1. Topology Definition

OPNET Modeler provides a successful startup wizard to define scale of the network and the objects to be used in simulation from the very beginning. As illustrated in Figure 28, we have selected to use “World” as a representation of global scale and the inherited world map as a background layout. On the other hand, we have defined an object palette (OTN_Palette) to access necessary node and link models under a simplified set.

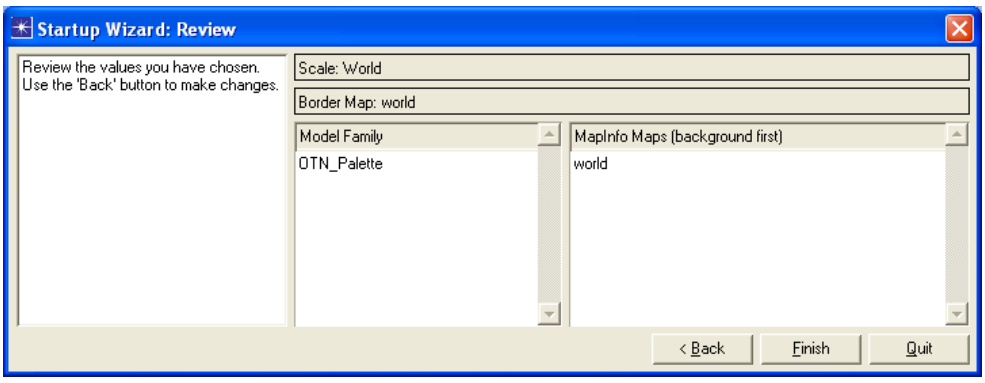


Figure 28 – Project Startup Wizard

Once we are in an empty scenario, the easiest way to populate a network is to use "Rapid Configuration" tool provided in the Topology menu. Figure 29 demonstrates how this tool can be used to automate the network deployment in three phases:

I. In the first phase we select a randomized mesh network topology among other alternatives, such as full mesh, bus, ring, star, and tree.
II. In the second phase we squeeze the list of available models to our previously created object palette via "Select Models" button.
III. In the third phase we define the type and number of node and link models. In accordance with the explanations given in section 5.3, we prefer to give lower and upper bounds for the number of links per node as 3 and 6, respectively.

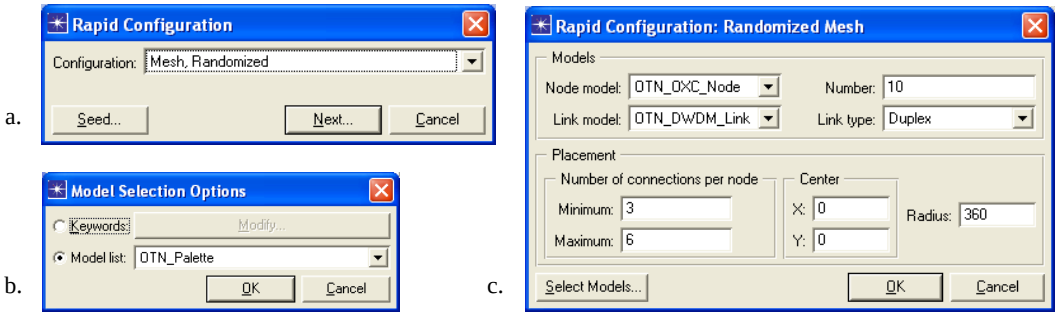


Figure 29 – Rapid Configuration Tool: a. Topology Configuration, b. Model Selection, c. Placement

After replacement of nodes to reasonable continental locations and slight modifications in the links for better looking interconnectivity, we end up with topologies similar to the one given in Figure 30.

We have defined 5 distinct topologies for 4 nodes, 6 nodes, 8 nodes, 10 nodes, and 12 nodes to analyze the network behavior with respect to the number of nodes. (We had to stop at 12, because CPU and RAM resources of our simulation environment could not run successfully on topologies of more nodes.) Other than saving the "*Number of Nodes*" in the topology as a global attribute for parametric studies, we have also included a "Failure Recovery" object to schedule node or link failures during simulation runs.

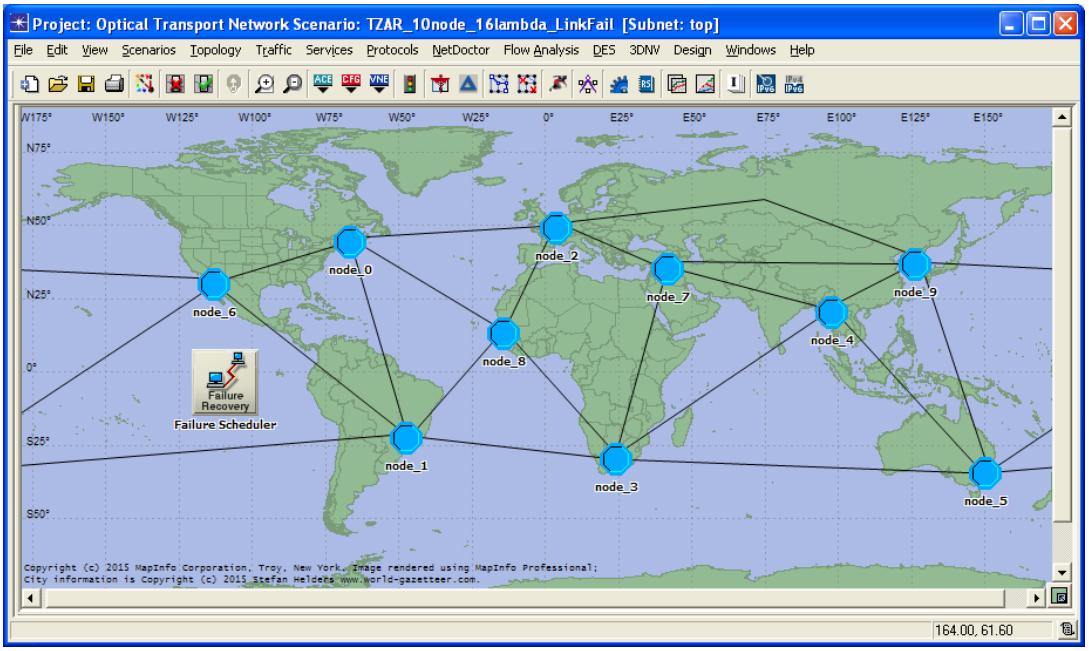


Figure 30 – A Sample OTN Scenario of 10 Nodes

5.4.2. Types of Failures

"Failure Recovery" object of OPNET Modeler library allows us to schedule failures for any number of links or nodes at any specified simulation time. Although there could be many options to test in that sense, we have decided to cover just the following two scenarios:

- **Link Failures**; are the most widely evaluated cases in literature, and we have also run half of our scenarios via scheduling an arbitrarily selected single link failure at 100s simulation time.
- **Node Failures**; can be considered as a kind of catastrophic situation, in which case all the surrounding links would also be disconnected from the network topology. Figure 31 illustrates how we schedule such a failure via selecting "*Node and attached Links*" as "Node Failure Mode". Another important consequence of any single node failure is the impossibility to recover lightpaths sourced/sank at the failed node. That appears as a natural degradation in recovery success ratio to be analyzed in the following subsections.

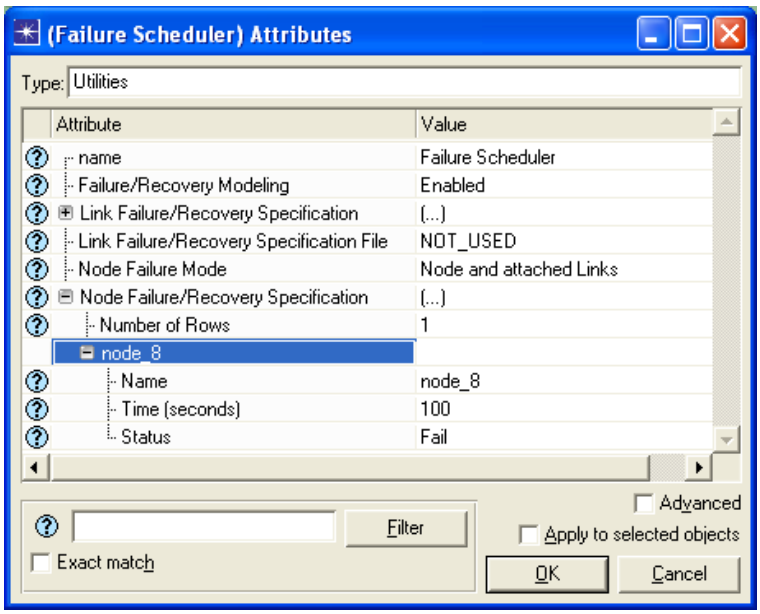


Figure 31 – Failure Recovery Object Attributes to Schedule a single Node Failure

5.4.3. Number of Wavelengths

We have performed all of our simulations on homogenously linked network scenarios, for which number of wavelengths per link varied in between 4 and 32 with increments of 4. Optical link model explained in 5.2 allows us to configure "Wavelengths" compound attribute as shown in Figure 32.

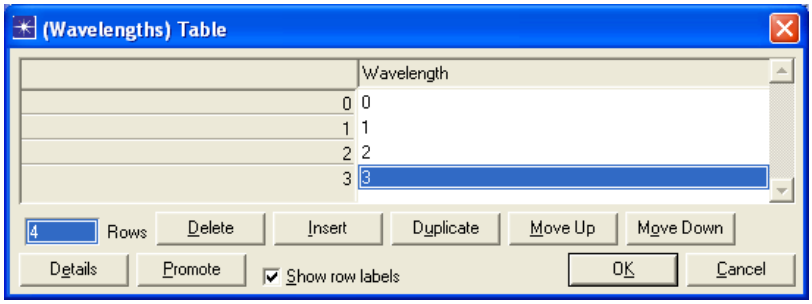


Figure 32 – Wavelengths Compound Attribute

After defining the available wavelengths in correct sequence we also set the "Propagation Speed" to 70% of speed of light, i.e. 210,000,000 meters/second. By selecting similar links and clicking on the "Apply to selected objects" option as illustrated in Figure 33, we make sure that all links in our network model have the same functional configuration.

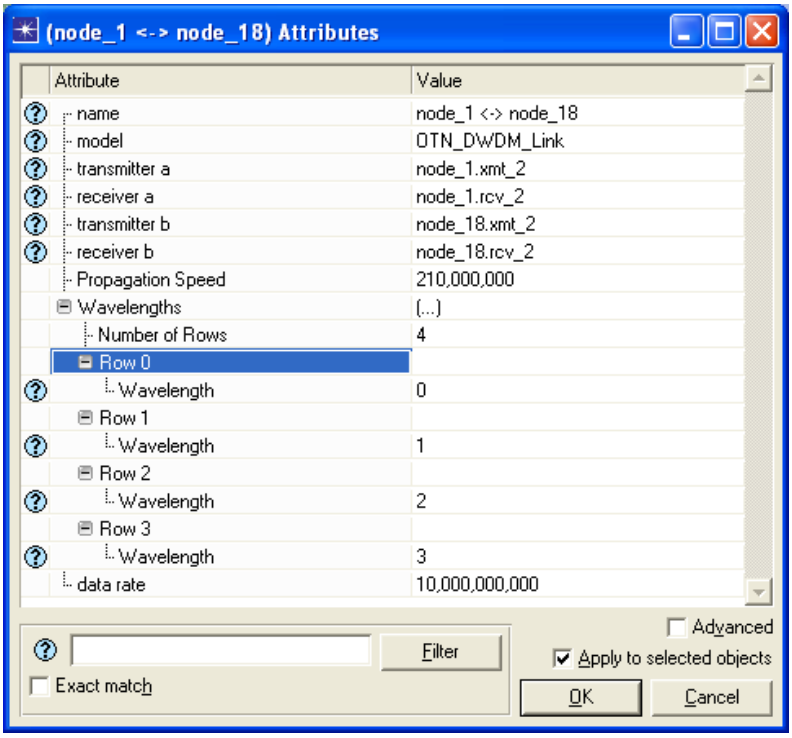


Figure 33 – DWDM Link Model Attributes

5.4.4. Lightpath Demand Factor

Some of the properties of each scenario are not necessarily defined on network level. Discrete Event Simulation (DES) Sequence is another useful mechanism to define parametric simulation runs. Figure 34 demonstrates a portion of scenario sets, all of which differ in at least one criterion. We typically have 8 such sets to represent various lightpath demand factors (i.e., the number of lightpaths sourced from a single node: 5, 10, 15, 20, 25, 30, 35, and 40).

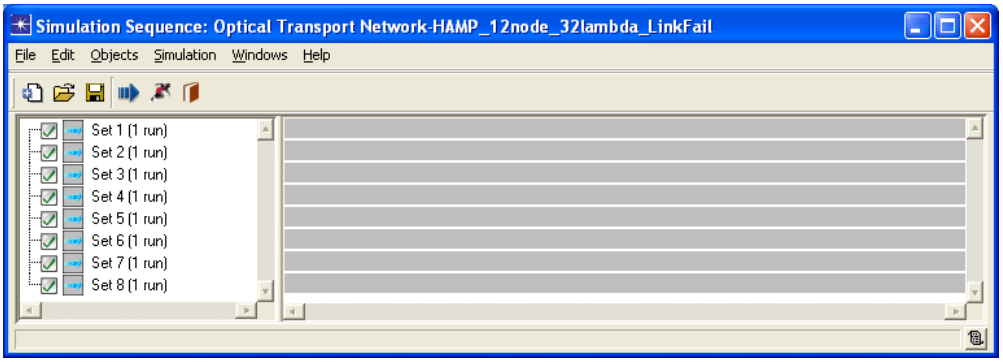


Figure 34 – A Sample Discrete Event Simulation Sequence

"Global Attributes", which are configurable within the above-mentioned simulation sequence scenario sets as illustrated in Figure 35 below, are so-called rendezvous points for DES parametric studies. They are not only being retrieved by process models via *op_ima_sim_attr_get()* sort of OPNET Modeler kernel procedures, but also interpreted as X or Y axis components of graphs to be plotted. [69]

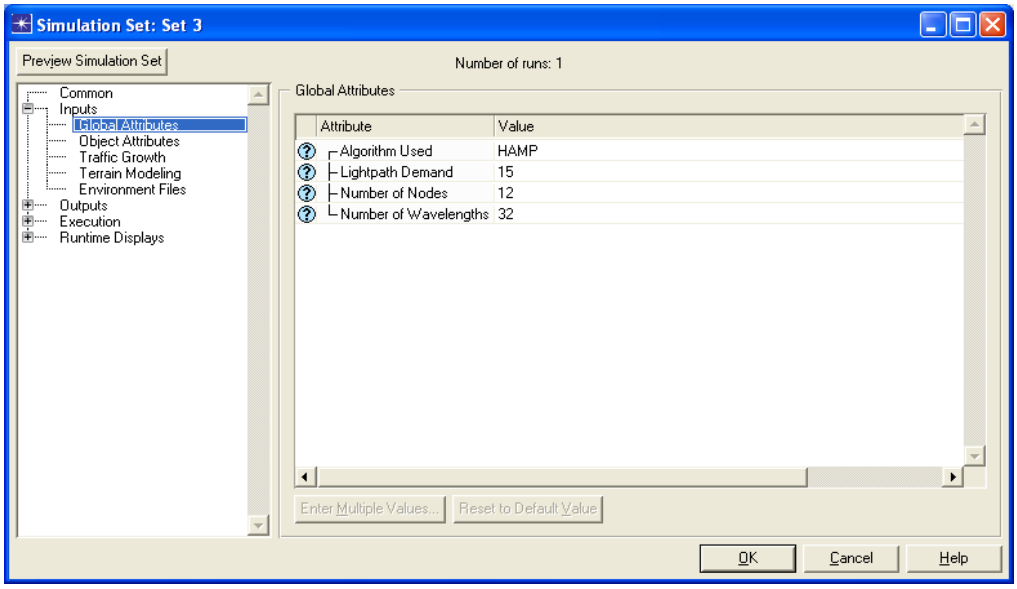


Figure 35 – Global Attributes Configuration in a Simulation Set

5.4.5. Algorithm Selection

All our simulation scenarios are run against four alternative protection switching algorithms, two of which are mentioned in section 3.3 and abbreviated as below.

- KSPF: k-Shortest Path First
- HAMP: Hamiltonian p-Cycle
- TZAR: Time Zone based Approximation to Ring
- TZAR-wc: Enhanced version of TZAR, in which embedded wavelength converters are assumed to exist at each node

Once we are done with preparations and configurations, we trigger the simulations via selecting collect/recollect in the "Manage Scenarios" screen given in Figure 36.

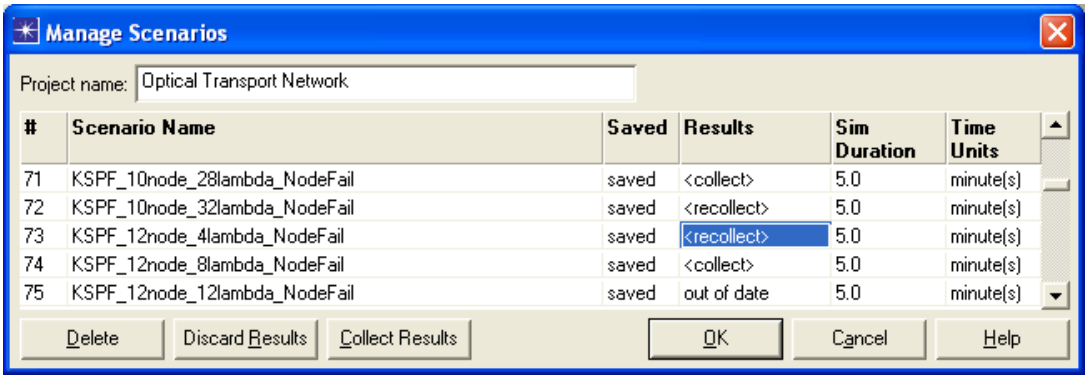


Figure 36 – Manage Scenarios Screen

5.5. Results Collected

During the simulation runs we can follow the summary of happenings, such as status and duration of the runs as well as the number of events and consumed memory for each run, through a popped-up screen as given in Figure 37. We recognize that the simulation runs of 4 node topologies with 4 supported wavelengths and 5 lightpath setup demands complete within sub-second durations for approximately 150 events. On the other extreme, simulation runs of 12 node topologies with 32 supported wavelengths and 40 lightpath setup demands complete in more than a minute period for approximately 4250 events. These numbers give us rough estimations regarding the proper run of the simulations. For detailed analyses of the results collected we have to switch to the "Results Browser", which will be covered in the following subsections.

Figure 37 – DES Execution Manager Window

5.5.1. Confidence Interval

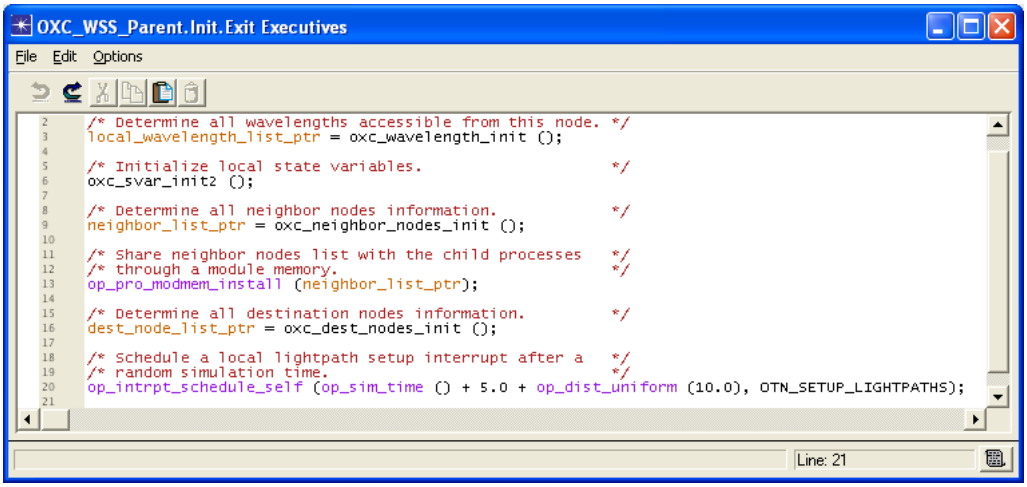
Although common sense and a little bit intuition would agree, that for instance blocking probably should decrease with increasing number of wavelengths, we have to validate any behavior of our process models' equivalence to real systems. Our measurements based on incremental analyses for alternative algorithms aim to achieve a plausible degree of confidence.

To ensure a sufficiently large number of independent experiments we have used altering random number generator seeds for different sets of simulation scenarios. 3 stochastic functions that we have used are dependent on those selected seeds:

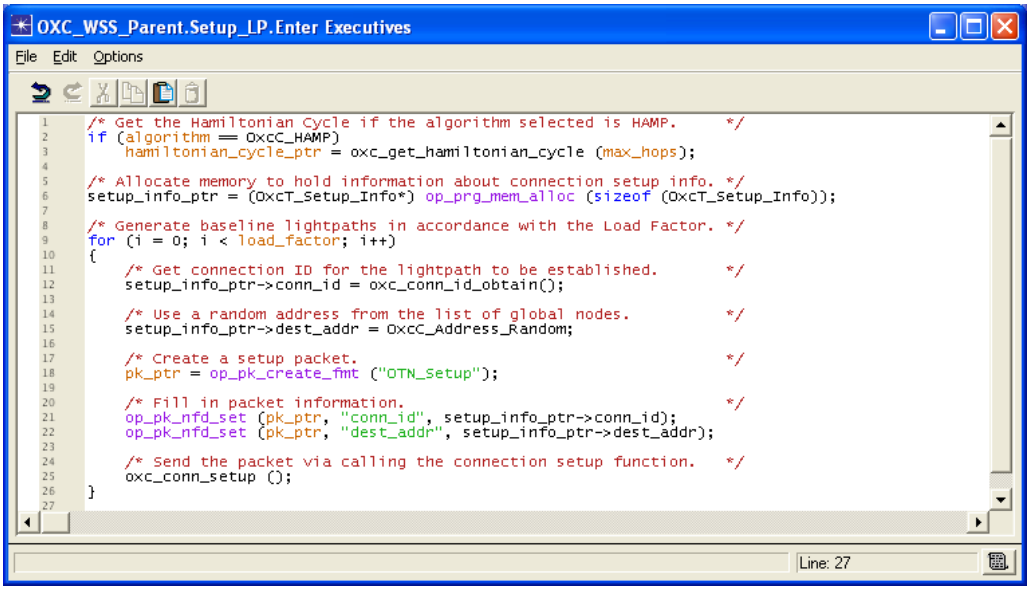
i. Order of primary lightpaths' setup depends on a self-triggered interrupt randomly distributed over 5-15 seconds as illustrated in Figure 38.a.
ii. Destination address of any lightpath to be established is set to be randomly generated among available destination nodes in the topology as illustrated in Figure 38.b.
iii. Signal_Fail many_casting operation in TZAR proceeds with a random selection among candidate neighbors as illustrated in Figure 38.c.

Since it is not possible to run infinite number of simulations to get the true mean μ for any scalar statistic, we are interested in the degree of precision that can be approximated via collected samples through N simulations. How good such approximations are done determines the confidence level of the results collected. For large enough N (typically more than 30), our randomized statistic $\bar{X}$ is assumed to have a normal distribution with a mean approaching to true mean μ. And according to central limit theorem, variance of $\bar{X}$ is σ^2/N, where σ^2 is the true variance. Standardized normal variable Z is then defined as $(\bar{x} - \mu)/\sigma_{\bar{x}}$, where the distance of a particular sample $\bar{x}$ from μ in terms of the number of standard deviations has a zero mean and a unity standard deviation. By the way, we can speak about a probability that a sample result $\bar{x}$ is within a bounded distance of μ as formulated in 5.1 below.

a.



b.



c.

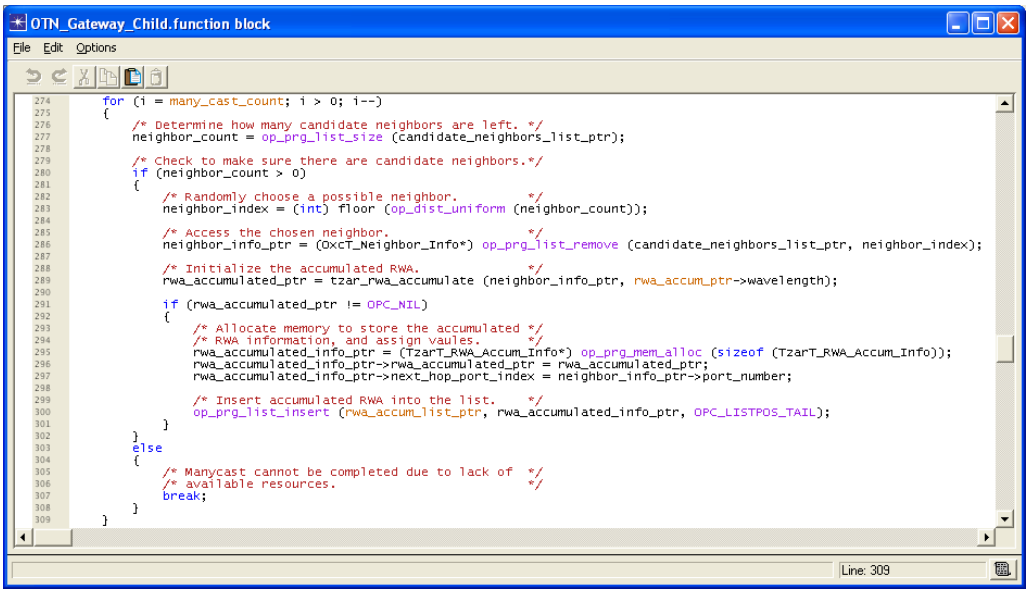


Figure 38 – Sources for Stochastic Behavior: a. Lightpath Setup Schedule, b. Destination Address Setting, c. Signal_Fail Many_Casting

$$Prob\left[\frac{|\bar{x}-\mu|}{\sigma_{\bar{x}}} < z_\alpha\right] = \alpha \quad (5.1)$$

$$Prob\left[\bar{x} - z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right) < \mu < \bar{x} + z_\alpha\left(\frac{\sigma}{\sqrt{N}}\right)\right] = \alpha \quad (5.2)$$

Formula 5.2 can also be obtained by replacing the standard deviation based on central limit theorem to introduce a notion of confidence interval for μ. This probabilistic argument states that μ stays in that interval with certainty level defined by α. Table 8 presents some popular values regarding such confidence levels.

Table 8 – Confidence Levels Matrix [68]

α	z_α	$t_{\alpha,}$ N = 3	$t_{\alpha,}$ N = 5	$t_{\alpha,}$ N = 10	$t_{\alpha,}$ N = 20
99%	2.575	9.925	4.604	3.250	2.861
98%	2.327	6.965	3.747	2.821	2.539
95%	1.96	4.303	2.776	2.262	2.093
90%	1.645	2.920	2.132	1.833	1.729
80%	1.282	1.886	1.533	1.383	1.328

Another dimension of confidence interval analyses described above is the possibility to define necessary number of simulation runs n to achieve targeted confidence levels. Formula 5.3 below is obtained simply rearranging 5.2. If we define the deviation from expected behavior as Δ, formula 5.4 gives us the number of required samples n to set an upper bound on Δ with probability α.

$$Prob\left[|\bar{x}-\mu| < z_\alpha\left(\frac{\sigma}{\sqrt{n}}\right)\right] = \alpha \quad (5.3)$$

$$\left(\Delta = z_\alpha\left(\frac{\sigma}{\sqrt{n}}\right)\right) \rightarrow n = \left(\frac{z_\alpha\sigma}{\Delta}\right)^2 \quad (5.4)$$

In case number of samples n is small (less than 30) OPNET Modeler uses a method called T-distribution rather than normal distribution. Sample variance s^2 is used instead of true variance σ^2, and the constant t_α instead of z_α is used in the confidence expression given in formulas 5.1-5.4. Some common values of t_α associated with the number of samples *N* are appended to Table 8.

5 levels of confidence intervals for 80%, 90%, 95%, 98%, and 99% are computed by Results Browser. Choosing "Edit Graph Properties" from a graph pop-up menu and selecting "Show Confidence Intervals" checkbox, we can display these results for the mean ordinate value of a set of entries at the same abscissa. Unless otherwise specified we prefer to present our results with 95% confidence.

5.5.2. Blocking Probability

The first issue to be figured out is the blocking probability during lightpath setup phase (starts at 10th second of simulation time) of our process models described in 5.3.2. This has nothing to do with the algorithms used for protection switching. However, it is critical to understand the effect of number of wavelengths available on the success of provisioning the initial demand. Figure 39 illustrates a significant decline in the blocking probability with increasing number of wavelengths.

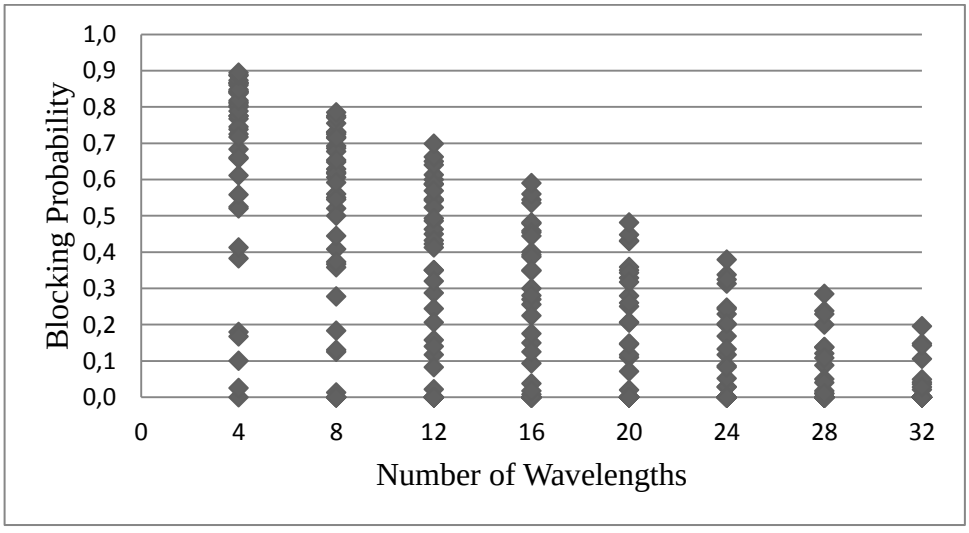


Figure 39 – Blocking Probability vs Number of Wavelengths (sample distribution)

Since a single dot in sample distribution may correspond to same results obtained by different scenarios, general trend regarding any simulation attribute is captured much better with mean values as exemplified in Figure 40.

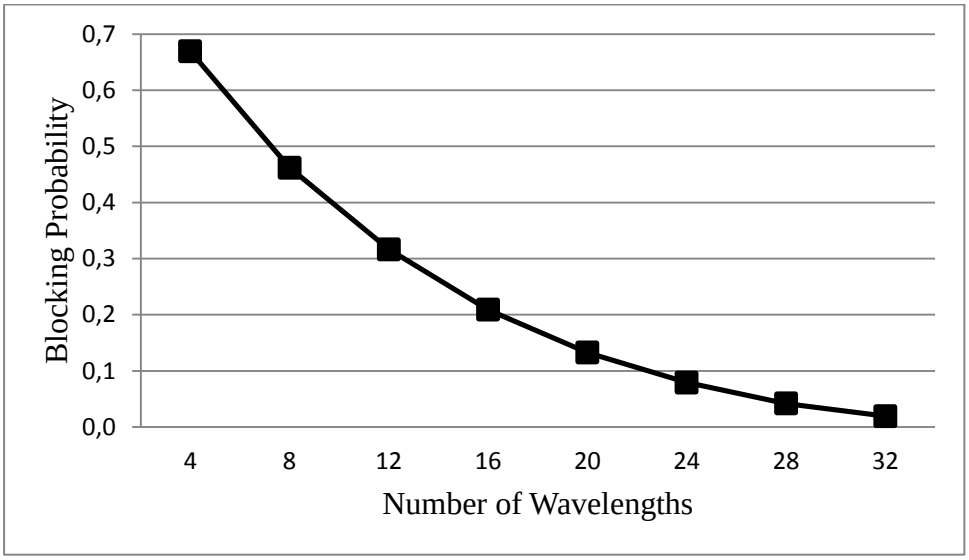


Figure 40 – Blocking Probability vs Number of Wavelengths (mean values)

On the other hand, we have to consider confidence intervals throughout the study. We provide these intervals in terms of +/- bars as illustrated in Figure 41, which means deviations that much above and below mean values are possible.

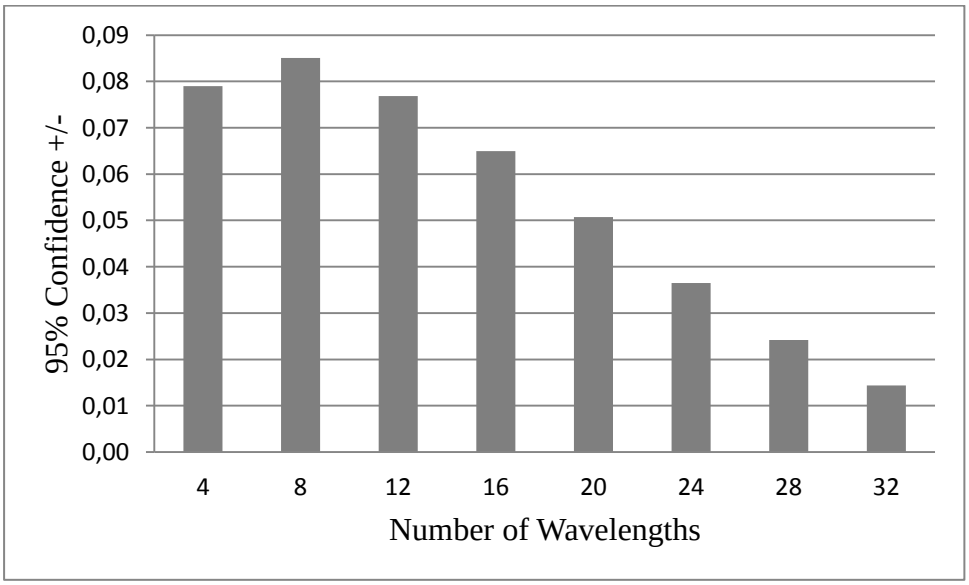
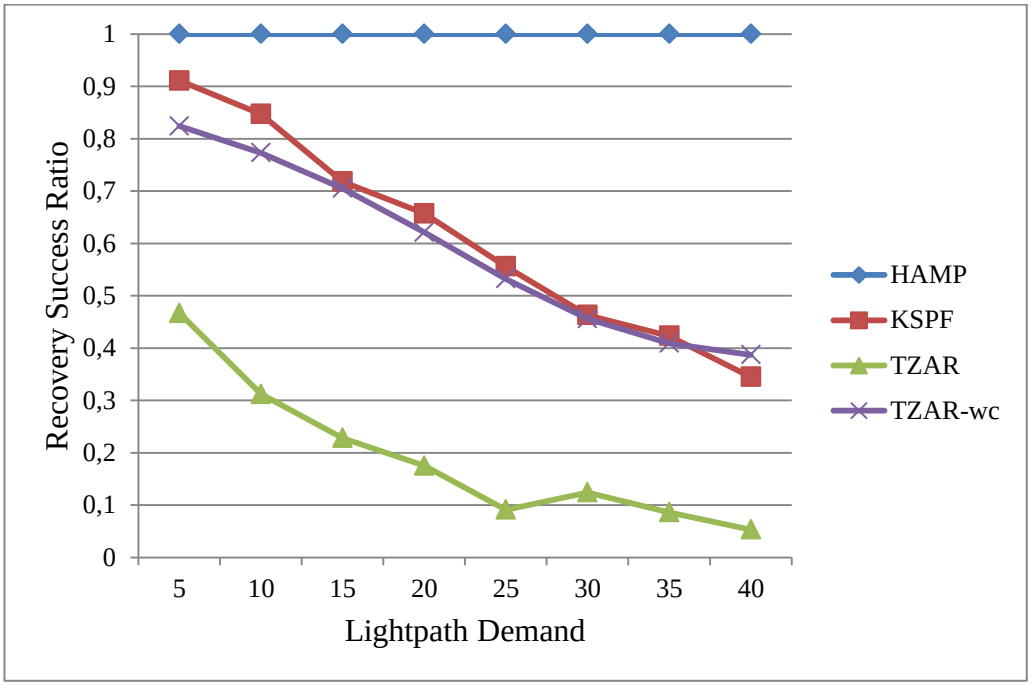


Figure 41 – Blocking Probability vs Number of Wavelengths (confidence intervals)

5.5.3. Recovery Success Ratio

The most critical feature to be analyzed within the scope of protection switching domain is recovery success ratio, which indicates the probability of successful provisioning of backup lightpaths in case of failures in the primary lightpaths. We present in Figures 42, 43, and 44 recovery success ratios obtained by using different algorithms versus lightpath demand, number of wavelengths, and number of nodes, respectively.

a.



b.

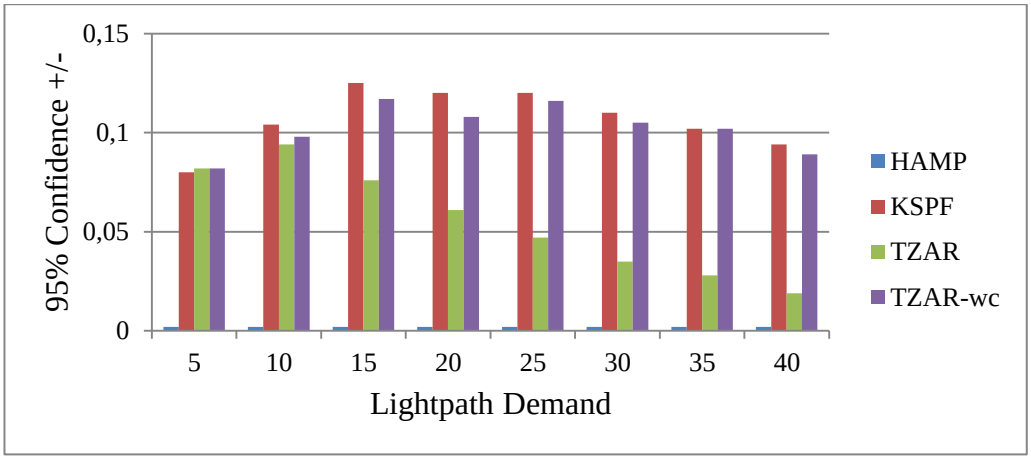


Figure 42 – Recovery Success Ratio vs Lightpath Demand: a. For link failures, b. Confidence interval for link failures, c. For node failures, d. Confidence interval for node failures

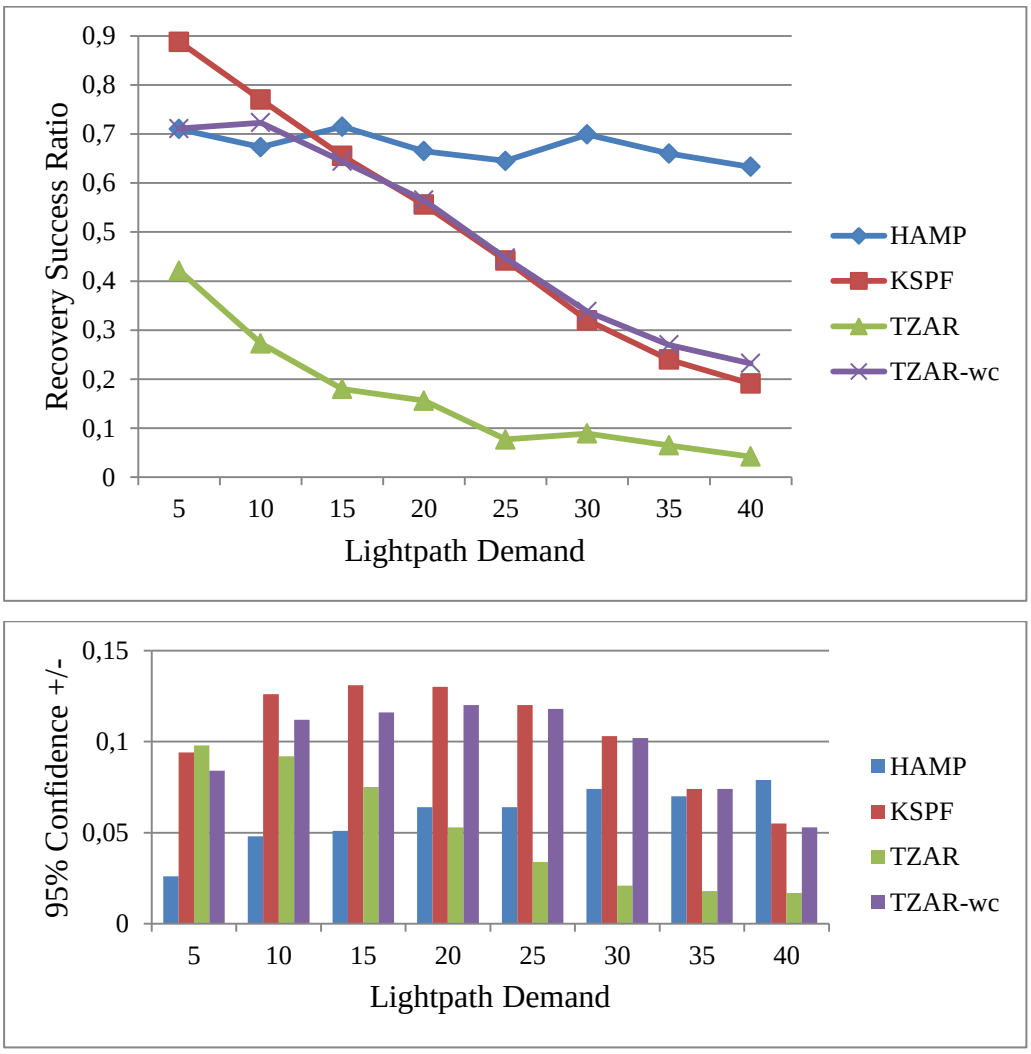


Figure 42 – Recovery Success Ratio vs Lightpath Demand (continued)

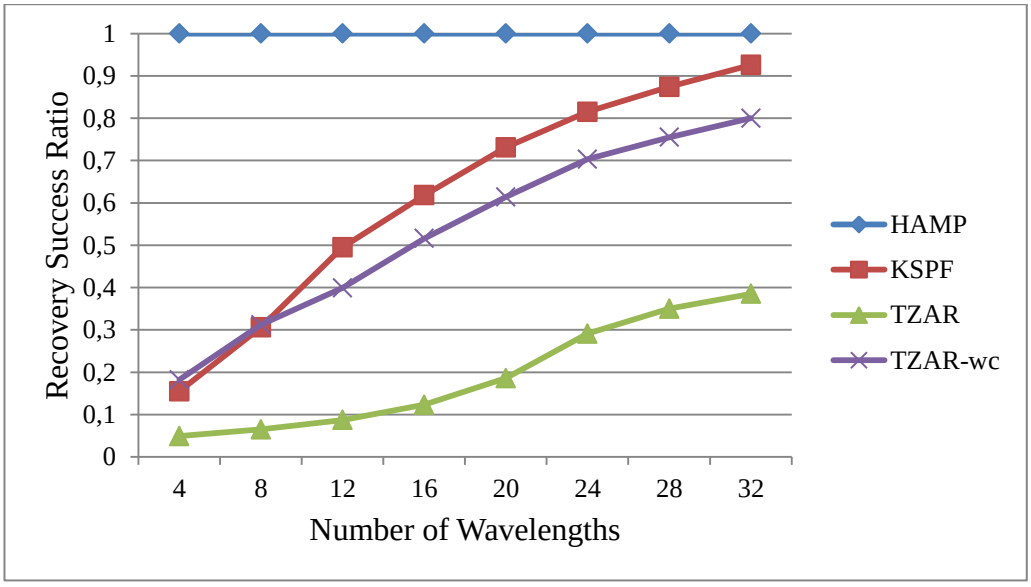
- **KSPF**; is a routing oriented algorithm, on which wavelength assignment is implemented as a kind of route cost metric. That is why, results of KSPF can be considered to be a benchmark in our analyses. We make the following deductions regarding KSPF:

  I. Recovery success ratio drops with increasing lightpath setup demand (42.a, 42.c) and decreasing number of wavelengths (43.a, 43.c). Peaks at confidence interval levels for 15-20 lightpath demands (42.b, 42.d) and 12-16 wavelengths (43.b, 43.d) address the threshold load factors and number of wavelengths, which result in the sharpest changes in recovery success ratios, respectively.

II. When we compare the results in 42.a, 43.a, and 44.a with that of 42.c, 43.c, and 44,c, we can argue that a decrease in recovery success ratios for node failure scenarios is natural, since recovery of a lightpath with a failed end node is impossible. And the ratio of that decrease is inversely related to the number of nodes in the topology. (31% for 4 nodes, 6% for 12 nodes (comparison from 44.a and 44.c))

III. Though relatively larger numbers of lightpaths are affected in node failures when compared to link failures, variances (which are presented in 42.b, 43.b, 44.b and 42.d, 43.d, 44.d, respectively) in recovery success ratios of those scenarios are not so different. This is a proof for the adequateness of our scenario variety.

a.



b.

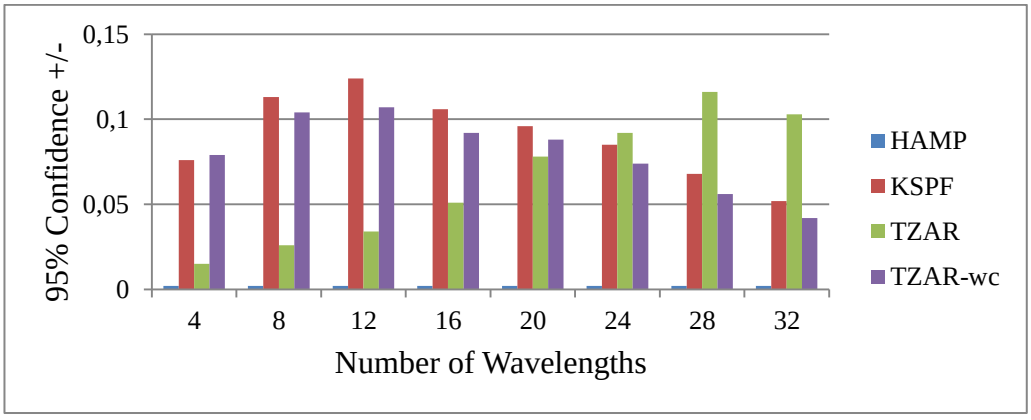
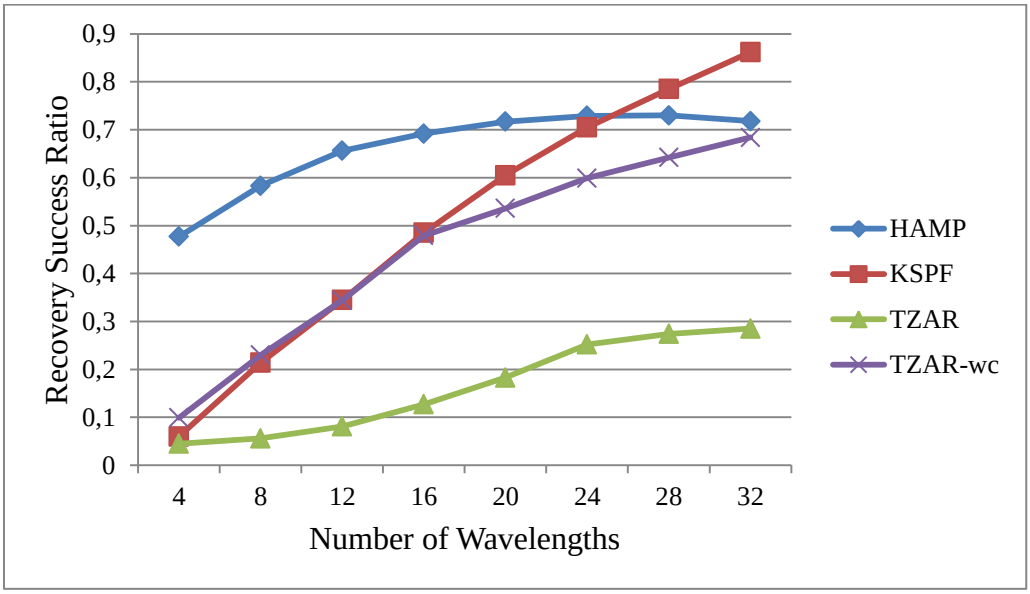


Figure 43 – Recovery Success Ratio vs Number of Wavelengths: a. For link failures, b. Confidence interval for link failures, c. For node failures, d. Confidence interval for node failures

c.



d.

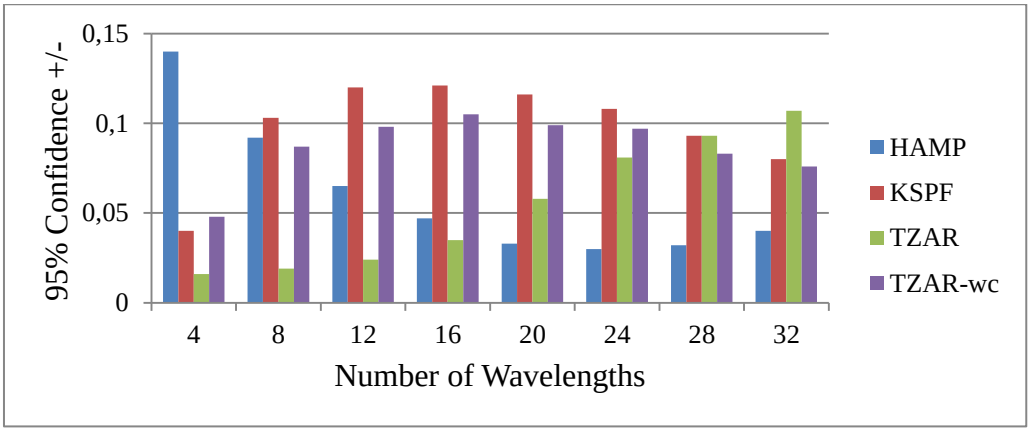


Figure 43 – Recovery Success Ratio vs Number of Wavelengths (continued)

- **HAMP**; is a ring oriented algorithm to protect lightpaths in mesh topologies via dedicated resources on a well-defined Hamiltonian Cycle. Because of those extra resources, wavelength assignment part of RWA is inherently supported. We make the following conclusions about HAMP:

  I. Regardless of the load factor and number of nodes, HAMP provides a perfect solution for link failures. Any single link can be assigned to at most W lightpaths (constraint 2.5 in section 2.4), where W is the number of wavelengths available on each link. As described in 5.4.3 we use homogenous links in terms of number of wavelengths, and reserved capacity on Hamiltonian p-Cycle is set to be equal to W.

Hence, we get recovery success ratio of 1 for link failure scenarios with HAMP as illustrated in 42.a, 43.a, and 44.a, all of which require protection for up to W lightpaths.

II. Recovery success ratios for node failure scenarios are least sensitive to the number of nodes (44.c), number of wavelengths (43.c) or lightpath demand (42.c) when compared to the other algorithms. That behavior makes HAMP a robust alternative for unknown traffic.

III. Accuracy of the results obtained in node failure scenarios is directly proportional to the number of wavelengths per link (43.d) and number of nodes in the topology (44.d), but there is an inverse relationship with lightpath setup demand (42.d). Therefore, running HAMP on properly configured topologies for known demand matrices proposes high-precision recovery success ratios.

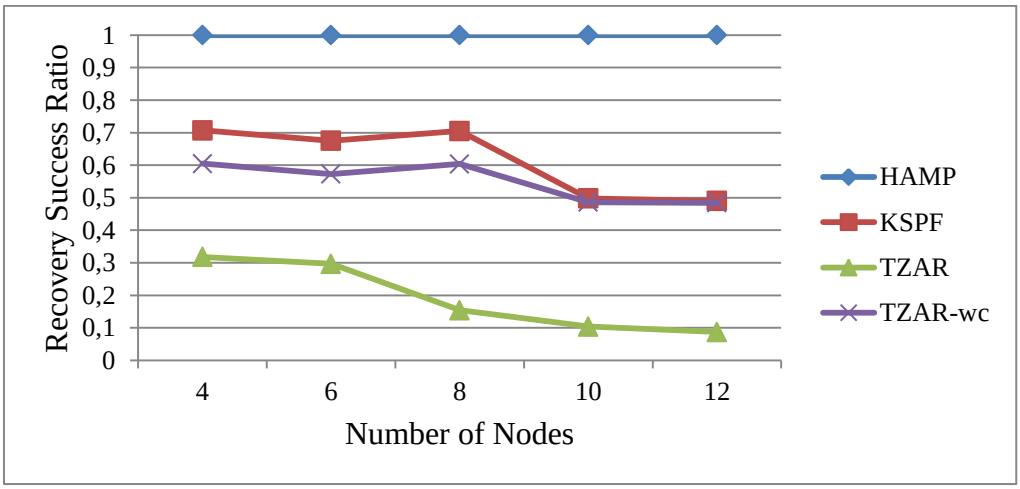
- **TZAR**; is also a routing oriented algorithm based on AODV. In contrary to KSPF, which is a link-state protocol, TZAR is a distance vector protocol. What is more, wavelength assignment part of RWA is not implemented with a prior knowledge along the whole lightpath, but accumulated on a hop-by-hop basis. We can read the results of original TZAR as a disappointment. When we drill down into the details of relevant simulation scenarios to comprehend the underlying reasons for much lower performance in terms of recovery success ratio, we come up with the following explanations:

  I. As illustrated in 42.a and 42.c, increasing lightpath setup demand minimizes the available resources for backup lightpath provisioning. This in turn results in much more RWA accumulation conflicts during SF message manycasting phase of TZAR. One way to eliminate such conflicts (i.e., contention for the same wavelength on a particular link) is to deploy wavelength converters within the network. Until recently, wavelength converters were considered to be expensive and low-performance components in optical networks due to their operation principles depending on OEO conversion.

However, new generation all-optical wavelength converters are being experimented in lab environments with promising results [70,71]. What is more, performance of tunable wavelength converters in conjunction with arrayed waveguide gratings and fiber delay lines are being evaluated to mitigate switching bottlenecks that may arise in IXP or CDN sort of data centers [72].

II. As illustrated in Figure 44, TZAR performance approaches closest to that of KSPF and HAMP for topologies of minimal number of nodes. This is not surprising especially for the marginal topology of 4 nodes, which is a full mesh with 3 links from each node. The only problem with such small networks is the percentage loss caused by any single node failure. Increasing number of nodes, on the other hand, results in higher number of hops per backup lightpath, which again means higher probability of RWA accumulation conflicts along the path.

a.



b.

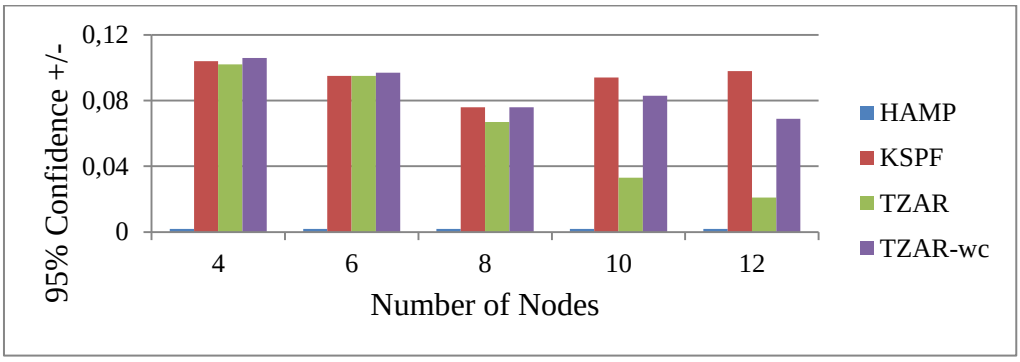
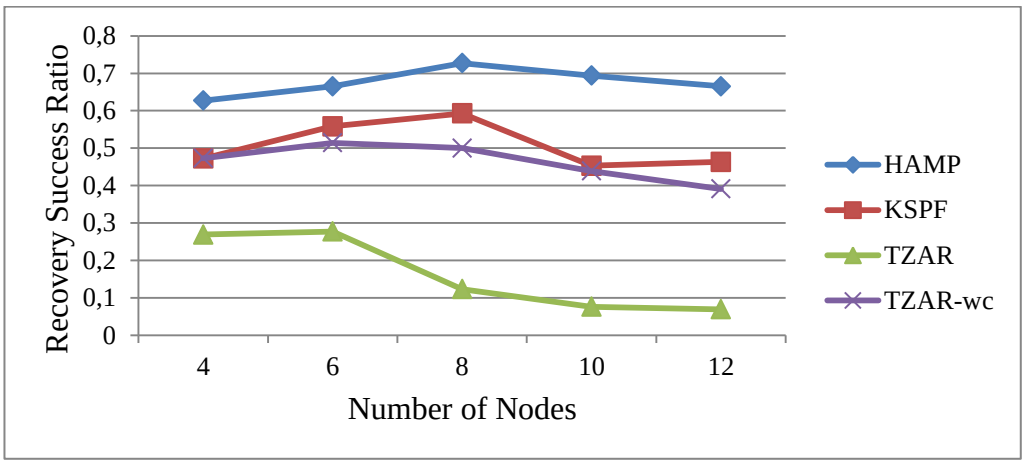


Figure 44 – Recovery Success Ratio vs Number of Nodes: a. For link failures, b. Confidence interval for link failures, c. For node failures, d. Confidence interval for node failures

c.



d.

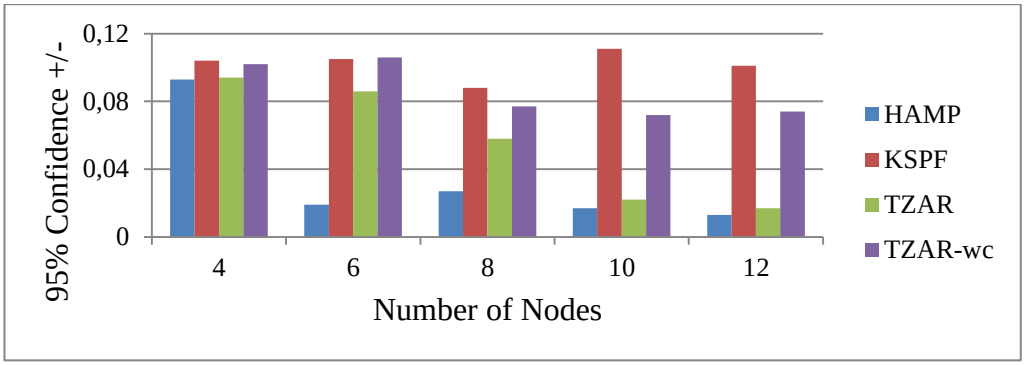


Figure 44 – Recovery Success Ratio vs Number of Nodes (continued)

- **TZAR-wc**; is an enhanced version of TZAR, which incorporates embedded wavelength converters at each OTN node to resolve the above-mentioned RWA conflicts during backup lightpath accumulation. Figures 42, 43, and 44 demonstrate whether comparative to KSPF and/or HAMP performance levels could be achieved, or not.

I. As explained in 2.4, implementing wavelength converters turns RWA problem into a kind of circuit switching. TZAR heuristics described in 4.3 allows us to accumulate RWA in various structure types to be accommodated in *rwa_accum* fields of SF and RR packets defined in 5.1. While we initialize wavelength at source and keep a list of nodes/links along the path for typical TZAR, we prefer a list of 3-tuples (node, link, and wavelength) to be able to switch on different wavelengths at each hop for TZAR-wc. By the way, we achieve recovery success ratios of up to 82% under low load (42.a).

II. As mentioned in 4.3, we propose Hold_RR and Max_Try_Count to coordinate protection switching activities subject to strict timing constraints. While tuning the network behavior, we set Hold_RR timers to 240 ms and 360 ms and Max_Try_Count values to 4 and 3 for original TZAR and TZAR-wc, respectively. By the way, we try to avoid more RWA conflicts in TZAR and to give chance for recovery over longer paths in TZAR-wc. Nevertheless, results in 43.a and 43.c still dictate a close dependency on the number of available wavelengths, which is a gauge for network capacity.

III. When we compare the results for TZAR-wc in Figures 44a and 44.c with that of KSPF and HAMP, we can observe a much less dependency on the number of nodes and the type of failures. Gap between recovery success ratios of KSPF for 4 node and 12 node topologies drop from 0.22 (0.71 - 0.49) to 0.12 (0.61 - 49) in TZAR-wc. On the other hand, gap between recovery success ratios of HAMP for link and node failures drop from 0.27 (1.0 - 0.73) to 0.12 (0.61 - 49) in TZAR-wc. These results confirm our diversity guarantee discussed in 4.2 regardless of the failed network object.

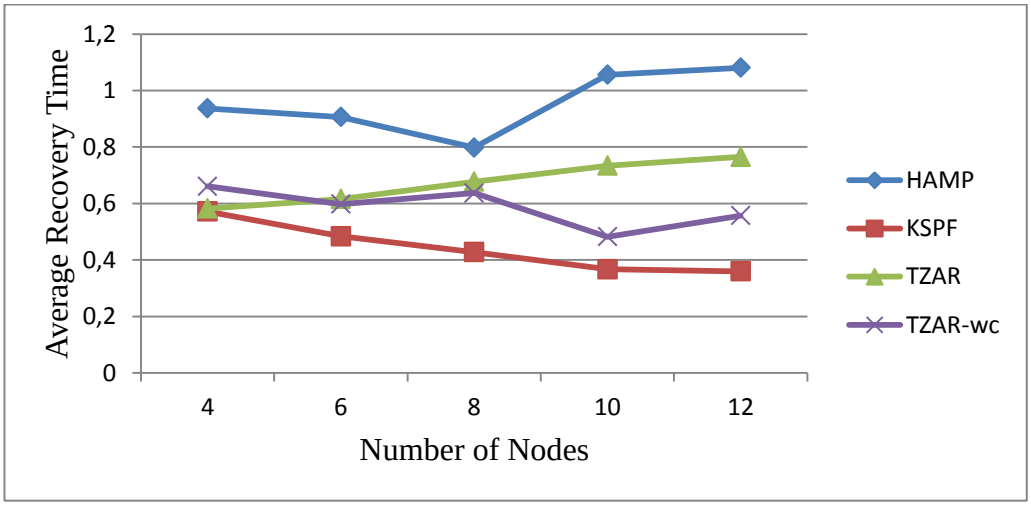
IV. Since shared resources are used for backup lightpaths as it was the case for KSPF, recovery success ratios drop with increasing lightpath setup demand (42.a and 42.c). However, wavelength conversion capability makes TZAR-wc outperform KSPF at high load (35<) and low wavelength (<8) region. Without any doubts, this is a natural result. Advantage of HAMP in that sense is the reservation of spare resources for only backup lightpaths.

5.5.4. Speed of Recovery

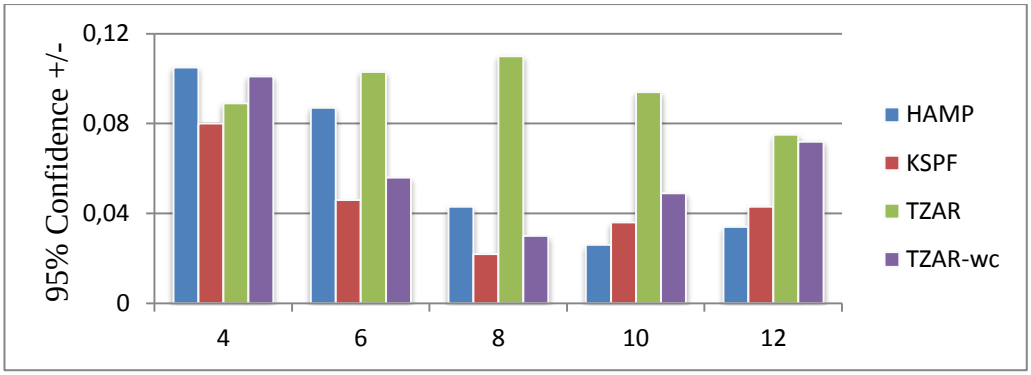
Finally, we have analyzed the average recovery time for the lightpaths that have successfully been recovered. That metric is an indicator of how fast OTN responds to failures. Since we need to avoid triggering the upper-layer protection switching mechanisms, we make our comparison on maximal values.

When we compare results for alternative algorithms on link failure and node failure scenarios presented separately in Figure 45, we can make the following observations regarding average recovery time:

a.



b.



c.

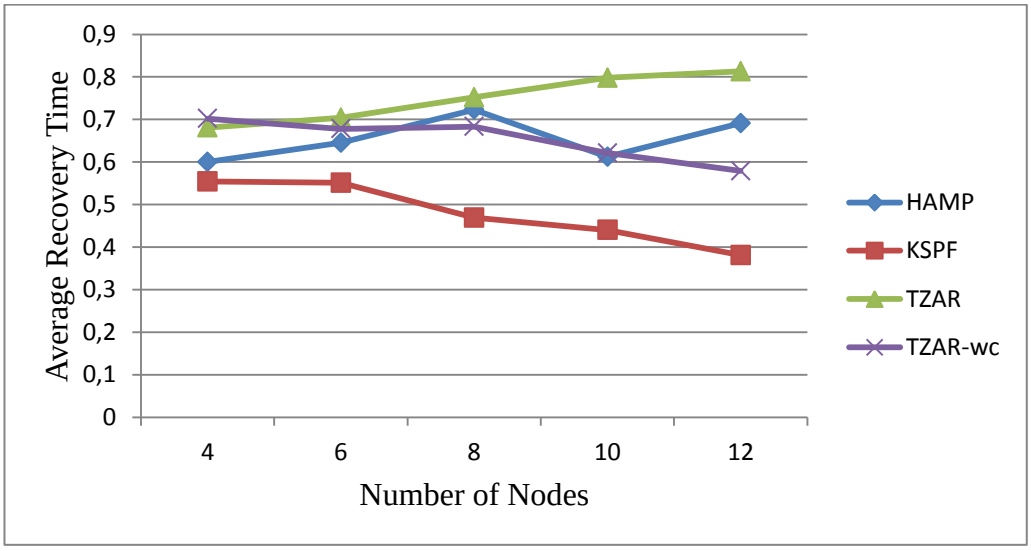


Figure 45 – Average Recovery Time vs Number of Nodes: a. For link failures, b. Confidence interval for link failures, c. For node failures, d. Confidence interval for node failures

d.

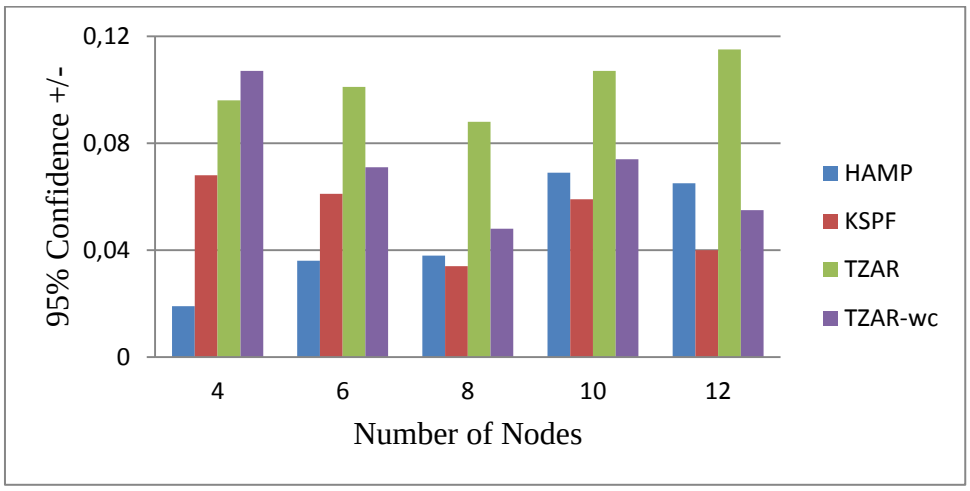


Figure 45 – Average Recovery Time vs Number of Nodes (continued)

I. Average recovery time decreases with increasing number of nodes for KSPF (45.a, 45.c). Since we keep the topology size constant on global scale, any increase in the number of nodes reduces the average inter-node distance. And as one of the major benefits of deploying KSPF in mesh optical networks, we provision backup lightpaths through least number of hops in minimal time. KSPF turns out to be an optimum solution with shortest (0.360 – 0.572 s.) and well bounded (0.022 – 0.080) recovery time values. However, in contrary to other algorithms analyzed, recoveries from node failures take 5-15% longer than recoveries from link failures for corresponding topological node densities.

II. Average recovery time has a tendency to increase with increasing number of nodes for HAMP. As explained in 3.3 Hamiltonian Cycle has to cover all nodes in a topology. When the failure type is a link failure (45.a); probability that it is an on-cycle link is considerably high, and all the protection paths have to traverse rest of the cycle in such cases. On the other hand, node failures (45.c) trigger straddling link protection for most of the time. That explains why average recovery times (0.80 – 1.08 s.) for link failure scenarios are higher than the ones (0.60 – 0.71 s.) for node failure scenarios. Nevertheless, HAMP approach seems not to be suitable for application on global scale due to exceeding recovery time targets given in 4.1, especially for growing topologies in terms of number of nodes.

III. There is an indirect correspondence on number of nodes for average recovery time values in TZAR. Lightpaths provisioned using our algorithm covers almost half of the planet, which sets a rather bounded propagation delay. Although referring to the temporal model discussed in 3.1 this delay does not depend much on the number of hops traversed along the path, gap between typical TZAR and TZAR-wc widens with increasing number of nodes. This is due to more loops (many_cast trials) between steps 14 and 2 of our heuristics in 4.3. In other words, implementation of wavelength converters in TZAR-wc increases the probability of successful RWA accumulation at earlier iterations of many_cast trials.

Other than the analytically discussed vital protection switching performance metrics above, we should also mention about the major metrics bothering OTN service providers regarding implementation costs and maintenance complexity. Our motivation is not to delve into pure mathematical derivations, but to concentrate on parameters, understanding the effects of which would suffice within the scope of our comparative performance evaluation.

- **Resource Efficiency**; is a measure of how effectively we utilize the overall network. Considering the amount of reserved resources for backup lightpath provisioning is a very serious dimension of protection switching operations. The more resources are reserved for protection switching, the more expensive the implemented network costs to the operator. According to our results figured out in 42 and 44, HAMP sets the upper bound for achievable recovery success ratios with respect to increasing lightpath demand and number of nodes. If we represent the number of total recovered lightpaths with R, $W \leq R \leq 2W$, where W is the number of available wavelengths (first W stands for all-on-cycle link failures, and second $2W$ stands for all-straddling link failures (which is also the case for node failure scenarios)). Although our results dictate that the number of recovered lightpaths is much lower in case of KSPF and TZAR variants, we have to formulate all the reserved resources for comparison purposes as follows:

i. HAMP consumes $C = W \times N$ (wavelength-link products), where C stands for protection cost and N stands for the number of nodes. Regardless of the number of lightpaths to be recovered, that much resource is allocated for the Hamiltonian p-Cycle.

ii. KSPF consumes $C = R \times P$ (wavelength-link products), where P stands for average path length of backup lightpaths. According to a detailed analysis in [73]; $P \cong \ln N / \ln D$, where D stands for the average degree of nodes. Since in our OTN domain we consider nodal degrees of 3 to 6, range for C is subject to $\ln N/1.8 \leq P \leq \ln N/1.1$. When we use the expression above relating R to W, even the upper bound for protection cost of KSPF turns out to be much smaller than the lower bound for that of HAMP for increasing number of nodes: $2W \times \ln N/1.1 \ll W \times N$.

iii. TZAR and TZAR-wc not only traverse longer backup lightpaths when compared to KSPF, but also consume transient resources on many_cast phase. However even for the largest possible P, i.e. $\ln N/0.7$ ($D = 2$), protection cost still stays slightly worse than KSPF but much better than HAMP.

- **Computation Complexity**; is a measure of how difficult it is to manage the protection switching framework. Rather than the space complexity, we do care about time complexity due to the strict timing constraints.

  i. KSPF finds k-shortest paths from a given source to any other node in the network within $O(m + n \log n + kn)$ time [74], where m is number of links, n is number of nodes, and k is the number of paths to be found.

  ii. Complexity of Hamiltonian Cycle Problem has evolved from $O(n!)$ to $O(n^3)$ using brute force search and divide-and-conquer methods, respectively. But it is also possible to construct 4-connected planar networks within linear time $O(n)$. [75]

  iii. TZAR and TZAR-wc do not introduce any algorithmic depth other than the complexity of enumeration of neighboring nodes, which stays in $O(1)$.

With the enlightenment of simulation results that we have discussed so far, we can summarize our understanding about the key benefits of each algorithm as given in Table 9. Although KSPF seems to be the champion in most of the metrics, its computation complexity is an important barrier to be surmounted. HAMP suffers badly from the dominance of very high propagation delays on intercontinental links. TZAR, on the other hand, has to wait for cheaper and finer-tunable wavelength converters to be considered again.

Table 9 – Protection Switching Algorithm Comparison

	KSPF	**HAMP**	**TZAR**	**TZAR-wc**
Recovery Success Ratio	Moderate	High	Low	Moderate
Speed of Recovery	High	Low	Moderate	Moderate
Resource Efficiency	High	Low	Moderate	Moderate
Computation Complexity	High	Moderate	Low	Low

CHAPTER 6

CONCLUSION

In this thesis, we first provide a brief overview of progress in optical transport networking from hardware architecture and software hierarchy points of views together with trends in protection switching through a peculiar taxonomy on computational, topological, and efficiency aspects. We then propose a new low computation complexity algorithm, TZAR, and its variety with wavelength conversion support, TZAR-wc. These algorithms fulfill the following requirements as expected in Appendix A based on time-zone awareness of OTN nodes:

- A.1, A.2, A.3, A.10, A.20, A.24; by utilizing the existing OOS channel for signaling and OTM hierarchy for encapsulation.
- A.4, A.23; by employing carrier and domain independent time-zone parameter as a cross-layer information.
- A.5, A.6, A.7, A.25, A.26; by using SF, RR messages on a granular basis on the levels of both lightpath clients and communicating nodes.
- A.11, A.12, A.14; by managing timers like Hold_RR and counters like Max_Try_Count.
- A.16, A.19; by keeping track of candidate interfaces and featuring Many_Cast operation.

Our detailed comparative analysis of TZAR/TZAR-wc show that we achieve $O(1)$ computational complexity while KSPF and HAMP algorithms have complexities that increase with the number of nodes and links in the topology. However, the simple implementation of TZAR/TZAR-wc cannot achieve the best values in

Recovery Success Ratio, Speed of Recovery and Resource Efficiency metrics compared to KSPF and HAMP.

Furthermore, our results show that in the presence of wavelength conversion capability, the quasi-ring decomposition of global mesh topologies is a sound routing alternative to be investigated further in literature. Meanwhile, "Time Zone" parameter may probably be the most natural argument to support the deployment of TZAR sort of approaches in next generation OTN systems. Though wavelength converters act as a key enabler to obtain new recovery success ratios, average number of wavelength converters on each node would be of concern.

In this study we have primarily focused on failure recovery framework in OTN. As future work one can suggest, investigating revertive mode of operation with wavelength conversion to evaluate how network behaves when failed resources come back into their initial working states. Consequently, expectations A.15 and A.22 would be satisfied. Once lightpath allocation and de-allocation mechanisms are defined, prioritization and preemption procedures can also be specified in a straightforward manner. By the way, expectations A.17 and A.21 could be satisfied. Utilizing a tighter integration with control and management planes might produce enough capabilities to monitor the real time status of transport plane. Satisfaction of expectations A.8, A.9, A.13, and A.18 would then follow to avoid contention for the shared resources while keeping sharing gain at reasonable levels.

To sum up, autonomous protection switching for failed lightpaths will continue to be a sophisticated traffic recovery framework demand especially when used in conjunction with BGP and GMPLS sort of upper layer protocols. Since most of Tier-1 ISPs running BGP has presence in multiple IXP sites and global CDN operators lease resources to be managed privately by GMPLS, global resilience on mesh OTN is of utmost interest in the nearest term. With its indeterminate nature TZAR would not be appropriate as a primary solution, but its adjustable behavior may address TZAR as a real-time backup for KSPF or HAMP sort of protection switching algorithms.

REFERENCES

[1] Alcatel-Lucent, “Alcatel-Lucent to double capacity of today’s data transport networks by being first to deliver a single-carrier 200G DWDM optical line card” “http://www.alcatel-lucent.com/press/2014/alcatel-lucent-double-capacity-todays-data-transport-networks-being-first-deliver-single-carrier”, 24 September 2014

[2] ITU-T Recommendation G.696.1, “Longitudinally compatible intra-domain DWDM applications”, Telecommunication Standardization Sector of ITU, July 2010

[3] Yoichi Maeda, Francesco Montalti, Gastone Bonaventura, Makoto Murakami, and Kazuyuki Shiraki, “Optical fibre, cables and systems”, ITU-T Manual, 2009

[4] Infinera Corporation, “Infinera Customers Deploy over one Petabit per second of Super-Channel Transmission Capacity Globally”, “http://www.infinera.com/j7/servlet/NewsItem?newsItemID=395”, 27 March 2014

[5] “The Zettabyte Era: Trends and Analysis”, Cisco, 10 June 2014

[6] Andrew Schmitt, “Global Service Provider Survey Excerpts: OTN, MPLS, and Control Plane Strategies”, Infonetics Research, Inc., June 2013

[7] Michael Ruddy on behalf of Terabit Consulting, “Submarine Telecoms Industry Report”, Submarine Telecoms Forum, 2014

[8] Ron Kline, “Vendor strategies: Tellabs fights back against larger full-service rivals”, Ovum, 16 June 2010

[9] “TrueNet Capabilities Overview”, ADC Telecommunications, Inc., 2009

[10] James P.G. Sterbenz, David Hutchison, Egemen K. Çetinkaya, Abdul Jabbar, Justin P. Rohrer, Marcus Schöller, Paul Smith, “Resilience and survivability in communication networks: Strategies, principles, and survey of disciplines”, Elsevier - Computer Networks, 2010

[11] ITU-T Recommendation G.709/Y.1331, “Interfaces for the optical transport network”, Telecommunication Standardization Sector of ITU, February 2012

[12] ITU-T Recommendation G.872, “Architecture of optical transport networks”, Telecommunication Standardization Sector of ITU, October 2012

[13] ITU-T Recommendation G.798, “Characteristics of optical transport network hierarchy equipment functional blocks”, Telecommunication Standardization Sector of ITU, December 2012

[14] Paul Littlewood, Fady Masoud, “Optical Transport Networking”, Ciena Expert Series, 2014

[15] Steve Gorshe, “A Tutorial on ITU-T G.709 Optical Transport Networks (OTN)”, PMC-Sierra, Inc., June 2011

[16] Richard A Steenbergen, “Everything You Always Wanted to Know About Optical Networking – But Were Afraid to Ask”, NANOG Meeting 57, February 2013

[17] Emmanuel Desurvire, “Erbium-doped fiber amplifiers: device and system developments”, J. Wiley & Sons, 2002

[18] Mahmud Wasfi, “Optical Fiber Amplifiers-Review”, International Journal of Communication Networks and Information Security (IJCNIS), April 2009

[19] ITU-T Recommendation G.694.2, “Spectral grids for WDM applications: CWDM wavelength grid”, Telecommunication Standardization Sector of ITU, December 2003

[20] ITU-T Recommendation G.694.1, “Spectral grids for WDM applications: DWDM frequency grid”, Telecommunication Standardization Sector of ITU, February 2012

[21] Dhritiman Banerjee, Biswanath Mukherjee, “A Practical Approach for Routing and Wavelength Assignment in Large Wavelength-Routed Optical Networks”, IEEE Journal on Selected Areas in Communications, June 1996

[22] Rajiv Ramaswami, Kumar N. Sivarajan, “Routing and Wavelength Assignment in All-Optical Networks”, IEEE/ACM Transactions on Networking, October 1995

[23] Matthieu Clouqueur, Wayne D. Grover, “Availability Analysis of Span-Restorable Mesh Networks”, IEEE Journal on Selected Areas in Communications, May 2002

[24] Richard A. Barry, Pierre A. Humblet, “Models of Blocking Probability in All-Optical Networks with and without Wavelength Changers”, IEEE Journal on Selected Areas in Communications, June 1996

[25] Byrav Ramamurthy, Biswanath Mukherjee, “Wavelength Conversion in WDM Networking”, IEEE Journal on Selected Areas in Communications, September 1998

[26] I. Chlamtac, A. Ganz, G. Karmi, “Lightpath communications: an approach to high bandwidth optical WAN's”, IEEE Transactions on Communications, July 1992

[27] Rajiv Ramaswami, “Optical Networking Technologies: What Worked and What Didn't”, IEEE Communications Magazine, September 2006

[28] Mohcene Mezhoudi, Chi-Hung Kelvin Chu, “Integrating Optical Transport Quality, Availability, and Cost Through Reliability-Based Optical Network Design”, Bell Labs Technical Journal, May 2006

[29] Laxman Sahasrabuddhe, S. Ramamurthy, Biswanath Mukherjee, “Fault Management in IP-Over-WDM Networks: WDM Protection Versus IP Restoration”, IEEE Journal on Selected Areas in Communications, January 2002

[30] ITU-T Recommendation G.8080/Y.1304, “Architecture for the automatically switched optical network”, Telecommunication Standardization Sector of ITU, February 2012

[31] ITU-T Recommendation G.808.1, “Generic protection switching – Linear trail and subnetwork protection”, Telecommunication Standardization Sector of ITU, May 2014

[32] ITU-T Recommendation G.808.2, “Generic protection switching – Ring protection”, Telecommunication Standardization Sector of ITU, November 2013

[33] ITU-T Recommendation G.808.3, “Generic protection switching – Shared mesh protection”, Telecommunication Standardization Sector of ITU, October 2012

[34] Eric Bouillet, Georgios Ellinas, Jean-François Labourdette, Ramu Ramamurthy, “Path Routing in Mesh Optical Networks”, John Wiley & Sons, 2007

[35] Nico Wauters, Gzim Ocakoglu, Kris Struyve, Pedro Falcao Fonseca, “Survivability in a New Pan-European Carriers’ Carrier Network Based on WDM and SDH Technology: Current Implementation and Future Requirements”, IEEE Communications Magazine, August 1999

[36] Hamza Drid, Bernard Cousin, Miklos Molnar, Samer Lahoud, “A survey of survivability in multi-domain optical networks”, Elsevier - Computer Communications, February 2010

[37] Mohit Chamania, Admela Jukan, “A Survey of Inter-Domain Peering and Provisioning Solutions for the Next Generation Optical Networks”, IEEE Communications Surveys & Tutorials, 2009

[38] ITU-T Recommendation G.873.1, “Optical transport network (OTN): Linear protection”, Telecommunication Standardization Sector of ITU, May 2014

[39] Timothy Y. Chow, Fabian Chudak, Anthony M. Ffrench, “Fast optical layer mesh protection using pre-cross-connected trails”, IEEE/ACM Transactions on Networking, June 2004

[40] John Strand, Angela L. Chiu and Robert Tkach, “Issues For Routing In The Optical Layer”, IEEE Communications Magazine, February 2001

[41] Hui Zang, Member, Canhui (Sam) Ou, Biswanath Mukherjee, “Path-Protection Routing and Wavelength Assignment (RWA) in WDM Mesh Networks Under Duct-Layer Constraints”, IEEE/ACM Transactions on Networking, April 2003

[42] Lei Song, Biswanath Mukherjee, “On The Study of Multiple Backups and Primary-Backup Link Sharing for Dynamic Service Provisioning in Survivable WDM Mesh Networks”, IEEE Journal on Selected Areas in Communications, 2008

[43] Dongyun Zhou, Suresh Subramaniam, “Survivability in Optical Networks”, IEEE Network, November/December 2000

[44] János Tapolcai, Pin-Han Ho, Péter Babarczi, Lajos Rónyai, “Internet Optical Infrastructure: Issues on Monitoring and Failure Restoration”, Springer, 2015

[45] J. Y. Yen, “Finding the K shortest loopless paths in a network”, Journal of Management Science, July 1971

[46] J. W. Suurballe, “Disjoint paths in a network”, Networks, 1974

[47] J. Rak, “k-Penalty: a novel approach to find k-Disjoint paths with differentiated path costs”, IEEE Communication Letters, April 2010

[48] P. Merindol, “An efficient algorithm to enable path diversity in link state routing networks”, Elsevier – Computer Networks, 2011

[49] Dominic A. Schupke, “Automatic protection switching for p-cycles in WDM networks”, Elsevier – Optical Switching and Networking, April 2005

[50] Ramin Saeedinia, “Protection Switching in Communication Networks”, IEEE UKRI – 16th European Conference on Networks and Optical Communications, 2011

[51] Mohammad S. Kiaei, Chadi Assi, and Brigitte Jaumard, “A Survey on the p-Cycle Protection Method”, IEEE Communications Surveys & Tutorials, 2009

[52] Wayne D. Grover, Demetrios Stamatelakis, “Cycle-Oriented Distributed Preconfiguration: Ring-like Speed with Mesh-like Capacity for Self-planning Network Restoration”, IEEE, 1998

[53] Hong Huang, John Copeland, “Hamiltonian Cycle Protection: A Novel Approach to Mesh WDM Optical Network Protection”, IEEE, 2001

[54] John Doucette1, Peter A. Giese1, Wayne D. Grover, “Combined Node and Span Protection Strategies with Node-Encircling p-Cycles”, IEEE, 2005

[55] Adil Kodian, Wayne D. Grover, “Failure-Independent Path-Protecting p-Cycles: Efficient and Simple Fully Preconnected Optical-Path Protection”, Journal of Lightwave Technology, October 2005

[56] ITU-T Recommendation G.841, “Types and characteristics of SDH network protection architectures”, Telecommunication Standardization Sector of ITU, October 1998

[57] ITU-T Recommendation G.8031/Y.1342, “Ethernet linear protection switching”, Telecommunication Standardization Sector of ITU, January 2015

[58] The Solutions Center, “Solution Guide: SAN Distance Extension Reference”, Brocade Communications Systems, 2007

[59] Tom Scholl, “BFD (Bidirectional Forwarding Detection) Does it work and is it worth it?”, NANOG Meeting 45, January 2009

[60] Dimitri Staessens, Didier Colle, Ilse Lievens, Mario Pickavet, Piet Demeester, Walter Colitti, Ann Nowé, Kris Steenhaut, Ricardo Romeral, “Enabling High Availability over Multiple Optical Networks”, IEEE Communications Magazine, June 2008

[61] Stephanie Silvius, “Internet Exchange Points”, European Internet Exchange Association Reports, January 2011

[62] Chengchen Hu, Kai Chen, Yan Chen, Bin Liu, Athanasios V. Vasilakos, "A Measurement Study on Potential Inter-Domain Routing Diversity", IEEE Transactions on Network and Service Management, September 2012

[63] Packet Clearing House, https://prefix.pch.net/applications/ixpdir/, May 2015

[64] Melanie Posey, "Is Your Application Delivery Approach Optimized to Meet the Needs of Your Globally Distributed User Base?", International Data Corporation (IDC), December 2014

[65] Amy Cravens, "How new devices, networks, and consumer habits will change the web experience", GigaOM Pro, January 2013

[66] Eytan Modiano, Aradhana Narula-Tam, "Survivable Lightpath Routing: A New Approach to the Design of WDM-Based Networks", IEEE Journal on Selected Areas in Communications, 2002

[67] C. E. Perkins, E. M. Belding-Royer, S. R. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing", IETF RFC 3561, July 2003

[68] OPNET Modeler 14.5.A PL8 – Educational Version, © 1986-2008 OPNET Technologies, Inc.[1]

[69] Zheng Lu, Hongji Yang, "Unlocking the Power of OPNET Modeler", Cambridge University Press, 2012

[70] Francesca Bontempi, Stefano Faralli, Nicola Andriolli, Giampiero Contestabile, "An InP Monolithically Integrated Unicast and Multicast Wavelength Converter", IEEE Photonics Technology Letters, November 2013

[71] Dimitrios Fitsios, Theonitsa Alexoudi, George T. Kanellos, Konstantinos Vyrsokinos, Nikos Pleros, Tolga Tekin, Matteo Cherchi, Sami Ylinen, Mikko

[1] OPNET Technologies, Inc. was acquired by Riverbed in October 2012. Since then OPNET Modeler is called Riverbed Modeler, and now a part of SteelCentral performance management and control product portfolio.

Harjanne, Markku Kapulainen, Timo Aalto, “Dual SOA-MZI Wavelength Converters Based on III-V Hybrid Integration on a μm-Scale Si Platform”, IEEE Photonics Technology Letters, March 2014

[72] Houman Rastegarfar, Alberto Leon-Garcia, Sophie LaRochelle, Leslie Ann Rusch, “Cross-Layer Performance Analysis of Recirculation Buffers for Optical Data Centers”, IEEE Journal of Lightwave Technology, February 2013

[73] P. Erdös, A. Renyi, “On the evolution of random graphs”, Publications of the Mathematical Institute of the Hungarian Academy of Sciences 5, 1960

[74] David Eppstein, “Finding *k* Shortest Paths”, Department of Information and Computer Science, University of California, Irvine, CA, 1997

[75] Norishige Chiba, Takao Nishizeki, “The Hamiltonian Cycle Problem Is Linear-Time Solvable for 4-Connected Planar Graphs”, Journal of Algorithms 10, Academic Press, 1989

APPENDIX A

PROTECTION SWITCHING REQUIREMENTS

Generic protection switching requirements for shared mesh networks given in [22];

A.1 Shall allow backwards compatibility with core structures/formats of technology-specific Recommendations.

A.2 Shall not impact usage of existing technology-specific linear and ring APS protection mechanisms and communications channels (i.e., co-existence with existing APS specifications).

A.3 Shall allow for any intra-/inter-operator applications for cascaded or nested protection deployments.

A.4 Shall allow for co-existence of ASON-based protection/restoration and SMP protection at inter-domain boundaries.

A.5 Shall be capable of supporting protection of one or more point-to-point bidirectional normal traffic signals from the ingress to the egress of the SMP domain.

A.6 Shall not require that multiple working transport entities sharing the same protection resource(s) have the same end points.

A.7 Shall monitor the status of the working transport entities for SMP protection switching triggers (e.g., SF, SD).

A.8 Shall monitor availability of the shared protection resources along the protection transport entities.

A.9 Shall include support for communicating information on the availability of the shared protection resources along the protection transport entities to the end points of the working transport entities that utilize the resources.

A.10 Shall include support for communicating information among network nodes to perform protection switching. The message encoding and communicating channel between the nodes depends on the specific technology.

A.11 Shall be capable of recovering a normal traffic signal from network failure(s) in a deterministic manner. For example, the protection switching shall complete within a finite (bounded) time, as described within the technology-specific Recommendations.

A.12 Shall include support for a mechanism to detect protocol failures.

A.13 Shall include support for a mechanism to detect possible inconsistencies in configuration between the ingress and egress nodes of an SMP domain.

A.14 Shall be capable of supporting nesting of multiple levels of protection (whether SMP or other schemes such as SNC protection). To achieve this, shall include support for mechanism(s) that allow for coordination of protection activities (e.g., hold-off timer).

A.15 Shall provide a mechanism to avoid protection switching flapping (e.g., wait-to-restore timer).

A.16 Shall include support for multiple links between nodes, allowing for link and node diversity, and should be scalable with respect to the number of links and nodes within the SMP protection domain.

A.17 Shall provide a contention resolution mechanism for permitting only one working transport entity to occupy protection resources in the case that these protection resources are shared by more than one working transport entity having the same priority (due to network topology and resource limitations).

A.18 Shall be capable of supporting the ability to set an upper limit on the maximum number of working transport entities that can share protection resources (which is governed by the specific technology).

A.19 Shall include support for the ability to set an upper bound on the fraction of link resources that can be allocated to protecting transport entities.

A.20 Shall allow for configuration (which may be via the management or control plane) of the protection transport entity identifiers, required bandwidth, and additionally for circuit SMP, the assignment of TSs to ensure the proper operation of the protection switching process.

A.21 Shall support assignment of priority to support the request of a higher-priority transport entity to pre-empt the shared protection resource taken by a lower-priority transport entity.

A.22 Shall only support revertive operation type.

A.23 Shall only support bidirectional switching type.

A.24 Shall be capable of supporting external commands from network operators.

A.25 Shall be capable of supporting protection for more than one failure, including failures that are concurrent and/or failures involving shared resources.

A.26 Shall be capable of protection switching activation initiated by either end or both ends (which may be simultaneous) of the SMP domain.

APPENDIX B

A SAMPLE DEMONSTRATION OF TZAR

The following demonstration of TZAR on a sample global topology for a randomly chosen lightpath would visualize the context covered in our thesis. With a series of simplified figures we emphasize the working principles of our heuristic algorithm. Aside by each figure we highlight the key computational processes.

1. **Initial State**; is shown in Figure 46. Here we see the primary lightpath setup in between nodes 3 and 21, which is represented with blue links.

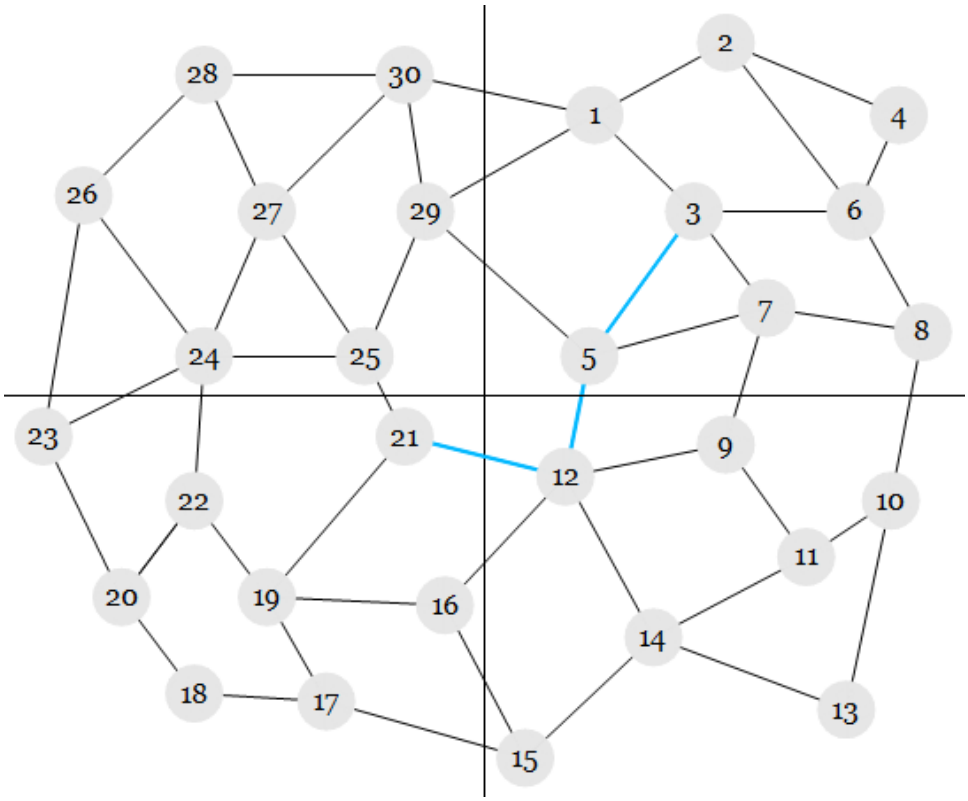


Figure 46 – TZAR Demonstration Phase 1

2. **Failure Detection**; phase is shown in Figure 47. Link between nodes 3 and 5 is broken. As soon as the failure is detected, the following happens on node 3, which is closer end-point of our sample lightpath to the failure:
   - Next-hop is selected based on Time-Zone (A protection switching table is kept for all lightpaths sourced on or destined to each node. Presence of that table as a priori makes our algorithm a sort of protection switching mechanism rather than a route restoration. While creating that table at network initialization, probabilistic nature is used to avoid deadlocks within time zones.)
   - SF message is sent
   - Source_Client process is initiated (Another process will also start from the other side of the lightpath (from node 21 in our sample). But we do not figure it out concurrently here not to complicate the visual trace of the algorithm. We may just consider these symmetric recovery processes as a kind of race condition. Since our main aim is to recover from failures as soon as possible, such parallel processing is beneficial.)

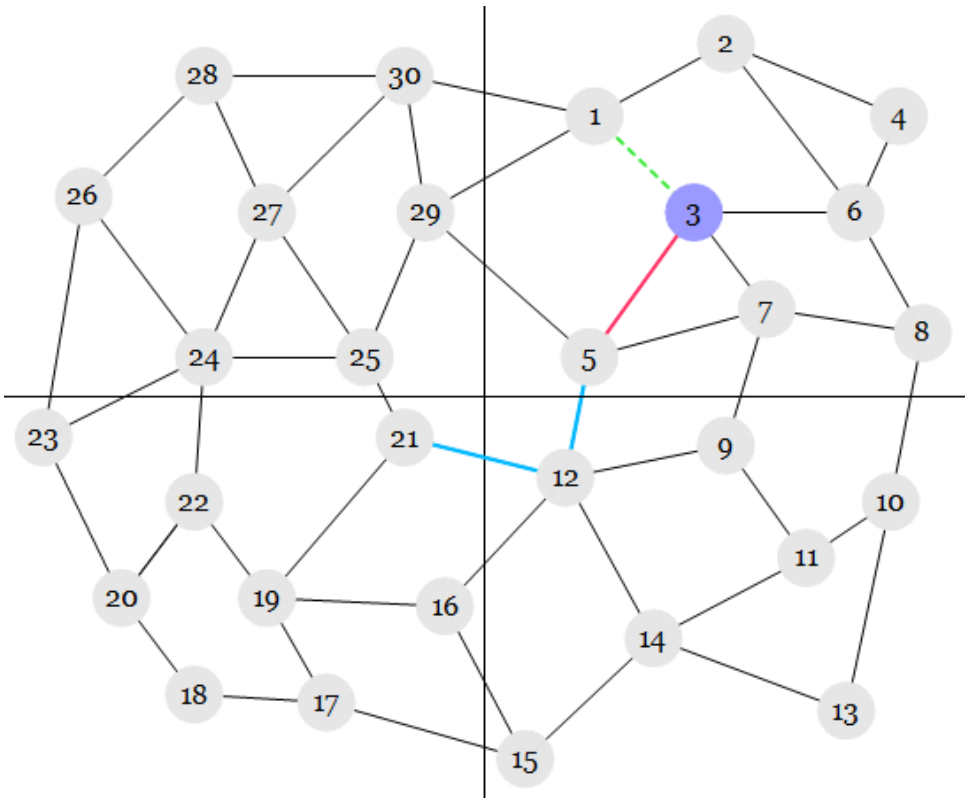


Figure 47 – TZAR Demonstration Phase 2

3. **SF Message Processing**; starts with node 1, which is the next hop after node 3 as shown in Figure 48. As soon as SF message is received on node 1;
   - Next-hop is selected based on Source_TZ and Candidate Interfaces (Candidate interfaces definitely exclude the one, from which that SF message was received. In our figures we mark such links as solid green lines. These green links also show us the consumed resources for a transient period, since relevant wavelengths are allocated for recovery processes of failed lightpaths.)
   - Probabilistic nature is used to avoid congestion (As described in our heuristics, we do not apply strict rules regarding time zone traversal. Not moving in east direction for a failure detected in west, or vice versa, sometimes results in a recovery within the vicinity of failure.)
   - TTL and RWA_Accumulated fields are updated
   - SF message is forwarded (We designate the links, through which SF messages are forwarded, with dashed green lines)
   - Source_Gateway process is initiated

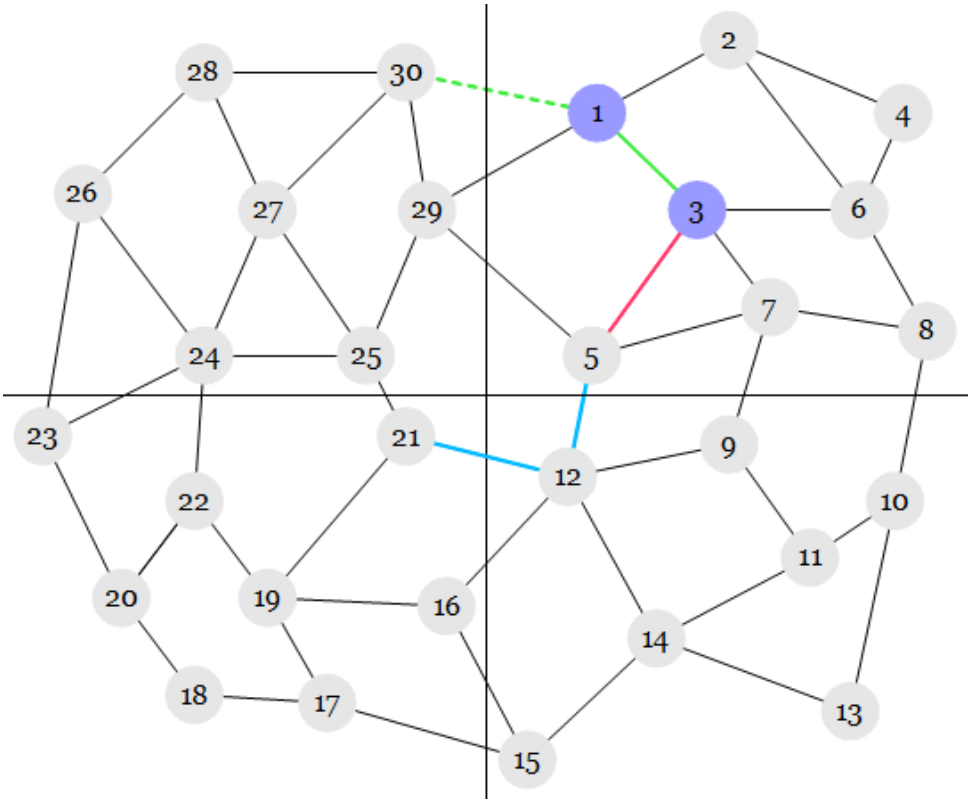


Figure 48 – TZAR Demonstration Phase 3

4. **SF Message Processing**; continues with node 30, which is the next hop after node 1 as shown in Figure 49. As soon as SF message is received on node 30;
   - TTL and RWA_Accumulated fields are updated
   - Many_Cast counter is updated based on TTL (The correlation between TTL and Many_Cast counter values can be regarded as an adjustable function of network size and average node degrees. Slower increase in many-cast density would mean a better fade away from faulty portion of the network, while faster increase would mean a much better recovery time at the cost of worse utilization of resources and a higher probability of contention for those resources.)
   - Next-hops are selected based on Source_TZ and Candidate Interfaces
   - 2 copies of SF messages are forwarded (2 is our new Many_Cast value)
   - Although two SF messages are forwarded, a single Source_Gateway process is initiated (There may be at most 2 such processes for a failed lightpath with a specific Conn_ID, i.e. one for each end point.)

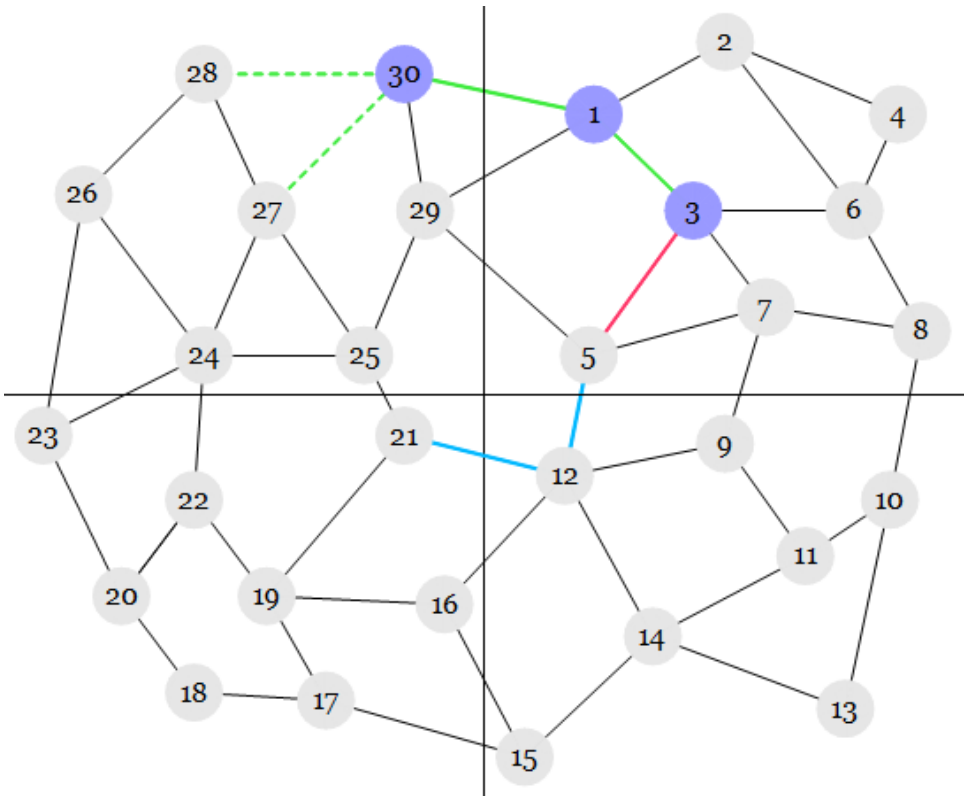


Figure 49 – TZAR Demonstration Phase 4

5. **SF Message Processing**; continues with nodes 27 and 28, which are the next hops after node 30 as shown in Figure 50. When SF message copies are received by nodes 27 and 28;
   - TTL and RWA_Accumulated fields are updated
   - Next-hops are selected based on Source_TZ and Candidate Interfaces
   - Different copies of SF messages are sent by 27 and 28 (RWA_Accumulated fields of those SF messages definitely differ on the last hop. Each node processing an SF message places itself on top of the route stack, which will then be used by RR messages in backward direction. When destination node will be reached, accumulated route will start to be used via popping from the stack on a hop-by-hop basis.)
   - Source_Gateway processes are initiated on each node receiving SF

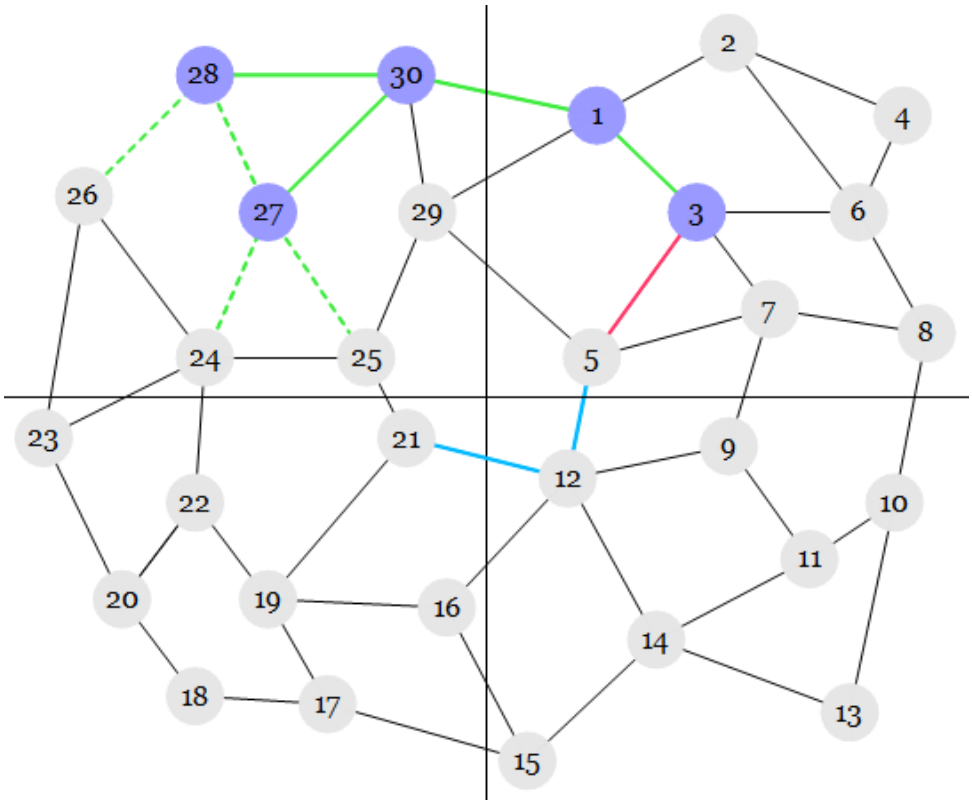


Figure 50 – TZAR Demonstration Phase 5

6. **SF Message Processing**; continues with nodes 24, 25, and 26, which are the next hops reached after the many-cast of nodes 27 and 28 as shown in Figure 51;

- TTL and RWA_Accumulated fields are updated
- Many_Cast counter is updated based on TTL (Note that the dominance of time zone difference in TZAR diminishes as the Many_Cast counter reaches to the level of node degrees.)
- Different copies of SF messages are many-casted by 24, 25 and 26 (Number of available outgoing ports on a node is another limiting factor for many-cast operation. In our sample topology for example; although the Many_Cast counter is updated as 3, node 26 can only forward the SF message through 2 links.)
- Source_Gateway processes are initiated for the first SF regarding a Conn_ID (As a side effect of many-cast operation, any node in the network may receive redundant SF messages regarding the same lightpath recovery. Redundant backup lightpaths setup is avoided by creating a single Source_Gateway process at any time for a specific Conn_ID/Dest_Addr pair. Additional SF messages with the same Conn_ID and Dest_Addr fields are discarded afterwards.)

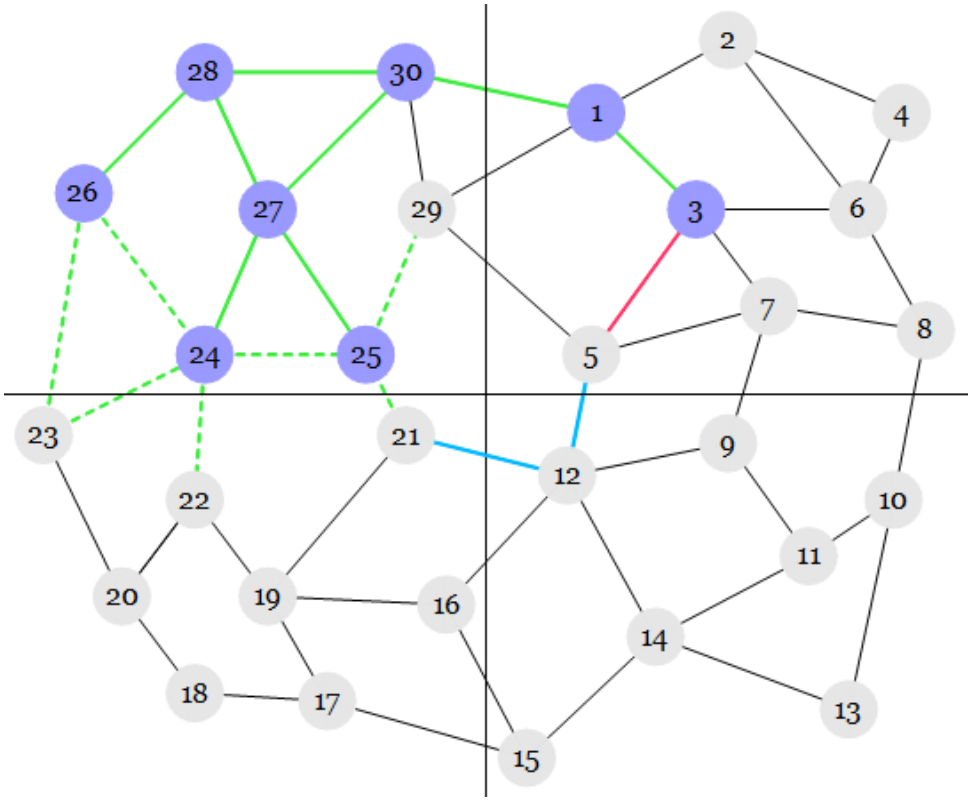


Figure 51 – TZAR Demonstration Phase 6

7. **Backup Lightpath**; is found whenever the first SF message reaches to the node with embedded Dest_Addr, which is node 21 for that sample demonstration as shown in Figure 52. Once backup lightpath is ready to be provisioned, a well-defined sequence of RR processing starts as follows:
   - RWA_Accumulated field in the first received SF is copied to the relevant RR (Next_Hop is retrieved via popping the top Node ID from the route stack.)
   - First RR message is sent by node 21 (RR messages are unicasted to the retrieved Next_Hop from the existing RWA_Accumulated field.)
   - Protection segment 21-25 is permanently allocated for backup lightpath
   - Previously working lightpath links are released not to utilize resources unnecessarily (How those links are released in terms of signaling is out of the scope of our TZAR implementation. However, we have to admit that this strategy might change when we will be considering revertive mode of operation for primary and backup lightpaths.)

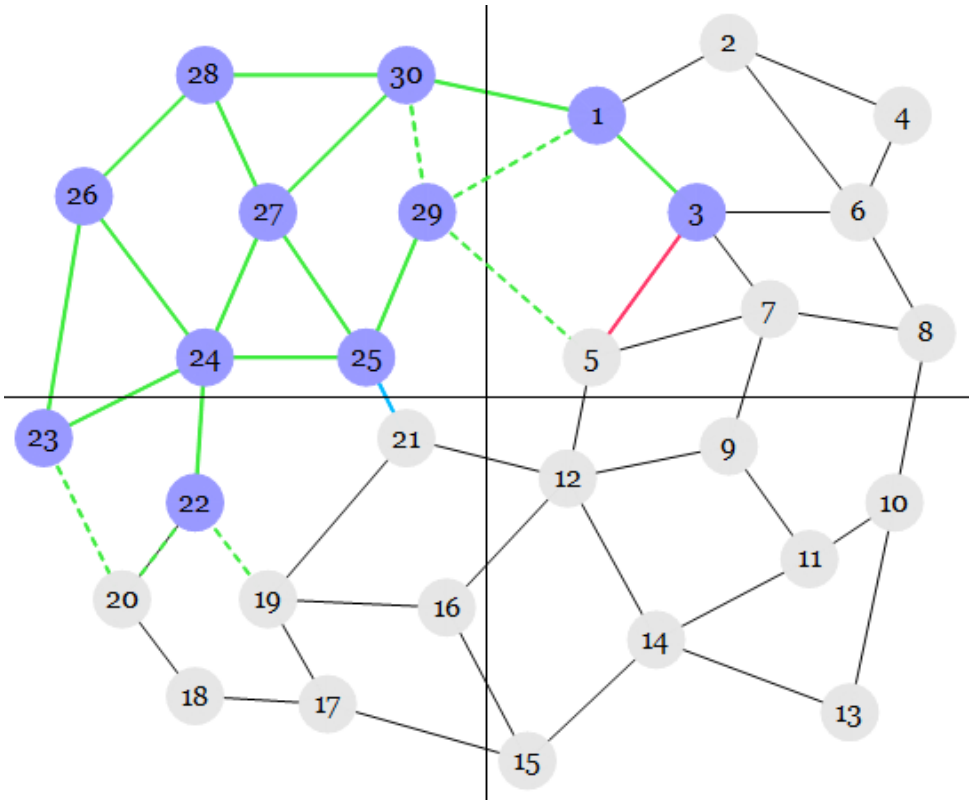


Figure 52 – TZAR Demonstration Phase 7

8. **RR Processing**; continues with node 25. Figure 53 shows the happenings afterwards as follows:
   - RR message is unicasted by node 25 to node 27
   - Next_Hop is selected based on RWA_Accumulated
   - Protection segment 25-27 is permanently allocated
   - Even though the best backup lightpath is found, SF Message Processing at some part of the network continues as indicated with yellow lines

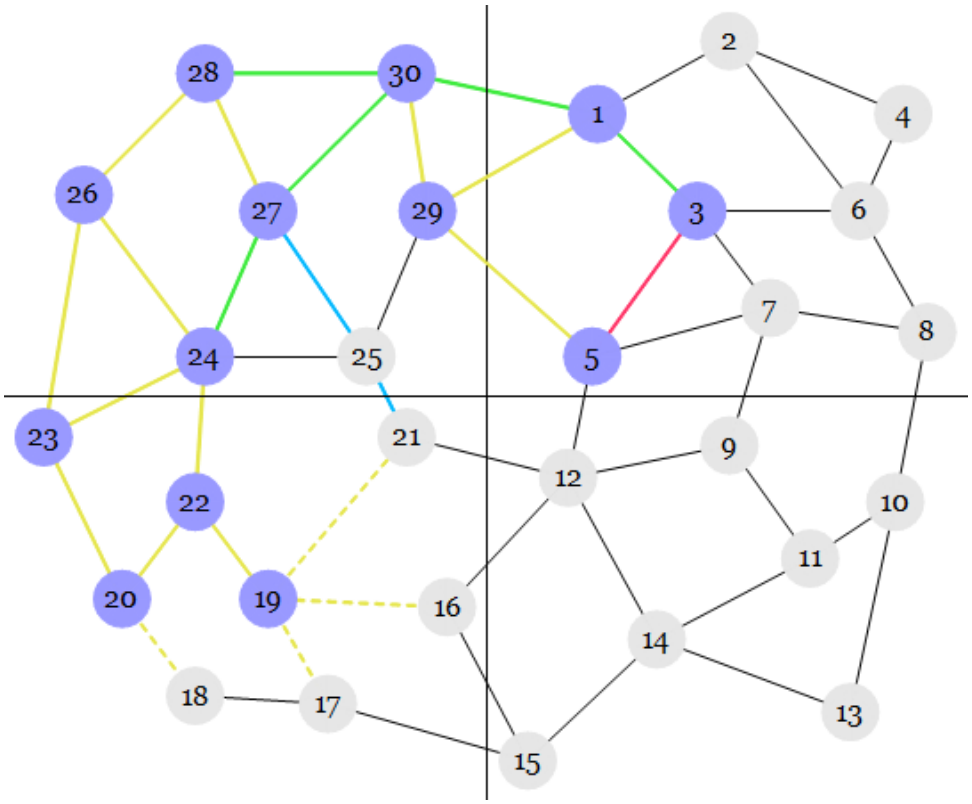


Figure 53 – TZAR Demonstration Phase 8

9. **Service Recovery**; is accomplished with the completion of backup lightpath provisioning as shown in Figure 54:
   - RR messages are processed and unicasted along the new lightpath in sequence by nodes 27, 30, and 1
   - Next_Hops are selected based on the stack information remaining in RWA_Accumulated field
   - Protection segments 27-30, 30-1, and 1-3 are permanently allocated to compose the newly found backup (i.e. recovery) lightpath

- Redundant SF messages many-casted in the network are dropped as their TTL values soon expire
- Client_Gateway processes of nodes not on the backup lightpath are killed after Hold_RR timers expire (Nodes that are marked blue, will never receive an associated RR message for the SF messages they have forwarded. For example, in our demonstration the only node, which can trigger such RR an message, is node 21. But it will respond to the first received SF through node 25. And it will simply discard the next SF messages for the same lightpath for 3 consequtive Hold_SF timers not to cause any fluctuating services.)

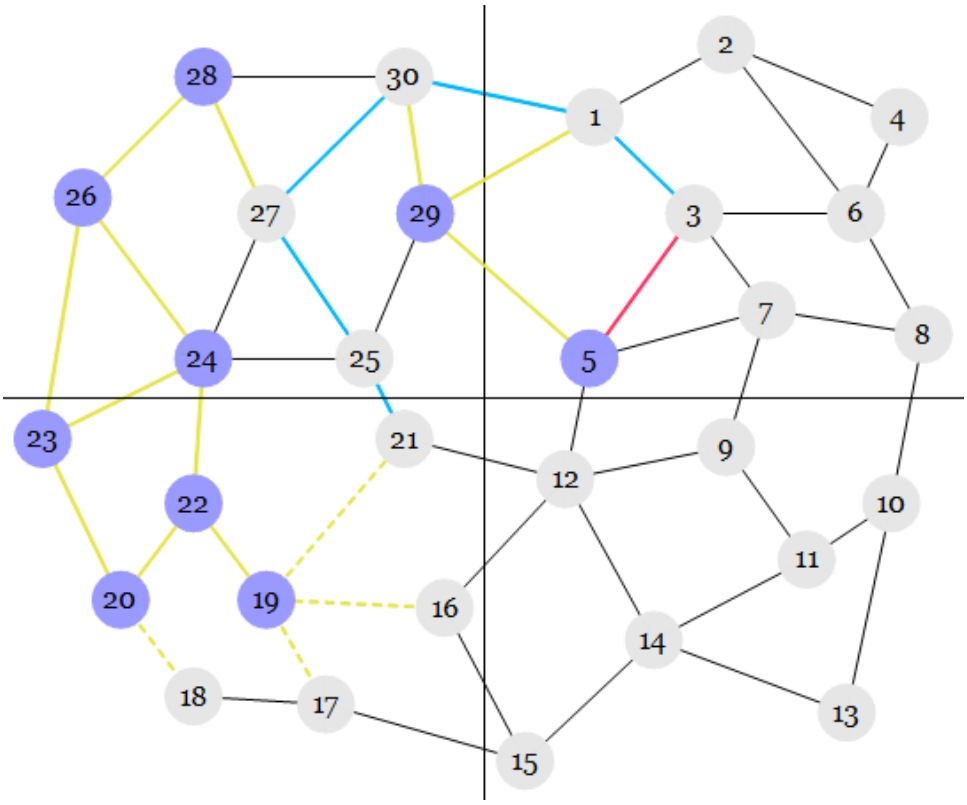


Figure 54 – TZAR Demonstration Phase 9