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Declaration of Authorship

I, Kenza GAIZI, declare that this thesis titled, "Study, Conception and Optimization of a Complete Security Framework for Wavelength Division Multiplexing Optical Networks (CSF-WDM)" and the work presented in it are my own. I confirm:

- This work was done wholly while in candidature for a research degree at this University.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. Except for such quotations, this thesis is entirely my own work.

Signed: Kenza Gaizi

Abstract

As of Q1 2020, we've reached 58.7 % global internet penetration, demand for bandwidth continues to rise, as a wide variety of optical network applications continues to expand, as well as growing transmission rates (70.46 Tb/s). The wide variety of applications contributes to extend the attack surface of the network, while the high transmission rates lead to highlighting nonlinear effects in Optical networks. My Ph.D. thesis, a Compressive Protection Architecture for WDM Optical Networks (CSF-WDM), discusses three key problems to bridge the gap between the growing demands on bandwidth, the broad variety of applications, the high transmission rate, and the expanding attack surface, and to take full advantage of optical networks. This Ph.D. designs a CSF-WDN optical network architecture to effectively and safely handle consumer demand.

I therefore proposed a static routing and wavelength algorithm for optical networks, modeled as a Mixed Integer Linear model, with objective functions to reduce network attackability while maximizing throughput. The algorithm satisfies prevention at design stage, where the minimum attackable virtual topology is selected for network routing requests, and the least blocking probability wavelength assignment algorithm (First Fit, Random Fit, Middle Channel, or Last Channel) is selected to assign the wavelengths in the network for each lightpath request.

Accordingly, I proposed a throughput and attack aware static Routing and Wavelength Assignment Algorithm for optical networks, modeled as a Mixed Integer Linear Model, with the objective functions to minimize attackability in the network while minimizing throughput. The algorithm satisfies prevention at design level, where the minimum attackable virtual topology is selected for routing request on the network, and the least blocking probability wavelength assignment algorithm (First Fit, Random Fit, Middle Channel, or Last Channel) is selected to assign the wavelengths in the network for each specific lightpath request.

Next, I modeled the physical layer nonlinear effects (SPM, SPM, and FWM) analytically and experimentally. Analytically, I saw the same effect within an optical fiber with only 1 Nano Watt power in bulk material with 1 Watt of power. I've also shown how fiber dispersion has little effect on XPM, while a significant negative impact on FWM, while more of it results in less SPM. Next, I have carried out experimental studies on how self-phase modulation contributes to self-

spectrum broadening. I found that cross-phase modulation causes self-Spectrum broadening and four-wave mixing causes new frequencies to be produced. In the examined WDM network, I have also identified the thresholds for each of these analyzed nonlinear effects.

In an attempt to borrow learnings from psychology and behavioral science studies, into optical networks management, I have conducted research in the psychological and behavioral science fields, learning on the promotion and prevention model, and have proposed a framework called behavior-realistic model, which is based on the prevention mindset, derived from Regulatory focus theory with regards to people's perception in decision making. Prevention Mindset cares about Safety and Security, which is the core of the network management model I proposed. This latter relies on internalizing prevention mindset in network management organizations, while implementing the ISO Functional areas of Network Management (FCAPS within the context of Optical Networks Management.

Following that, I have introduced a new, creative solution suggesting using self-similar simulation of WDM lightpaths requests within Optical Networks. My implementation of WDM Traffic Generation Pareto models has been shown to be consistent over several iterations and form variables. This makes it a realistic and practical model for Optical Network Simulators Traffic Generation Modules, as opposed to the commonly used Poisson distribution model.

Next, I studied how QoS Shaping & Policing techniques can be used for WDM Networks, and how Bandwidth utilization fairness could be achieved with WFQ, as a creative solution to the dynamic RWA problem, while highlighting possible configuration vulnerabilities in snmp3 protocols and mechanisms to address them.

The above will help achieve organizational goals and respond to users' needs in the domain of operation, both safely and securely.

Résumé

Au premier trimestre 2020, nous avions atteint 58,7% de pénétration mondiale d'Internet, la demande de bande passante continue d'augmenter alors qu'une grande variété d'applications de réseaux optiques continue de croître, ainsi que les taux de transmission croissants (70,46 Tb / s). La grande variété d'applications permet d'étendre la surface d'attaque du réseau, tandis que les taux de transmission élevés conduisent à mettre en évidence des effets non linéaires dans les réseaux optiques. Ma thèse de doctorat, « une architecture de protection compressive pour les réseaux optiques WDM (CSF-WDM) », examine trois problèmes clés pour combler l'écart entre l'augmentation des demandes de bande passante, la grande variété d'applications, le taux de transmission élevé et l'attaque en expansion de la surface, et pour prendre pleinement avantage des réseaux optiques. Ce doctorat conçoit une architecture de réseau optique CSF-WDN pour répondre efficacement et en toute sécurité aux demandes des consommateurs.

J'ai donc proposé un algorithme de routage statique et de longueur d'onde pour les réseaux optiques, modélisé comme un modèle linéaire mixte en nombres entiers, avec des fonctions objectives pour réduire l'attaquabilité du réseau tout en maximisant le débit. L'algorithme satisfait la condition de prévention au stade de la conception, où la topologie virtuelle attaquable minimale est sélectionnée pour les demandes de routage réseau, et l'algorithme d'attribution de la longueur d'onde de probabilité de blocage du blocage (First Fit, Random Fit, Middle Channel ou Last Channel) est sélectionné pour attribuer les longueurs d'onde dans le réseau pour chaque demande de chemin optique.

Ensuite, j'ai modélisé les effets non linéaires de la couche physique (SPM, SPM et FWM) de manière analytique et expérimentale. Analytiquement, j'ai vu le même effet dans une fibre optique avec seulement 1 Nano Watt de puissance dans un matériau en vrac avec 1 Watt de puissance. J'ai également montré comment la dispersion des fibres a peu d'effet sur le XPM, tout en ayant un impact négatif significatif sur le FWM, alors qu'une plus grande quantité entraîne moins de SPM. Ensuite, j'ai mené des études expérimentales sur la façon dont la modulation de phase propre contribue à l'élargissement du spectre propre. J'ai trouvé que la modulation phase-phase provoque l'élargissement du spectre naturel et le mélange avec quatre ondes provoque la

production de nouvelles fréquences. Dans le réseau WDM examiné, j'ai également identifié les seuils pour chacun de ces effets non linéaires analysés.

Dans une tentative d'emprunter les enseignements de la psychologie et des sciences du comportement à la gestion des réseaux optiques, j'ai mené des recherches dans les domaines des sciences psychologiques et comportementales, appris sur le modèle de promotion et de prévention, et j'ai proposé un cadre appelé modèle réaliste du comportement, qui est basé sur la mentalité de prévention, dérivée de la théorie de mise au point réglementaire en ce qui concerne la perception des gens dans la prise de décision. L'état d'esprit de prévention se soucie de la sûreté et de la sécurité, qui est au cœur du modèle de gestion de réseau que j'ai proposé. Ce dernier s'appuie sur l'intériorisation de l'état d'esprit de prévention dans les organisations de gestion de réseau, tout en mettant en œuvre les domaines fonctionnels ISO de gestion de réseau (FCAPS dans le contexte de la gestion des réseaux optiques).

Par la suite, j'ai présenté une nouvelle solution créative, suggérant l'utilisation d'une simulation auto-similaire des demandes de chemin optique WDM dans les réseaux optiques. Mon implémentation du modèle Pareto pour la génération de trafic WDM s'est avérée cohérente sur plusieurs itérations et variables formelles. Contrairement au modèle de distribution de Poisson couramment utilisé, cela en fait un modèle pratique et réalisable pour le module de génération de trafic du simulateur de réseau optique.

Ensuite, j'ai étudié comment les technologies de mise en forme et de régulation de la QoS sont utilisées dans les réseaux WDM, et comment utiliser WFQ comme solution créative au problème RWA dynamique pour obtenir une utilisation équitable de la bande passante, tout en me concentrant sur les vulnérabilités de configuration possibles dans les protocoles snmp3 et les mécanismes pour y remédier.

Les éléments ci-dessus aideront à atteindre les objectifs organisationnels et à répondre aux besoins des utilisateurs dans le domaine opérationnel de manière sûre et fiable.

Acknowledgment

Welcome to my doctoral thesis, a window of years of continuous hard work on my research subject entitled: Study, Conception and Optimization of a Complete Security Framework for Wavelength Division Multiplexing Optical Networks (CSF-WDM)

On this journey, I welcome you to see the world of optical networks from my lens, or rather IP and GPS, as I surfed the research space learning about the topic, as well as the industry leaders ' conferences on applications for optical networks, their challenges, their opportunities, and the main players in the ecosystem. During this journey, now reflecting on it coming to a milestone, and only marking the end of a phase, as I personally don't believe research ever ends.

I would like to thank Allah for guiding me in carrying on with this study, as a proud Muslim, I am honored to conduct scientific research, as that is one thing that an active Muslim who represents Allah on earth means. It is a blessing and honor to pursue such a worthy road, by both human and divine standards. I'm grateful to Allah for my loving parents without whom I couldn't t have done this.

Another round of thanks, that, I owe to the supervisors I respect. Since my first Network classes in the Masters ' degree, Pr. Dr. Fouad Mohammed Abbou has encouraged me, through his wise vision, to explore optical networks as an important area of research, not only for the hour but also the next X years. Pr. Dr. Farid Abdi, a respected academic, had saved me tremendously time from reinventing the wheel by mentoring me on key methodologies for research that will remain with me for life. His and Pr. Dr. Fouad Mohammed Abbou's work has been tremendous in providing relevant pointers, precious resources, and challenging topics to examine!

My beloved Mother is not only the most incredible person in the world to me, but also an important supervisor to myself in this work. Yeah, you've read it right :) my mother's supervision over all of the last PhD years, too, was unofficial but not figurative. She is such an intelligent, talented leader, and compassionate supervisor. At times, her kind love and strict leadership in others kept me on my way through this research journey. My mom never stopped learning! She has a proven record of leadership, problem solving, and empathy. She was also the best in her

mathematics class. I've been fortunate to get mom's empathy. Moreover, I had a great opportunity with my mother to try and explain my investigations to someone who is not in the field. After all, engineers and scientists solve problems and problems can fall into several categories, so it was the idea to solve the major problems regardless of the application domain. That was the reason why I talked with my delightful mom & supervisor about the high standard of things, making them a bonding, fun and scientific experience. If anyone is extremely critical in this work, it's my mother, from her initial suggestion to apply for her PhD, to her taking emotional care of me during the journey, to her love and support, and sometimes also her supply of interesting food combos to give me energy. I remember as an anecdote my mom gave me cheese filled dates. They tasted strange but until now it has always been connected with great souvenirs; milestones in my research. It was also something that makes me smile every time I remember it.

I am also grateful to my dear dad for planting in me the love of education and learning, for accompanying me in his younger years with bedtime stories, and for working together on creative projects, turning random objects into meaningful creations. This was my story of my infancy, but even as an adult it stayed with me. Creativity and design are a gift that my beloved dad gave to me, helping me to shape and to make use of my whole life. I would also like to thank my father, who is an incredible father who offers all for our comfort, for all his love and care and support. Thank you very much for all your pious prayers for me too, my grandmother.

Having said that, I have to admit that I have been also a good student :) that I have been planning my tasks, and I have been very interested in them. I've learned how and when to seek breadth, depth, or both. I have also learnt to control my desire to extend my research beyond my tasks and to remain focused, regardless of how tenting it was to explore other fields. That is not true: I've gotten to the field of psychology and behavioral science, but wait, I knew that I could make something from combining both safety and psychology with the optical networks; I did publish a paper, that I would call success, because the effort wasn't wasted, and it remained delicately aligned with my subject, while at the same time satisfying my curiosity. Optimization, isn’t it? Yes, ladies and gentlemen, it is :) and I thank you for making it till here already. I wish you a wonderful journey as my PhD chapters unfold over the pages to come. Get your favorite coffee, tea or even water, and enjoy the trip!

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Nomenclature

Abbreviation	Definition
2G	Second generation cellular wireless mobile telecommunications
3G	Third generation cellular wireless mobile telecommunications
3R	Re-amplification, Re-shaping, Re-timing
4G	Fourth generation cellular wireless mobile telecommunications
5G	Fifth generation cellular wireless mobile telecommunications
6G	Sixth generation cellular wireless mobile telecommunications
AAA	Authentication, Authorization, Accounting
ABC	Artificial Bee Colony
AENOR	Asociación Española de Normalización y Certificación (Spanish Association for Standardization and Certification)
$\textbf{Acceptable}_{BP}$	Acceptable Blocking Probability
ACE	African Coast to Europe
ACO	Ant Colony Optimization
AD	Anderson Darling
ADM	Add Drop Multiplexer
AES	Advanced Encryption Algorithm
AI	Artificial Intelligence
AON	All Optical Network
ARIMA	Autoregressive Integrated Moving Average
ASIC	Application Specific Integrated Circuit
ASTM	American Society for Testing and Materials
ATM	Asynchronous Transfer Mode
AUR	Uncontrolled Adaptive Routing
BBU	Baseband Unit
BER	Bit Error Rate
BP	Blocking probability
BPON	Broadband Passive Optical Networks
BSI	British Standards Institution
BSS	Business Support System
CB RSA	Cluster Based Routing and Spectrum Allocation
CBR	Case Based Reasoning

CDR	Call Data Records
CMIP	Common Management Information Protocol
CRAN	Or C-RAN: Centralized or Cloud Radio Access Network
CR-Model	Coudert and Rivano Model
CPU	Central Processing Unit
CSF-WDM	Comprehensive Security Framework for WDM networks
$\mathbf{Current_{BP}}$	Current Blocking Probability
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
D2D	Device to Device
dBm	decibel-milliwatts
DEA	Differential Evolution Algorithm
DES	Data Encryption Standard
DFF	Dispersion Flattened Fiber
DIN	Deutsches Institut für Normung German national organization for standardization
DLE	Dynamic Lightpath Establishment
DLP	Data Loss Prevention
DS	Danish Standards Foundation
DBV ASI	Digital Video Broadcasting Asynchronous Serial Interface
DWDM	Dense Wavelength Division Multiplexing
E1	Digital transmission link with total transmit and receive rate of 2.048 Mbps
E-NNI	External Network to Network Interface
EDFA	Erbium Doped Fiber Amplifier
EON	Elastic Optical Networks
FA	Firefly Algorithm
FAA	Federal Aviation Administration
FA + SA	Firefly Algorithm + Simulated Annealing algorithm
FBAG	Fluorescein Doped Boric Acid Glass
FBG	Fiber Bragg Grating
FC	First Channel
FCAPS	Fault, Configuration, Accounting, Performance, and Security
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction

EFAH-URA	Energy and Fatigue Aware Heuristic with Unnecessary Reconfiguration Avoidance
FICON	Fiber Connection
FIPS	Federal Information Processing Standards
FLAG	Fiber Optic Link Around the Globe
FP	Flowers ' Hybrid Pollination (FP) Algorithm
FPGA	Field-Programmable Gate Array
FQ	Fair Queueing
FR	Frame Relay
FSM	Fused Single Mode
FTTB	Fiber To The Building
FTTC	Fiber To The Curb
FTTCab	Fiber To The Cabinet
FTTH	Fiber To The Home
FWM	Four Wave Mixing
GA	Genetic Algorithm
GaAs	Gallium Arsenide
Gbits	Gigabits
GDWA	Graph Decomposition based Wavelength Assignment
GFP	Generic Framing Procedure
GHz	Gigahertz
GOST	Also Known As ГОСТ in Russian. Refers to Technical Standards maintained by the Euro-Asian Council of Standardization Metrology and Certification
GPS	Generalized Processor Sharing
GoF	Goodness of Fit
HDLS	High-Level Data Link Control
HDTV	High Definition Television
HEMS	High-Level Entity Management System
HetNet	Heterogeneous Network
HR	Human Resources
IAM	Identity Access Management
ICMP	Internet Control Message Protocol
IDS	Intrusion Detection System
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming

InGaAsP	Indium Gallium Arsenide Phosphide
IOS	Internetwork Operation System
IoT	Internet of Things
IP	Internet Protocol
IPO	Input Process Output
IPX	Internetwork Packet Exchange
ISO	International Standardization Organization
ISP	Internet Service Provider
IT	Information Technology
ITU	International Telecommunication Union
ITUT	International Telecommunication Union Telecommunication Standardization Sector
JSA	Japanese Standards Association
LAN	Local Area Network
LAR	Lightpath Attack Radius
LAZER	Light Amplification by Stimulated Emission of Radiation
LBR	Load Balanced Routing
LC	Last Channel
LEC	Local Exchange Carriers
LP	Lightpath
LRR	Link Reversal Routing
LSM	Least Square Method
LTE	Long Term Evolution
M2M	Machine to Machine
MaxLAR	Maximum Lightpath Radius
MBH	Mobile Backhaul
MC	Middle Channel
MD5	Message Digest 5
MIB	Management Information Base
MILP	Mixed Integer Linear Programming
MIMO	Multiple Input Multiple Output
ML	Machine Learning
MM	Multi-Mode
MM-Wave	Millimeter Wave
MPLS	Multiprotocol Label Switching
MRPR	Minimum Reconfiguration Probability Routing

MTBF	Mean Time Before Failure
MTTR	Mean Time To Recovery
Mux/Demux	Multiplexer/Demultiplexer
mW	milliwatt
µW	microwatt
N/W	Network
NASA	National Aeronautics and Space Administration
NDSF	Non-Dispersion-Shifted Fiber
NLS	Nonlinear Schrodinger
NLSE	Nonlinear Schrodinger equation
NMF	Non-negative Matrix Factorization
NMS	Network Management Software
NN	Neural Network
NP	Nondeterministic Polynomial time
NPFC	Naval Publications and Forms Center
NSF	National Science Foundation
NSFNET	National Science Foundation Network
nW	Nanowatt
OADM	Optical Add Drop Multiplexer
OCh-O	Optical Channel Overload
OCh-P	Optical Channel Payload
OCh	Optical channel
ODU OH	Optical Data Unit overhead
ODU	Optical Data Unit
OEO	Optical-Electrical-Optical
OFNP	Optical Fiber Nonconductive Plenum
OMS	Optical Multiplex Section
OOK	On-Off Keying
OPU OH	Optical Payload Unit overhead
OPU	Optical Payload Unit
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
OSS	Operations Support System
OTDR	Optical Time Domain Reflectometer
OTN	Optical Transport Network
OTS	Optical Transmission Section

OTU OH	Optical Transport Unit overhead
OTU	Optical Transport Unit
OXC	Optical Cross Connect
P	Polynomial time
PDFWM	Partially Degenerate Four Wave Mixing
PDL	Polarization Dependent Loss
PER	Packet Error Rate
PGPS	Packet-by-packet Generalized Processor Sharing
PhD	Doctor of Philosophy
PHI	Protected Health Information
PII	Personally Identifiable Information
PM	Polarization Maintaining
PMD	Polarization Mode Dispersion
PNL	Nonlinear Polarization
PoI	Point of Interest
POF	Plastic Optical Fiber
PON	Passive Optical Network
POS	PPP over SONET/SDH
POTS	Plain Old Telephone Service
PPP	Point-to-Point Protocol
PRP	Parallel Redundancy Protocol
PSOLbest	Particle Swarm Optimization with Less number of informers
PXC	Photonic Cross Connect
Q-factor	Quality Factor
Q-Learning	Quality Learning
QoS	Quality of Service
QoT	Quality of Transaction
RAN	Radio Access Network
RC	Random Channel
Rec	REquest Confirmation
RFC	Request For Comments
RP	Routing Problem
RRA	Routing with Regenerators Assignment
RSA	Routing and Spectrum Allocation
RWA	Routing & Wavelength Assignment
RX	Receive

SA	Simulated Annealing algorithm
SAE	Society of Automotive Engineers
SAN	Storage Area Network
SAT	Satisfiability problem
SBS	Stimulated Raman Scattering
SCB	Sub-Clusterbased Routing and Spectrum Allocation algorithm
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networking
SGMP	Simple Gateway Monitoring Protocol
SHA-1	Secure Hash Algorithm 1
SIEM	Security Information and Event Management
SiO2	Silicon Dioxide
SLE	Static Lightpath Establishment
SM	Single Mode
SMF	Single Mode Fiber
SNMPv1	Simple Network Management Protocol version 1
SNMPv2	Simple Network Management Protocol version 2
SNMPv3	Simple Network Management Protocol version 3
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifiers
SONET	Synchronous Optical Networking
SPM	Self-Phase Modulation
SRS	Simulated Raman Scattering
SS	Self-Steepening
SVM	Support Vector Machine
T1	Digital transmission link with total transmit and receive rate of 1.544 Mbps
Tbps	TeraBits Per Second
TBPS	Time Based traffic Policing and Shaping
TBPSW	Time Based traffic Policing and Shaping Weibull model
TCM	Tandem Connection Monitoring
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TDM	Time Division Multiplexing
Thr_list	Throughput List
THz	Terahertz

TON	Transparent Optical Network
TPC-5	Trans-Pacific Cable 5
Triple DES	Triple Data Encryption Standard
TFF	Thin Film Filter
Tx	Transmit
UDP	User Datagram Protocol
UNI-C	User Network Interface Customer edge
UNI-N	User Network Interface Network Implementation
UV	Ultraviolet
UWOC	Underwater Optical Communication
UWON	Underwater Optical Network
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNI	Virtual Network Interface
VOA	Variable Optical Attenuator
VON	Virtual Optical Network
WA	Wavelength Assignment
WAN	Wide Area Network
WCC	Wavelength Continuity Constraint
WDM	Wavelength Division Multiplexing
WFQ	Weighted Fair Queuing
WPA2	Wi-Fi Protected Access version 2
WPA	Wi-Fi Protected Access
XPM	Cross Phase Modulation
Yb	Ytterbium

Introduction

Motivation

Besides their critical role to everyday communication across the globe, optical networks don't only represent the backbone of the internet, they're also strongly present in a multitude of areas, including Medicine, Commerce, Industry, Military, and Space [1][2][3][4][5] and many more. One might be wondering what makes such networks highly appealing to a range of domains. The answer lies in the core of these networks, the fiber. This substance has a set of advantages like its low production cost, its light weight relative to copper, its ability to carry massive amounts of data (60 Tb/s as of 2016 [6]), its ability to carry a variety of independent signals on the same fiber, while also being able to accommodate for long distance communications of thousands of kilometers without a need for regeneration [7]. Let's take a close look at the main aspects that motivated me to pursue this research:

Increasing bandwidth demand: In the 70s, Moore's Law had been known for predicting that CPU power would double every two years, or more precisely for the computer scientists out there, the number of transistors would actually double every couple years [8]. This concept didn't take long before it was borrowed in other domains, namely the telecommunication and broadband areas. In 1998, Jacob Neilsen presented a law stating that user's bandwidth doubles on an annual basis. Nelson named this law Nelson's Law of Internet Bandwidth [9].

High transmission rate: It's become widely recognized by now that Optical Fiber handles way higher bandwidth than copper while having low attenuation. Optical Networks is used for both short (LAN) and long-haul communications. For these networks, Bus, Ring, Star, and Mesh topologies are all possible, and usable based on the pros and cons of each where they're suited best. Speaking about Transmission rates, the technology continues to advance as a recent paper published in January 2018 demonstrates the transmission of 70.46 Tb/s Over 7,600 km and 71.65 Tb/s Over 6,970 km Transmission in C+L Band Using Coded Modulation with Hybrid Constellation Shaping and Nonlinearity Compensation [10].

Breadth of application areas: Optical Networks core application is in transmitting tremendous amounts of data, voice, and video over both short and long-haul distances. Depending on the domain, the usage of Optical Network is shaped. For instance, in the Telecommunications Industry, Carriers use the optical fiber to transmit Plain Old Telephone Service, a.k.a POTS across their network [11]. Local exchange carriers (LECs) use it to transmit POTS between central office switches either locally, or to users doors (Fiber To The Home: FTTH) [11]. Interesting note about the FTTH is that though this is only recently gaining a lot of momentum and attention at scientific conferences and industrial expos, this technology was initially discovered way earlier in the past. Actually, applications of fiber optics for Home saw the light with William Wheeler. Back in 1880, this inventor designed a system composed of light pipes that are lined with a highly reflective coating where the result was to illuminate homes using light from an electric arc lamp that is placed in the basement, then directing that light around the entire home with the pipes [12]. Financial Firms need secure and speedy connections for high value financial transactions where speed and real-time events matter (Take stock exchange as an example). Multinationals use fiber to connect their offices around the globe, which makes it appealing and quite cost-effective in the long run especially if the linked sites are strategically in line with the business growth and the users' base. Television firms are also heavily dependable on fiber optics to deliver HDTV telecasts, digital video, and data services [11]. In the multimedia area, it's equally important to note that the fiber optics technology was discovered in 1895 by Henry Saint-Rene who created a system of bent glass rods for directing light images in an early effort at television [12]. In the 1930 Heinrich Lamm was the first person to transmit an image through a bundle of optical fibers [12]. Other applications of the optical fiber are in the domain of Internet of things, from Smart Traffic Lights Management to Changeable Message Signs, to Smart Roads and other utilities within the city [11]. The Medical or rather biomedical domain is no exception to the applications of fiber optics. Fiber optics are especially useful for imaging and illumination components of endoscopes. A set of rigid and flexible multi fibers made of step-index fibers as well as graded-index imaging rods utilized are extensively used to illuminate, and hence visualize internal organs and tissues accessible through natural or surgical openings [1]. Illuminating internal organs using optical fiber was initially discovered by Vienna Doctors Roth and Reuss in 1888. Ten years later, the same technology was used in dentistry [12]. Optical Fibers are also used for sensory purposes (e.g. blood pressure near blocked vessels). The Automotive domain was relying on Plastic optical fiber (POF) since 1998 [13], Military, Space and Industrial sectors [11].

Cost-effectiveness and revenue potential: Optical Transport Equipment Market expected to reach the $16 BILLION by 2022, projected DELL'ORO GROUP, an independent research firm in the US and founded since 1995, in their 2018 released "Optical Transport 5-Year Forecast Report" [1]. The same report projects a 95% contribution of WDM Systems in Optical Transport Revenue. The Vice President of Dell'Oro Group foresees demand and use of optical equipment and WDM systems to continue rising as service providers continue to expand their fiber footprint by installing more optical transport capacity between their global data centers [14].

What makes WDM of such valuable importance: WDM is a hotkey in Optical Networking as it's a technology that enables to expand network capacity as well as increasing bandwidth through transmission of large amounts of various types of data streams at different frequencies, but all down the same line. Who says multiple transmissions of various data using various protocols all down one fiber link, also says lower maintenance cost and effective resource management as well as low operational cost for the operators, and since it's fiber that's the subject here, that's high bandwidth and speed for the user, which makes it an appealing solution to both parties. Traditionally, telecom carriers and service providers would have been easily associated with desire for adopting WDM technology. Nowadays, this mindset had shifted and more organizations: Governments, Corporations, Financial Firms, and more have joining the boat.

What makes Security such a hot topic for WDM Networks: Who says transparent optical networks, says no Optical Electrical Optical conversion. This also means erroneous signals ability to propagate through the network, going undetected. Several potential attacks would be of interest in such environment: Power Jamming Attacks, and of course without forgetting about various types of interferences, crosstalks, and nonlinear effects. Including conversion capabilities means higher costs, so to manage a low-cost WDM transparent optical network, security considerations listed above should be taken into consideration, at design, implementation, testing, and monitoring levels.

Fiber Transmission

Optical fiber communication is a technology of communication using light pulses to transfer information by means of an optical fiber from one point to another [59]. Fiber is essentially a thin glass filament acting as a waveguide. A waveguide is a physical medium or a pathway that enables electromagnetic wave propagation like light [61]. The core of the waveguide has a slightly higher refractive index than the outside medium, which allows a full internal reflections to guide lighting pulses along the axis of the fiber. Single mode step index optical fiber is less than 10 micrometers in diameter and only allows one path of light [59]. Multimode step index optical fiber has a core diameter of 50 micrometers or more and allows for a number of light paths leading to modal dispersion [59]. Whether it's single or multimode, light passes by vacuum with a $c = 3 \times 10^8$ m / s speed. Light can travel through any transparent material as well, but the speed of light in the material will be slower than in a vacuum. The angle at which light is transmitted in the second material depends on the refractive indices of the two substances and the angle at which light hits the interface between these materials if the light passing from materials of the given refractive indicator to materials with a different refractive index (i.e. when refraction occurs) [61].

Now, whoever talks about fiber transmission should not forget about calculating fiber loss. Light can propagate the length of a fiber with little loss, which is illuminated as follows, due to the physical phenomenon of total internal reflection [61]. Loss in the fiber is given as:

$$\text{Loss} = P_{out} / P_{in} \tag{1.1}$$

With P_{in} is the fiber input power, and P_{out} is the fiber output power. The above equation is a simplistic one. More commonly, fiber loss is represented in terms of decibels as follows:

$$\text{Loss}_{dB} = 10 \log P_{out} / P_{in} \tag{1.2}$$

Fiber optic communication systems consists of an optical transmitter to convert an electrical signal to an optical signal for transmission through the optical fiber, a cable containing several bundles of optical fibers, optical amplifiers to boost the power of the optical signal, and an optical receiver to convert the received optical signal back to the original transmitted electrical signal [59]. The figure below shows a generic setup of a fiber optical wavelength division multiplexing transmission system:

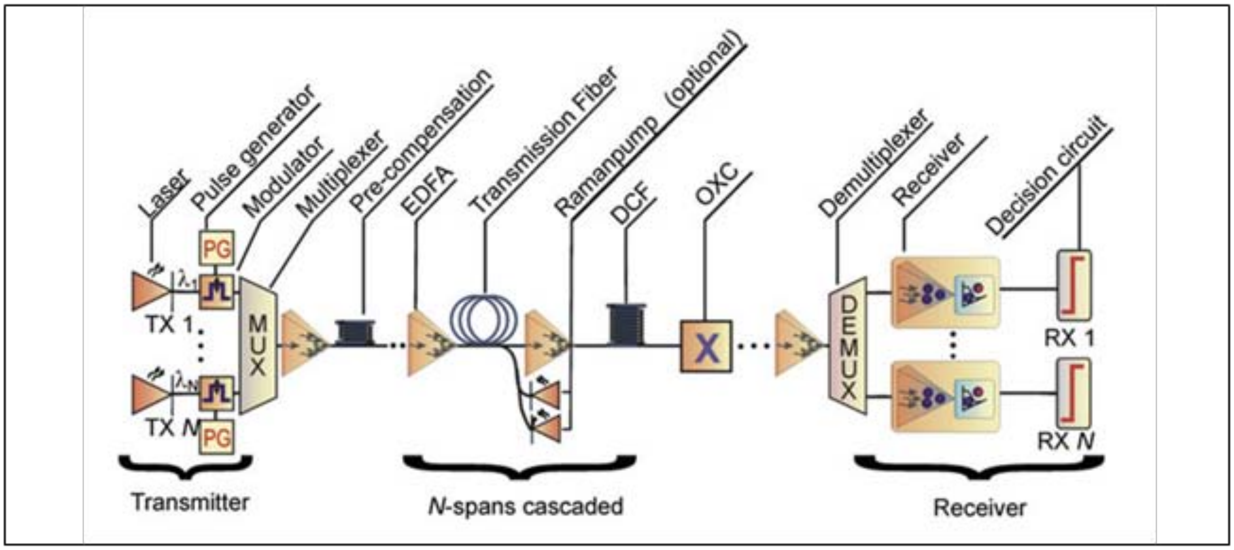


Figure 1 Generic setup of a fiber optical wavelength division multiplexing transmission system [60]

A typical transmission system consists of the optical carrier generation array of lasers with differing wavelengths [60]. An external modulator modulates each laser to impress the data signal. Fiber optics is not electrical in nature, unlike the copper transmission form. A basic fiber optic system consists of a transmitting device converting an electrical signal into a light signal, an optical fiber cable carrying the light, and a receiver accepting the light signal and converting it back into an electrical signal [60]. Lasers are usually used for 1310- or 1550-nm single-mode applications. LEDs are used for 850- or 1300-nm multimode applications. These wavelengths have been selected because they best match the transmission properties of available light sources with the optical fiber transmission qualities. Each range is known as an operating window as illustrated in the table:

TABLE 1 Fiber Optic Transmission Windows [60]

Window	Operating Wavelength
800 – 900 nm	850 nm
1250 – 1350 nm	1310 nm
1500 – 1600 nm	1550 nm

The importance of WDM

The use of a multitude of transmitters using different wavelengths can make high fiber bandwidth efficient. This is called Wavelength Multiplexing Division (WDM). Under WDM the spectrum of optical transmission is divided into a number of non-superpositive (or frequency) bands, each of which is supported at the desired rate by a single transmission channel [61]. Moreover, WDM devices are easier to implement, as only electronic speeds are normally required to operate all the components on WDM devices [61]. In addition, WDM Networks are also being increasingly deployed by telecom network operators all over the world and the Internet is employing WDM-based optical backbones, leading to IP-over WDM networks.

The importance of WDM can also be highlighted by looking up the industry standards on the topic as depict the figures below [62] showing a total of 383621 recent active standards on "wavelength Division Multiplexing", developed by 405 publishers.

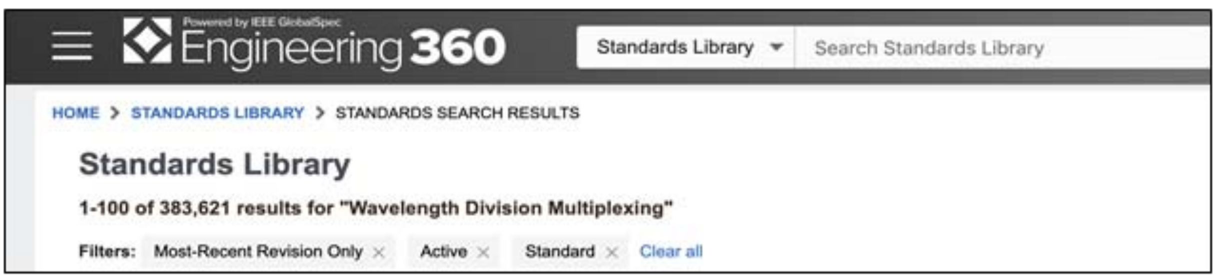


Figure 2 "Wavelength Division Multiplexing" on IEEE Engineering360 Standards Library [62]

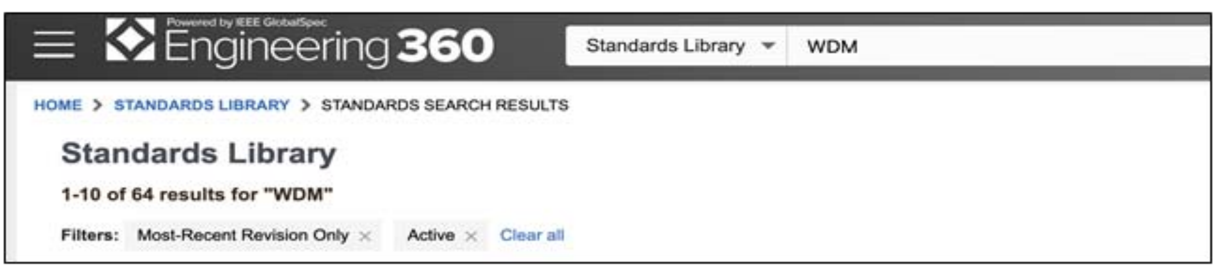


Figure 3 "WDM" search results on IEEE Engineering360 Standards Library [63]

I've downloaded these standards, figure below, but they were only available in raw format, which doesn't make it easy to derive insights. I have hence compiled the downloaded data into columns of publisher and publications, sorted in descending order, as well as some interesting statistics of contribution of each in the WDM effort and their publishers' data and analyzed it into Table 1.2 below. Talking high level stats, 12 publishers contributed to over 10K publications.

These publishers are: NPFC, DIN, BSI, ISO, GOST, DS, ASTM, JSA, ITU-T, AENOR, SAE, and FAA. Speaking numbers, highlighting a few well known publishers, NPFC leads by publishing 68704 standards, that is 17.91% of all developed recent Active standards on the topic. ISO published 39212 standards (10.22% of total), and ITU-T contributed by 13572 standards (3.54% of total). Following that, 30 publishers contributed to 23.28% of all WDM standards. These publishers include IEEE contributing with 2435 WDM standards, NASA contributing with 1511 standards (0.39% of total). Find more on the rest of the publishers in Table 1.2 below.

"Wavelength Division Multiplexing" Most Recent Standards Publishers										
ITU-T (10,799)	ASTM (23,258)	CSA (3,062)	GMW (2,689)	NFPA (569)	GME (834)	ALI/LADDER (9)	AA (73)	PFI (43)	AFS (4)	EI (13)
IETF (3,027)	CLSI (200)	TAPPI (564)	JEDEC (606)	DOT (1,113)	ADA (91)	ANS (92)	NATO (16)	UNI (992)	AI/ASPHALT (24)	IME (17)
TIA (1,179)	NPFC (29,821)	UL (1,471)	NEMA (621)	SAIA (20)	DOL (62)	ASQ (188)	IEST (61)	EU/EC (53)	AIA/ARCH (124)	HOLDEN (196)
SAE (9,875)	DOD (5,584)	GOST (32,634)	PIP (621)	NACE (433)	EPA (30)	B11/STD (35)	CTI (62)	EPI (4)	AIHA (144)	NCSL (24)
SCTE (352)	IES (150)	EUROCAE (168)	NAVY (2,264)	SAE-ITC (3,364)	FM (185)	BICSI (19)	AISC (52)	CS UK (140)	AOCS (33)	PCI/CONCRT (15
JSA (11,069)	ATIS (835)	NAVISTAR (563)	AAMI (266)	RTCA (249)	NTIS (1,875)	ESTA (65)	AVIXA (11)	JSAE (696)	AWC (21)	RIA (24)
IEC (6,687)	CIE (246)	ULC (498)	AMCA (51)	AASHTO (757)	GMKOREA (625)	FCI (28)	EEC (256)	AES (86)	AWCI (22)	SDI/DOOR (22)
CEI (5,906)	AWPA/WOOD (16	AIA/NAS (1,410)	ASCE (275)	AIAG (135)	NG (494)	HI/HYDRAUL (61	THHILL (7)	AABC (10)	CMAA (5)	DOE (132)
DS (30,674)	SAI (7,385)	ISUZU (312)	ASSP (98)	PPI (88)	STI/SPFA (11)	HPS (36)	ACGIH (220)	AHRI (134)	IIAR (9)	ABMA/BOIL (17)
BSI (39,638)	API (1,453)	ESD (99)	AWWA (347)	NFPC (3)	FAA (10,804)	IFI/FASTNR (71)	AFCEN (17)	CSI (3)	J-STD (1)	GA (7)
DIN (28,895)	ASA (141)	MODUK (1,407)	BHMA (48)	ARMY (1,979)	SN (91)	INCITS (285)	AHAM (20)	HPVA (24)	NRC (26)	IMO (72)
SMPTE (783)	AENOR (11,523)	ASHRAE (456)	CGA/GAS (346)	AGMA (523)	PIA (149)	MPIF (31)	AIST (38)	NECA (51)	SJI (14)	NCRP (129)
ICC (188)	ECMA (275)	ASME (870)	CSA/AM (126)	NSF (123)	AIAA (74)	MSS (93)	ASC/O5 (8)	NRCA (13)	WMMA (3)	GMSA (31)
ISA (337)	ANSI (1,236)	NASA (1,258)	EEMUA (65)	ACI (505)	SNV (527)	NISO (69)	ASIS (22)	SES (8)	DELPHI-I (2,160)	ARMA/INTL (6)
ARINC (290)	SNZ (1,124)	ASABE (270)	GPA (72)	NEN (35)	ASC/X9 (103)	NIST (11)	ASNT (159)	SMACNA (67)	GPO (10)	ACCA (6)
ISO (34,451)	ASD-STAN (2,142	ASSE (70)	IAPMO (390)	PTI (34)	SSPC (128)	VITA (90)	HEI (11)	TMS (1)	KODEKS (330)	CRSI (10)
ITU-R (3,759)	ICEA (65)	DNVGL (769)	ICAO (1,480)	AGA (116)	A4A (50)	AWS (144)	NETA (6)	EJMA (2)	APA (242)	KSA (198)
FORD (5,342)	LIA/LASER (12)	ECIA (638)	IPC (846)	CI/CHLOR (51)	AATCC (159)	AFNOR (1,927)	NFRC (3)	9000STORE (154	NPES (44)	NCMA (18)
IEEE (1,993)	CTA (111)	GMNA (654)	ISEA (16)	VDI (18)	ABMA (44)	AF (1,398)	BNAE (46)	ABS (4)	USGBC (31)	NSC (67)
(NFPA) (49)	GSA (637)	DOA (41)	AVS (1)	CEMA (7)	ESL (5)	IEE (1)	MCGRAW (1)	NSSF (5)	SVIA (1)	VDA (81)
ALSC (1)	ACS (8)	LC (38)	AWI (1)	CEN/ON (2)	ETSI (4)	IHS/GMBH (14)	METASOL (1)	OIML (162)	SWI (2)	VGB (21)
IFAI (1)	SWRI (10)	AAMVA (1)	BCS (2)	CENELEC (1)	FEM (30)	IMI (2)	MHI (2)	PCMCIA (14)	TCA (4)	WCMA (2)
PDI/PLUMB (9)	TEMA (5)	AAPL (1)	BENMEADOWS (	CEPAA (1)	FEMA (10)	INFILE (1)	MTI (2)	PEI (12)	TCIA (11)	WILLIAM (1)
AITC (1)	AIIM (75)	AAR (1)	BERNAN (3)	CFR (235)	FOF (6)	IPS (11)	MUNSELL (5)	PICMG (16)	TEC-EASE (1)	WRC (1)
CAGI (5)	ABA (2)	ACDE (1)	BFPA (1)	CGA/CANADA (2)	FSA (1)	IRI (7)	MUSTER (2)	PMI (5)	TECHAMER (4)	
CIMA (20)	NAAMM (2)	AEC (5)	BIA/BRICK (1)	CPA (5)	FTZ (2)	ISANTA (1)	NADCA (1)	RAC (45)	TELECINE (1)	
NAR (107)	VA (20)	AEIC (19)	BIFMA (2)	CSMA (1)	GANA (2)	ISDI (2)	NAHAD (1)	RACAL (1)	THE (1)	
SPI (110)	IP (52)	AIA/INSURN (1)	BSMI (384)	CTI/TILE (2)	HHS (21)	ISS (4)	NAHB (1)	RTCM (5)	TI/UK (7)	
ICAC (4)	EIA (28)	AIM (25)	CAA (8)	DATA (25)	HIBC (1)	ISSA (1)	NAS (1)	RVIA (4)	TPI (3)	
AISI (16)	NAIMA (1)	ALBATIK (1)	CAM-I (3)	DATAPACK (13)	HMSO (2)	ISTA (20)	NATICK (1)	SAWE (3)	TRA (5)	
CISPI (5)	BEN WEESE (6)	ALI/LIFT (3)	CARL (4)	DBS (1)	HSB (1)	ITS (2)	NBBI (1)	SDI/DECK (6)	TRB (1)	
NEBB (17)	CEPT (5)	ALPEMA (1)	CARWIN (5)	DDN (7)	HUD (1)	IWCA (2)	NCSC (3)	SEMI (780)	TTMA (2)	
SFSA (21)	SBCCI (11)	ALPHAGRAP (1)	CASE (2)	DEMA (4)	HUGHES (1)	JAA (7)	NFPA/FORST (3)	SFA (1)	TUV (21)	
DOC (277)	IHS/NORDIC (6)	ANLA (1)	CCPA (1)	DHI (19)	IADC (2)	JEITA (3)	NIOSH (10)	SIS (12)	UAMA (27)	
AICHE (72)	NRC/NUC (502)	ANMC (6)	CCTA (1)	DISA (2)	IAEI (1)	KCMA (1)	NLB (5)	SMA/SCREEN (1	UCC (5)	
HFES (3)	FCC (40)	APSP (14)	CDA (7)	EASA/AV (5)	IATA (15)	KEY (3)	NMEA (4)	SPE/PETROL (4)	UIC (195)	
HI/HYDRON (31)	VDE (14)	AREMA (4)	CEB (1)	EOP (14)	ICELANDIC (1)	LPI (1)	NMTBA (8)	STAHLSCHLU (3	UN (1)	
IHS (453)	DOI (3)	ATA/TRUCK (1)	CEC (1)	ESA (1)	IDEA (1)	MBMA (20)	NRMC (2)	STATE/CAL (3)	USPS (8)	

Figure 4 "Wavelength Division Multiplexing" results on IEEE Engineering360 Standards. Adapted from [62]

TABLE 2 "Wavelength Division Multiplexing" Publishers, IEEE Engineering360 Standards Library - analytical overview

Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.
NPFC	68704	AIA/NAS	1413	AWWA	365	CTA	133	IEST	61	RIA	24
DIN	41155	ASME	1250	SCTE	353	NCRP	129	AISC	60	SDI/DOOR	24
BSI	39958	SNZ	1162	ISUZU	319	NSF	128	NFPA)	57	HHS	24
ISO	39212	UNI	1022	RTCA	299	SSPC	128	EU/EC	53	VGB	23
GOST	35866	ATIS	963	AAMI	298	AIA/ARCH	124	IP	52	ASIS	22
DS	35444	SEMI	910	INCITS	294	AGA	122	LC	52	AWCI	22
ASTM	23279	IPC	890	ARINC	290	SPI	110	CI/CHLOR	51	GPO	22
JSA	17781	SMPTE	882	ASCE	279	ASC/X9	109	PFI	51	SAIA	21
ITU-T	13572	GME	836	ECMA	275	NAR	107	NECA	51	BICSI	21
AENOR	13258	AASHTO	794	ASABE	275	MSS	102	A4A	50	SFSA	21
SAE	11611	DNVGL	781	EEC	256	ESD	100	BHMA	48	ISTA	21
FAA	10812	NFPA	704	CIE	253	ASSP	100	ABMA	48	TUV	21
IEC	8029	JSAE	696	APA	245	ADA	94	DOA	48	AHAM	20
CEI	7679	ECIA	672	CFR	238	SN	91	BNAE	46	NCMA	20
SAI	7490	GMNA	657	ACGIH	234	VITA	90	NPES	44	CIMA	20
DOD	5904	ASHRAE	654	CLSI	204	PPI	88	B11/STD	43	VA	20
FORD	5387	GSA	645	ICC	201	AES	87	NEN	41	MBMA	20
CSA	3982	NEMA	627	KSA	198	VDA	86	USGBC	39	AISI	19
ITU-R	3760	GMKOREA	625	UIC	195	ASSE	77	AIST	38	AEIC	19
SAE-ITC	3482	JEDEC	624	ASQ	191	AIIM	77	HPS	36	DHI	19
GMW	3089	PIP	622	FM	187	AIAA	75	PTI	34	ISEA	18
IETF	3027	NRC/NUC	608	EUROCAE	181	AA	75	AOCS	33	VDI	18
NTIS	2961	TAPPI	601	DOE	179	IMO	73	EPA	32	AFCEN	18
NAVY	2885	SNV	593	CSA/AM	178	AICHE	73	NRC	32	IME	17
ARMY	2755	NAVISTAR	563	IES	173	GPA	72	MPIF	31	ABMA/BOIL	17
IEEE	2435	AGMA	526	ASNT	170	IFI/FASTNR	71	GMSA	31	NEBB	17
AF	2284	ACI	521	AWPA/WOOD	167	NISO	69	HI/HYDRON	31	NATO	16
DELPHI-I	2160	ULC	508	OIML	164	FCC	68	EIA	31	PICMG	16
ASD-STAN	2154	NG	497	ANS	163	EEMUA	67	FEM	30	EI	15
UL	2114	HOLDEN	484	CS UK	162	SMACNA	67	FCI	28	PCI/CONCRT	15
AFNOR	2049	IHS	456	AATCC	160	NSC	67	UAMA	27	VDE	15
API	1699	NACE	439	9000STORE	160	ICEA	66	AWC	26	IATA	15
TIA	1644	KODEKS	415	PIA	151	AMCA	65	NCSL	25	JAA	15
ICAO	1603	DOC	414	ASA	148	ESTA	65	AIM	25	SJI	14
NASA	1511	IAPMO	403	AIHA	145	DOL	63	DATA	25	APSP	14
ANSI	1506	BSMI	387	AWS	144	RAC	63	EOP	25	IHS/GMBH	14
MODUK	1464	CGA/GAS	378	AIAG	136	CTI	62	HPVA	24	PCMCIA	14
DOT	1437	ISA	367	AHRI	134	HI/HYDRAUL	61	AI/ASPHALT	24	NRCA	13

Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.	Publisher	# Publi.
DATAPACK	13	IHS/NORDIC	6	NFRC	3	MUSTER	2	IEE	1
EASA/AV	13	ANMC	6	CSI	3	NRMC	2	INFILE	1
NIOSH	13	ATA/TRUCK	6	WMMA	3	SWI	2	ISANTA	1
TCIA	13	FOF	6	HFES	3	TTMA	2	ISSA	1
LIA/LASER	12	ITS	6	ALI/LIFT	3	WCMA	2	KCMA	1
THHILL	12	SDI/DECK	6	BERNAN	3	TMS	1	LPI	1
SES	12	UCC	6	CAM-I	3	J-STD	1	MCGRAW	1
PEI	12	CMAA	5	GANA	3	ALSC	1	METASOL	1
SIS	12	CAGI	5	HUD	3	IFAI	1	NADCA	1
STI/SPFA	11	CISPI	5	JEITA	3	AITC	1	NAHAD	1
NIST	11	TEMA	5	KEY	3	NAIMA	1	NAHB	1
AVIXA	11	CEPT	5	NCSC	3	AAMVA	1	NAS	1
HEI	11	AEC	5	NFPA/FORST	3	AAPL	1	NATICK	1
SBCCI	11	CARWIN	5	SAWE	3	AAR	1	NBBI	1
IPS	11	CPA	5	STAHLSCHLU	3	ACDE	1	RACAL	1
ALI/LADDER	10	ESL	5	STATE/CAL	3	ADS	1	SFA	1
AABC	10	MUNSELL	5	TPI	3	AIA/INSURN	1	SMA/SCREEN	1
CRSI	10	NLB	5	EJMA	2	ALBATIK	1	SVIA	1
PDI/PLUMB	10	NSSF	5	ABA	2	ALPHAGRAP	1	TEC-EASE	1
SWRI	10	PMI	5	NAAMM	2	ANLA	1	TELECINE	1
FEMA	10	RTCM	5	BCS	2	AVS	1	THE	1
IIAR	9	TRA	5	BENMEADOWS	2	AWI	1	TRB	1
DOI	9	EPI	4	BIFMA	2	BFPA	1	UN	1
CAA	9	ABS	4	CASE	2	BIA/BRICK	1	WILLIAM	1
ASC/O5	8	AFS	4	CEN/ON	2	CCPA	1	WRC	1
ACS	8	ICAC	4	CGA/CANADA	2	CCTA	1		
NMTBA	8	AREMA	4	CTI/TILE	2	CEB	1		
USPS	8	CARL	4	DBS	2	CEC	1		
GA	7	DEMA	4	DISA	2	CENELEC	1		
CDA	7	ETSI	4	FTZ	2	CEPAA	1		
CEMA	7	ISS	4	HMSO	2	CSMA	1		
DDN	7	NMEA	4	IADC	2	ESA	1		
IRI	7	RVIA	4	IAEI	2	FSA	1		
TI/UK	7	SPE/PETROL	4	IMI	2	HIBC	1		
NETA	6	TCA	4	ISDI	2	HSB	1		
ARMA/INTL	6	TECHAMER	4	IWCA	2	HUGHES	1		
ACCA	6	NFPC	3	MHI	2	ICELANDIC	1		
BEN WEESE	6	ALPEMA	3	MTI	2	IDEA	1		

Stats	# of publishers
≥ 10K publications	12
1K ≤ publications < 10K	30
100 ≤ publications < 1K	84
publications < 100	279

Contributing Publisher	% of all
NPFC	17.91%
ISO	10.22%
ITU-T	3.54%

The importance of Security

The NSA proved in 2013 that protecting links between data centers is essential to ensuring the integrity of personal and business information [64]. Protecting information at rest is critical, but also protecting it in transit. Hence why securing networks comes next as a key topic. Securing the network against attacks means preventing service disruption and hence the operations relying on such services, as well as the stakes at hand, from hospitals running heart monitoring machineries whose well-functioning is crucial to patients' lives, to banks and financial institutions managing people salaries and financial investments, to factories operating huge machinery producing various kinds of goods essential for humanity, to ISPs connecting people with each other and with services around the world. Although presented in the early Engineering books as a nonfunctional requirement (Figure below [65]), I think that one could only be naive to think of it as such, especially now, with all what's at stake involving security.

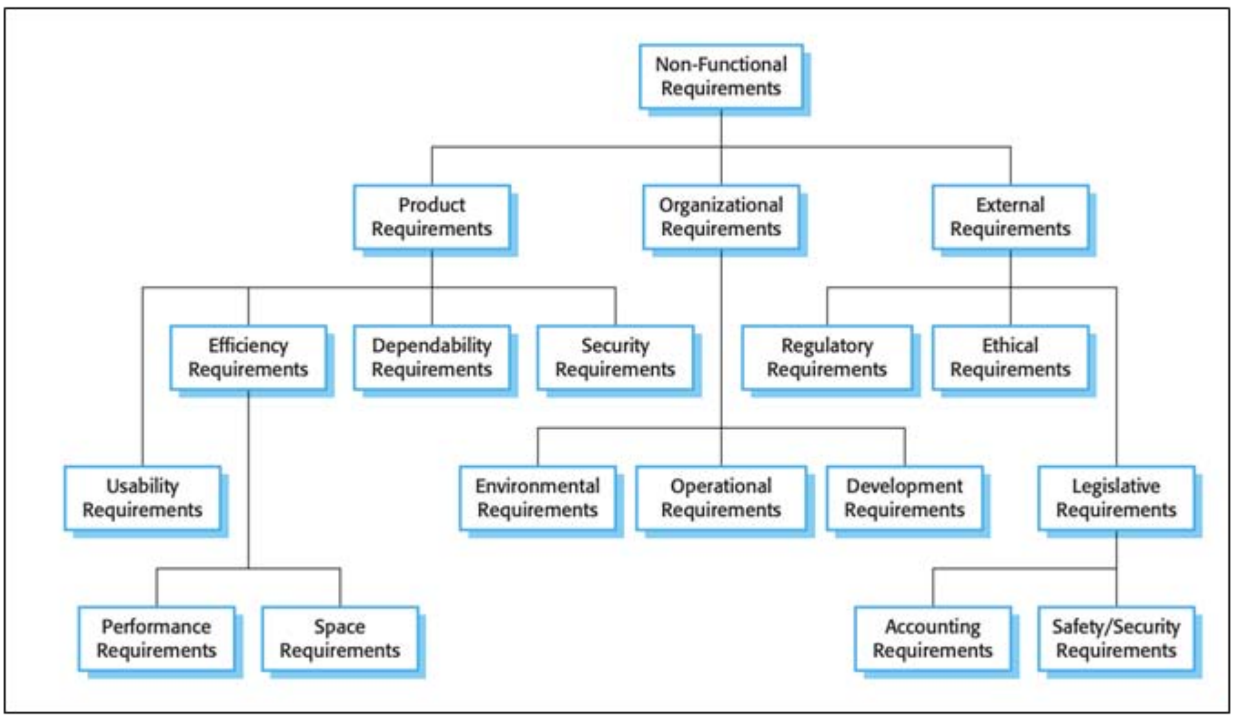


Figure 5 Engineering Requirements - Nonfunctional requirements [65]

Optical Networks are especially of interest given the multitude of roles they're playing in our life nowadays. There are various attack vectors for optical networks, inheriting all existing attack vectors from traditional telecommunication networks, and adding some more specific to the optical domain. More details on optical networks attack can be found in upcoming chapters. As a matter of fact, not very long ago, Industry leaders have admitted this at some of the biggest, and most respected worldwide conferences on Optical Networks. In 2016, Chris Janson, Optical Product Marketing at Nokia, stated at the Optical Networking and Communication Conference & Exhibition, 2016, how Optical networks are not protected against intrusion, and that standardized methods such as AES-256 for physical layer encryption are used by industry and certified by standards like FIPS-140-2 and Common Criteria to tackle this [64].

Generally speaking, one could say that they really care about having it reach the final destination when transmitting traffic over a network. However, security engineers have more concerns in mind when it comes to such transmission. The transmitted traffic should respond to essential security requirements. It is required to first, ensure that all received traffic is authentic. In this context, authentication means that the traffic sender is actually the one who claims to be and not the intruder. Second, the integrity of the traffic received must be ensured. A modified traffic, either during transmission or in transit, is of no or low value to the receiver. Third, ensuring that traffic is confidential, so a man in the middle attack intruder doesn't figure out what messages are being exchanged. In other words, the traffic has to be encrypted and the cryptographical material needs to be securely exchanged so that encrypt / decrypt operations are executed safely. If this has been done correctly, they will find it encrypted and thus unreadable even if an intruder (man in the middle) tried to intercept our traffic.

The need for such security requirements may indeed vary based on the purpose behind the communication and the intention of the Communication Parties. Therefore, some of these requirements may be obligatory while others can be optional. However, it remains important to pay close attention to the domain of application, identify the assets at risk, and the riskiness of comprising each of these requirements: Authentication, Authorization and Accounting, and design suitable security controls to address such risks.

These requirements are especially known and used in Identity System Management, however, their use cases go far beyond that. Cisco has shown an example, talking about network resources configurations for AAA in one of its published best practices guidelines: Cisco IOS Security Configuration Guide [66]. With that being one example, there are certainly other examples or potential use cases in other areas where such principles matter.

Problem Definition

In a world with a global internet penetration of nearly two thirds, a continuous high demand for bandwidth, a growing breadth of optical network applications, as well as growing transmission rates approaching a hundred Tb/s, the wide variety of applications contributes to extend the attack surface of the network, while the high transmission rates lead to highlighting nonlinear effects in Optical networks.

Aims and Objectives:

This Ph.D. thesis aims at designing a Comprehensive Security Framework for WDM optical networks (CSF-WDM) to bridge the gap between the growing demands on bandwidth, the broad variety of applications, the high transmission rate, and the expanding attack surface in WDM Optical Networks, all while handling users bandwidth demands effectively and safely.

Research Methodology

In this thesis, I've started by explaining the motivation behind the choice of the problem statement. In particular I focused on the fiber transmission and the importance of Security WDM Optical. I studied related work in the literature, then I dived into the topic as follows:

To study nonlinear effects impact in WDM Optical Networks, I've split this into an analytical study and an experimental one. Analytically, I studied the impact of nonlinear effects in WDM. Analytically I've relied on Maxwell and Schrodinger equations for our analytical model study. I divided our research into two section. The first studies the propagation of one signal within the optical fiber, and the second studies the propagation of multiple signals within the optical fiber. Under the single signal propagation branch, I focused on studying and comparing nonlinearities effects in bulk material and optical fiber. I also studied light propagation in optical fiber in the presence of such nonlinearities. Under the other branch of multiple signals propagation in one fiber, I studied cross phase modulation and four wave mixing. Experimentally, I carried out our experiments using OptiSystem 15 64-bit Simulation Software. Modules such as the Optical Spectrum Analyzer and the Optical Time Domain analyzer were used to depict the effects on the output signal. I have plot SPM signal effects using Optical Spectrum Analyzer. To simulate the effects of XPM in WDM networks, I setup a layout composed of two Optical Gaussians Pulse Generators fed by 2 User Defined Bit Sequence Generators, I also had an Ideal Multiplexer, as well as a set of auxiliary components for visualization and I studied the XPM signal effects using Optical Spectrum Analyze. For FWM, I combined the signals together using a WDM Multiplexer and I launched the combined signal in a nonlinear optical fiber, and studied the effects using the Optical Spectrum Analyzer. Our study of FWM took into consideration two different system designs: 2 signals with 2 different frequencies in the first system design, and a powerful signal resulting in 2 sidebands in the second system design.

I finished our study by conducting simulations of Nonlinearities in WDM focusing on Power fluctuation, Bit Error Rate (BER), Packet Error Rate (PER), etc., testing the results by varying the number of channel, channel spacing, traffic load, input power, checking all of this and its impact on nonlinear effects in WDM Networks such as SRS, XPM, and FWM.

Next, I proposed a throughput and attack aware static Routing and Wavelength Assignment Algorithm for optical networks, modeled as a Mixed Integer Linear Model, with the objective functions to minimize attackability in the network while minimizing throughput. The algorithm satisfies prevention at design level, where the minimum attackable virtual topology is selected for routing request on the network, and the least blocking probability wavelength assignment algorithm (First Fit, Random Fit, Middle Channel, or Last Channel) is selected to assign the wavelengths in the network for each specific lightpath request.

To simulate traffic generation, I have presented a novel, creative solution using self-similar simulation of WDM lightpaths requests within Optical Networks. I showed that my Implementation of Pareto model simulation for WDM Traffic Generation is consistent over multiple iterations and shape variables, making it a realistic model, practical to be used for Traffic Generation Modules for Optical Networks Simulators.

Moving to the security aspect, and knowing that WDM Market is big and bandwidth demand is increasing, I’ve shown how WDM Transparent Optical Networks are prone to attacks. I’ve then explained how Attack awareness could be planned at the design phase. I’ve studied how QoS Shaping & Policing techniques can be used for WDM Networks, and how Bandwidth utilization fairness could be achieved with WFQ, as a creative solution to the dynamic RWA problem.

Finally, without framework with best practices and recommendations for both the technology, processes, and the people and their motivational fits, the organization could prepare itself for failure. It's become nowadays critical more than ever before, to ensure the big picture is obtained right and the vital areas of the organization are run by strong independent yet collaborative processes, connected thanks to an effective governance that recognizes and enforces prevention as a core value and where each entity is clear on their responsibilities and where the flow is determined, communicated, and customized to fit as much as possible, to ensure successful operations strategically aligned with business vision and mission as well as the higher goals of the prevention oriented mindset framework to achieve organization goals and respond to users' needs in the domain of operation, safely and securely.

The organization of this thesis

This thesis is organized in 3 parts. The Introduction introduces us to this work thanks to the first chapter discussing the motivation, problem statement, and this very own section that describes the organization of the thesis (inception, huh!). Chapter 1 presents literature review on Routing and Wavelength Assignment (RWA) algorithms, RWA Security, and WDM Nonlinear effects, tackling a background study of wavelength division multiplexing, routing and wavelength assignment algorithms, as well as nonlinear effects in WDM networks. Chapter 2 presents an analytical and experimental study of WDM Nonlinear Effects. Chapter 3 presents a Prevention Security Oriented Mindset in Managing Optical Networks, a Novel Optical Networks Management Behavio-Realistic Framework, a revolutionary creative aspect as it presents a prevention oriented Security Framework for managing Optical Networks, with roots in psychology and behavioral science research. The same chapter also presents a Realistic Traffic Generation Model Attack and Throughput-Aware Routing and Wavelength Assignment Algorithm in Transparent Optical Networks. Finally, the chapter completes by presenting a Novel approach Applying Security-Aware Traffic Policing and Shaping strategies with Dynamic Routing and Wavelength Assignment Attack Aware Algorithms in WDM Optical Networks Chapter 4 proceeds studying the RWA static case and presenting a MILP solution and graph coloring technique with security and throughput design level configurable capabilities. Chapter 5 is split into two parts; The first extends Chapter 4 algorithms to allow for selecting the optimal, resulting in the minimum blocking probability, wavelength assignment algorithm (among First Fit, Middle Fit, Random Fit, and Last Fit) for each flightpath request in the network, while the second part puts into play all the previous contributions in a Comprehensive Security Framework for WMD Optical Networks to connect the dots and close the gap presented in

Chapter 6 (Future work) suggests leveraging the techniques utilized for static RWA of attack-awareness, nonlinear effects management, and blocking probability reduction, and developing a Dynamic RWA, nonlinear effects & security aware algorithm. The design and architecture and some development in this area has already been started and will continue as part of future works. Next, there's a dedicated chapter that summarizes the main conclusions from the previous chapters of the thesis, as well as directions and recommendations. Following this, comes Appendix which presents an overview on background foundation and related studies on optical networks fundamentals including hardware, software, protocols, architecture, security, design, deployment, and monitoring. The thesis concludes with a chapter for references.

The novel contribution of this thesis

This thesis presents 8 contributions, First, an attack and Throughput-Aware RWA Algorithm, with a MILP model to solve the static RWA algorithm, with design built-in security controls preventing from the worst-case scenario attacks right from the network virtual topology design phase. Second, is a realistic traffic generation model to allow to accurately simulate Internet Traffic when testing RWA algorithms. Third, is an analytical and experimental model of nonlinear effects in WDM networks, focusing of SPM, XPM, and FWM. Fourth, is a novel psychology & behavioral science-based prevention-oriented mindset framework to manage WDM networks from a managerial and technical perspective, linking technical expertise with operational management. Fifth, is the use of Shaping and Policing Traffic Control mechanisms in Dynamic WDM Networks RWA algorithms. Sixth, proposing a blocking probability aware wavelength assignment algorithm, Seventh, extending the static attack and throughput aware RWA algorithm, and making the wavelength assignment algorithm blocking probability aware as it selects the optimal WA among First Fit, Middle Fit, Random Fit, and Last Fit to accommodate for ensuring the minimum blocking probability for the requested lightpath request.

The Eight and final contribution consists at putting into play all the previous contributions in a Comprehensive Security Framework for WMD Optical Networks.

Chapter 1: Literature Review

Wavelength Division Multiplexing (WDM)

The laser invention and its demonstration date from 1960. In 1970, a breakthrough happened if losses in the wavelength region near 1000 nm could be reduced to less than 20 dB / km [67]. The simultaneous availability of compact sources and low - loss optical fibers led to a worldwide effort to develop optical fiber communication systems [67]. The real phase of fiber optic communication research started around 1975. Thirty years later, an enormous progress was achieved in the field, over four phases [67], summarized in the table below:

TABLE 1.1 Fiber-optic communication systems research phases. Adapted from [67]

Phase	Characteristics	Standards
Phase 1	• Systems operated near 850 nm • GaAs Semiconductor lasers • Multimode fibers • Bit rate between 34 and 45 Mbits/s • Repeater spacing of 10 Km • 0.2 dB/km loss realized (1979) • Gen1 systems commercialized (1980)	• ITU-T G.651 • ITU-T G.956
Phase 2	• InGaAsP semiconductor lasers • Detectors operating near 1300 nm • Bit rate of up to 100 Mbit/s due to dispersion in multimode fibers • Transmission of 2 Gbit/s over 44 km of single-mode fiber (1981) • Gen2 systems, bit rates of up to 1.7 Gbit/s with a repeater spacing of ~50 km commercialized (1988).	• ITU-T G.652 • ITU-T G. 957 • ITU-T G.956 (extended)
Phase 3	• InGaAsP semiconductor lasers not used due to pulse spreading resulting from simultaneous oscillation of several longitudinal modes. • lightwave systems operating at 1550 nm over single-mode fiber • Repeaters spacing between 70-80 km • Fiber dispersion near 1550 nm • Dispersion-shifted fibers designed to have minimum dispersion near 1550 nm (1980s) • Limiting laser spectrum to a single longitudinal mode for minimum dispersion (1980s)	• ITU-T G.653 • ITU-T G.652 (extended) • ITU-T G.955 (extended) • ITU-T G.957 (extended) • ITU-T G.974 • (Submarine apl.)

	● Bit rates of up to 4 Gbit/s over distances in excess of 100 km (1985) ● Gen3 lightwave systems of 2.5 to 10 Gbit/s commercialized in 1992. ● Dispersion-shifted fibers & lasers oscillating in a single longitudinal mode get best performance.	
Phase 4	● Gen4 Systems use optical amplification to increase repeater spacing (1989) ● Gen4 Systems use WDM to increase aggregate bit rate (1989) ● WDM doubled system capacity bi-yearly ● EDFAs (C-band) commercialized in 1990 ● Fiber loss in WDM compensated by EDFAs with spacing of 70-80 km ● Data transmission possible over 21 000 km at 2.5 Gbit/s and over 14 300 km at 5 Gbit/s using a recirculating-loop configuration ● Transmission over 11600 km at a bit rate of 5 Gbit/s shown via submarine cables (1996) ● Commercial transatlantic and transpacific cable systems commercialized (1996) ● Submarine lightwave systems deployed worldwide.	● ITU-T G.655 ● ITU-T G.694.1 ● ITU-T G.694.2 ● ITU-T G.959.1 ● ITU-T G.698.1 ● ITU-T G.698.2 ● ITU-T G.696.1 ● ITU-T G.973 ● ITU-T G.977 ● ITU-T G.695
Phase 5	● Long-haul systems fiber capacity increase ● Transmitting more channels through WDM in C-band (1530 - 1565 nm) ● Reducing WDM channel spacing ● Optical channels deployed in C, S, & L-band ● Terrestrial systems of 1.6 Tbit/s (160 optical channels at 10 Gbit/s) and 25 GHz spacing commercialized ● Raman Amplification Techniques used for C, S, and L-bands ● Low water peak fiber (low fiber loss of 1.3-1.65 μm over entire wavelength region) ● Larger number of WDM channels on a single optical fiber, at 40 Gbit/s (2000) ● Systems operating up to 110-130 Gbit/s per channel proven feasible (2006) ● Dealing with polarization time variant effects (1st and 2nd order PMD, PDL, etc.) ● Reducing pricy OEO conversions in OTN ● DWDM systems carry light for 1000s of km with no electrical regeneration	● ITU-T G.656 ● ITU-T G.959.1 ● ITU-T G.680 ● ITU-T G.657 ● ITU-T G.651.1 ● ITU-T G.983 x–series ● ITU-T G.984 x–series

	● Photonic cross-connect (PXCs) and optical add-Drop multiplexers (OADMs) available for telecommunication networks usage. ● All optical networks (AONs) could extend to all potential routes of the backbone network of a medium size country with optical paths up to around 2 000 km. ● Implementation of multiple OEO regenerators at ~ cost as optical amplifier ● On-chip 40 WDM channels, 40 Gbit/s each channel ● Ability to put OEO regenerators in all the nodes of the network. ● The additional OEO cost could compensate for impairments accumulation, planning rules, optical monitoring, etc., in AONs. ● PON systems used WDM signal multiplexing technique transmitting downstream and upstream channels at different wavelengths. ● PONs could be deployed in a FTTH (fiber to the home) architecture or in a FTTB (fiber to the building), a FTTC (fiber to the curb) or a FTTCab (fiber to the cabinet) architecture	

Let's go back to WDM, our main topic, after the above historical overview. The WDM talk calls for mentions of high bandwidth, high performance and low BER [68]. Wait, but what is WDM? Wavelength Division Multiplexing is a technology that multiplexes numerous optical carrier signals onto one optical fiber, making use of different laser light wavelengths (light colors) [69]. Light colors get combined on the same fiber so as signals don’t interfere with each other [70] as shows the figure:

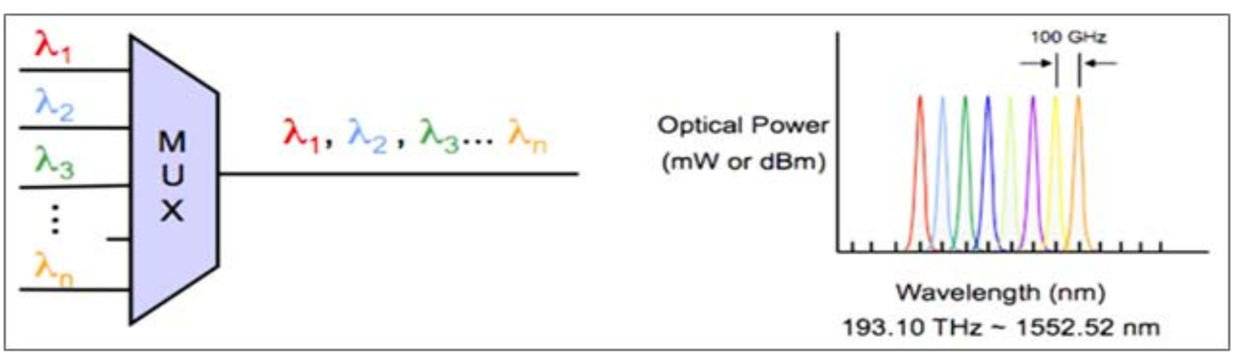


Figure 1.1 WDM [70]

There are two types of WDM: CWDM and DWDM, the descriptions are presented below.

Coarse WDM (CWDM)

CWDM stands for conventional/coarse wavelength-division multiplexing, a method of fiber optic transmission, based on integrating multiple light waves at different wavelengths [70]. CWDM disseminates wavelength channels rather of keeping them at close proximity from one another, resulting in a slight increase in the number of channels in the fiber strands, where this number of channels is slightly more than in WDM but less than in Dense Wavelength Division Multiplexing [70]. CWDM technology main use case is in the Broadband Passive Optical Networks (BPONs) [70].

Dense WDM (DWDM)

DWDM stands for dense wavelength-division multiplexing, a method that split the optical spectrum into wavelength channels, expanding by that the capacity of the optical fiber [70]. Opposite to CWDM, DWDM tries to keep wavelength channels close to each other, allowing to fit the passage of a big number of channels through the optical fiber [70].

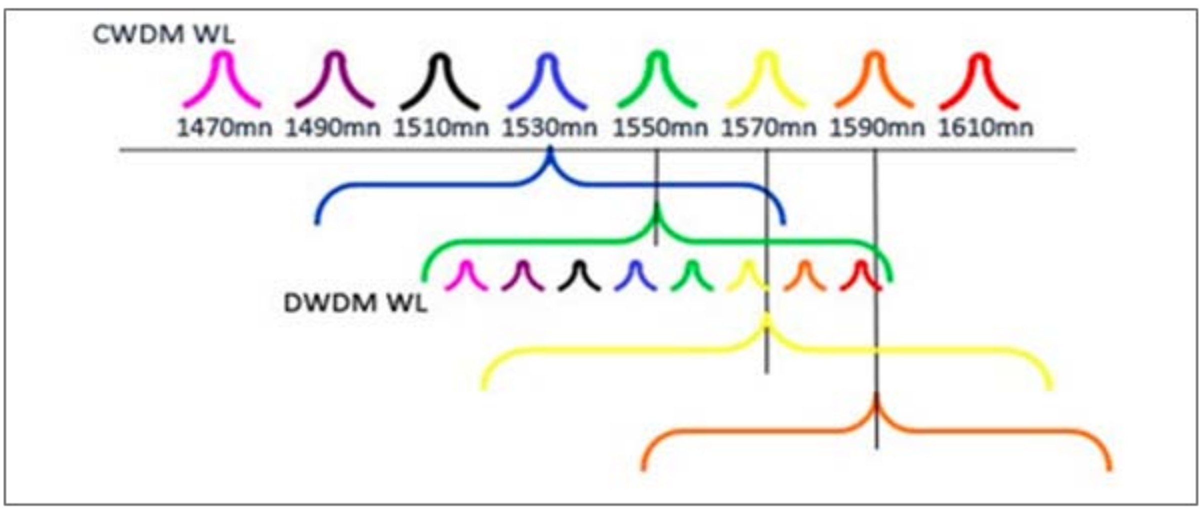


Figure 1.2 CWDM and DWDM Illustration [70]

Routing and Wavelength Assignment (RWA)

RWA Background

At the heart of all the research papers [71][72] [73] [74] [75] [76] [77] [78] that discuss RWA in Optical Networks, I noticed that a good part of these papers is just dedicated to understand this problem. A Problem that's been proved to be NP-Complete. Let's just pause a moment to remind what's a NP-Complete problem. Undefined Behaviors content creator [79], presents a simple definition of the concept. Reminding of basis of P, vs. NP, where: P problems are characterized by their ease of solving, by a deterministic Turing machine [80], in polynomial time: $O(n^k)$, as well as their ease of verification [79]. NP problems could either be easy or hard to solve $\omega(n^k)$ but are easy to verify, in polynomial time: $O(n^k)$ [79]. In contrast with P problems, NP problems can be solved using a nondeterministic Turing Machine in polynomial time [80]. NP-Complete problems, requires referring to the Cook-Levin theorem first. Moreover, it is also needed to recall SAT, the first NP-complete problem (Cook, 1971), with practical applications in a multitude of areas: such as Model Checking, Automatic Test Pattern Generation, Automated Theorem proving, Graph coloring, Linear Programming, and more [79][81]. Ok, that great, but what is SAT?

SAT, or Boolean Satisfiability Problem is the problem where with a Boolean formula $F(x_1, x_2, x_3, \ldots, x_n)$, the question asked is if F can evaluate to 1 (true) or not, and in case F is satisfiable, to return values to x_i's (satisfying assignment) that make F true [81]. This problem SAT, is the hardest problem in NP. Besides, any problem in NP can be transformed into a version of SAT. NP-complete problems are the hardest problems in NP set. A decision problem L is NP-complete if L is in NP and every problem in NP is reducible to L in polynomial time [80]. Now, with that, there must surely be some first NP-Complete problem proved by definition of NP-Complete problems. This problem, is the SAT (Boolean satisfiability problem) proved by Cook.

Now, back to our RWA problem. The Routing and wavelength Assignment problem has as objective to minimize the number of used wavelengths, while also maximizing the number of successfully established lightpaths [82]. The RWA Problem, also referred to in the literature as the Static lightpath establishment (SLE) has been proven to be an NP-complete [83]. The proof is that the SLE problem is equivalent to the n-graph-colorability problem [84], [85]. In other words, it would suffice to identify the chromatic number of certain (general) graphs to determine the minimum number of wavelengths that satisfy the demands. Oftentimes, in the literature, the RWA problem was getting solved by solving the Routing (R) and Wavelength Assignment (WA) subproblems separately.

RWA Literature Review

With RWA a key problem to solve in WDM Networks, infrastructural backbone technology, a review over the past recent years of some of the most important RWA algorithms with the major accomplishments is key.

In 2019, Natalino, Carlos, et al. introduced The Energy and Fatigue Aware Heuristic with Unnecessary Reconfiguration Avoidance (EFAH-URA) algorithm, showing that these three aspects can be effectively balanced [86]. On the one hand, EFAH-URA significantly improves the average availability of connections for both unprotected and protected connections compared with pure energy-aware strategies, achieving five 9's availability. On the other hand, energy saving costs are reduced [86]. In the same year, Kaur, Harpreet and Munish Rattan, presented a solution to the RWA problem in WDM networks using the Flowers ' Hybrid Pollination (FP) Algorithm as well as Simulated Annealing (SA) algorithm (FA+SA) with and without wavelength conversion capability at the nodes of the network. The research showed a blocking probability of 1.25×10^{-5} could be achieved. Moreover, it has been shown that hybrid algorithm of FP and SA is potentially more efficient than Differential Evolution Algorithm (DEA), Firefly Algorithm (FA), Particle Swarm Optimization with Less number of informers (Psolbest), SA and Genetic Algorithm (GA) differential evolution algorithm (DEA) algorithms for the light path establishment in an optical network [87].

C. Hsu, S. Sie, H. Fu, J. Zheng and S. Chen, proposed an Efficient Resource Management Model to enhance the Routing and Spectrum Allocation (RSA) execution efficiency in Elastic Optical Networks (EONs). In these networks, RSA is very similar to RWA in WDM networks [88]. The work focuses on a new resource management unit called cluster to simplify the spectrum assignment phase, referred to as Cluster-Based RSA (CB) aiming at reducing Spectrum Allocation (SA) time complexity to O(1); the RSA's overall time complexity could be dominated by the routing problem [88]. The issue was the CB RSA version was the intra-fragmentation, which was then addressed by the design of Sub-Clusterbased RSA, referred to as SCB, loosening the link-disjoint constraint, resulting in a performance increase between 13% and 55%, with a bandwidth blocking rate of less than 0.01 for 380 Erlangs, and slightly above 0.1 for 540 Traffic Load Erlangs [88].

H. Rabbani, L. Beygi, S. Ghoshooni, H. Rabbani and E. Agrell, they presented a joint routing, wavelength, and power allocation method for optical network planning. The proposed scheme takes physical-layer impairments into account, using the enhanced Gaussian noise nonlinear model with focus on maximizing the network achievable rate and minimum Signal-to-Noise Ratio (SNR) margin of networks with partial spectrum utilization in their links, relevant to the majority of empirical metro network scenarios. According to numerical results, the network achievable rate can be improved around 17% by performing power optimization over the individual launch power of network lightpaths compared to optimizing a single flat (equal) launch power for all the lightpaths. Moreover, the minimum SNR margin of the simulated network is improved by about 2.3 dB. Finally, it is observed that maximizing the network minimum SNR margin needs the launch power of each lightpath to be proportional to the total nonlinear interference noise efficiency influencing the lightpath [89].

Musumeci, Francesco et al present an overview of the application of Machine Learning to optical communications and networking, concluding with new possible research directions [90]. Taking QoT estimation, the paper showed how supervised ML algorithms with various methodologies (kriging, L2-norm minimization or Least Square Method (LSM), NN, CBR, SVM, and others), and taking different inputs types (Historical OSNR, lightpath route, source-destination nodes, link occupation, and others) in order to output various types of performance metrics including (OSNR, BER, blocking probability, Q-factor, SNR, etc.), using either real or synthetic data [90]. For Traffic prediction and virtual topology (re)design, the paper reviewed two sets of algorithms supervised and unsupervised ML ones. Under the supervised ML bucket methodology bucked, for traffic prediction and virtual topology design, the paper reviewed methodologies such as ARIMA, NN, Recurrent NN, and Reinforcement learning, taking various kinds of inputs based on the methodology, ranging from historical real-time traffic matrices, to historical end-to-end maximum bit-rate traffic, to historical aggregated traffic at different BBU pools, and outputting performance data such as predicted traffic matrix, predicted end-to-end traffic, predicted BBU pool traffic, after being trained on real or synthetic data [90]. On the unsupervised ML front, the paper reviewed methodologies like NMF, clustering, taking as input CDR and PoI matrix, outputting similarity patterns in base station traffic, following real data training [90].

Saeed, Nasir et al presented in their work an overview of Underwater Optical Wireless Networks (UOWNs), as well as design and operation & security challenges in each layer [91]. Underwater Optical Wireless Communication (UOWC) is an emerging area of research as a substitute for high data and latency acoustic systems. Topics covered under such area include: Network architectures, physical layer challenges (propagation, modeling, and modulation), data link layer issues (configuration, budgeting, performance metrics, and access), network layer challenges (routing algorithms), transport layer concerns (connectivity, reliability, flow and congestion control), UOWN applications and application layer targets, and localization and its impacts on UOWNs layers [91]. The study classified the architecture of UOWNs based on three factors: types of channel (acoustic, optical, or hybrid), mobility scheme (stationary or mobile), and spatial coverage (1-D, 2D, or 3-D) [91]. The authors also compared the performance metrics of acoustic, RF, and optical waves in UOWNs, showing Optical waves leading in propagation speed (≈ 2.25 ×108 m/s, almost the speed of light), data rate (Gbps), and physical layer security (against eavesdropping) [91]. There were also a few routing protocols surveyed for UOWNs, such as source-based routing, location-based routing, hop-by-hop routing, cross-layer routing, clustered routing, and reinforcement learning based routing [91]. One example of such algorithms is the Focus beam routing, where each node knows its location and the location of the destination node, where each intermediate node decides on a next hop. Focus beam routing is a good UOWN candidate because of its nature as a directive from source to destination [91]. Another example is the source based routing, where the route having the minimum transmission delay from source to sink nodes gets chosen [91]. The cross layer routing utilizes several layers' information to making its routing decision: including the delay of transmission, sink distance, channel conditions and the candidate node buffer size [91]. The surveyed reinforcement learning routing protocols employ the Q-learning method for network states and adapt to changing topology [91].

Always within the area of Machine Learning, and in the same year, researchers in [92] have presented a dedicated survey of uses of AI for optical networks performance monitoring, nonlinearities mitigation, and better estimation of transmission quality. Six AI sub-categories have been surveyed for this context. Those are: 1) Search methods and optimization theory (e.g. MILP [93][94], breadth-first search [93][94], local search algorithms and metaheuristics such teaching-learning based optimization [95], simulated annealing [96][97][98], tabu search, genetic algorithms [99][100], swarm intelligence with its variances such as ant colony optimization

[101][102][103][104][105][106][107], artificial bee colony algorithm [108], gravitational search algorithm [108], Fire-Fly algorithm [108], and Particle Swarm optimization [109]; 2) Game Theory (e.g. [110][111][112]); 3) Statistical models (e.g. Bayesian networks [113][114][115][116][117], Hidden Markov models [118][119], and Kalman filtering [120][121]); 4) Decision Making Algorithms (e.g. Markov decision processes [122][123][124][125][126]); 5) Knowledge-based reasoning and planning methods (E.G. [127][128][129][130][131][132]); and finally 6) Learning methods with their subcategories 6.1) Learning probabilistic methods (e.g. Bayesian Learning [133][134][135], Maximum a posteriori learning [136][137], and Maximum-likelihood learning [138][139][140]) and 6.2) Supervised learning (e.g. Neural networks [141][142], support vector machines [143][144], linear regression [145][146], logistic regression [146], random forests [147], instance-based learning: K-nearest neighbors & case-based reasoning [148][149][150]) Unsupervised learning (e.g. principal component analysis [151], clustering K-means [152]), and finally Reinforcement Learning (e.g. Q-Learning [153][154] and Learning and automata [155]).

Mohan Kumar presented a detailed study on the Minimum Reconfiguration Probability Routing (MRPR) algorithm and the assessment of its results in comparison to Uncontrolled Adaptive Routing (AUR) and the LLR algorithms. Under changing load conditions, the researcher showed that he has minimized the effects of failures on network connection and router failure, and with using Kalman Filter (KF) techniques, the computational complexity was shown reduced too [156]. The minimum reconfiguration probability routing (MRPR) algorithm selects the most reliable routes and assigns wavelengths to connections in a manner that efficiently uses the light path (LP) established to consider all possible requests. MRPR resulted in an 8% increase in performance compared to AUR and LLR algorithms [156].

Algorithm 1: Energy and Fatigue Aware Heuristic with Unnecessary Reconfiguration Avoidance (EFAH-URA)

```
Data: power state of fiber links and traffic realization from previous traffic period (R^prev), R, K, M, λ, α, β, N
Result: RWA for all r∈R, power state f_am of each fiber link f ∈ F at current time period
foreach src, dst ∈ V | src ≠ dst do                                                        // Initialization
    R^prev_{src,dst} ← working lightpaths established in R^prev from src to dst in the reverse order of the number of used wavelength
      resources;
    R_{src,dst} ← lightpath requests in R from src to dst;
    if |R^prev_{src,dst}| > |R_{src,dst}| then
        toRelease ← |R^prev_{src,dst}| − |R_{src,dst}|;
        release the first (toRelease) lightpaths from R_{src,dst};
        copy remaining (|R^prev_{src,dst}| − toRelease) lightpath realizations from R^prev_{src,dst} to R_{src,dst};
    else
        copy all lightpath realizations from R^prev_{src,dst} to R_{src,dst};
R^rem = lightpath requests from R that were not copied from R^prev during the Initialization phase, sorted by the descending order of
  the wavelength resources used by each r∈R on their 1+N shortest disjoint paths                    // RWA
foreach r ∈ R^rem do
    minWeight ← M;
    lp_{n=1...1+N} ← null;
    foreach k_{n=1...1+N} ∈ K | k^src_{n=1...1+N} = r_src ∧ k^dst_{n=1...1+N} = r_dst ∧ ff(k_{n=1...1+N}) ≥ 0 ∧ f_failed = 0, ∀f ∈
      fibers(k_{n=1...1+N}) ∧ disjoint(k_{n=1...1+N}) do
        switchesOn ← 0;
        noSleep ← 0;
        foreach f ∈ fibers(k_{n=1...1+N}) do
            if f_am = 0 then
                switchesOn ← switchesOn + |f_ola|;
            if f_free = λ then
                noSleep ← noSleep + |f_ola|;
        w = α × switchesOn + noSleep;
        if w < minWeight then
            minWeight ← w;
            lp_{n=1...1+N} ← k_{n=1...1+N};
    if lp_{n=1...1+N} ≠ null then
        perform RWA for r using paths lp_{n=1...1+N} and wavelength ff(lp_{n=1...1+N});
        put OLAs of fiber links in lp_{n=1...1+N} into AM;
    else
        Block d;
foreach f ∈ F do                                                                          // Post-RWA
    if f_free = λ ∧ ∄ ola_AF > β ∀ola ∈ f_ola then
        put fiber link f into SM;
```

Figure 1.3 Energy and Fatigue Aware Heuristic with Unnecessary Reconfiguration Avoidance (EFAH-URA).[86]

Formulation Method	Objective	Conclusion	Reference ,Year
ILP, relaxed ILP	Max-RWA	1. Upper bound is derived for the carried traffic of connections. 2. Lower bound on the blocking probability	[R. RAMASWAMI,et al 28] , 1995
ILP	RP, Max-RWA	1. Expanded node representation for regenerators node. 2. Routing with regenerators assignment (RRA) & Max-RWA problem.	[T. LEE, et al 29] , 2012
0-1 ILP	Max-RWA	1. Reconsider for comparison 2. Two formulation given by changing wavelength continuity constraint. → R. M. Krishnaswamy & K. N. Sivarajan, "design of logical topology" → New proposed in this by author. 3. Take less memory and less computational time.	[KRISHNASWAMY,et al 25] , 2001
ILP	Max-RWA	1. CR- model consider. 2. Lower and upper bound for symmetrical and asymmetrical is given.	[JAUMARD.et al 10] , 2004
IP	Min-RWA	1. Column generation technique. 2. Branch-and-price procedure.	[T. LEE,et al 29] , 2000
LP	Min-RWA	1. Formulation is given for opaque, translucent & transparent network. 2. Integer optimal solution even integrality constraint are relaxed and if not then network is opaque. 3. Minimizing the call blocking probability. 4. Optimal multi commodity routing.	[OZDAGLAR,et al 26] , 2003
LP	Min-RWA	1. Randomized rounding technique takes care of LP. 2. Graph coloring approach for wavelength assignment.	[D. BANERJEE,et al 27] , 1996

Figure 1.4 ILP algorithms comparative study [157]

RWA Definition

As this PhD builds on this research, a good chapter will be developed to describe the RWA problem and the key goals of a modified RWA attack aware algorithm.

The simplest description of the problem states that given a set of lightpaths, the Routing and Wavelength Assignment Problem is to route those lightpaths and assign wavelengths to each one of them. The main purpose of the RWA problem is to improve the number of established connections such that each request is assigned a physical link and a specific lightpath within that route.

RWA Objectives

The main objectives as stated by the research papers and referred to in this chapter are to minimize the number of wavelengths used to carry data across the network [71]. Another objective is to reduce the blocking probability following the increase of the number of established connections [71]. Thus, RWA problem addresses the issue of minimizing the number of wavelengths per physical link by rerouting the requests that exceed the number of wavelengths in a specific link in order to avoid the probability of congestion, which is caused by nonlinear effects of fiber optic, in the route.

RWA Categories

Routing and Wavelength Assignment can be divided into three main categories: static, dynamic [77], and incremental [76]. The first category refers to the RWA problem for static traffic (off-line) and it is known as the Static Lightpath Establishment (SLE) problem [76]. In this category, the connections (lightpaths) requests are known in advance, which makes routing decisions based on full knowledge of the network traffic [77]. The second category is that dealing with dynamic traffic (on-line). This problem is known as the Dynamic Lightpath Establishment (DLE) problem [76]. RWA given this traffic category means that the lightpath routing and the wavelength assignment of each lightpath is done independently of other lightpaths [77]. With DLE, whenever a connection request arrives, there is a lightpath that's set up, this lightpath is relinquished after a finite amount of time [76]. The difference between this type of RWA problem and the last type (the incremental-traffic) based, is in the fact that the established lightpaths stay in the network indefinitely [76].

RWA as an NP hard problem

RWA is considered one of the NP hardest problems [77]. Moreover, when trying to solve an RWA problem given large size networks, this can be even infeasible in a practical amount of time. Actually, there are two ways of solving the RWA problem. The first method is to consider both the routing and wavelength assignment jointly; however, this approach is very difficult to deal with. Thus, the second approach reduces the complexity by subdividing the problem in two sub-problems, which means to find the route (Routing problem) and then assign the wavelength within that route (Wavelength problem). This second approach reduces the complexity of the problem and makes it possible to solve.

Routing sub-problem

All nodes in a physical network topology are connected via physical fiber optic links. The routing sub problem emphasizes on determining the physical route for every lightpath request. In order to accomplish this task, the next section presents three of the most commonly used algorithms: [76] fixed routing, alternate routing, and adaptive routing.

Fixed Routing

The easiest way to route a connection request is to choose the same fixed route for a source-destination pair, each single time. The fixed shortest path routing is an algorithm that helps achieving this. For each source-destination pair, the shortest route is determined off-line by means of typical shortest track algorithms such as Dijkstra or Bellman-Ford, and all connections between node-pairs are established using those offline determined fixed paths [76].

Fixed Alternate Routing

This algorithm is an improvement of the previous one. In order to make the fixed routing algorithm more reliable, this improvement [76] focuses on having several routes for each lightpath demand. Therefore, whenever a congestion/failure occurs, the fixed alternate routing algorithm selects another route from the stored list of routes. This approach adds an overhead in terms of storage capacity [76]; however, it solves to some extent the problem of network failure cause by the previous algorithm. Although this method seems to be adaptive, it still causes a failure if all the stored routes are congested [76].

Alternate Routing

In this approach, the physical route between two nodes is chosen dynamically. It considers the changing network state and congestions occurring before making the choice [76]. For example, the choice may be based on the shortest path since it is the least costly links or the least congested paths in case the shorter ones are congested or likely to be congested [76].

Wavelength Assignment sub-problem

After selecting the appropriate physical link, solving by this the routing sub-problem, the wavelength assignment problem takes place. Since fiber optic supports several wavelengths to send the data through, the algorithm has to select the needed one from the list of available wavelengths. This selection is done based on several approaches: first fit, least used (spread), most used (pack), and random [76].

First Fit Approach

In this approach, wavelengths are indexed in a sequential order and each lightpath demand is assigned the least index wavelength available on the entire physical link (without need of wavelength conversion) [76]. This method is one of the most widely used approaches in assigning wavelengths since it is the simplest one. Finally, the complexity of this approach is O(w), with ‘w’ being the number of available wavelengths [76].

Random Approach

In this approach, the wavelength is assigned randomly among the available ones. This is one of the most used methods since it is very simple in terms of implementation as well as it has the same complexity as the previous method O(w) with ‘w’ being the number of available wavelengths [76].

Least Used Approach (Spread)

This method aims to balance the load among available wavelengths by assigning a lightpath request to the wavelengths that is least used. This method is also known as “spread” since it spreads the load between all available wavelengths [76]. This approach requires more storage and computations of the use rate of a wavelength. This makes this approach perform poorly compared to the previous two approaches [76]. However, it is still practical in centralized networks since all computations will be performed and stored only in the centralized server.

Most Used Approach (Pack)

Similar to the spread approach, pack method performs poorly in terms of blocking probability and is practical in centralized networks [76]. The only difference between this approach and the previous one is that pack method tries to collect all lightpath requests in minimum number of wavelengths in order to reduce the number of used wavelengths to decrease the fiber optic nonlinear effects such as FWM.

The wavelength assignment problem is reduced to graph coloring problem [76], meaning that it is by itself an NP-complete problem. This problem (WA problem) has two major constraints.

The first constraint is named clash constraints and consists of prohibiting the assignment of the same wavelength to more than one lightpath that will traverse a common portion of the physical route. In addition, the wavelength continuity constraint (WCC), which is the second constraint, ensures that each lightpath is assigned the same wavelength along its entire physical path.

5G

Having served for decades, traditionally, copper based time multiplexing (TDM) circuits such as several bonded T1 or E1s are used by 2G and 3G mobile networks to connect cellular sites through the Mobile Backhaul (MBH) mobile network to a nearby mobile switching center [158]. MBH upgrades are already taking place worldwide to convert legacy copper-based MBH serving cell sites to packet-based fiber transport, enabling far higher capabilities to deliver the best future-proof MBH networks [158]. MBH fiber upgrades are accelerated by the increased adoption of 4G LTE and LTE-Advanced mobile network technology, to be leveraged by future 5G networks [158].

The 5G wireless networking is the fifth generation of mobile networks that's planned to follow from 4G. This new generation is expected to be operationalized in 2020s, with unprecedented performance targets promised for wireless networks [159]. These promises include increased bandwidth (+1000 times), connected devices (+100 times), connection rates (10 Gbps), perceived network availability (99.999%), perceived network coverage (100%), decreased delay (1ms), as well as massive savings in network energy utilization (-90%) [158]. These promises fueled debates to compare Fiber and 5G performance, while the situation doesn't allow for such comparison at all. This is because when 5G, will be operationalized, it will be thanks to the fiber it'll run over. So, comparing 5G and Fiber from that aspect simply makes no sense. Ciena's Brian Lavallée, Senior Director of Portfolio Marketing with global responsibility for Ciena's 5G, Packet, and Submarine networking solutions, also explains how 5G mobile networks will have a huge impact on both the wireless side and the wireline side of the global network infrastructure [160]. The excellent network performance objectives of 5G are dependent on and are highly dependent on the availability of fiber at cell sites.

5G is an upgrade of 4G to solve Latency, Capacity, and Reliability issues. Starting with latency, there are some Internet of Things (IoT) devices that need real time connection, without any latency. Researchers worked on a new architecture to solve the latency issue. The other 4G issue is capacity (e.g. each house has 5 devices), with IoT, each house would be expected to have much more devices connected to the Internet. 4G had targets. With a bandwidth of 8 Megabits per second, 2 people in the household, dividing by 2 yields 4 Megabits per second per person, if there are more devices dialing in, there's even a need for more capacity available to tap into. Capacity is another benefit: How many customer can it serve. 4G is not equipped to support the increasing number of IoT devices that need fast, reliable connection. In fact, IoT devices are projected to reach 125 billion by 2030 [161]. 5G operates on different radio spectrum frequencies, connects many more devices to the internet, minimizes delays and delivers ultrafast speeds, and running on optical networks, is expected to be the future for mobile networking. Below is an overview of 5G Technologies and beyond, adapted from [162] and [163].

5G Technologies and beyond	
Architecture	**Physical Layer**
• Radio N/W Evolution • Advanced Air Interface • Next Generation Smart Antennas • Split Plane - SDN Cent • Architecture - CRAN • HetNets (Heterogeneous network)	• MM-Wave Channel • Adaptive Beamforming • Sectorized Antenna • Massive MIMO • Full Duplex Radio Technology
MAC layer	**Application Layer**
• Spatial Beam Patterns • Directional MAC Protocols • Advanced 5G Multiple Access • Alternate Methodologies	• D2D Communications • M2M Communications • IoT • Vehicular Communication • Healthcare & wearables • Misc. Applications
Quality	**Sustainability**
• Quality of Service • Quality of Experience • Self-Organizing Networks	• Energy Aware Base Station • Energy Efficient Backhaul • Energy & Cost-Effective N/W • C-RAN: Reduced Overhead & Energy
Issues & Challenges	**A Vision of 6G**
• Coverage • Emerging applications • D2D vulnerabilities • Mobile edge computing • Open smart RAN • Network Orchestration & slicing	• Network Intelligence • Fast spectrum reallocation • Enhances senses • Battery duration & energy • Quantum Networks • Privacy & Security • Virtual Operators

Figure 1.5 Literature Review overview of 5G Technologies & beyond. Adapted from [162][163]

Security in RWA

Security in RWA is a hot topic that's been in the work. The transparency of the network, while studying WDM and Transparent Optical Networks (TON) makes me particularly attractive for malicious activities to attack and propagate through the network. Besides the usual network faults, some of them could be initialized by malicious parties to eavesdrop the network, interfere with the service provided, or alter it and transfer corrupt data instead. Attacks on the network aren't limited to external parties, but also include internal ones.

According to Cybersecurity Insiders, 2018 insider threat report, based on a survey of 472 cybersecurity professionals, from technical managers to managers and IT security professionals, representing different-sized organizations in all industries, the report shows that 90% of companies feel vulnerable to attacks performed by insiders [164]. Too many users with excessive access rights (37 %), the growing number of devices accessing sensitive information (36 %) and the increasing complexity of information technology (35 %) form part of the major risk factors [164]. In the previous 12 months, a majority of 53 percent confirmed insider attacks against their organization (typically less than five attacks and twenty-seven percent of organizations say that insider attacks have become more frequent [164]. Companies are focusing on the detection of insider threats (64 %), followed by deterrence methods (58 %) and forensics analysis and post-violation (49 %) [164]. Using a combination of deterrent controls (off the shelf or built in house) such as Intrusion Detection Systems (IDS), Data Loss Prevention (DLP), Log Management, Identity and Access Management (IAM), Security Information and Event Management (SIEM), companies are trying to better detect active insider attacks on their networks and its assets [164].

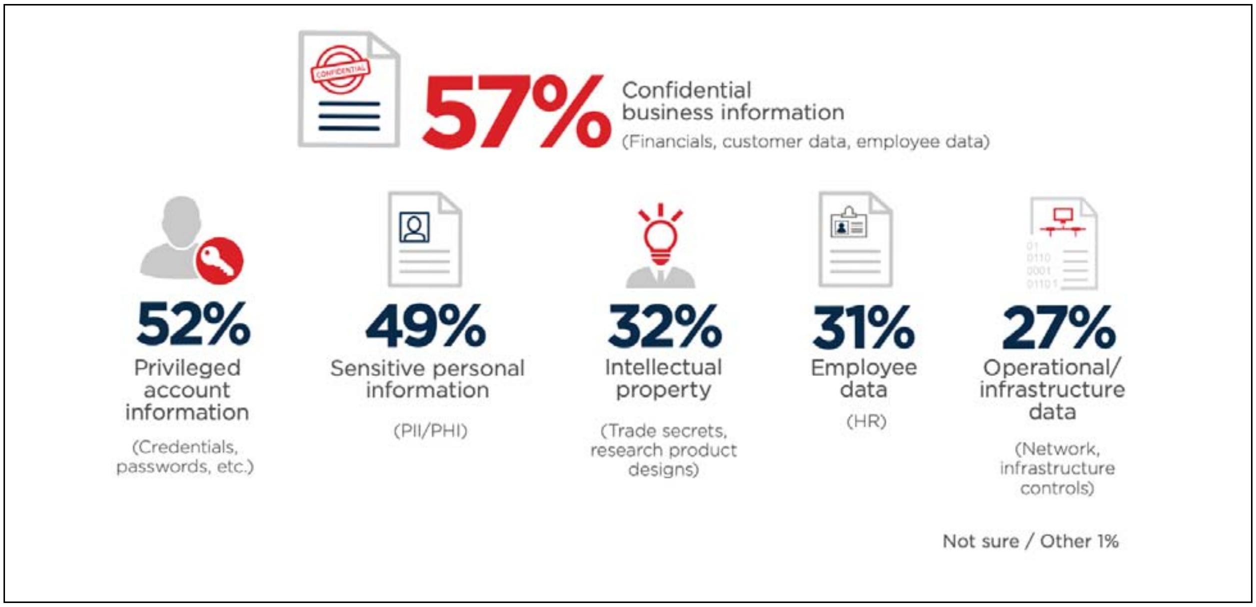


Figure 1.6 Most vulnerable Data Types to Insiders Attacks [164]

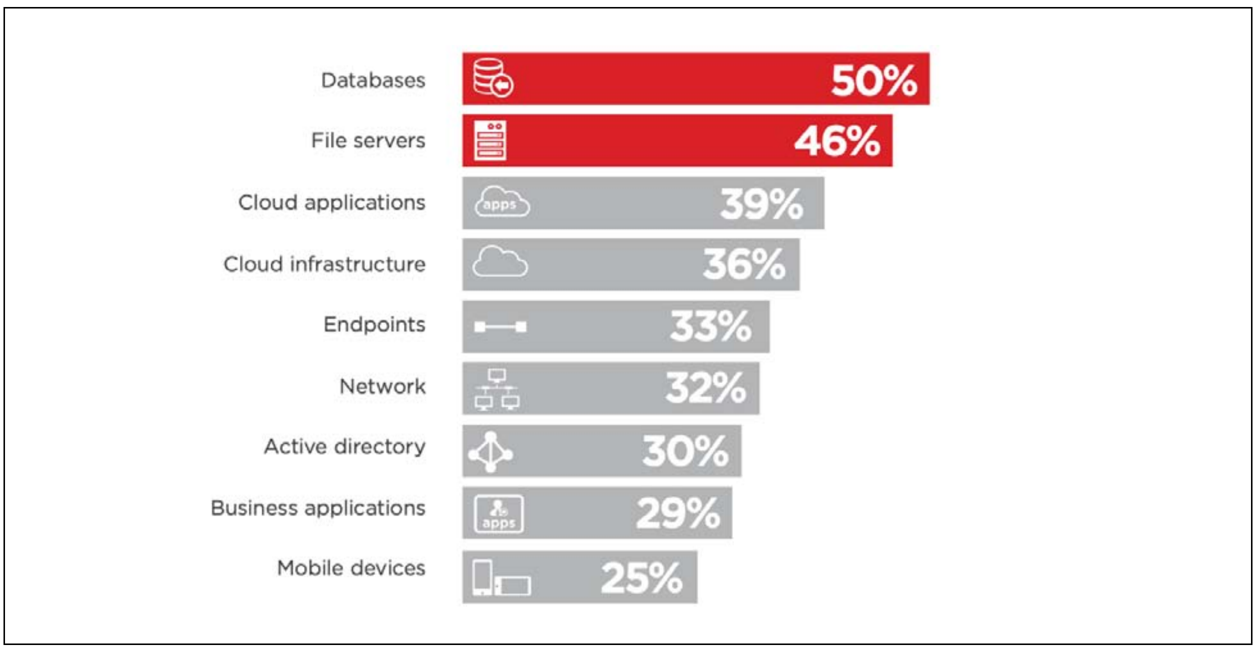


Figure 1.7 Most Vulnerable IT assets to insider attacks [164]

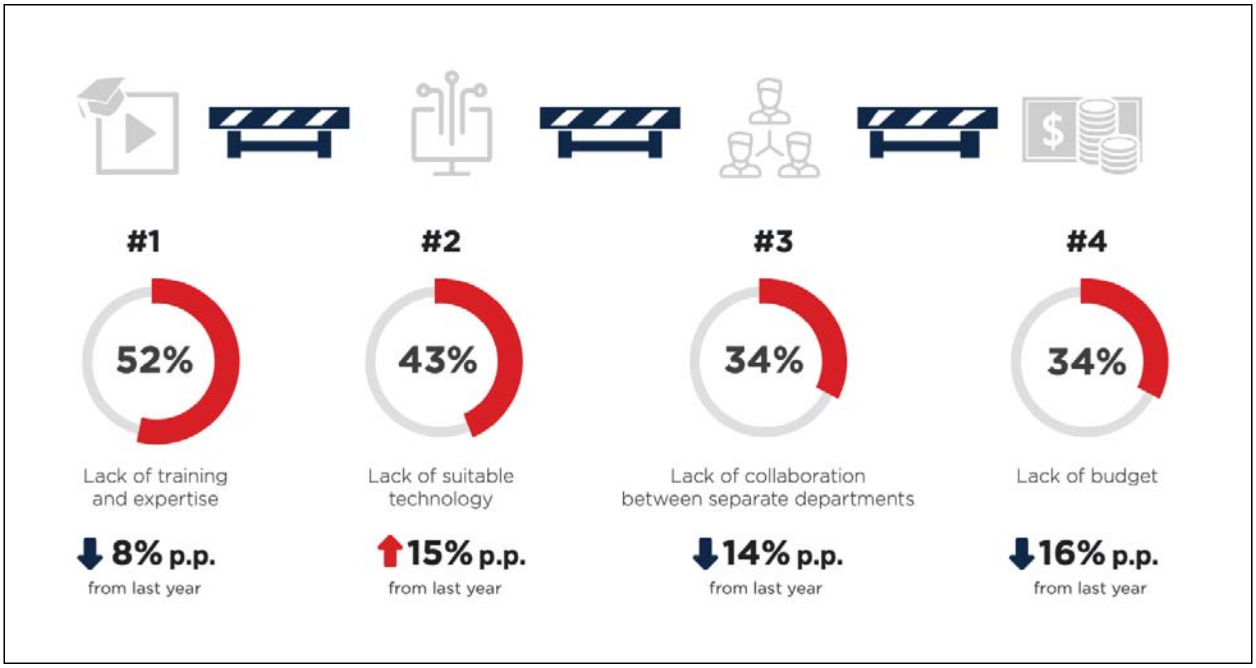


Figure 1.8 Most common barriers to effective insider threat management [164]

On the network level, below is a summary table of some of main security issues but this time, at the level of the network, and independently of them being insider or outsider attacks. Summarized in the table below, listing various attack strategies and proposes security controls to mitigate the associated risks on the network and its assets:

TABLE 1.2 Selected Transparent Optical Networks Physical Layer Attacks and Security Controls

TON Physical Layer Attack	Strategy	Security Control
EDFA Attacks	Exploiting Erbium Doped Fiber Amplifiers' gain competition, depriving other signals of power, while increasing its own power [78].	Automatic Gain Control Amplifiers as they have power monitoring functionality, The functionality sends an alarm when detecting abnormal high power.
Low Power QoS Attacks	Attacking a splitter at the head of a link to attenuate propagation power to a certain amount. This also results in	QoS degradation monitoring Systems. Paper X proposed a QoS degradation monitoring System based on OOK

	degrading the performance metrics (QoS) of attacked lightpaths and may result in attack propagation If there is optical cross connect (OXC) equalization at network nodes [78].	signaling, monitoring the following criteria: BER level, time during which that BER level was sustained, False Positives and False Negatives [165].
Correlated Jamming Attack	Bending the fiber to tap part of the signal, injecting noise at the tapping point, resulting in eavesdropping or degradation of the SNR on the attacked signal [78].	There are a few options to note such as: 1) Threshold power detector systems to detect the jamming attack, 2) Optical Spectrum Analyzers (OSAs) as they can detect jamming attacks that severely impact the optical spectrum, 3) Optical time domain reflectometers (OTDR) detecting the jamming signal superimposed on the OTDR probe signal [166].
Cross talk based Attack	Intra-channel crosstalk: In Wavelength-selective switches, channels on the same wavelength can interfere and cause intra-channel crosstalk. Inter-channel crosstalk: Long distances and high-power signals can introduce	Any system that can detect the change in signal power would do. Such system should be able to detect and monitor power levels at multiplexers, demultiplexers, as well as on switch plane, monitoring if power at any of these exceeds the expected value [166].

	nonlinearities in fiber and cause inter-channel crosstalk, High power jamming signal injected on a link can interact with other channels via nonlinear effects [78].	
Tapping Attack	The attacker requests a channel and does not send on it, cross talk occurs between neighboring channels, the attacker's wavelength carries leaked data from this cross talk, the leakage signal is then amplified, resulting in a strong tapped signal of data which gets delivered directly to the attacker via their channel [78].	One simple method to prevent from this is encryption! Where even if the attacker tries tapping the fiber, there will be no readable data as it would have been encrypted!
Cutting the Fiber Attack	Unambiguously means what it says, resulting in a Denial of Service, if there are no backup fibers [78].	Secure premises, surveillance, and defense in depth mechanisms should prevent intruders from getting onsite and tampering with the fiber infrastructure.

WDM Nonlinear Effects

Optical communication performance may suffer significantly from the effect of the nonlinear physical impairments. Examples of these impairments are as follow:

Nonlinear effects types

Self-Phase Modulation (SPM)

When travelling through the medium, an ultrashort pulse of light, will induce a varying refractive index of the medium as a result of the optical Kerr effect. [167]. This refractive index variation generates a phase shift in the pulse, changing by that the pulse frequency spectrum.

Cross Phase Modulation (XPM)

Similar to the FWM, XPM is a nonlinear type of optical cross talk [168]. This happens as a result of optical signal(s) intensity changes, which cause the refractive index of the fiber to change [169]. Consequently, the phase of all optical pulses that are sharing the same fiber will be modulated. A concrete example of the impact is the broadening and distortion of the signal's shape [72] [168].

Four Wave Mixing (FWM)

In optical fiber, when three wavelengths operating [170]. At frequencies f1, f2, and f3 respectively interact; a fourth wavelength is generated [171]. In fact, the scattering of the incident photons generates the fourth photon [72]. Translating this to frequencies, these three input frequencies f1, f2, and f3 will mix and result in a four wave multiplexing on a fourth frequency f0 where: $f0 = f1 \pm f2 \pm f3$ [171]. FWM can result in interference, crosstalk and noise increase [72] which may reduce the performance of the network. However, according to [170] and [64], FWM can be reduced by unequally spacing channels.

Nonlinear effects remedies

Now that the problem has been studied, it's time to study the solutions. On comparing the situation causing or aggravating nonlinear effects in a medium to congestions with the situation in a highway, then one of the solutions would be to increase the lanes, and have extra spacing between them, to limit cars crashing into each other as they move near each other, or in our context, to prevent from signals interference.

How about lasers? I've determined that the acceptance angle in the fiber is dependent on the refractive index difference between the core and the cladding. Daav Kleiner and Jeff Kaplow found that bending the fiber also affects how the core accepts light. They also recognized that the single mode or the fundamental mode propagates down the fiber with a slightly lower numerical aperture than any of the higher modes. The combination of a low numerical aperture in the core and a bend in the fiber allow the higher mode to escape, leaving the fundamental mode, as shows the figure below. The evanescent field of the single mode beam expands to fill the core diameter, avoiding nonlinear effects. Moreover, the amount of energy that escapes as a higher mode is minimum. Serious, extremely high beam quality fiber laser were now possible. Laser technology has evolved over the past half century [172].

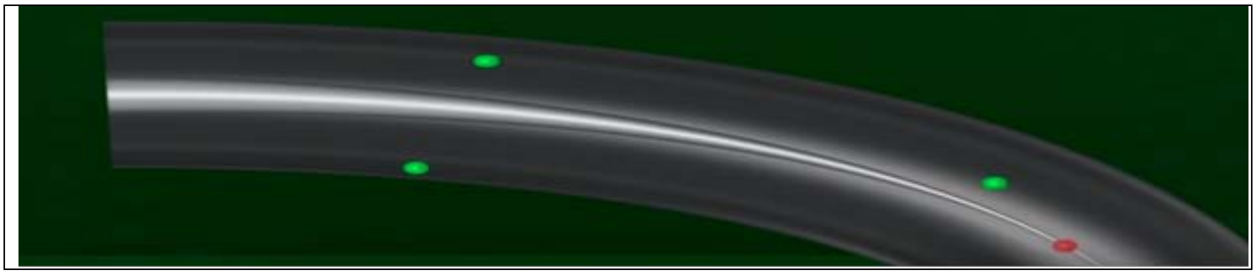


Figure 1.9 Fundamental mode in the core, while higher modes escaping. [172]

Residual pump strippers? Added to the end of the output of the fiber. The stripper has a higher refractive index than the nominal cladding on the fiber. This then catches the high numerical aperture light remaining from the pump and releases out of the fiber as long as lost thermal energy.

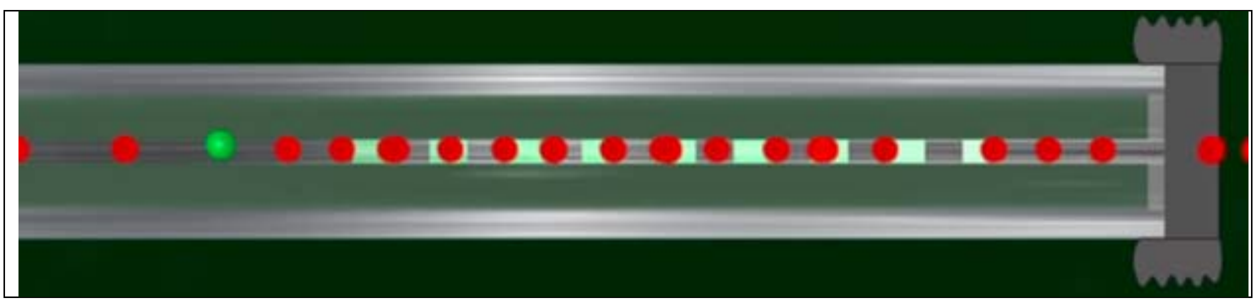


Figure 1.10 Residual Pump Stripper [172]

Summarized key literature review areas

The below tables represent key selected area from literature review studied in the following areas: Optical Networks Attacks; Physical Layer Nonlinearities; Routing & Wavelength Assignment; Wavelength Assignment; and Routing & Network Management

Author	Attack	Attack Strategy	Security Control
B. Chandrasekaran,	EDFA Attacks	Injecting high-power jamming signal in EDFA's passband to deprive other signals of power and increase attacker's own.	Use Automatic Gain Control Amplifiers
Tao Deng ; S. Subramaniam; Cisco	Low Power QoS Attack	Attacking an optical splitter at the head of a link to attenuate the propagation power: Degrading the performance metrics (QoS) of attacked lightpaths, and potential attack propagation in case of OXC equalization at network nodes.	Use QoS degradation monitoring Systems based on OOF signaling, monitoring the following criteria: BER level, time during which that BER level was sustained, FP and FN.
Ioannis Tomkos, Maria Spyropoulou, et al.;	Correlated Jamming Attack	Bending fiber, injecting noise at the tapping point, resulting in eavesdropping or degradation of the SNR on the attacked signal	Use Threshold power detector systems, Optical Spectrum Analyzers, or Optical time domain reflectometers.

Figure 1.11 Optical Networks Attacks Key literature review areas [279][280][281]

Author	Physical Layer Impairment	Conclusion
Politi, C. T., Matrakidis, C., & Stavdas, A.	Self Phase Modulation (SPM)	The interplay between SPM and fiber dispersion distorts the received waveform, degrades receiver sensitivity and limits transmission distance and optical amplifier output power.
T. R. SWAIN	Cross Phase Modulation (XPM)	Nonlinear type of optical cross talk which causes the refractive index of the fiber to change. Consequently, the phase of all optical pulses that are sharing the same fiber will be modulated and will impact is the broadening and distortion of the signal's shape.
B. Batagelj, M. Vidmar and S. Tnmazic*	Four Wave Mixing (FWM)	Occurs when phase matching condition is satisfied, In particular, for signals with very similar frequencies propagating near the zero dispersion wavelength of the fiber.

Figure 1.12 Physical Layer Nonlinearities Key literature review areas [282][283][284]

Author	Algorithm	Conclusion
I. Chlamtac, A. Ganz, G. Karmi	First Fit	All wavelengths are numbered. The wavelength with the lowest number is selected from the available wavelengths.
R.A. Barry, P.A. Humblet	Random Fit	A wavelength is selected randomly from the available wavelengths.
Rajiv Ramaswami, Galen H. Sasaki	Most-used	The most-used wavelength from the available wavelengths on the path is selected.

Figure 1.13 Wavelength Assignment Key literature review areas [285][286][287]

Author	Algorithm	Conclusions
A. Girard	Fixed Routing	The path for each source destination pair is calculated off-line using Dijkstra Algorithm.
H. Harai, M. Murata, H. Miyahara	Fixed Alternate Routing	Instead of calculating one path for each pair, fixed alternate routing calculates off-line several paths for each pair.
A. Mokhtar, M. Azizoglu	Adaptive routing	The paths are calculated on-line, depending on the network state, which reflects the resource usage.

Figure 1.14 Routing and Network Management Key literature review areas [288][289][290]

Author	Algorithm	Conclusions
R. Ramaswami, et al	ILP, relaxed ILP (Max-RWA)	- Upper bound is derived for the carried traffic of connections - Lower bound on the blocking probability
Banerjee, et al	LP (Min-RWA)	- Randomized rounding technique for LP - Graph Coloring approach for wavelength Assignment
M. Kumar	MRPR	The minimum reconfiguration probability routing (MRPR) algorithm selects the most reliable routes and assigns wavelengths to connections in a manner that efficiently uses the light path (LP) established to consider all possible requests.

Figure 1.15 Routing and Wavelength Assignment Key literature review areas [291][292][293]

Conclusion

This chapter has presented an overview of WDM with its types, Routing & Wavelength Assignment Algorithms Background and Motivation, Literature Review, Definition, Objectives, Categories, Classification as an NP hard problem, as well as a discussion of its sub-problems and some of the main algorithms to implement each. This chapter has also given an overview of 5G and its relation to WDM networks, its main areas of focus and impact, as well as challenges and vision for 6G. Moreover, the chapter reviewed Security challenges and controls in RWA, and finally had given a view of some of the most prevalent nonlinear effects in WDM Networks.

Chapter 2: Nonlinear Effects

Nonlinear Effects in WDM Networks, Analytical Study

This chapter studies nonlinear effects in WDM Network. The focus is on both the propagation of a unique signal as well as a set of them in optical fibers in a WDM network. The chapter presents an analytical model to study the effects of having nonlinearities in a WDM system. Three main nonlinear effects are studied here are Cross Phase Modulation, Self-Phase Modulation, and Four Wave Mixing. Simulations are performed on up to 265 channels WDM System.

Introduction

Before diving into the subject, it is important to distinguish between two types of Fiber Optics: (1) Linear and (2) Nonlinear. The Linearity of the first category comes from the fact that the medium properties of the fiber do not depend on the signal. On the other hand, when the material properties of the fiber get affected by the signal itself, then this will be classified under the second category of Nonlinear Fiber Optics. This chapter discusses the propagation of signal in the fiber taking into account nonlinear effects. The target is to answer the following question: If the medium properties change in a fiber due to nonlinear effects, what are the implications on the signal?

Analysis

Propagation of one signal within the optical fiber

The 80s were marked as an era during which many researchers were invested in experimental work to establish the equivalence of light and electromagnetic propagation [173]. Marking the beginning of radio telecommunications, in 1887, Heinrich Hertz was able to generate and detect radio waves in the laboratory [174]. This came validating Maxwell's electromagnetic theory [175], according to which, electromagnetic waves could be emitted from an oscillating electric dipole, propagating via space at the speed of light; while exhibiting wave-like characteristics of light propagation [173], [174]. Taking an example of a pulse that needs to be transmitted on the optical fiber in the linear domain. The properties of the propagation of such pulse are only decided by the medium properties [176] [177]. One way to go about this, could simply require solving the wave equation without worrying about the amplitude of the pulse, and then get the normal distribution, propagation constant and find out about the propagation characteristics of a path. Now imagine that the medium properties are modified by the pulse itself. Let's say that the refractive index of the optical fiber is related to the intensity of light. Now, let's assume that the refractive index increases with the intensity of light. This means that the whole pulse is actually not going to see the same propagation parameters. That is to say, at the center of the pulse when the light is intense, the refractive index seen by the pulse is different than on the edge of the pulse when the light is less intense. Because of that, the refractive index on the edge is less than the refractive index seen by the pulse in its center. If one tries to send a continuous signal in the optical fiber, any small perturbation will break the signal into pulses. This is phenomenon is referred to, in the fields of nonlinear optics and fluid dynamics, as modulation instability. What happens here is that the deviations from a periodic waveform are reinforced by nonlinearities, generating by that spectral sidebands while also causing a breakup of the waveform into a set of pulses (wave trains) [178], [179], [180]. Given this, it's important to remember that without taking into consideration the pulse nature of the signal, the nonlinear propagation will not be very effective.

In this chapter, I will present a simple formulation and I'll answer the question why is nonlinear fiber optics important. I'm also going to investigate if it is important to include the effects of nonlinearity into fiber optics communications or not. If the answer is yes, then, I'm going to study if one can make use of these nonlinear effects to improve the signal propagation from the optical communication point of view?

1. Analytical Model

I'm going to begin with taking a very basic model. When the electric field is imposed on a dielectric material, the result is a tiny, compared to the scale of atom dimensions, displacement of both positive and negative charge. Every molecule of the material is characterized by an induced dipole moment and the material is 'polarized' [181]. The induced polarization in the material given by susceptibility of the medium. Normally, only the first order susceptibility is considered, due to the dielectric material. However, that's just an approximation. In real life, when light intensity is high, the first order term is simply not adequate and one needs to consider higher order terms into the polarization of the material to account for nonlinear effects. A medium is considered nonlinear, if there's a nonlinear relation between the induced polarization P and the applied electric field E [182]. In general, the induced polarization in the material is P, given as:

$$P = \varepsilon_0 \left\{\chi^{(1)} .\ \bar{E} + \chi^{(2)} :\ \bar{E}\,\bar{E} + \chi^{(3)} :\ \bar{E}\,\bar{E}\,\bar{E} + \cdots\right\} \tag{1}$$

Where:

$\chi^{(1)}$ *is the first order susceptibility*

$\chi^{(2)}$ *is the second order susceptibility*

$\chi^{(3)}$ *is the third order susceptibility*

$\bar{E}$ *is the imposed electric field*

The dominant term from the Induced Polarization equation is (1) and it contributes to dielectric constant, the second term (2) is small for glass (SiO2), and the third term (3), also known as the third order susceptibility says that the refractive index is proportional to the square of the electrical field, and that's the one that'll contribute in glass to the nonlinear effects. Notice here that when the intensity is very low, the second and third terms are negligible [183].

$$\bar{n}(\omega, |E|^2) = \bar{n}(\omega) + n_2|E|^2 \tag{2}$$

n_2 is the nonlinearity coefficient (a.k.a Kerr nonlinearity) [184]. It is material dependent and also dependent on the third order susceptibility of the medium as shown below:

$$n_2 = \left(\frac{3}{8}\, n\right)\chi^{(3)} \approx 2.3 \times 10^{-22}\, m^2/v^2\ (for\ glass) \tag{3}$$

Comparing the nonlinear coefficient of glass to other materials, one can see that the glass's coefficient is 2 orders of magnitude smaller. Now if this is the case for glass compared to other bulk materials, should one really care about the effects of nonlinearities in optical networks at all? To properly answer this question, there's a need to understand how do nonlinearities manifest in optical fibers compared to the bulk materials and if there's situational difference.

- *Nonlinearities in Bulk Material*

Let's start with the bulk material. When the light beam enters the bulk material, the nonlinear interaction will be in the light and the matter of that bulk material. On the other hand, when the light enters the fiber, it travels a long distance during which it keeps interacting with the fiber, resulting in a cumulative nonlinear effect. To compare between the bulk and the fiber material, one can check how much enhancement of nonlinear interaction takes place in fiber material compared to a bulk material. Let's now define a figure of merit or efficiency parameter for nonlinear interaction, where:

$$\eta \sim I \times L_{eff} \tag{4}$$

I is the intensity of light, which is the power intensity per meter area (w/m^2), L_{eff} is the interaction length in (m) [183]. Equation (4) shows that increasing efficiency of nonlinear interaction can be achieved by either increasing the intensity of light, the interaction length, or both if that's possible. Let's say, one would like to increase the light intensity in some bulk material. To do that one would need to focus the light beam using a lens. So, by focusing of the light, the spot size becomes smaller and smaller and then the light intensity can be enhanced.

Having a Gaussian Light Beam, with a spot radius of ω_0 radius, or a diameter of $2\omega_0$, it is possible to represent the Intensity of Light I as the optical beam power divided by the area of the spot as per the equation:

$$I = \frac{P}{\pi\, \omega_0^2} \tag{5}$$

Where P is the light beam power and ω_0 is the light spot radius in the bulk material from this equation, it can observed that the length over which the beam focus is related to the size of the spot. So, in a bulk medium, when trying to tightly focus the optical beam, the interaction length gets affected as well [183]. The Interaction length in bulk optics is:

$$L_{eff} = \frac{\pi\, \omega_0^2}{\lambda} \tag{6}$$

Let's now compute the figure of merit:

$$\eta_{bulk} = I \times L_{eff} = \frac{P}{\pi\,\omega_0^2} \times \frac{\pi\,\omega_0^2}{\lambda} = \frac{P}{\lambda} \tag{7}$$

This above equation shows that the figure of merit, or the interaction efficiency is independent of the size of the focusing beam. So, in bulk material, if one want to enhance the effect of nonlinearity, and want to do a certain wavelength, the only option available is to increase the optical power. So for research focusing on bulk material nonlinearities, high power is required so that nonlinearities can start getting induced effectively and allow researchers to study their effects.

- *Nonlinearities in Optical Fiber*

Now, let's compare the situation with Optical Fiber. In Optical fiber, when the light gets in, it remains focused, or confined to a region which is the size of the core. Since the loss on the optical fiber is very small, the intensity reduces but very slowly, allowing it to remain almost constant over some tens of kilometers. In the fiber case, let's define the radius of the optical fiber core as a [183]. Hence, the light intensity I would be defined as:

$$I = \frac{P}{\pi\,\alpha^2} \tag{8}$$

When the light propagates through the optical fiber, it exponentially decreases. Let's define the power attenuation constant as α, and the power function as per [183] [185] below:

$$P(z) = P(0)\,e^{-\alpha z} \tag{9}$$

Now, taking a distance: $z_0 = \frac{1}{\alpha}$ this will result in:

$$P(z_0) = P(0)\,e^{-\alpha z} = P(0)\,e^{-\alpha\frac{1}{\alpha}} = P(0)e^{-1} \tag{10}$$

In the case of optical fiber, $L_{eff} \approx \frac{1}{\alpha}$. Now, let's compute the figure of merit for the optical fiber:

$$\eta_{fiber} = I \times L_{eff} = \frac{P}{\pi\, a^2} \times \frac{1}{\alpha} \qquad (11)$$

- *Nonlinearities in Bulk Material and Optical Fiber*

In order to determine how much interaction efficiencies increase in the optical fiber compared to bulk material, let's take the ratio of η_{bulk} and η_{fiber} as shown below:

$$\frac{\eta_{fiber}}{\eta_{bulk}} = \frac{\frac{P}{\pi\, a^2} \times \frac{1}{\alpha}}{\frac{P}{\lambda}} = \frac{\lambda}{\pi\, a^2 \alpha} \qquad (12)$$

Let's put some parameters for a typical optical fiber:

$$a \sim 2\ \mu m \qquad (13)$$

$$\alpha = 0.2 \frac{dm}{Km} = 0.2\ \times\ 10^{-3} \frac{db}{m}$$

$$\lambda \sim 1550\ nm = 1.55\ \mu m$$

$$\frac{\eta_{fiber}}{\eta_{bulk}} = \frac{\lambda}{\pi\, a^2 \alpha} = 10^9$$

So for the same parameters, the nonlinear effects inside optical fibers is enhanced by 1 billion times than those inside of the bulk material. This also means that whatever affects one can see in bulk material with 1 Watt of power, the same effect inside optical fiber can be seen with only 1 nW of power. This means that with the power dealt with in Optical Fiber in the order of microwatt or mW, the nonlinear effects will certainly be present because once the power will be confined in optical fiber, it will keep interacting with the fiber over long kilometers.

Comparing the Light intensity required to get nonlinear effects in Fiber vs. in bulk material, it has been shown that in Fiber, such Intensity is at least two orders of magnitude smaller. Now, in fiber optic communications, it is not a matter of working with single fibers, but rather with complex systems of multi fiber optics such as WDM and DWDM. Assuming an intensity of 1 mW/ m^2 induced per fiber, in a 100 channels WDM System that'll already be 100 μW / m^2.

WDM systems are using currently way more channels that this example, and the power intensity inside optical fiber is certainly going to be large enough to really worry about the nonlinear effects in these system while giving us great motivation to study them and analyze ways to make the best use out of them to rather make improvements to the system.

- *Light Propagation in Optical Fiber with Nonlinearities*

To analyze the propagation of light in the optical fiber in the presence of nonlinearity, I'll start from the very basic Maxwell's Equations [175] below:

$$\nabla \times \bar{E} = -\frac{\delta \bar{B}}{\delta t} = -\mu_0 \frac{\delta \bar{H}}{\delta t} \tag{14}$$

This is assuming that permeability is not a function of time. Also since it is a matter of a dielectric material, one can assume that the permeability is the same as that of free space, hence μ_0.

$$\nabla \times \bar{H} = \frac{\delta \bar{D}}{\delta t} \qquad \bar{J} \equiv 0 \qquad \textit{Assuming the conduction } \bar{J} \textit{ of the medium is } 0 \tag{15}$$

$$\nabla \times \bar{D} = 0 \qquad \bar{\delta} \equiv 0 \qquad \bar{D} \textit{ is the replacement} \tag{16}$$

$$\nabla \times \bar{B} = 0 \tag{17}$$

$$\bar{D} = \varepsilon_0 \bar{E} + \bar{P} \tag{18}$$

$$\textit{And since}: \quad P = \varepsilon_0 \left\{\chi^{(1)}. \bar{E} + \chi^{(2)}: \bar{E}\bar{E} + \chi^{(3)}: \bar{E}\bar{E}\bar{E} + \cdots\right\} \tag{19}$$

$$\textit{Then}: \quad \bar{D} = \varepsilon_0 \bar{E} + \varepsilon_0 . \chi^{(1)} E \tag{20}$$

In normal situations, neglecting the other terms (21)

$$\bar{D} = \varepsilon_0 \left\{1 + \chi^{(1)}\right\} \bar{E} \quad \leftarrow \text{Linear Case}$$

The quantity: $\{ 1 + \chi^{(1)}\}$ is the dielectric constant of the medium. In general such quantity is complex especially if there are losses in the medium.

$$\nabla \times \nabla \times \bar{E} = -\nabla \times \left\{\mu_0 \frac{\delta \bar{H}}{\delta t}\right\} = -\mu_0 \frac{\delta}{\delta t}\{\nabla \times \bar{H}\} = -\mu_0 \frac{\delta}{\delta t}\left\{\frac{\delta \bar{D}}{\delta t}\right\} \tag{22}$$

$$= -\mu_0 \frac{\delta^2}{\delta t^2}\{\varepsilon_0 \bar{E} + \bar{P}\} = -\mu_0 \frac{\delta^2}{\delta t^2}(\varepsilon_0 \bar{E}) - \mu_0 \frac{\delta^2 \bar{P}}{\delta t^2}$$

$$P = \varepsilon_0 \left\{\chi^{(1)}.\ \bar{E} + \chi^{(2)} :\ \bar{E}\,\bar{E} + \chi^{(3)} :\ \bar{E}\,\bar{E}\,\bar{E} + \cdots\right\} \tag{23}$$

$$\nabla(\nabla.\bar{E}) = -\nabla^2 \bar{E} = -\frac{1}{c^2}\frac{\delta^2 E}{\delta t^2} - \left\{\mu_0 \frac{\delta \bar{H}}{\delta t}\right\} = \mu_0 \left\{\frac{\delta^2 P_L}{\delta t^2} + \frac{\delta^2 P_N}{\delta t^2}\right\} = 0 \tag{24}$$

Where: P_N: Nonlinear Polarization, P_L: Linear Polarization

The wave equation: $\nabla^2 \bar{E} - \frac{1}{c^2}\frac{\delta^2 \bar{E}}{\delta t^2} = \mu_0 \frac{\delta^2 P_L}{\delta t^2} + \mu_0 \frac{\delta^2 P_N}{\delta t^2}$ (25)

Where:

$$\bar{E} = E_0\, e^{j\omega_0 t}\ with\ \omega_0\ the\ signal\ frequency$$

$$\bar{E}\ a\ function\ of\ space(r)\ and\ time(t)$$

$$\hat{E}(\bar{r}, \omega - \omega_0) = \int_{-\infty}^{\infty} E\,(\bar{r}, t) e^{-j(\omega - \omega_0)t} dt \tag{26}$$

That is Fourier Transform, spectrum of the electric field as a function of distance:

$$\nabla \hat{E} + \varepsilon(\omega) K_0^2 \hat{E} = 0 \tag{27}$$

$$\varepsilon(\omega)\ is\ given\ as: \qquad \varepsilon(\omega) = 1 + \chi^{(1)}(\omega) + \varepsilon_{NL} \tag{28}$$

$$\hat{E}(\bar{r}, \omega - \omega_0) = F\ (\delta, \varphi)\hat{A}(z, \omega - \omega_0)\ e^{-j\beta_0 z} \tag{29}$$

$$\nabla^2 \perp\ \bar{F} + \{\varepsilon(\omega)K_0^2 - \hat{\beta}^2\}F = 0 \tag{30}$$

$$-2j\beta_0 \frac{\delta \hat{A}}{\delta z} + \left(\hat{\beta}^2 - \hat{\beta_0}^2\right)\hat{A} = 0 \quad and\ \frac{\delta \hat{A}}{\delta z}\ is\ negligible \tag{31}$$

- *Summary*

To summarize, when the light is intense, the induced polarization has high order susceptibility terms also and they cannot be neglected [186]. For a material like glass, the second order susceptibility contribution is negligible because S_iO_2 molecule is symmetric, so third order susceptibility term is what contributes to the nonlinear effects. Even if the glass is not a very good nonlinear material because its nonlinear coefficient is two orders of magnitude smaller compared to many well-known nonlinear materials, since the interaction length inside the optical fiber is very large, the nonlinear effects are very pronounced inside the optical fiber.

Compared to the bulk material, it has been shown that the interaction efficiency in optical fiber is a billion times more so this is a strong case to investigate the nonlinear effects inside the optical fiber. Next, it has been shown how starting from the Maxwell's equations [175] the wave equation was written in terms of the polarization which includes the nonlinear terms.

Propagation of Multiple Signals within the Optical Fiber

The previous section studied what happens inside of the optical fiber if there's one signal propagating. The section below studies what happens inside the optical fiber with multiple signals propagating through it. As part of this, the following section treats two phenomenon: Cross Phase Modulation and Four Wave Mixing. Both phenomena are related to the term which is due to third order susceptibility.

1. Cross Phase Modulation

The electric field has two frequency components. The first having an amplitude E_1 and a frequency 1 and the second has the amplitude E_2 and the frequency 2 as per the equation:

$$E = E_1 e^{j\omega_1 t} + E_2 e^{j\omega_2 t} \quad (32)$$

Substituting this into the polarization expression, one will get the nonlinear polarization PNL created inside the material. This polarization multiple nonlinear components: One at ω_1, another one at ω_2 and other components in the same frequency range as the previous two.

$$P_{NL} = P_{NL}(\omega_1)e^{j\omega_1 t} + P_{NL}E_2 e^{j\omega_2 t} + P_{NL}(2\omega_1 - \omega_2)e^{j(2\omega_1 - \omega_2)} + \cdots \quad (33)$$

With: $P_{NL}(\omega_1) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}\, E_1$

$$P_{NL}(\omega_2) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}\, E_2$$

$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\}$$

With j being the frequency and n_2 the nonlinear coefficient. Note from the delta of the refractive index above, that the nonlinear effects of another signal are twice as higher than those of the signal itself. When the term $|E_{3-j}|^2 = 0$, the refractive index change will be only dependent on the signal itself as the signal phase in this case gets modified by itself. This change in the refractive index gives a phenomenon that's called the Self Phase Modulation:

$$\Delta n_j \approx n_2\{|E_j|^2\} \quad (34)$$

When that term $|E_{3-j}|^2$ is different than 0, this means that the change in the refractive index is not only dependent on the signal itself but due also to other signal that's propagating. The phase then is going to be changed by both the signal as well as the other coexistent signal. This phenomena is called the cross phase modulation (XPM):

$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\} \quad (35)$$

In WDM Systems, there will be multiple channel transmissions within the optical fiber and XFM. In WDM Systems, if large number of channels propagate and if there's sufficient power in these channels, there will be a change in the phase of each signal due to the existence of the other signals. Also note here, if n channels are transmitting, then, each channel is going to be affected by the power present and remaining in 1-n channels. The collective effect of Cross Phase Modulation is way stronger than what one will see from self-phase modulation. Now in order to formulate the problem, the field distribution for the j channel can be written as:

$$E_j = F_j(x,y)A_j(z)e^{-j\beta_0 jz} \tag{36}$$

Following the same steps as were done for the Self Phase Modulation, this results in two equations: One for the field distribution: $F_j(x,y)$ and one for the evolution of the envelope: $A_j(z)e^{-j\beta_0 jz}$ is a function of distance on the optical fiber. Taking the nonlinear variation of the Schrodinger equation, that is the Nonlinear Schrodinger (NLS) equation, an equation belonging to classical field theory [187]. This equation has, among others, applications related to the propagation of light in nonlinear optical fibers [188]. The NLS equation is given as:

$$\frac{\delta A_j}{\delta z} + \beta_{1j}\frac{\delta A_j}{\delta t} - \frac{j\beta_{2j}}{2}\frac{\delta^2 A_j}{\delta t^2} + \frac{\alpha_j}{2}A_j = -j\frac{n_2\omega_j}{c}\{f_{jj}|A_j|^2 + 2f_{jk}|A_k|^2\} \tag{37}$$

Where:

$\frac{\delta A_j}{\delta z}$ *is the rate of the change as a function of distance*

$\beta_{1j}\frac{\delta A_j}{\delta t}$ *is the group velocity*

$\frac{j\beta_{2j}}{2}\frac{\delta^2 A_j}{\delta t^2}$ *is the group velocity dispersion*

$\frac{\alpha_j}{2}A_j$ *is the attentuation*

f_{jj} *is the overlap intergral, amount of overlap between each two signals*

$= -j\frac{n_2\omega_j}{c}\left\{f_{jj}|A_j|^2 + 2f_{jk}|A_k|^2\right\}$ *is the nonlinear term*

The overlap integral is given as:

$$f_{jk} = \frac{\iint |F_j(x,y)^2|\,|F_k(x,y)^2|dx\,dy}{\iint |F_j(x,y)^2| \iint |F_k(x,y)^2|\,dx\,dy} \tag{38}$$

If j=k, then $f_{jk} = \frac{1}{A_{eff}} = \frac{1}{Effective\ Area}$ capturing how effective is the interaction between these two channels j and k. If frequencies are widely reduced, the overlap will be low and the value f_{jk} will be reduced. The nonlinear Schrödinger (NLS) equation will become:

$$\frac{\delta A_1}{\delta z} + \frac{1}{v_{\delta 1}}\frac{\delta A_1}{\delta t} - \frac{j\beta_{21}}{2}\frac{\delta^2 A_1}{\delta t^2} + \frac{\alpha_1}{2}A_1 = -\gamma_1\{|A_1|^2 + 2|A_2|^2\}A_1 \quad \text{with } \gamma_1 = \frac{n_2\omega_1}{c\,A_{eff}} \tag{39}$$

In fiber where dispersion is large, there will be sign difference between the velocity of the two signals, and then the walk off time will be very short, so the nonlinear interaction between these two pulses will be very small. Now if one uses the Dispersion Flattened Fiber (DFF), which is a fiber characterized by a smaller mode-field diameter which concentrates optical power in a smaller volume where the increased power density in fiber can cause nonlinear effects [189]. The velocity of the signals going through the DFF will be almost similar, the walk off time will be very long, and the nonlinear interaction between these pulses will be quite significant in a way that will increase the effect of Cross Phase Modulation.

To avoid Cross Phase Modulation effects in the WDM signal, it is desirable to keep some dispersion into the system. In the WDM system where number of channel is very high, say 128 channels WDM System every channel will have the effect of the remaining 127 channels. Moreover, every channel, even if it just carries the order of 2-3 mW, the total power of 128 channels will be easily in the order of 500 mW, and then the nonlinear phase which will be created because of this will be significant. So, in a WDM System one will see that the Cross Phase Modulation will be much stronger than the Self Phase Modulation because each channel will still carry a power that is very small say 2-3 mW. At such power, the Self Phase Modulation will be very weak, but collectively, the Cross Phase Modulation will be very strong. In a WDM System where it is desired for channels not to get affected by neighboring channels due the Cross Phase Modulation, a fiber that has dispersion could be used. One might have read in the literature, that it's desirable to make the dispersion small [190] [191], so that the pulse broadening do not take place. However, in the case of WDM channels, making dispersion 0 is not a good option, as channels then will start interacting and there will be Cross Talk between these channels. So, XPM affects the signals in different frequencies, it also gives the same phenomenon like the spectral broadening which is not symmetrical around the original frequency. The asymmetric spectrum can develop because of this phenomenon of Cross Phase Modulation. The same phenomenon gives another phenomenon called Four Wave Mixing, which will be discussed in the following section.

2. Four Wave Mixing

Four Wave Mixing in the optical system is similar to inter channel mixing or intermodulation products in the electrical system. When an amplifier goes into saturation, if one puts two frequencies inside the amplifier, the third frequency is generated because of the nonlinearities. These 2 frequencies give the product which is sum and difference of frequencies. The same phenomenon is seen in optical fibers because of the third order susceptibility. Consider a nonlinear polarization with 3 signals, or 3 frequencies simultaneously put in the optical fiber:

$$P_{NL} = \varepsilon_0 \chi^{(3)} \vdots \; E_1 E_2 E_3 \tag{40}$$

$$\omega_2 = \omega_1 + 2\Delta\omega \tag{41}$$

$$\omega_3 = \omega_1 + \Delta\omega \tag{42}$$

$$\omega_4 = \omega_1 + \omega_2 - \omega_3 = \omega_1 + \ \omega_1 + 2\Delta\omega - \omega_1 + \Delta\omega = \omega_1 + \delta\omega = \omega_3 \tag{43}$$

These three frequencies will produce a fourth frequency $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$ and they will be having the wave numbers:

$$k = k_1 \pm k_2 \pm k_3 \tag{44}$$

So from three frequencies: $\omega_1, \omega_2, \omega_3$ the following frequencies will be generated:

$$\omega_1 + \ \omega_2 - \omega_3, \omega_1 + \ \omega_3 - \omega_2, \omega_3 + \ \omega_2 - \omega_1, 2\omega_1 - \ \omega_2, 2\omega_1 - \ \omega_3, 2\omega_2 - \omega_3, 2\omega_2 - \ \omega_1, 2\omega_3 - \ \omega_2 \tag{45}$$

Figure 2.1 Equispaced 3 channels in WDM System

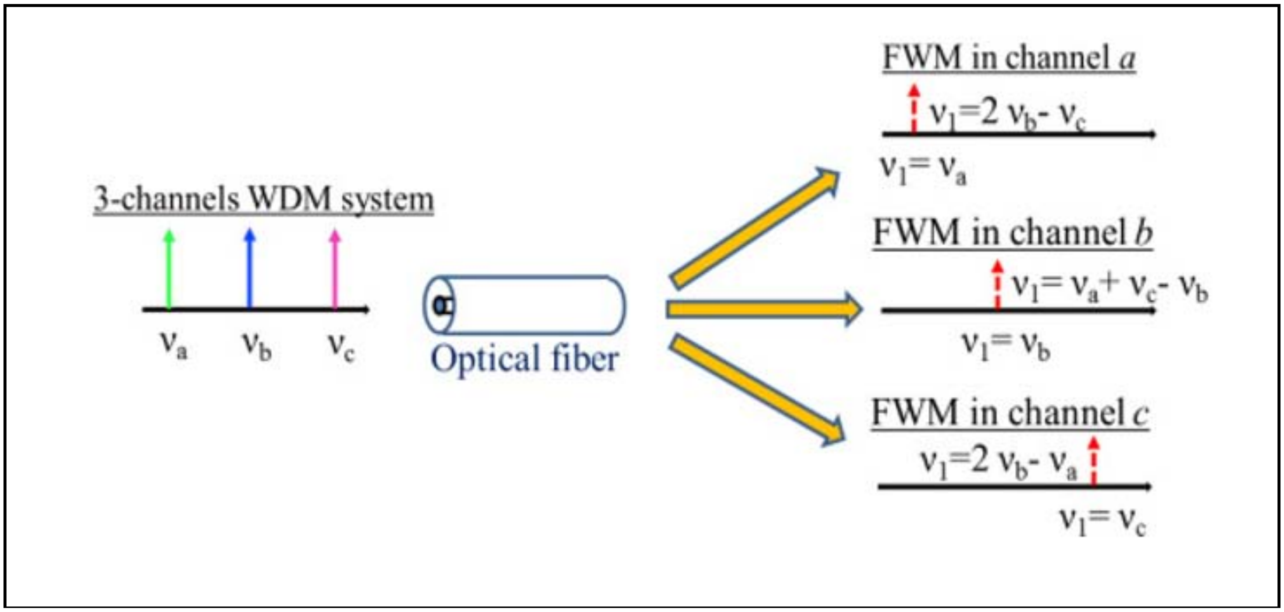


Figure 2.2 WDM in a 3 Channels WDM System

From the previous sections, PNL is defined as:

$$P_{NL} = P_{NL}(\omega_1)e^{j\omega_1 t} + P_{NL}E_2 e^{j\omega_2 t} + P_{NL}(2\omega_1 - \omega_2)e^{j(2\omega_1-\omega_2)} + \cdots \tag{46}$$

With: $P_{NL}(\omega_1) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}\, E_1$

$$P_{NL}(\omega_2) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}\, E_2$$

$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\}$$

From the above, it is observed that the frequency quantities from equation (44) and (45) have the same range or lie within the same frequency band while equation 45's frequency quantities fall in a different band altogether. For instance, ω_4 is almost three times ω_1. Those are not of interest. The phenomenon that frequencies of equation 45 will lie within the same frequency band is what is called Four Wave Mixing, which is also called the inter modulation. This phenomenon is exactly what one can see within an amplifier. Let's consider a WDM system where there are 3 channels and m wavelengths that are equispaced.

This means by this nonlinear process, the two channels ω1 and ω2 are going to put power into ω3. That could be interpreted in terms of Cross Talk between ω1 and ω3 and ω2 and ω3. There will be a Cross Talk phenomenon between all WDM Channels. To avoid this phenomenon, it looks like channels that are equispaced shouldn't propagate. Making dispersion 0 on optical fiber is not a good option. One should rather be keeping some residual dispersion to reduce the nonlinear effects in a multichannel transmission. As a side note, it is worth mentioning that the phenomenon of Four Wave Mixing is not always considered undesirable. It is actually quite beneficial for wavelength conversion. In paper [192], the authors have shown that using a length of 1 mm in Semiconductor Optical Amplifiers (SOAs) improves the efficiency by 20 dB with respect to standard devices, which is 0.5 mm long.

Simulation

The graph in figure 2.3 represents the number of mixing product terms (M) as a function of number of wavelength where:

$$M = N^2 \frac{N-1}{2} \tag{47}$$

As seen from the previous section, for a total of 3 input wavelengths, a total of 9 mixing product terms is obtained.

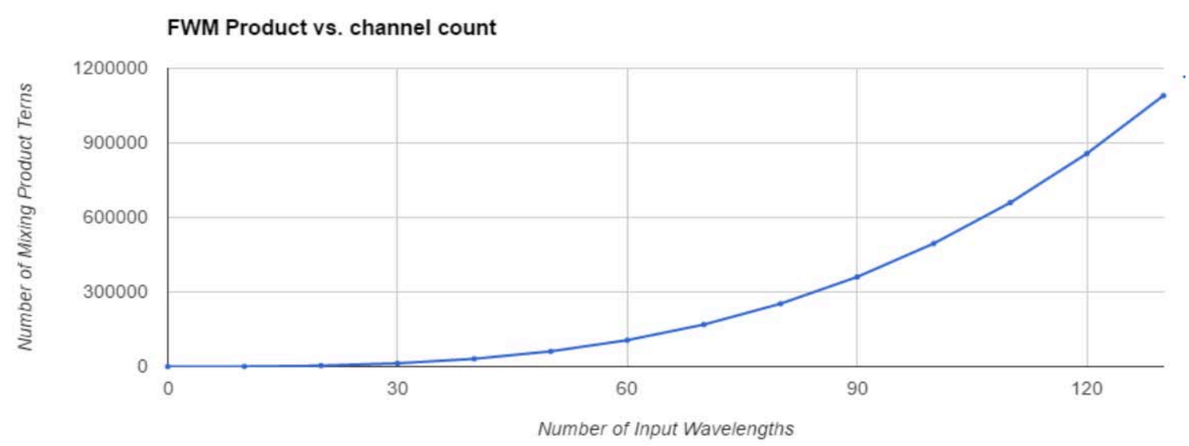


Figure 2.3 FWM Product vs. Channel Count

Figure 2.3 represents how this product is changing as the number of input wavelengths increases. As can be seen on the graph, for an input of 10 wavelengths, there are 450 mixing product terms. On tripling the number of input wavelengths to 30, this results in 13050 total mixing products. That is 2900 times higher. This is almost a turning point in the graph. Post that, it is observed that the FWM product continues to increase very rapidly reaching 1,090,050 terms for only 130 input wavelengths.

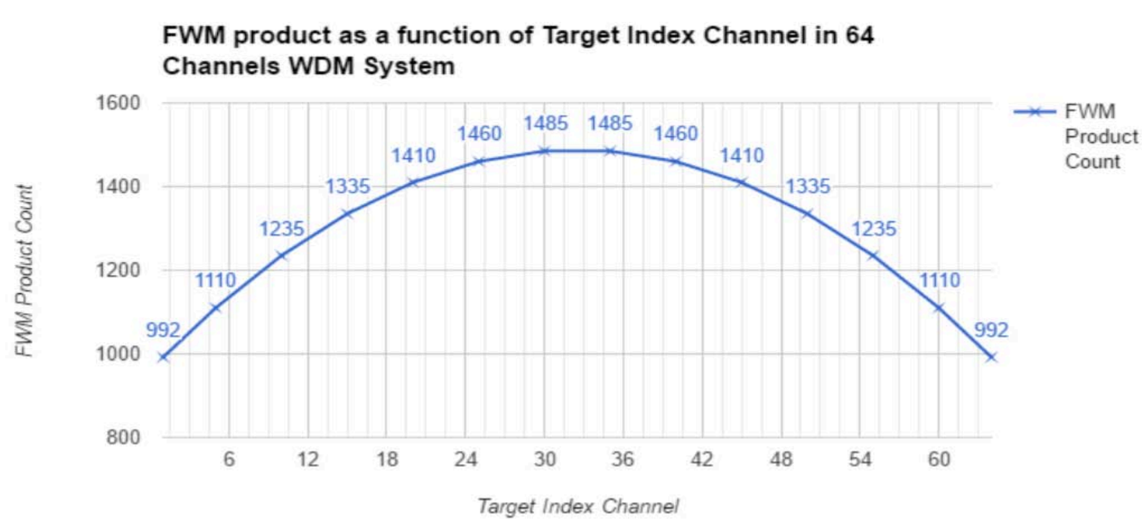


Figure 2.4 FWM product as a function of Target Index Channel in 64 Channels WDM System

The next graph in figure 2.4 depicts Four Wave Mixing as a function of the Target Index Channel in 64 Channels WDM System. In the case considered with 64 subcarriers, the 33th target index (subcarrier) plays a role in around 1485 FWM combinations while the 1dt and the 6^{4th} subcarriers have contribution to only approximately 1000 FWM combinations.

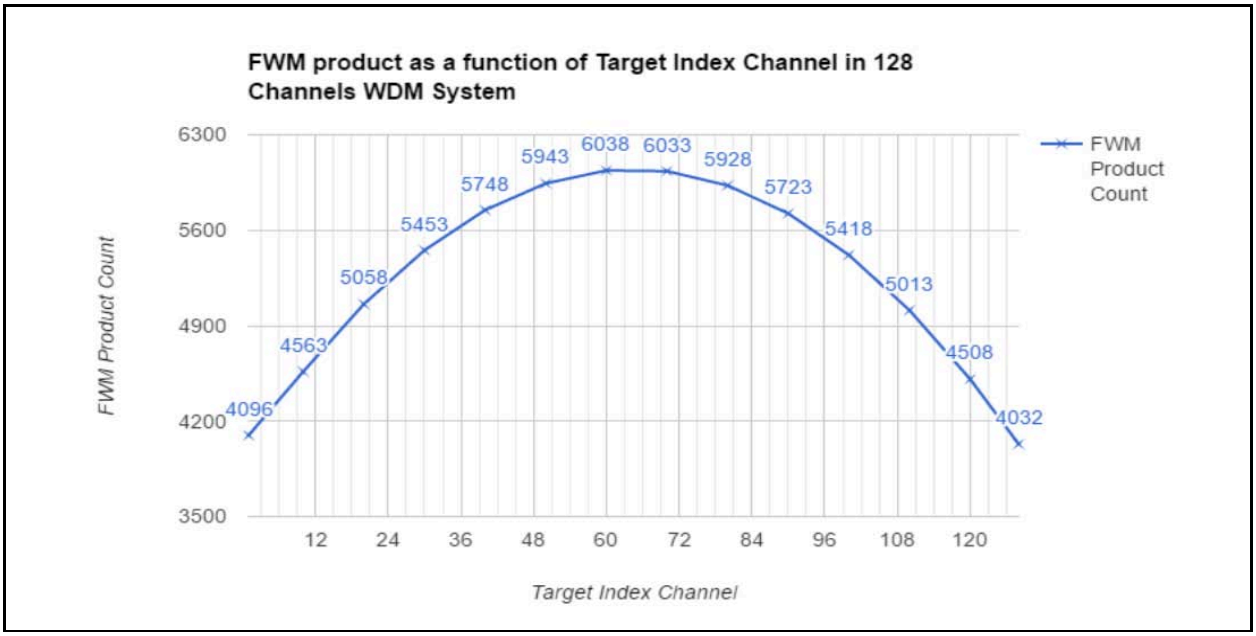


Figure 2.5 FWM product as a function of Target Index Channel in 128 Channels WDM System

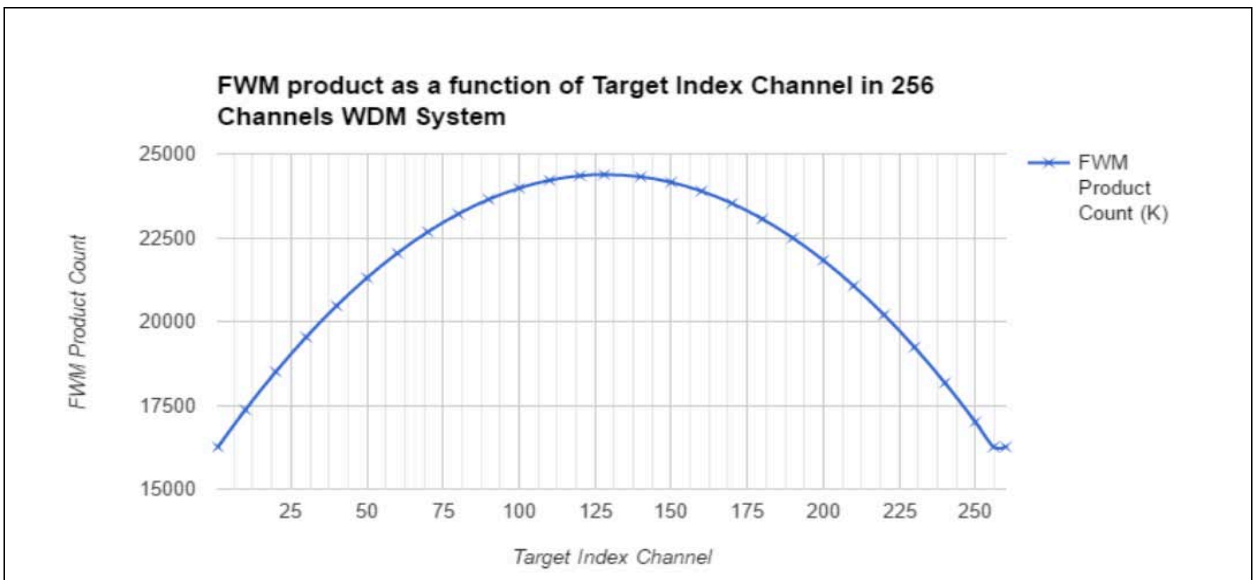


Figure 2.6 FWM product as a function of Target Index Channel in 256 Channels WDM System

Figures 2.5, and 2.6 represent the same principle but for cases of more subcarriers: 128, and 256 consecutively.

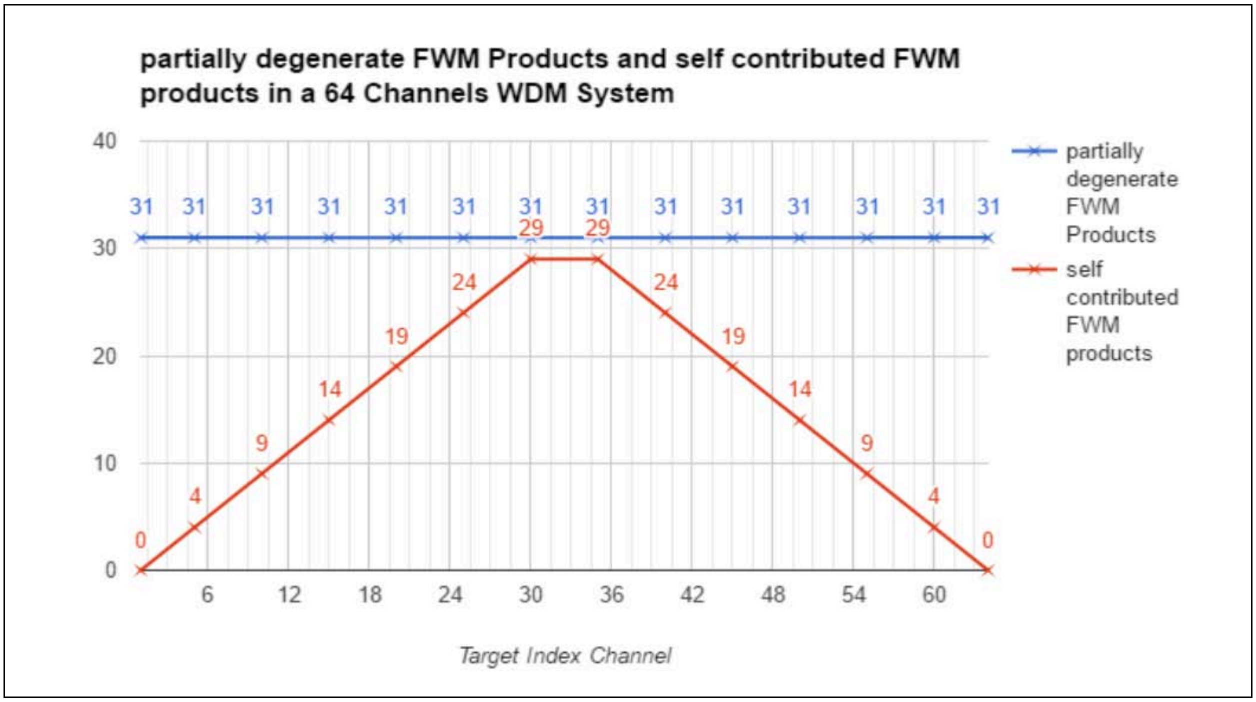


Figure 2.7 Partially degenerate FWM Products & self-contributed FWM products in a 64 Channels WDM System

In the next graph in Figure 2.7 a representation of the partially degenerate FWM products in a 64 Channels WDM System. Before explaining what's on the graph, a quick recall of the theory is necessary. Four Wave Mixing, is known as a 3rd order nonlinear process where 3 frequencies ($\omega_{pump-1}, \omega_{pump-2}, and\ \omega_{original}$) mix in a nonlinear medium, resulting in 2 extra frequencies (lower frequency $\omega_{strokes}$ and higher frequency $\omega_{antiStrokes}$) [193] [194].

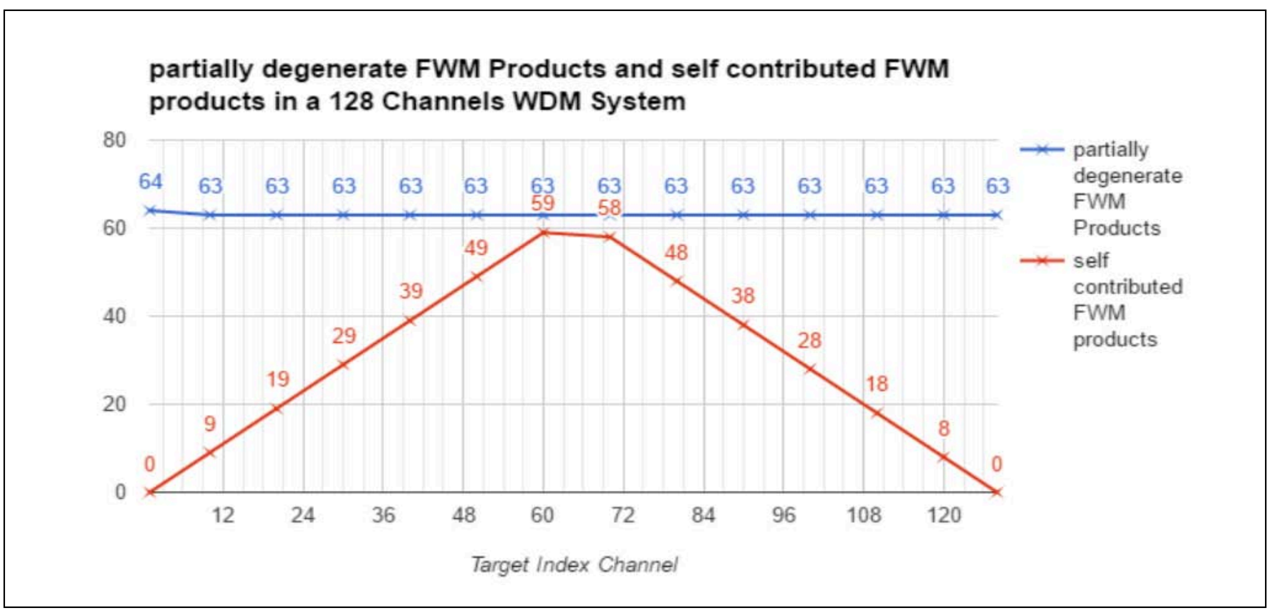


Figure 2.8 Partially degenerate FWM Products & self-contributed FWM products in a 128 Channels WDM System

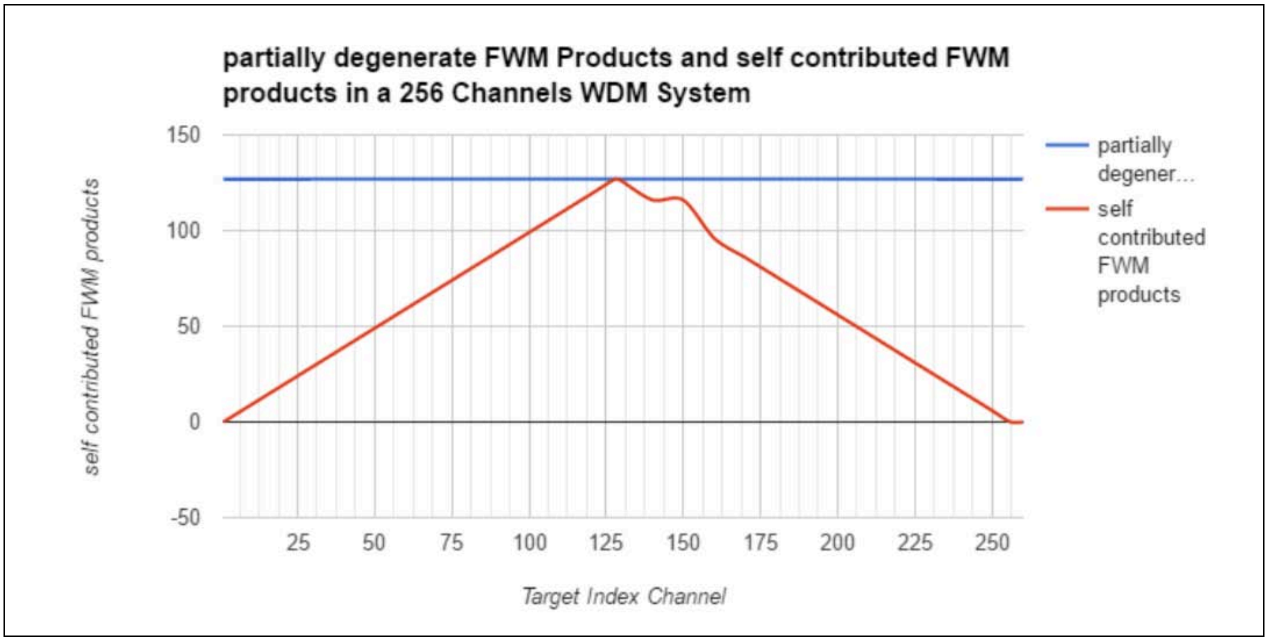


Figure 2.9 Partially degenerate FWM Products & self-contributed FWM products in a 256 Channels WDM System

When $\omega_{pump-1} = \omega_{pump-2} = \omega_{pump}$, the process is referred to as Partially Degenerate Four Wave Mixing (PDFWM). The graph shows that the degenerate products number is constant within the subcarrier band, meaning that these subcarriers are affected in an equal fashion. The same principle applies to WDM Systems of 128 and 256 Channels, in Figure 2.8 and 2.9.

Summary

In summary, the chapter begun with analyzing nonlinear effects in bulk material vs. fiber and found that high power is required so that nonlinearities can start getting induced effectively and allow researchers to study their effects. Specifically, one can see in bulk material with 1 Watt of power, the same effect inside optical fiber can be seen with only 1 nW of power. The following section of the study focused on the propagation of light within the optical fiber and showed how very pronounced inside the optical fiber, nonlinearities are, as a result of the very large interaction length inside the optical fiber. It has also been show that fiber dispersion has little effect on XPM, while a big negative impact on FWM, while more of it results in rather less SPM. The next sections highlighted the analytical model of these nonlinear effects as well as their simulations following the same pattern as testing continued with increasing number of channels within the WDM System.

Nonlinear Effects in WDM Networks, Experimental Study

Introduction

If an intense pulse propagates through a nonlinear medium such as fluorescein-doped boric acid glass (FBAG) for instance, the induced Polarization P can disperse into a power series of E representing a nonlinear relationship between the Polarization P and the electric field E as represents the following equations:

$$P = \varepsilon_0 \left\{ \chi^{(1)} .\ \bar{E} + \chi^{(2)} :\ \bar{E}\,\bar{E} + \chi^{(3)} :\ \bar{E}\,\bar{E}\,\bar{E} + \cdots \right\} \tag{48}$$

Where:

$\chi^{(1)}$ *is the first order susceptibility*

$\chi^{(2)}$ *is the second order susceptibility*

$\chi^{(3)}$ *is the third order susceptibility*

$\bar{E}$ *is the imposed electric field*

The polarization is directly proportional to the electric field. P is the polarization, $_0$is the permittivity of free space, $\chi^{(1)}$, $\chi^{(2)}$, $\chi^{(3)}$ are the susceptibility parameters, where $\chi^{(1)}$ describes linear optics, and $\chi^{(2)}$ and $\chi^{(3)}$ are for nonlinear optics. $\chi^{(2)}$ could be ignored, so this only leaves us with $\chi^{(3)}$ which is the lowest higher order susceptibility that affects the optical fiber and causes nonlinear phenomena in the fiber: $n = n_0 + n_2 |E|^2$ where the nonlinear refractive index is $n_2 = (3/8n_0)\ \chi^{(3)}$ for glass $n_2 = 3.2 \times 10^{-12}\ m^2/W$. $\chi^{(1)}$ and $\chi^{(3)}$ in this order, represent the linear and 3rd order nonlinear susceptibility. The real and imaginary parts of P and χ are shown below:

$$\begin{cases} P^{(1)} = P_R^{(1)} + iP_I^{(1)} \\ P^{(3)} = P_R^{(3)} + iP_I^{(3)} \end{cases} \quad (1) \qquad \begin{cases} \chi^{(1)} = \chi_R^{(1)} + i\chi_I^{(1)} \\ \chi^{(3)} = \chi_R^{(3)} + i\chi_I^{(3)} \end{cases} \quad (2) \tag{49}$$

It is required to distinguish between a set of nonlinearity manifestations, where the real part $\chi_R^{(1)}$ is responsible for Self-phase modulation (SPM), Cross-Phase modulation (XPM), Self-Steepening (SS), as well as Four-wave mixing (FWM). The imaginary part $\chi_I^{(1)}$ is responsible for Stimulated Brillouin Scattering (SBS), and Stimulated Raman Scattering (SRS).

Self-phase modulation (SPM): Imagine a very intensive signal such as continuous-wave (CW) or pulsed amplification (radar). This high intensity signal changes the properties of the medium of propagation, resulting in spectrum widening. SPM is modeled by Nonlinear Schrodinger Equation (NLSE). There are many modulation techniques. The variation of field is proportional to the intensity as shows the equation below:

$$\frac{\partial A}{\partial z} = j\gamma |A|^2 A \qquad with \quad \gamma = \frac{n_2 \omega_0}{c\, A_{eff}} \tag{50}$$

With cross phase modulation, there are two optical signals, the first signal changes the properties of the medium of propagation, while the medium of propagation affects the second signal, as shown below:

$$\frac{\partial A_1}{\partial z} = j\gamma_1 [|A_1|^2 + 2|A_2|^2] A_1 \;\; and \;\; \frac{\partial A_2}{\partial z} = j\gamma_2 [|A_2|^2 + 2|A_1|^2] A_2 \tag{51}$$

Four wave mixing is a 3rd order susceptibility in optical fiber. The phenomena happens as a result of 3 different optical frequencies mixing to produce a fourth intermodulation product:

$$v_{ijk} = v_i + v_j - v_k \tag{52}$$

FWM may cause cross talk, which could be explained in the following examples:

1. Two signals ν_1 and ν_2 at different frequencies, result in two new signals $2\nu_1 - \nu_2$ and $2\nu_2 - \nu_1$
2. One powerful signal generate 2 sidebands, symmetrical to the source signal.

Simulations

The experiments were carried out using OptiSystem 15 64-bit Simulation Software.

SPM

Below is the system design put in place to measure the effects of Self Phase Modulation.

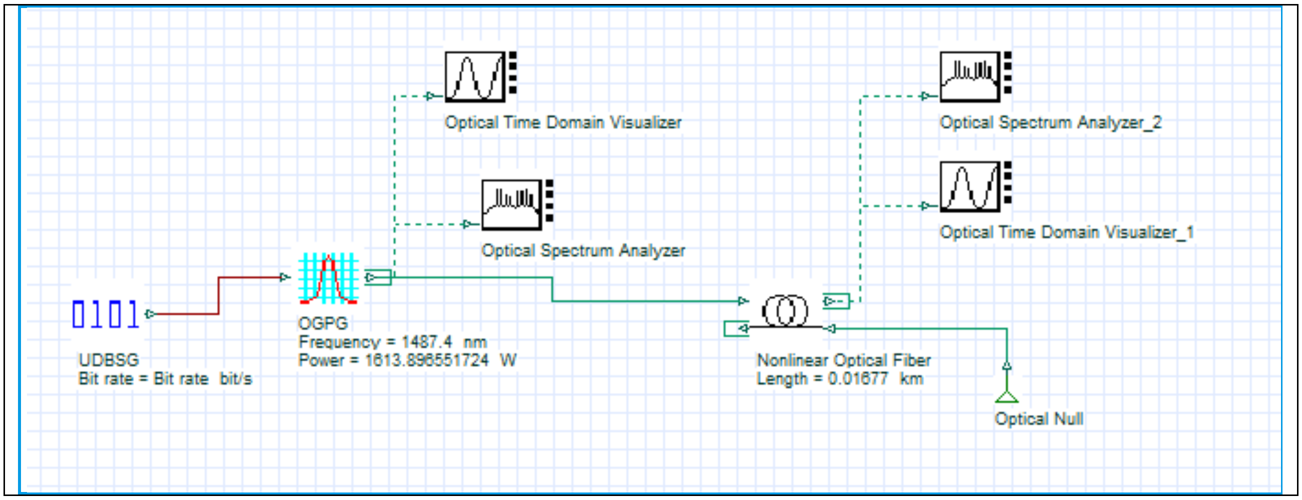


Figure 2.10 Optiwave SPM System Design

The experiment swept on a Power starting from 1 W with iteration #1, up until 1800 W with Iteration #30. The figure below shows the input signal as depicted by the Optical Spectrum Analyzer before entering the fiber, the Optical Time Domain analyzer depicting the power, and the Optical Spectrum Analyzer depicting the effects on the output signal. Iteration #1 (thin output signal) to iteration #30 (widened signal: SPM).

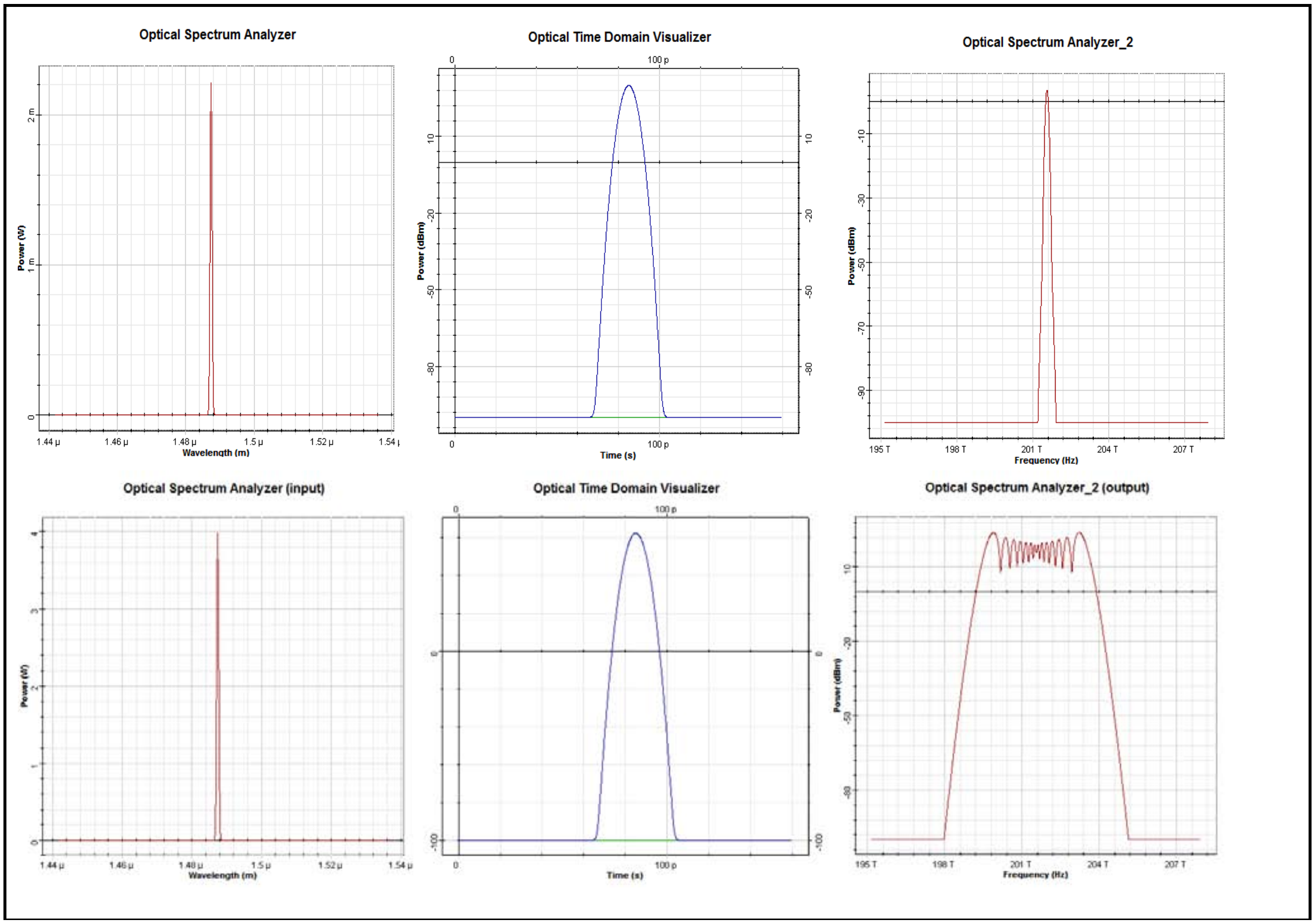
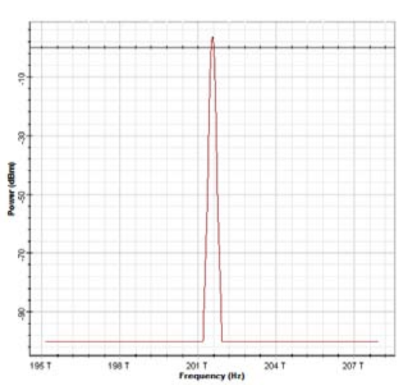
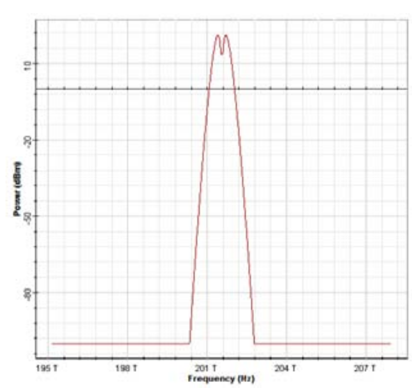
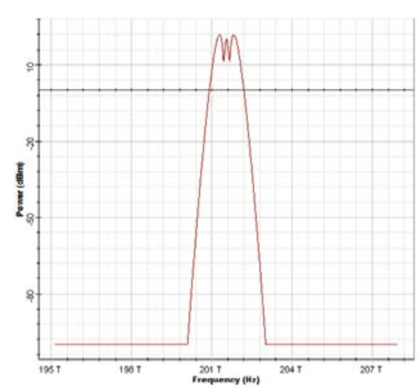
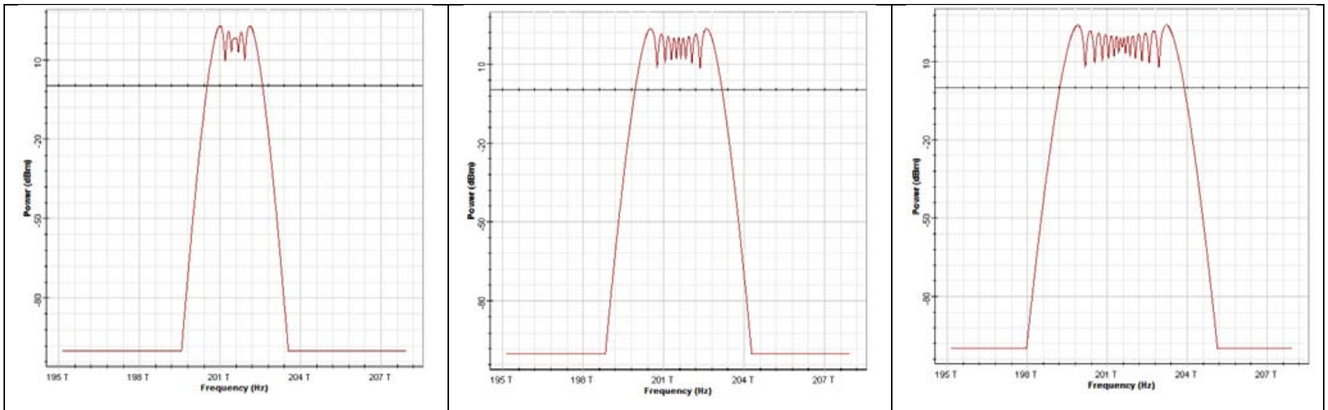


Figure 2.11 SPM signal effects using Optical Spectrum Analyzer

Below are progressive figures for the output signal after going through nonlinear fiber per iteration:

		
Iteration #1	Iteration #5	Iteration #7



Iteration #12	Iteration #20	Iteration #30

Figure 2.12 SPM effects captured Optical Spectrum Analyzer (30 iterations)

XPM

To simulate the effects of XPM in WDM networks, the setup layout was composed of two Optical Gaussians Pulse Generators fed by 2 User Defined Bit Sequence Generators, as well as an Ideal Multiplexer, a delay timer to highlight the difference when the these two signals overlap (xpm) versus when they don’t, a Nonlinear Optical Fiber (our propagation medium), as well as a set of auxiliary components for visualization.

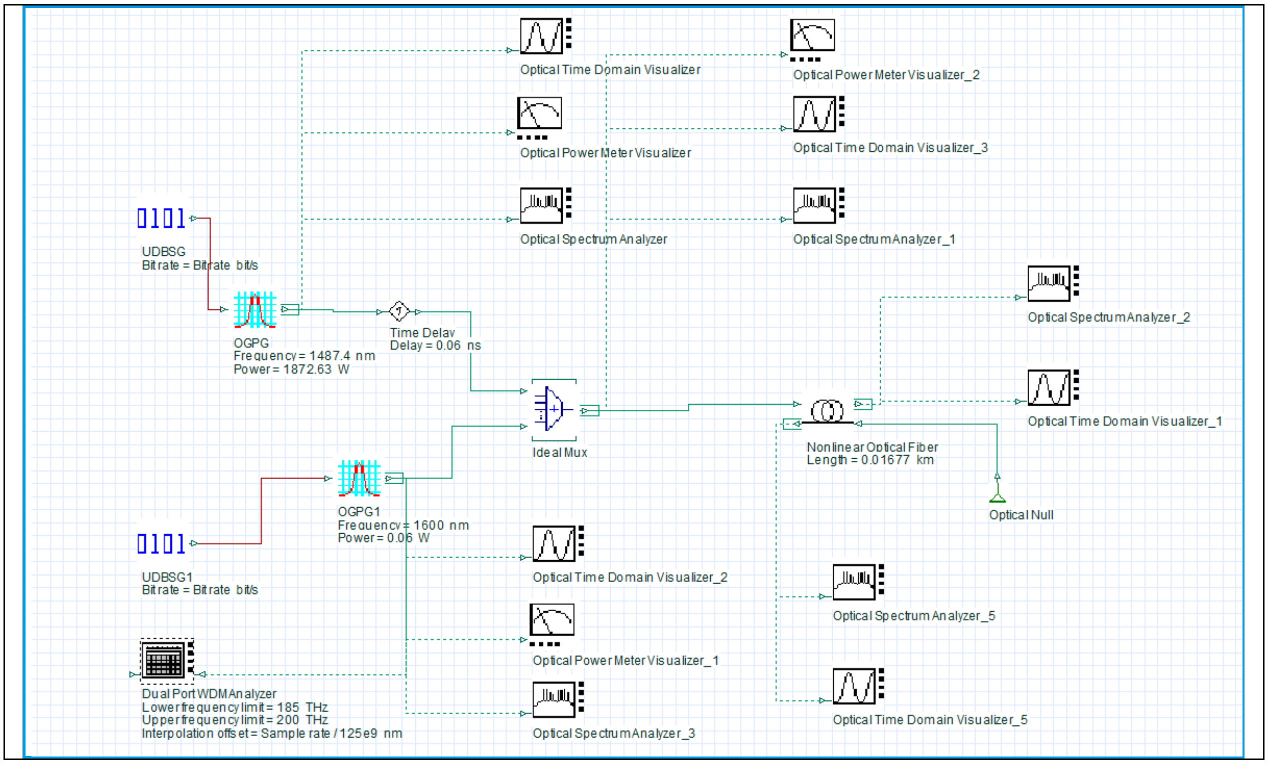


Figure 2.13 XPM System Design

It was observed that the Optical Spectrum Analyzer linked to the Nonlinear Optical Fiber on the figure. I've run the program for 30 sweeps on different power values as shown below. In the first iteration, with a delay of -0.06 ns to add the first signal (power: 1872.63 W) to the second signal (power: 0.06 W), the figures below show the input signals, then the power corresponding to each signal illustrated on the second graph (the blue one). Power has an effect on SPM in nonlinear optical fibers. This is also what was seen experimentally in the output Optical Spectrum Analyzer where SPM was observed on the first signal but not on the second.

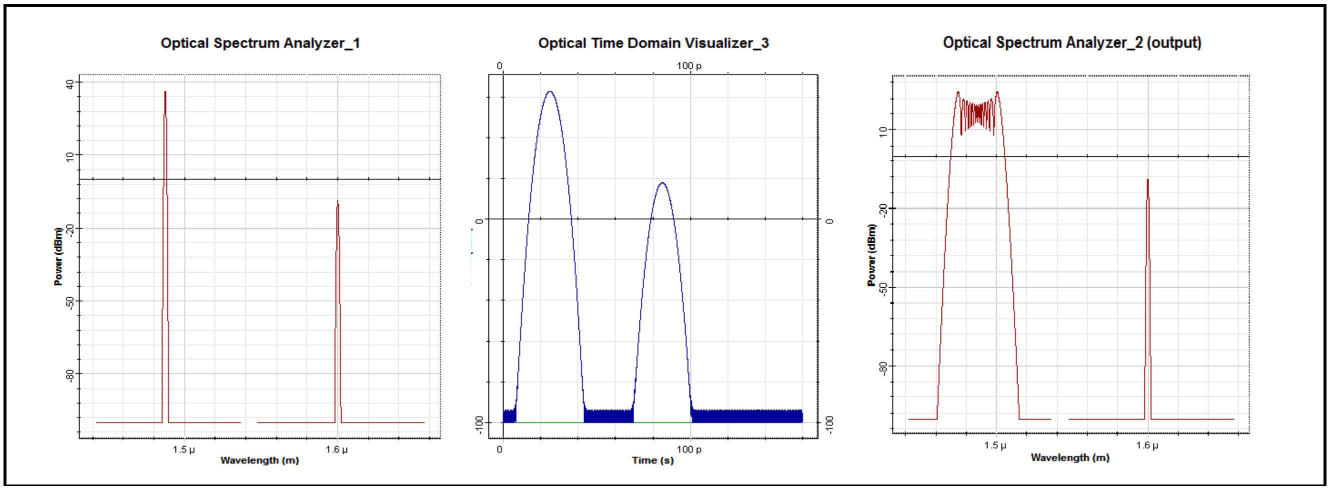


Figure 2.14 XPM signal effects using Optical Spectrum Analyzer (1st Iteration)

In the six iteration, with a time delay of -0.039-0.0144827586206931034482759 ns, things started to change. The first pulse (the powerful one on the left) has been observed getting closer to the second one (on the right).

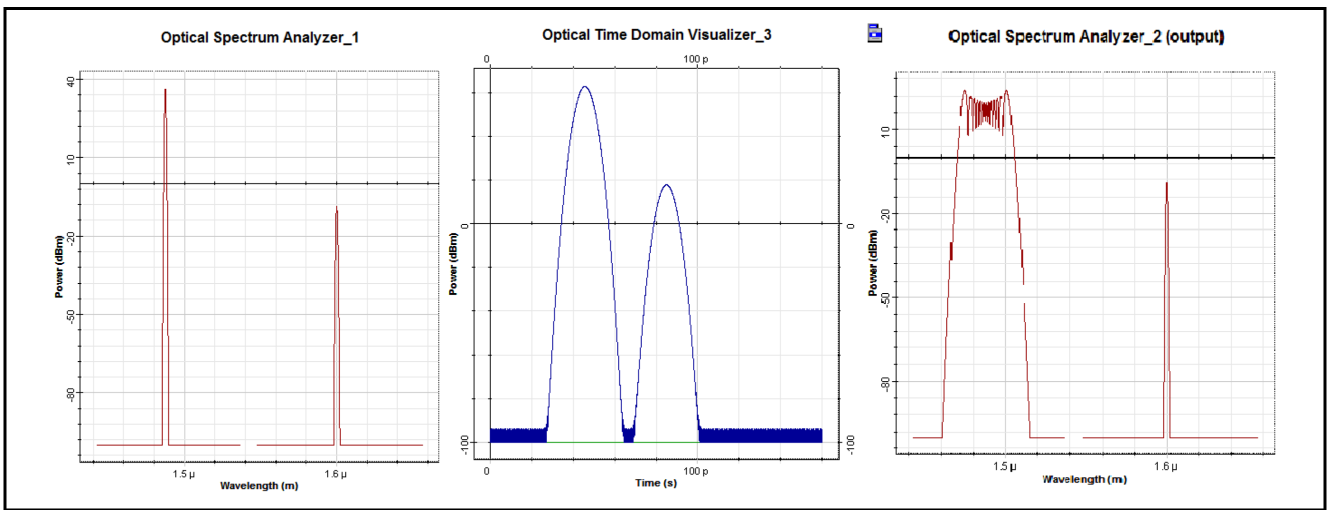


Figure 2.15 XPM signal effects using Optical Spectrum Analyzer (6th Iteration)

The 12th iteration below is the turning point, at a time delay of: -0.01448275862069, as the two pulses are beginning to overlap, SPM was observed beginning to appear on the second pulse. This new SPM that appeared on the second pulse is due to the first pulse.

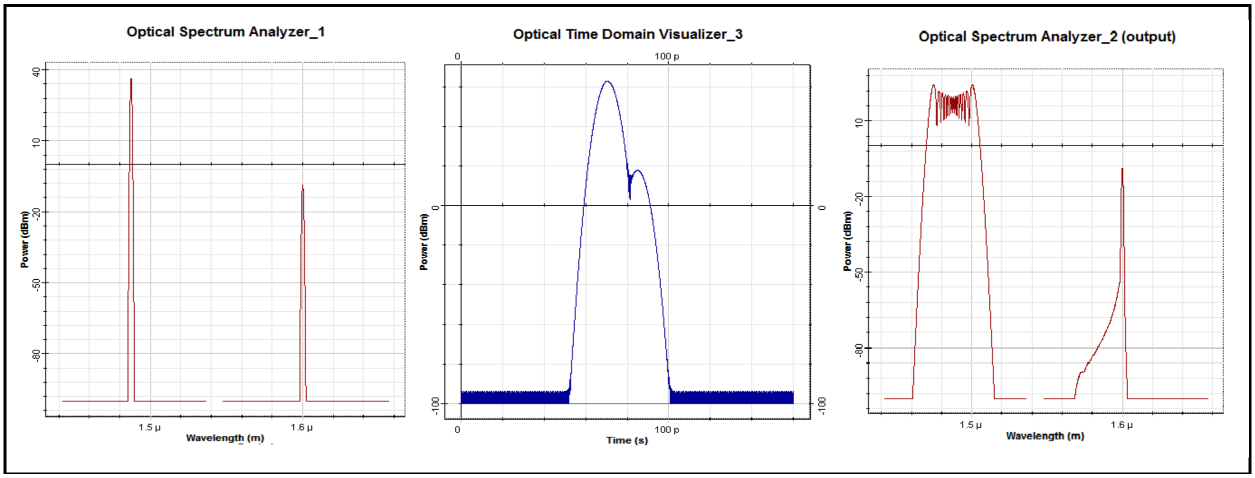


Figure 2.16 XPM signal effects using Optical Spectrum Analyzer (12th Iteration)

The effect of the first pulse on the second continues to show clearly as the two pulses get more close to each other in iteration 13 (first row of Figure 2.17 below) until they fully overlap in iteration 15 (second row of Figure 2.17).

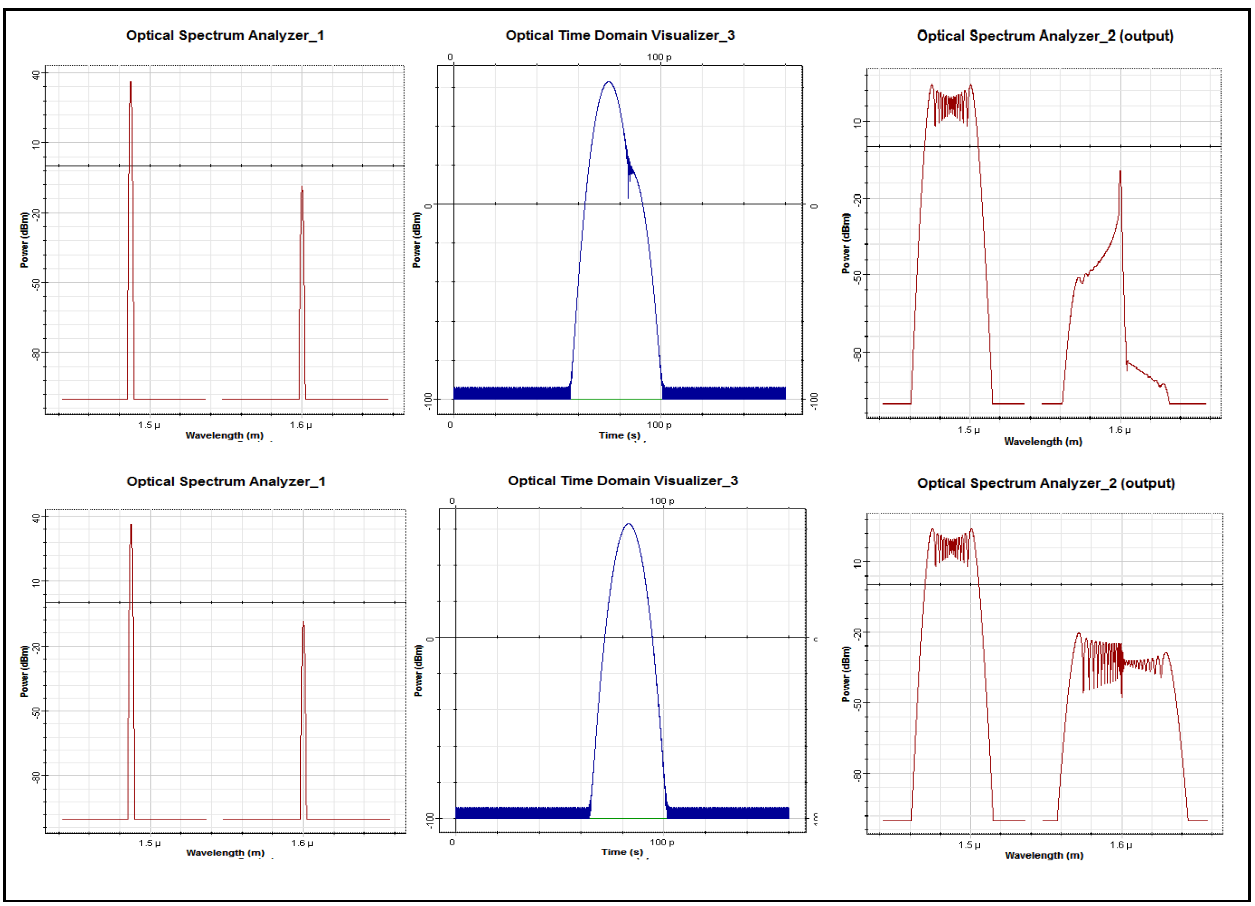


Figure 2.17 XPM signal effects using Optical Spectrum Analyzer (13th and 15th iterations)

From Iteration 17 onwards, things take a different turn, with the signals separating and the second pulse no longer exhibiting SPM phenomenon. Iteration 26 below depicts these changes:

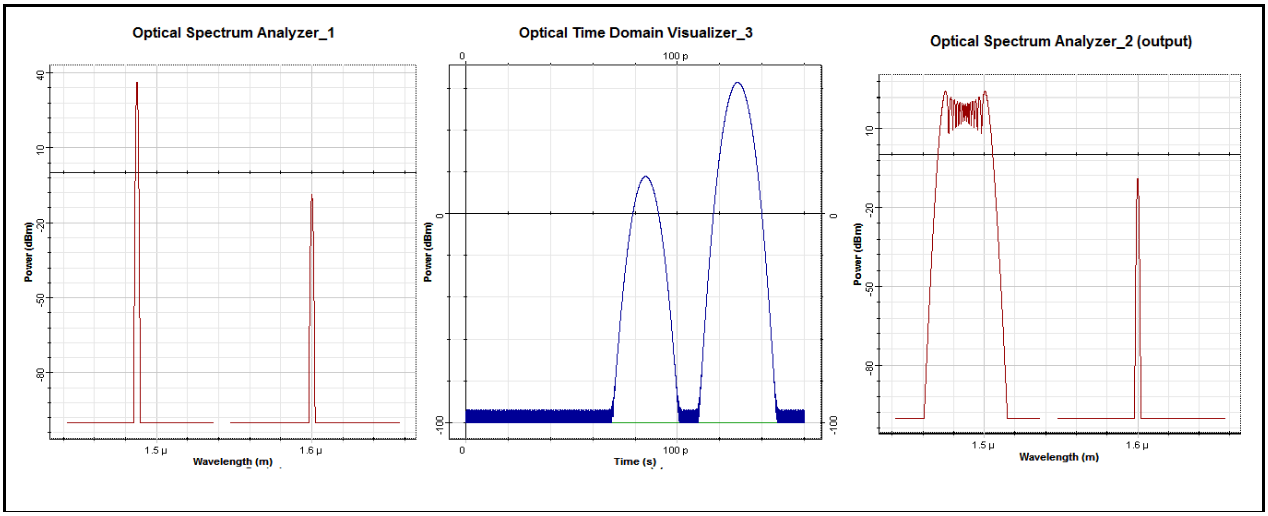


Figure 2.18 XPM signal effects using Optical Spectrum Analyzer (17h iteration)

To summarize, with XPM, with two pulses where one of them is very powerful, that pulse affects the medium, which then affects the second pulse, causing the spectrum broadening on the second pulse.

FWM

Below is the system design put in place to measure the effects of FWM. Starting with example 1 of the 2 signals having different frequencies where the first is centered at 1540 nm, while the second one is centered at 1540.5 and both have 1 mW. The experiment consisted of combining the signals together using a WDM Multiplexer, then launching the combined signal in a nonlinear optical fiber of 10 Km, and finally running 30 sweeps to observe the results.

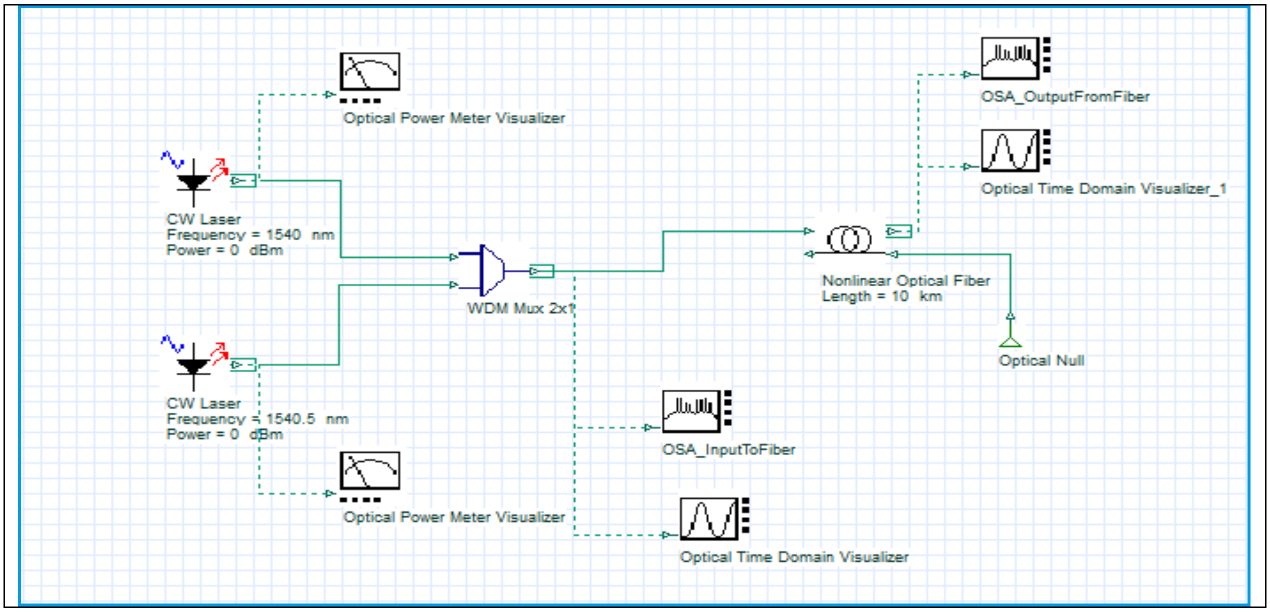


Figure 2.19 FWM System Design (1st Example: 2 signals with 2 different frequencies)

Below are the graphs the Optical Spectrum Analyzer of the signals before entering the nonlinear fiber, and after entering it where 2 new signals appear as shown on the right graph. It has been validated that the new signals are centered at 2ν1 - ν2 =1539.5 and 2ν2 - ν1= 1541 respectively as shows the figure below.

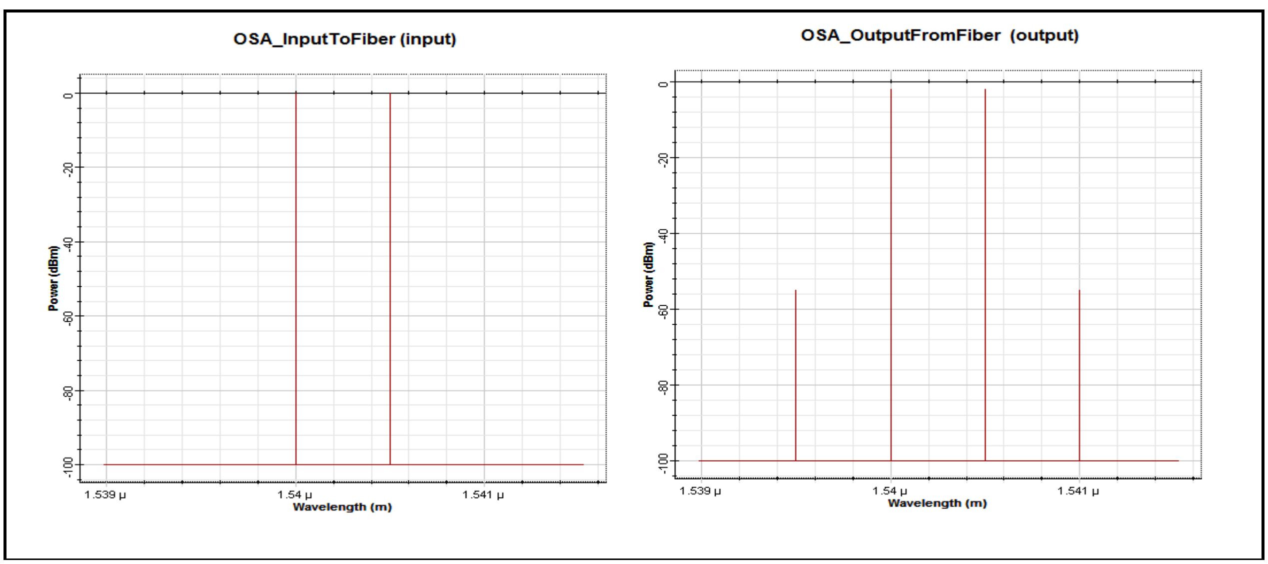


Figure 2.20 FWM signals effects using Optical Spectrum Analyzer (1st Example)

Next was setting up the system design to simulate the second example (powerful signal resulting in 2 sidebands), where the power of one signal set at 35 dBm and the power of the other at a very low power of -100 dBm (equivalent to 0):

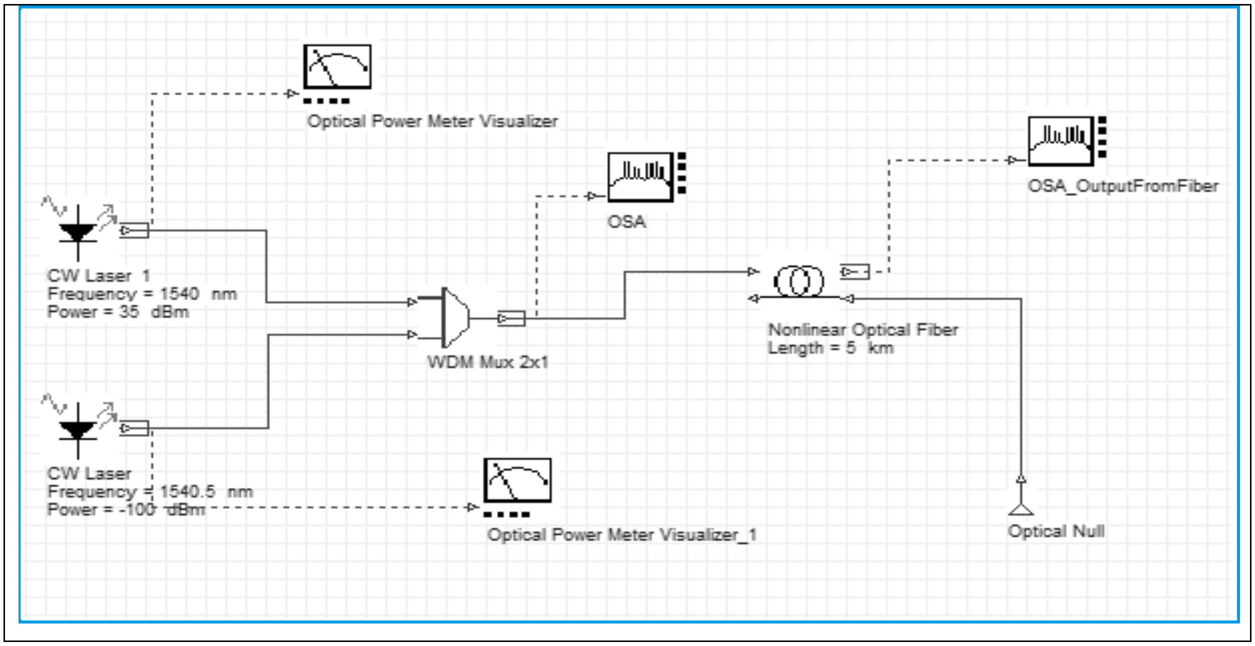


Figure 2.21 FWM System Design (2st Example: Powerful signal resulting in 2 sidebands)

The outcome of transmitting the combined signal via the nonlinear fiber is 2 new sideband signals:

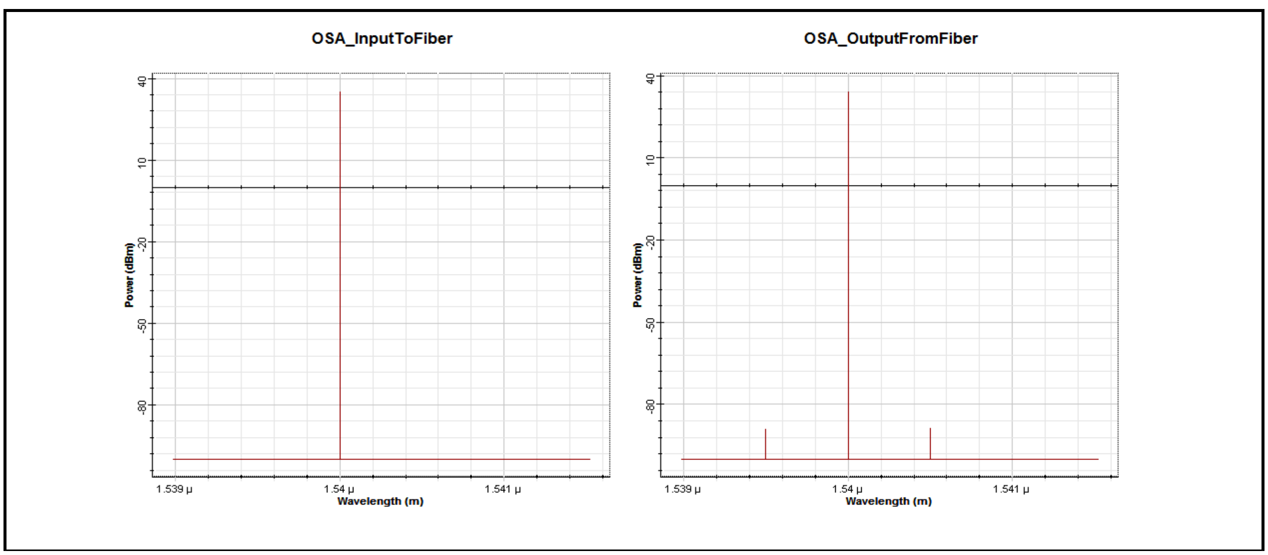


Figure 2.22 FWM signals effects using Optical Spectrum Analyzer (2nd Example)

Conclusion

It has been seen from the experiments above how Self Phase Modulation results in self-Spectrum broadening. It has also been seen that Cross Phase Modulation causes Mutual Spectrum Broadening, while Four Wave Mixing is responsible for generating new frequencies. The conducted experiments have also enabled to observe the thresholds for each of these nonlinear effects in the observed WDM Network.

Simulations on WDM Nonlinearities (Power, BER, PER ...)

Below are various simulations of Nonlinearities in WDM focusing on Power fluctuation, Bit Error Rate (BER), Packet Error Rate (PER), etc., testing the results by varying the number of channel, channel spacing, traffic load, input power, checking all of this and its impact on nonlinear effects in WDM Networks such as SRS, XPM, and FWM.

FWM Interferences X Channels Y nm Spacing ZWDM

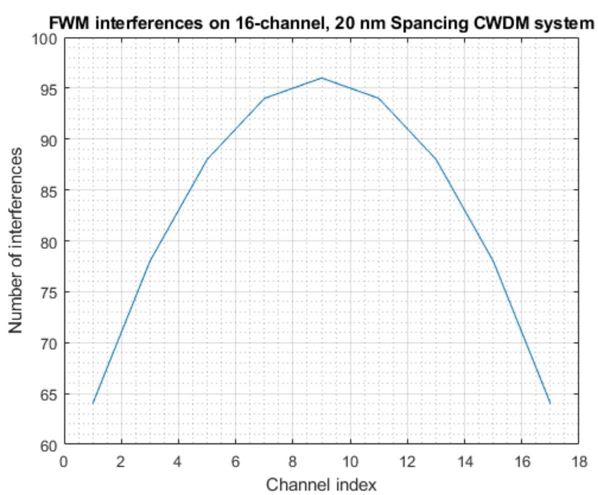


Figure 2.23 FWM interferences on 16-channel, 20 nm spacing, CWDM System

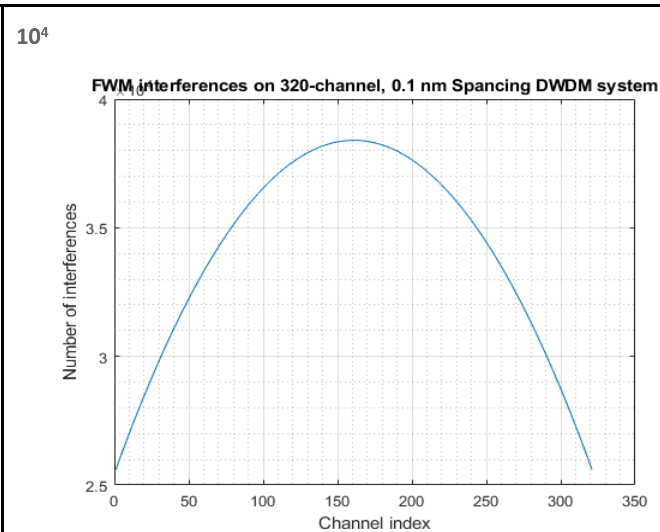


Figure 2.24 FWM interferences on 320-channel, 0.1 nm spacing, DWDM System

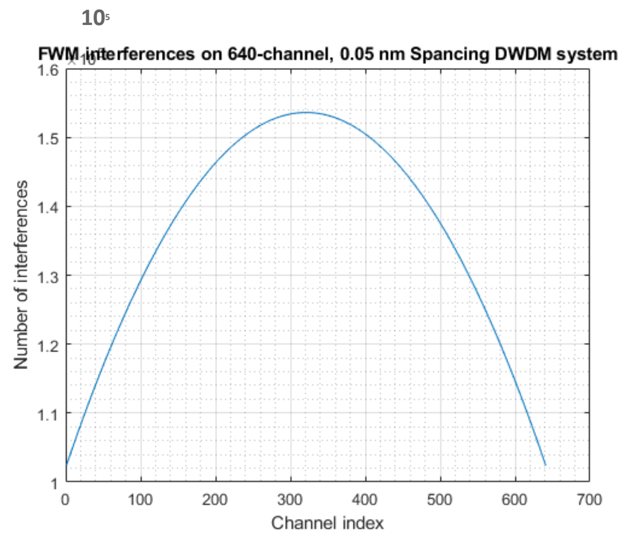


Figure 2.25 FWM interferences on 640-channel, 0.05 nm spacing, DWDM System

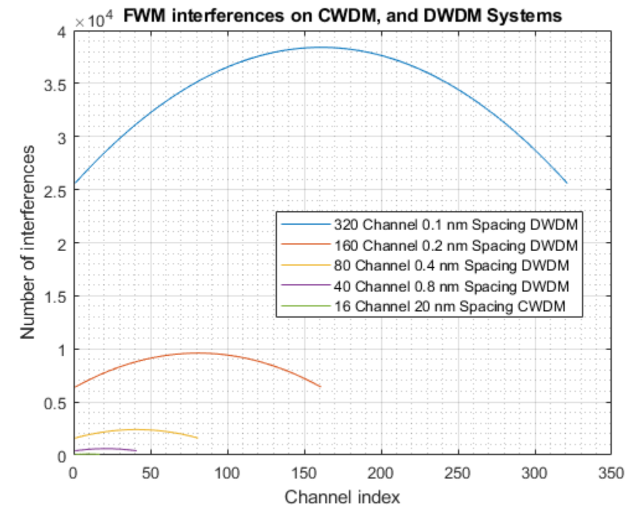


Figure 2.26 FWM interferences on CWDM and DWDM systems

Observations:

- The central channel is the most affected by FWM.
- The more channels, the least spacing between them, the worst is the effect of FWM.

FWM Power Fluctuation X Channels Y nm Spacing ZWDM

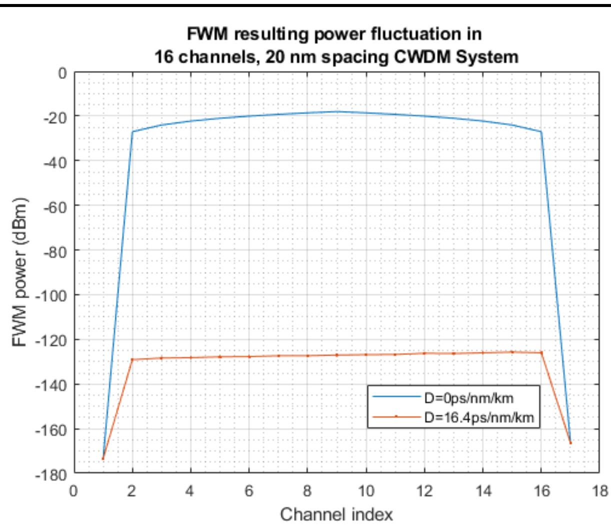


Figure 2.27 FWM resulting power fluctuation in 16 channels, 20 nm spacing, CWDM System

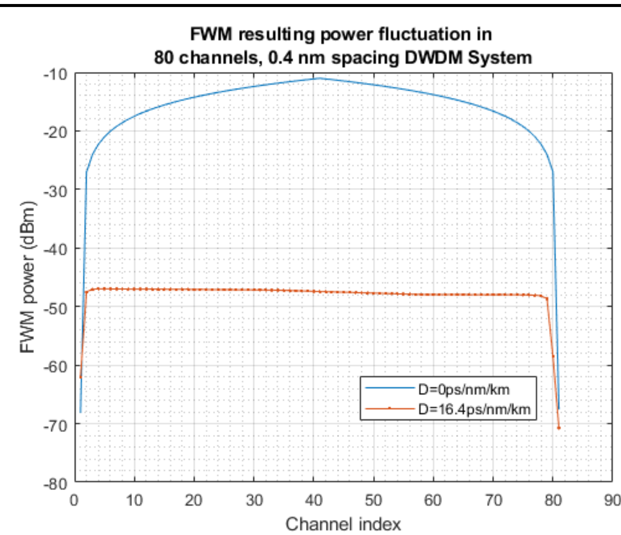


Figure 2.28 FWM resulting power fluctuation in 80 channels, 0.4 nm spacing, DWDM System

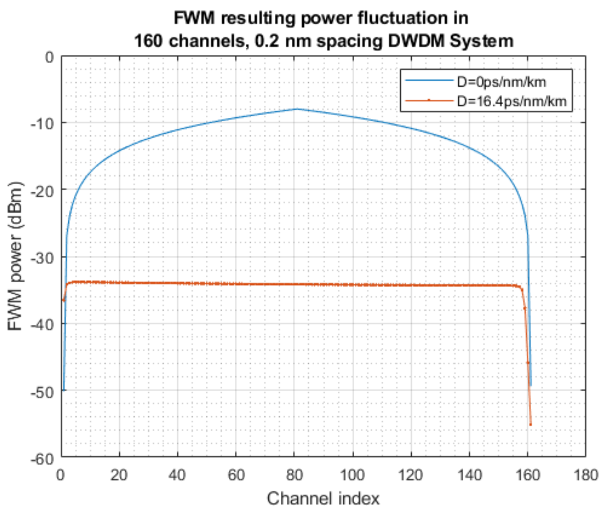


Figure 2.29 FWM resulting power fluctuation in 160 channels, 0.2 nm spacing, DWDM System

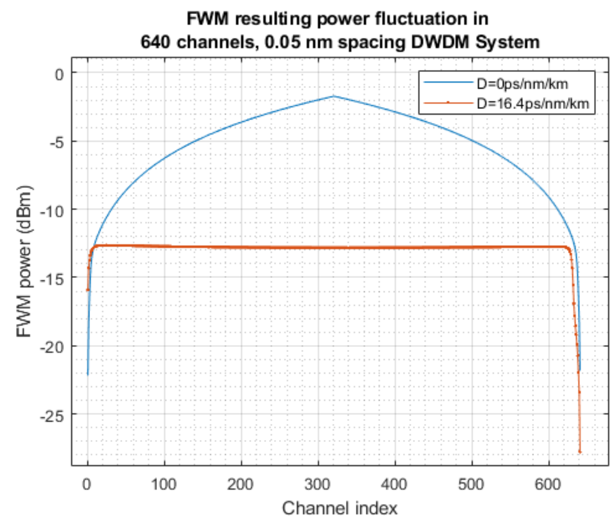


Figure 2.30 FWM resulting power fluctuation in 640 channels, 0.05 nm spacing, DWDM System

Observations:

- FWM is worst at center channel frequency for Dispersion shifted fiber
- Using a NDSF (SMF) decreases the effect of the FWM.
- Positive correlation between number of channels and FWM

BER versus Traffic Load caused by FWM - X Channels

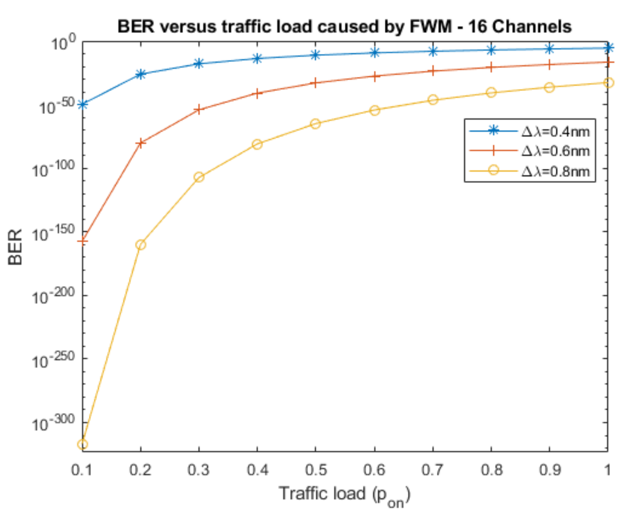


Figure 2.31 BER versus traffic load caused by FWM – 16 Channels

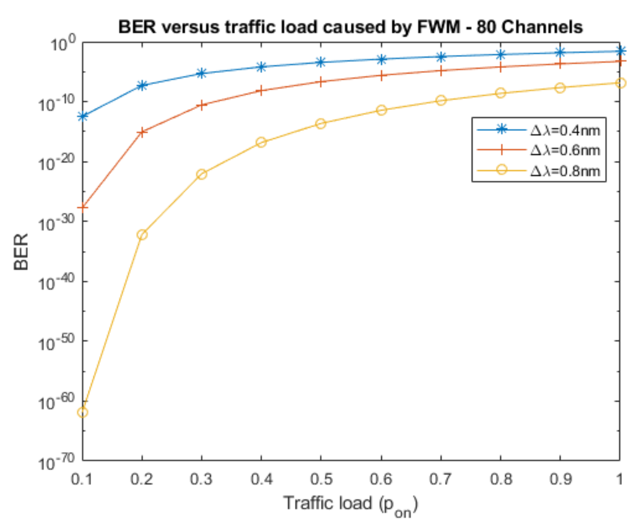


Figure 2.32 BER versus traffic load caused by FWM –80 Channels

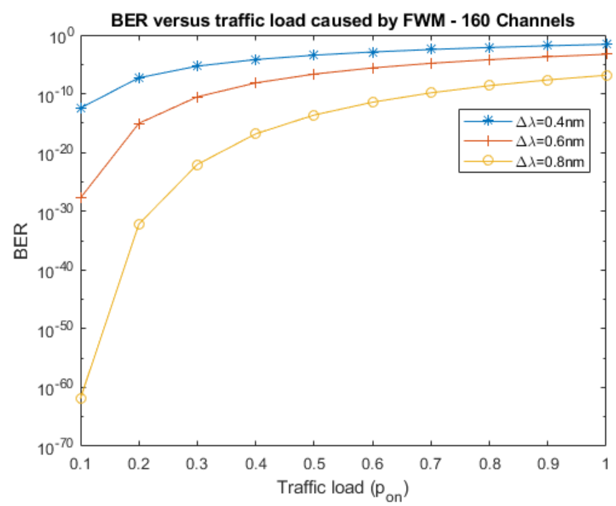


Figure 2.33 BER versus traffic load caused by FWM - 160 Channels

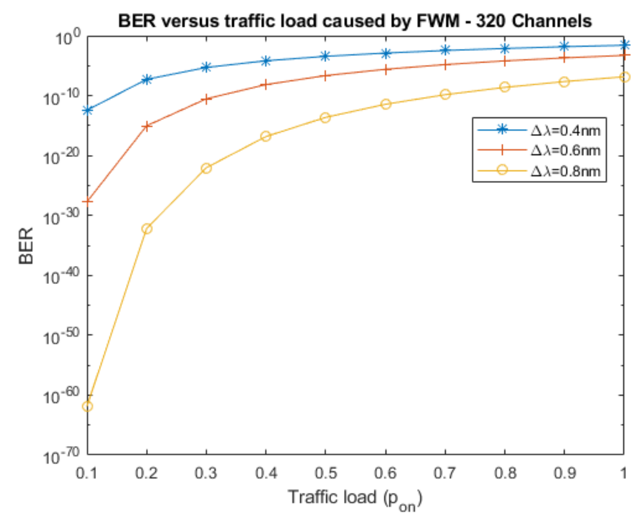


Figure 2.34 BER versus traffic load caused by FWM-320 Channels

Observations:

- Positive correlation between the BER and the traffic load.
- Positive correlation between the BER and the number of channels - No difference between 80 & 320 Channels
- For the same traffic load, the bigger the channel spacing the lower the BER.

PER versus traffic load & Packet Length - X Channels

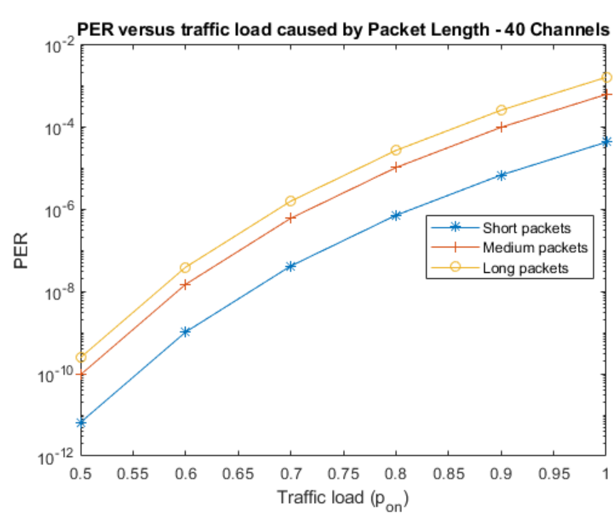


Figure 2.35 PER versus traffic load caused by packet length-40 Channels

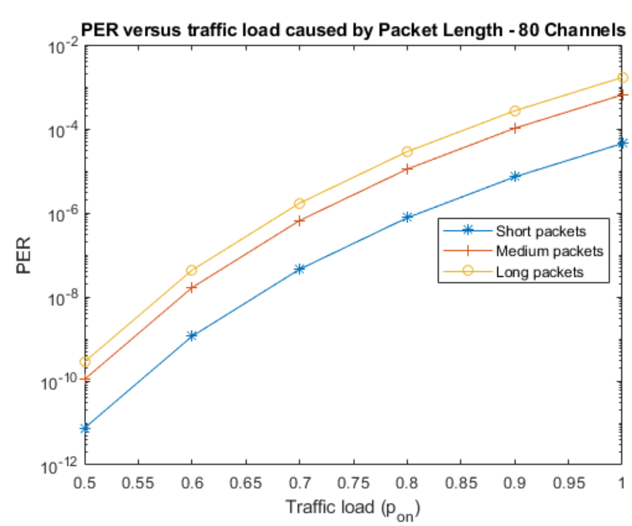


Figure 2.36 PER versus traffic load caused by packet length - 80 Channels

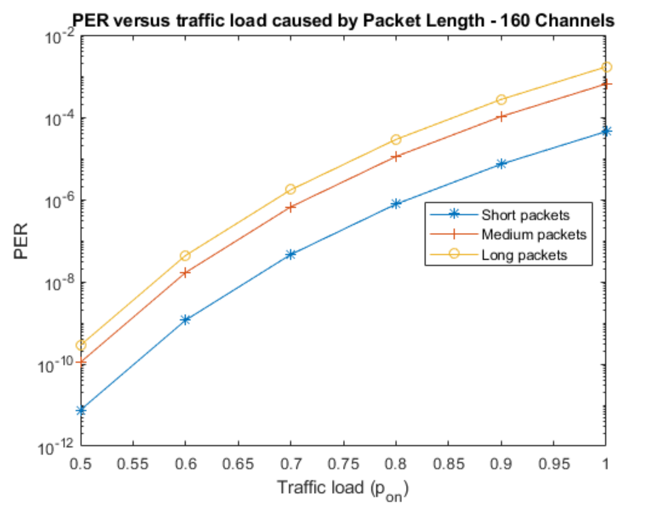


Figure 2.37 PER versus traffic load caused by packet length-160 Channels

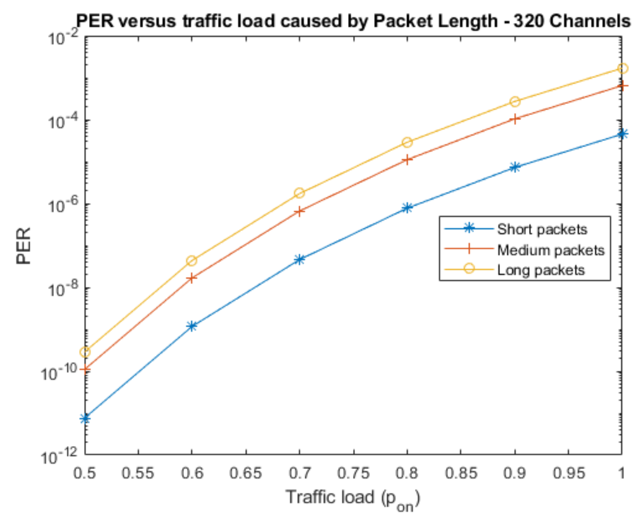


Figure 2.38 PER versus traffic load caused by packet length- 320 Channels

Observations:

- No correlation between PER and number of channels
- Positive correlation between the PER and Packet length (Long Packet → High PER)
- PER is ~2 Orders of magnitude lower for short packets when compared with long packets

PER versus Traffic Load caused by SRS - X Channels

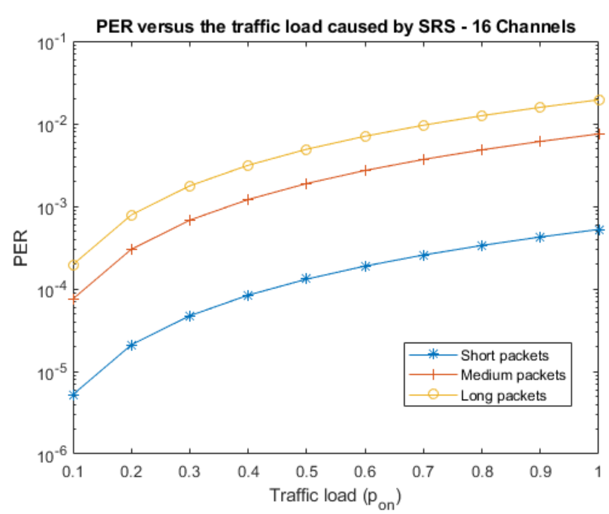


Figure 2.39 PER versus traffic load, caused by SRS - 16 Channels

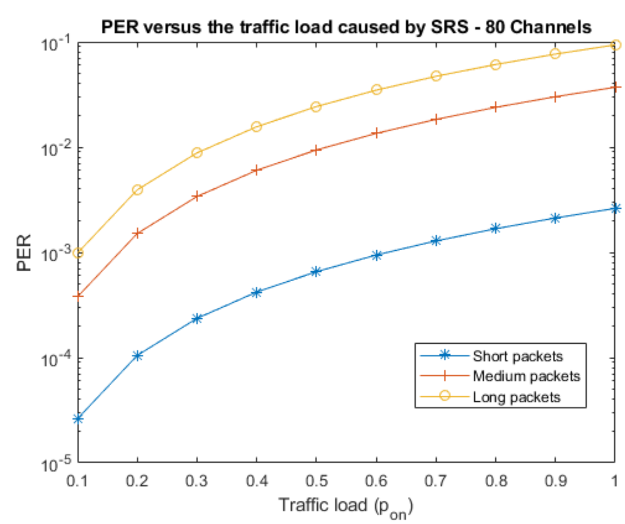


Figure 2.40 PER versus traffic load, caused by SRS - 80 Channels

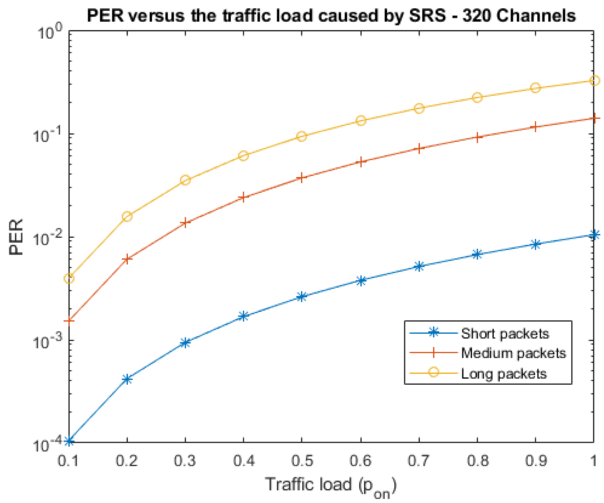


Figure 2.41 PER versus traffic load, caused by SRS – 320 Channels

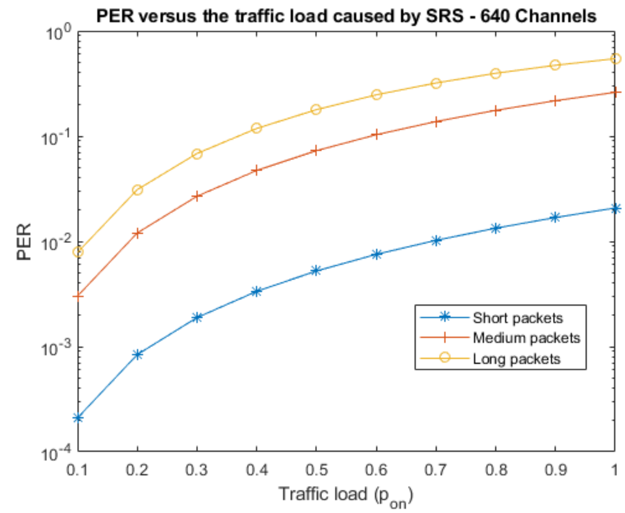


Figure 2.42 PER versus traffic load, caused by SRS –640 Channels

Observations:

- Positive correlation between PER and packet size (low PER for short packets)
- Positive correlation between PER and the traffic load
- Positive correlation between number of channels and BER

PER versus Traffic Load caused by XPM - X Channels

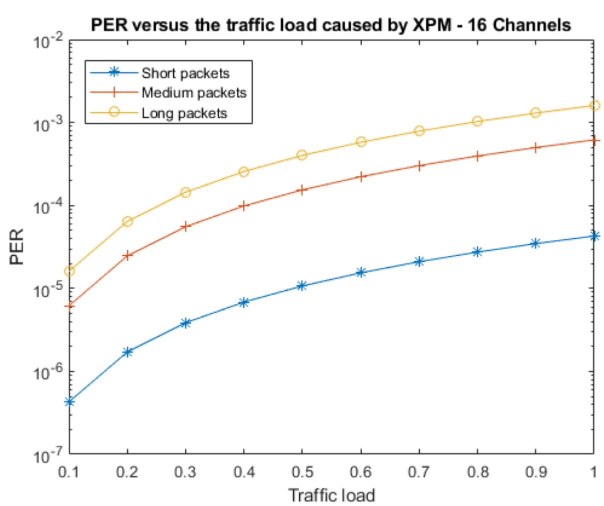


Figure 2.43 PER versus traffic load caused by XPM –16 Channels

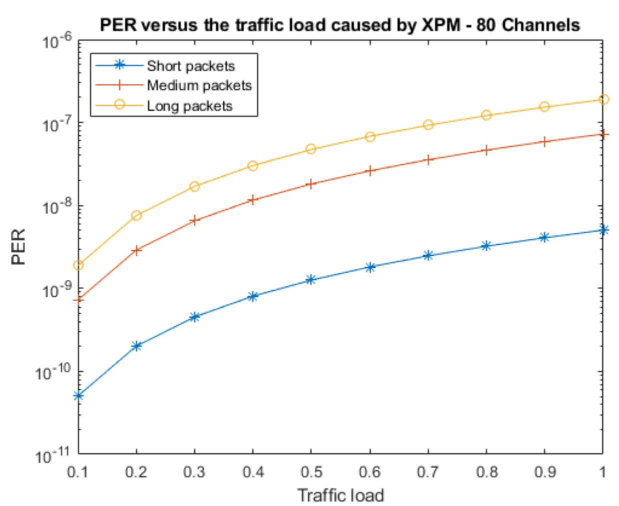


Figure 2.44 PER versus traffic load caused by XPM – 80 Channels

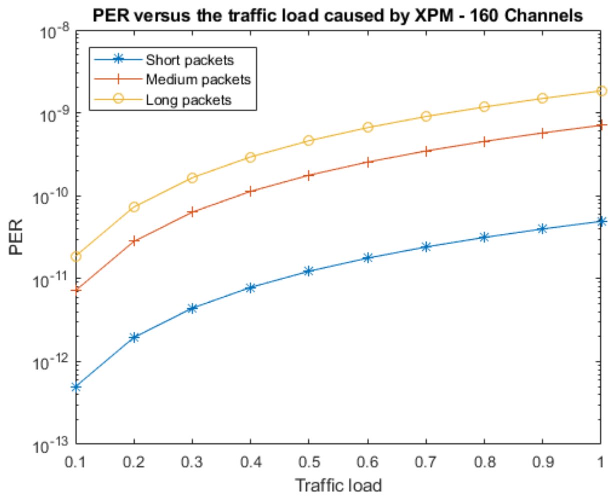


Figure 2.45 PER versus traffic load caused by XPM –160 Channels

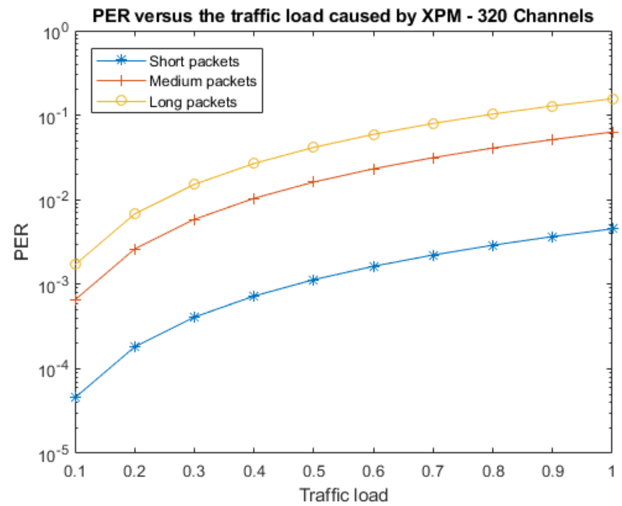


Figure 2.46 PER versus traffic load caused by XPM –320 Channels

Observations:

- Positive correlation between PER and packet size (low PER for short packets)
- Positive correlation between PER and the traffic load
- Positive correlation between number of channels and PER

BER versus input power cause by SRS - X Channels

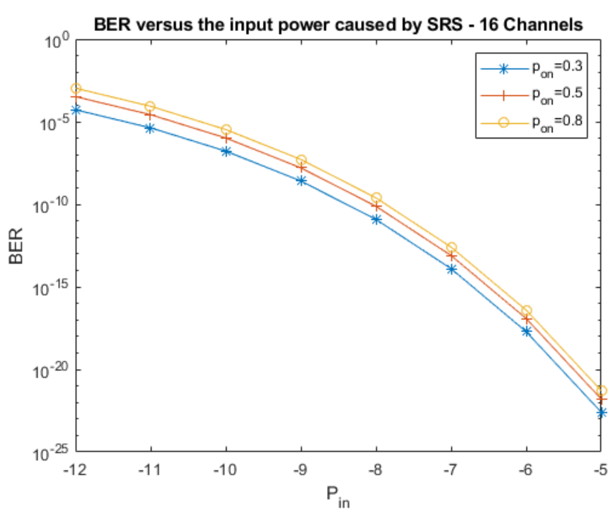


Figure 2.47 BER versus input power caused by SRS –16 Channels

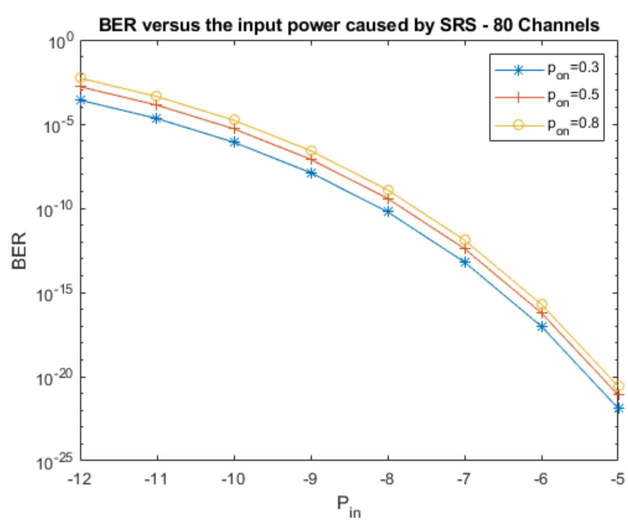


Figure 2.48 BER versus input power caused by SRS – 80 Channels

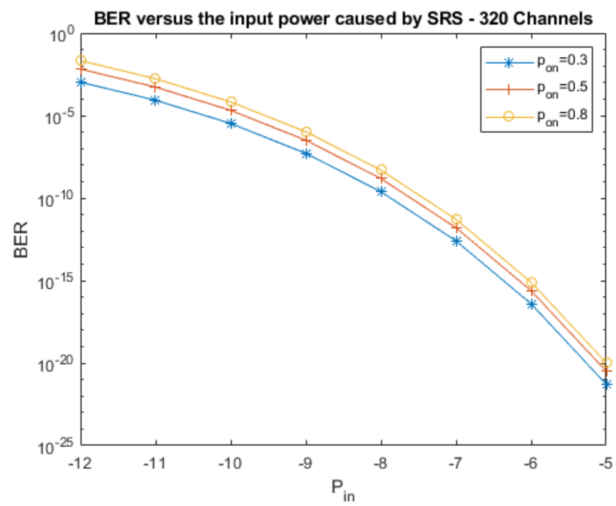


Figure 2.49 BER versus input power caused by SRS – 320 Channels

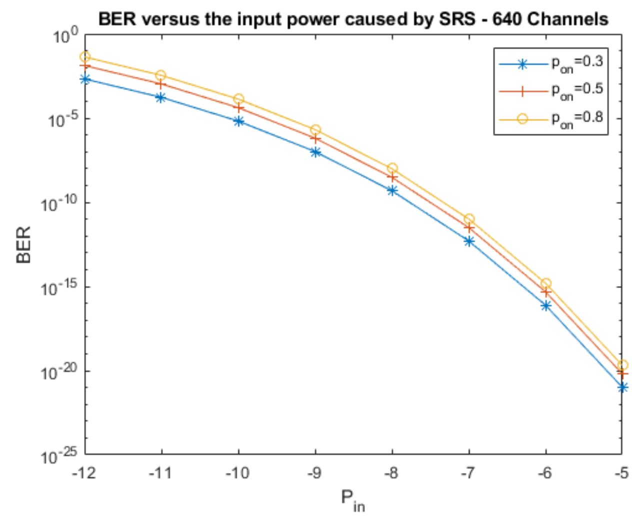


Figure 2.50 BER versus input power caused by SRS –640 Channels

Observations:

- Negative correlation between BER and Input power
- Positive correlation between number of channels and BER

Conclusions

It has been seen from the experiments above how Self Phase Modulation results in self-Spectrum broadening. It has also seen that Cross Phase Modulation causes Mutual Spectrum Broadening, while Four Wave Mixing is responsible for generating new frequencies. It has also been observed what the thresholds are for each of these nonlinear effects in the studied WDM Network. From the WDM Nonlinearities simulations, it has been seen that the central channel is the most affected by FWM. The more channels there are, and the least spacing between them, the worst is the effect of FWM. The more channels, the worst are the effects of FWM. It has also been observed that FWM is worst at center channel frequency for Dispersion shifted fiber. Using a NDSF (SMF) decreases the effect of the FWM, and there is a positive correlation between number of channels and FWM. There is a positive correlation between the BER and the traffic load, as well as positive correlation between the BER and the number of channels - No difference between 80 & 320 Channels. For the same traffic load, the bigger the channel spacing the lower the BER. There was no correlation observed between PER and number of channels. There is a positive correlation between the PER and Packet length (Long Packet → High PER). Moreover PER is ~2 Orders of magnitude lower for short packets when compared with long packets. There is also no correlation between PER and number of channels. There was an observed positive correlation between PER and packet size (low PER for short packets), a positive correlation between PER and the traffic load, as well as a positive correlation between number of channels and BER. Finally, there was a negative correlation between BER and Input power that has been noticed.

Chapter 3: Optical Network / Traffic Generation

Towards a prevention security-oriented mindset in managing Optical Networks

Reading the title of this section, chances are, one cannot help but notice two main axes. The first relates to the prevention mindset, while the second is about network management within the context of Optical Networks. The section aims to address this over four stages. In the first stage, I present a research inventory covering recent studies on preventative mindset characteristics within psychology, and behavioral science domains. In the second stage, I perform, yet another research inventory, but this time on papers related to network management in general, and optical networks in particular. In the third stage, I present the latest optical networks characteristics, applications, and industry trends. While in the last stage, I analyze, synthesize, and propose a novel behav-realistic framework, designed based on recent psychology and behavioral science research on prevention mindset, as well as the latest characteristics, applications, and industry trends associated with optical networks and their management. The combination of these two areas of "behavioral" science and "realistic" expectations based on recent trends is what inspired us to call this novel framework a "behav-realistic" framework that I'll be presenting in this work.

Introduction

Besides their critical role to everyday communication across the globe, optical networks don't only represent the backbone of the internet, they're also strongly present in a multitude of areas, including Medicine, Commerce, Industry, Military, and Space [195] [196] [197] [198][199] and many more. One might be wondering what makes such networks highly appealing to a range of domains. The answer lies in the core of these networks, the fiber. This substance has a set of advantages like its low production cost, its light weight relative to copper, its ability to carry massive amounts of data (60 Tbps as of 2016 [200]), its ability to carry a variety of independent signals on the same fiber, without interference, while also being able to accommodate for long distance communications of thousands of kilometers without a need for regeneration [201].

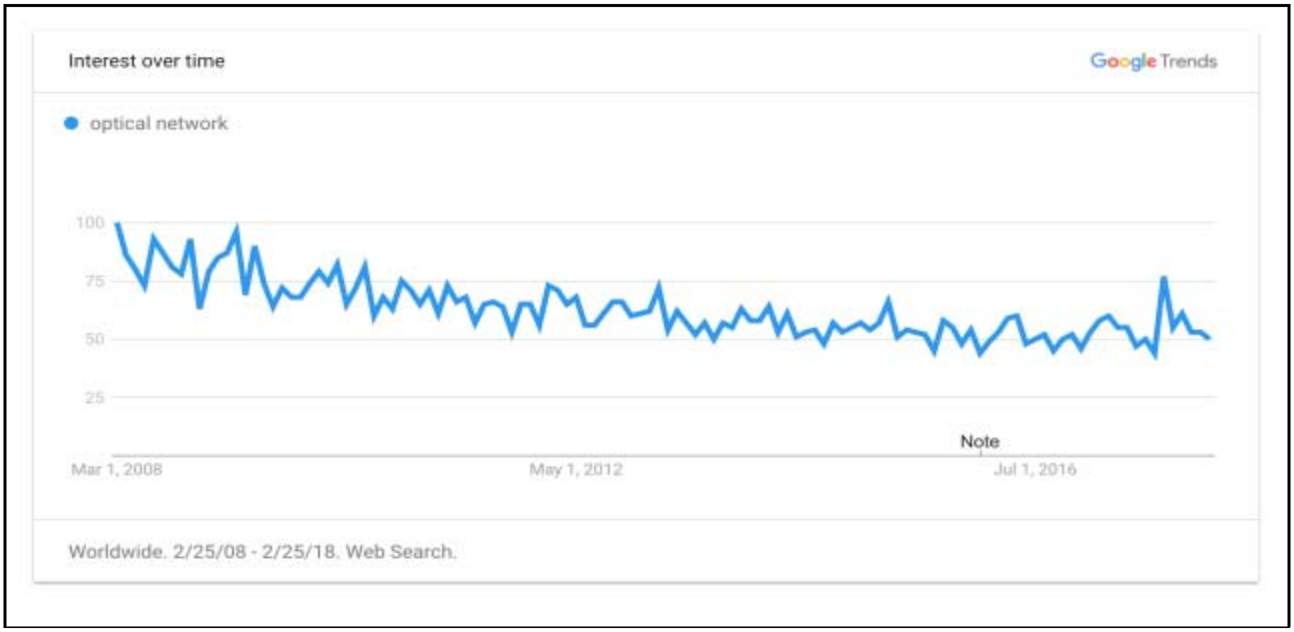


Figure 3.1 Google Trends Results for "Optical Network" over the past 10 years [202]

As I aim to present a prevention security oriented mindset in managing optical networks, I needed to first understand the current mindset, and then get some insights and inspirations to motivate the work. To get a rough understanding of the current mindset of Internet users in relation to this topic, I decided to look at Google Trends, a public data visualization tool by Google that shows how often a specific term or set of terms were looked up on Google Search Engine, relative to the total search volume given the specified region and language where the search was performed. I looked up various terms related to optical networks over the past 10 years and observed the trend for each of these globally. The results returned on Google Trends are interpreted as follows; the x-axis represent the years, while the y-axis refers to the search interest. A value of 100 on that axis refers to the peak popularity for the searched term, a value of 50 means that the term is half as popular, while a score of 0 means there was not enough data for this search term. Figure 3.1 [202] depicts results for looking up the term "Optical Network" over the past 10 years. The term scored high popularity in 2008, with fluctuating popularity between the 50 and 75 score.

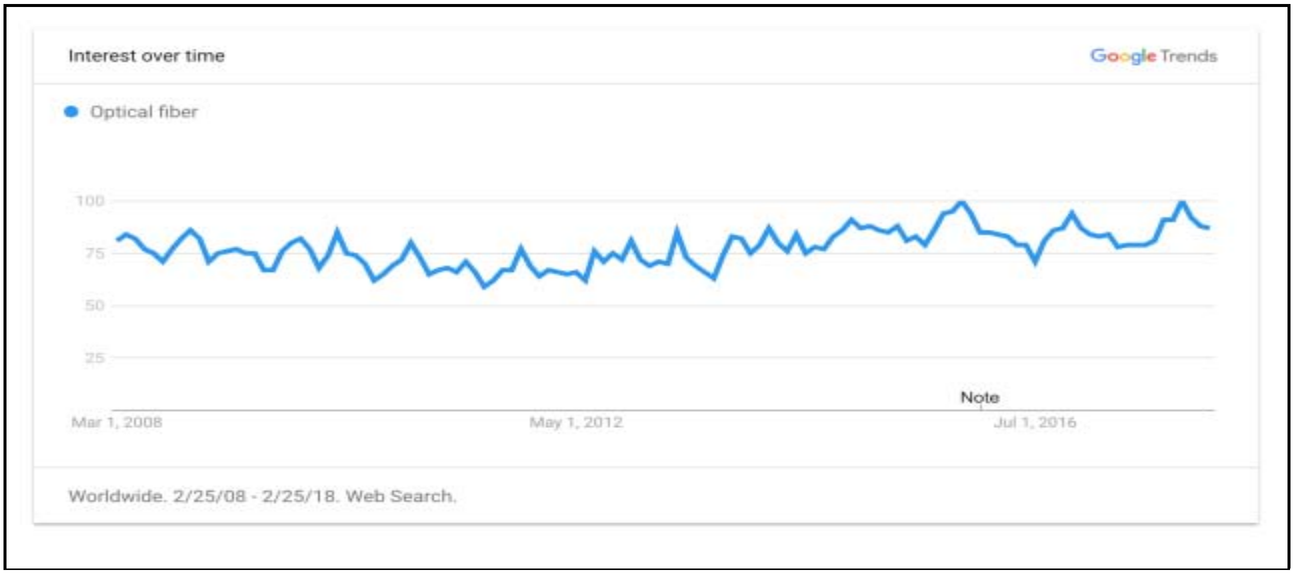


Figure 3.2 Google Trends Results for "Optical Fiber" over the past 10 years [203]

Figure 3.2 [203] depicts the popularity of the term "Optical Fiber" which has been, and is still very popular, nearing the 100 score, up until very recent years. After looking at the popularity of the terms "Optical Network" and "Optical Fiber", checking research publications in the area is the next step to understand the interest of the research community in such topics. I've looked into the number of publications published on Google Scholar for these two terms, using SCHOLAR PLOTR [204], a public online tool to visualize trends in scholarly research using Google Scholar results.

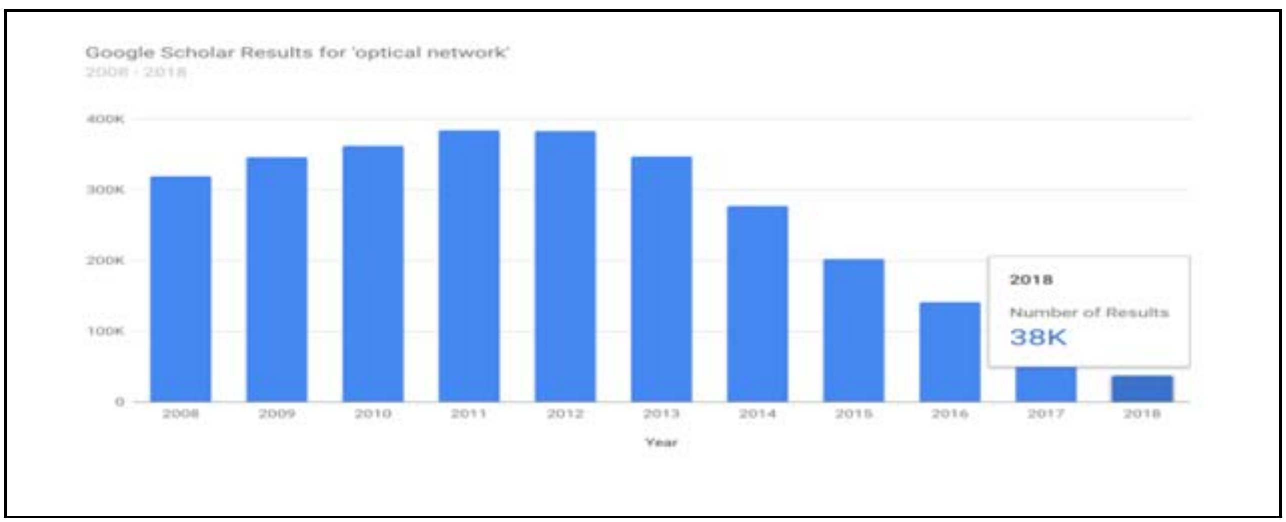


Figure 3.3 Google Scholar Results for "Optical Network" over the past 10 years [204]

Figure 3.3 [204] depicts the number of Google Scholar publications on “Optical Network” in the last 10 years. This number got near 38K publications in 2018!

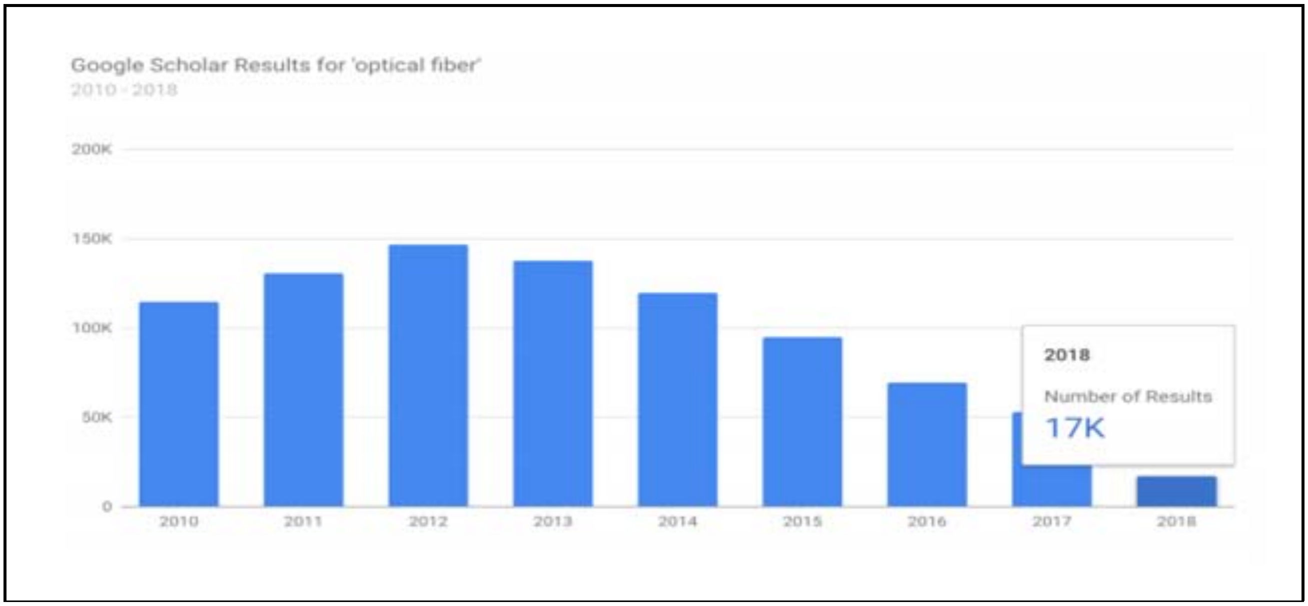


Figure 3.4 Google Scholar Results for “Optical Fiber” over the past 10 years [204]

Looking at publications on “Optical Fiber” on Google Scholar, Figure 3.4 [204] depicts that for the last 10 years with near 17K Google Scholar publications in 2018. Now that I had a look at the popularity and publication volume for the previous terms “Optical Network”, and “Fiber Network”, I have moved next to study the Network Management space.

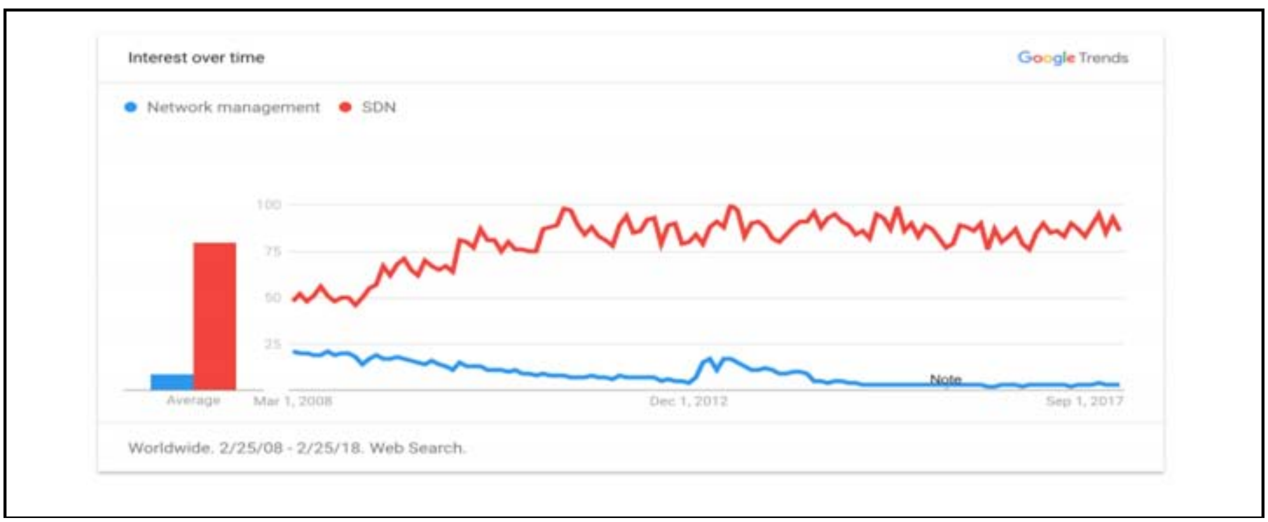


Figure 3.5 Google Trends Results for “Network Management” vs. “SDN” over the past 10 years [205]

Using Google Trends again, and this time comparing the term “Network Management” with “SDN” that stands for Software Defined Networks, as a new term representing using software and visualization in managing networks, the results clearly show a shift toward this later topic as depicted by Figure 3.5 [205].

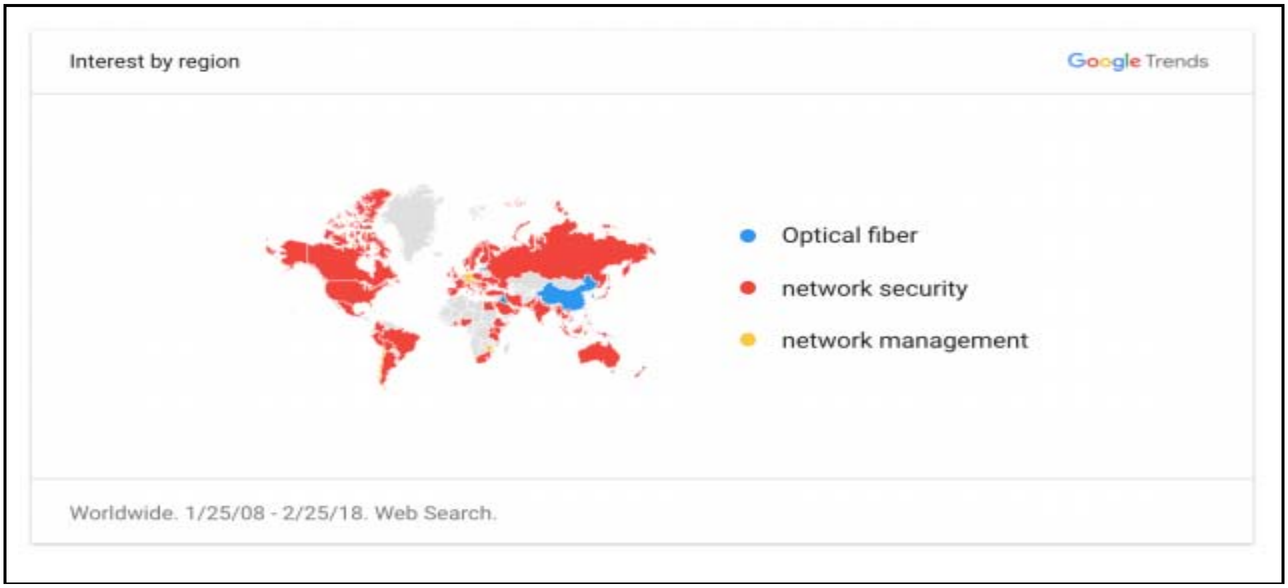


Figure 3.6 Google Trends Results for “Network Security” vs. “Optical Networks” vs. “Network Management” interest by region over the past 10 years [206]

Let’s now look at the global interest in “Network Security”, “Optical Fiber” and “Network Management” over the past 10 years across the globe. Figure 3.6 [206] depicts a global interest in these topics, showing an increased popularity of the topic.

Stage 1: Prevention Mindset

As opposed to Promotion Mindset, Prevention Mindset works by focusing one’s attention on the negative outcomes. These two mindsets are derived from Regulatory focus theory presented by Higgins in 1998 [207]. According to him, the Promotion Mindset focuses on growth and advancement, while the Prevention Mindset cares about Safety and Security [207]. Now, while some might pose the question, why wouldn’t one go with the promotion mindset as it appears more appealing and positive? It is only at face value that it appears as such. In a way, think of it as the carrot approach here as opposed to the stick approach, by which the motivation is escaping the punishment, a.k.a, the prevention mindset.

Looking at research done in the space, I've looked at an interesting research by Dr. Heidi Grant Halvorson and Dr. E. Tory Higgins based on twenty years of work, exploring both causes and consequences of promotion and prevention mindset/focus in multiple aspects of humans' lives [208]. In their book, the authors categorize humans based on their attitude in life as either promotion focused, described as green light individuals, or prevention focused, described as red light people. The first camp's goals are to minimize loss, avoid failure, and feel secure, while, the second camp goals are to maximize gains, feel nurtured, and cease opportunities and take risk even if it involves the possibility of making mistakes [208]. The book also highlights though how people might all be either Promotion-focused or Prevention Focused depending on the situation. Think of taking the flu shot for instance where most those going for it would be doing from with a prevention mindset rather than a promotion one.

A more recent study published in 2010, by the Journal of Consumer Research, explains the behavior of Prevention and Promotion mindset oriented individuals from a consumption point of view. In that research, studies showed how subjects were willing to pay more at a restaurant based on how the menu was either organized in a big picture category for the Promotion Oriented subjects, vs. in a list based detailed manner for the Prevention oriented subjects [209]. It is key to keep that in mind if one is a vendor interested in pitching their prevention product line to their audience, they need to tailor the pitch accordingly. If they're a head of a network operations unit, they would have to motivate their team when working on a new project, aiming at having the tasks tailored according to each team member's motivational fit. This won't just help the organization be more effective, but also result in more satisfied individuals as in 2009, Mehdi Mourali, and Frank Ponshas showed through their study entitled: Regulatory fit from attribute-based versus alternative-based processing in decision making, how the motivational fit approach results in significantly more satisfied subjects with their selections in contrast to when this wasn't taken into account [210].

In this chapter I focus on prevention, hence will be studying below what it is that will make individuals, working in the optical networking industry, more inclined to adopt the prevention focused mentality towards securing their network and operations, but let's first begin with some key definitions and terminology.

Definition & Terminology

Regulatory Focus

According to Higgins' definition [207], an individual's regulatory focus is a specific strategic and motivational orientation that they adopt during their goal pursuit.

Regulatory Fit

According to research published in [211][212][213] and [214], Regulatory fit is the experience one goes through when they pursue a goal in such a way that their regulatory focus (prevention or promotion) is satisfied. That regulatory fit is what makes one feel right about what they are doing, which can definitely influence judgment, especially if the regulatory fit subject is not aware of it [215] while at the same time also having a positive effect on increased judgment and avoiding temptation and distraction when pursuing a goal [216].

Stage 2: Network Management

Not that long following the birth of the Internet in 1983, network management protocols/systems efforts started to emerge. In October, 1987, The High-Level Entity Management System (HEMS) was published in RFC 1021 as a result of some server network management issues the community was running into following the increased number of vendors, the incredible growth of the connected IP networks (aka Internet), as well as the various non standardized network management protocols designed by each of the vendors [217] The effort came to limit those effects through a standard protocol where three types of management activities were defined: status monitoring (including occasionally retrieving monitoring information), firefighting (where worst cases are assumed as sites would be trying to locate and fix a network problem), and event reporting (including status info) [217]. In the same year, the ITUT Recommendation X.711 entitled 'Information Technology – Open Systems Interconnection – Common Management Information Protocol: Specification' was approved. Simple Gateway Monitoring Protocol (SGMP) was published that year RFC 1028 [218].

In August 1988, RFC 1067 entitled 'A Simple Network Management Protocol' (SNMP) was published [219]. This memo defines a protocol, architecture, and system to carry out management of network information by logically remote users, with this network being either a TCP/IP internet, or the Internet itself [219]. The Simple in SNMP comes from the simple number of message types of the protocol, limited to just 3, which are get, set, and trap. Get allows the SNMP manager to get the MIB objects from the SNMP agents, Set allows the SNMP manager to set the MIB values at the agents, while Trap is used by SNMP agents to tell the SNMP manager about significant events (e.g. a fault) [220]. SNMP addresses 3 functional areas of FCAPS ISO telecommunication management model and these are Configuration Management, Fault Management, and Performance Management. This protocol had been defined at the time to address the short term needs of network vendors and operators [221]. It was also not as secure as one would desire as one of the fields 'community string' (a password like field enabling to devices statistics) has been transmitted in clear, with no encryption [220]. Common Management Information Protocol (CMIP) came one year layer to address the long term needs on the networking community [219] [221]. In 1990, SNMP was recognized as a standard protocol with a recommended status (RFC 1157) [222]. SNMPv2 came 3 years later as a proposed standard (RFC1442), where the main difference was the counter size that got upgraded to 64 bits instead of 32 in SNMPv1. In 2002, SNMPv3 (RFC3413-3415) became an Internet Standard with extra focus on security with Authentication (SHA-1 and MD5) and privacy (DES, TripleDES, AES) as well as better administration with logical context and remote configuration abilities [223].

Stage 3: Optical Networks

According to [224], it's estimated that global IP traffic will reach 131.6 Exabytes (1018 bytes) per month by 2018 which is more than 26 times all of the words ever spoken by mankind [225]. Compared to that, Optical Networks are present nowadays almost everywhere and especially prominent as they make up our backbone Internet connecting continents all over the world. According to The Submarine Cable Map, an electronic map that is a free and regularly updated resource from TeleGeography [226], as per 2017 statistics, nearly 428 submarine optical cables of near 1.1 million kilometers are currently in service around the globe.

Latest Optical Networks Characteristics

It's become widely recognized by now that Optical Fiber can handle way higher bandwidth than copper, while having low attenuation. Optical Networks can be used for both short (LAN) and long-haul communications. For these networks, Bus, Ring, Star, and Mesh topologies are all possible, and usable based on the pros and cons of each where they're suited best. If I am to speak about Transmission rates, the technology continues to advance as a recent paper published in

January 2018 demonstrates the transmission of 70.46 Tb/s Over 7,600 km and 71.65 Tb/s Over 6,970 km Transmission in C+L Band Using Coded Modulation with Hybrid Constellation Shaping and Nonlinearity Compensation [227].

Optical Networks Applications

Optical Networks core application is in transmitting tremendous amounts of data, voice, and video over both short and long-haul distances. Depending on the domain, the usage of Optical Network is shaped. For instance, in the Telecommunications Industry, Carriers use the optical fiber to transmit Plain Old Telephone Service, a.k.a POTS across their network [228]. Local exchange carriers (LECs) use it to transmit POTS between central office switches either locally, or to users doors (Fiber To The Home: FTTH) [228]. Financial Firms need secure and speedy connections, as well as multinationals, connecting their offices around the globe, which makes it appealing and quite cost effective in the long run especially if the linked sites are strategically in line with the business growth and the users' base. It is important, of course not forget about Cable television firms who heavily depend on fiber optics to deliver HDTV telecasts, digital video, and data services [228]. Other applications of optical fiber are in the domain of Internet of things, from Smart Traffic Lights Management, to Changeable Message Signs, to Smart Roads and other utilities within the city [228]. The Medical, or rather biomedical domain is no exception to the applications of fiber optics. In this one, one example for using the technology is to transmit digital diagnostics images. The Automotive domain was relying on Plastic optical fiber (POF) since 1998 [229], Military, Space and Industrial sectors [228].

Stage 4: Proposed Optical Networks Management Behavio-Realistic Framework

The Proposed framework is based on the prevention mindset research of stage I of this chapter, plus the ISO Functional areas of Network Management (FCAPS) as it distinguishes 5 main Functional Areas as depicted in the graph below within the context of Optical Networks.

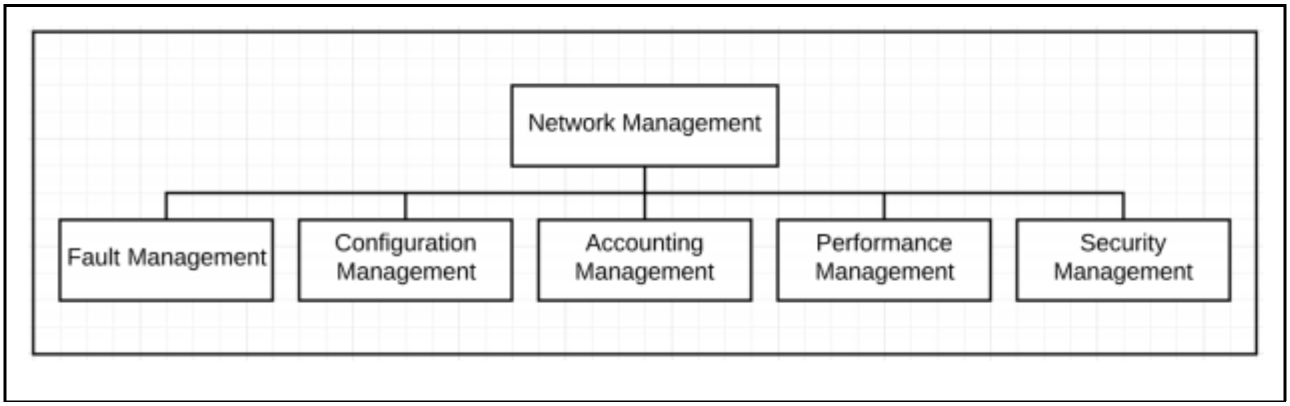


Figure 3.7 ISO Functional Areas of Network Management

Definitions & Terminology

Before proceeding further, it is key to begin by defining the ISO Functional areas of Network Management first:

Fault Management Functional Area:

The focus here is on identifying and logging abnormal network events, then isolate and deal with such events as appropriate. Distinguishing between 3 areas of fault management: The first is Error Detection (During normal network operations, as well as reliability engineering tests), the second is Error Diagnosis (During analysis of logs), and the third is Error Recovery (Including follow up actions of software/hardware replacement).

Configuration Management Functional Area

This one is concerned with monitoring and controlling the day to day network operations. It takes care of questions like: do network component X or Y exist? What are their names, addresses, routing details, relationship with other components as well as other interesting networks characteristics data that network managers collect out of this module.

Accounting Management Functional Area

This module is responsible for collecting data on resource/service usage by users or devices. Such data is helpful in determining monetary amount to charge to cost centers associated with these services in the network. It is also used to get trends and data insights, while also allowing to deal with operational tasks of adding and deleting users from services, managing their privileges, as well as quotas.

Performance Management Functional Area

This is the area where concepts such as Availability for instance come into play. Defining the availability of a subsystem as follows:

$$Availability = \frac{MTBF}{(MTBF + MTTR)} \quad (1)$$

With:

MTBR: Mean Time Between Failures

MTTR: Mean Time To Resolution

The Availability of a System composed of N Subsystems is defined as follows:

$$A_{Sys} = A_{Subsys1} \times A_{Subsys2} \times A_{Subsys3} \times \ldots \times A_{SubsysN} \quad (2)$$

Security Management Functional Area

In this area, the focus is on three subareas: Access Control, Authentication, and Encryption.

Framework Aim

The aim of the proposed framework is to endorse the latest internet standards and protocols in managing optical networks, while ensuring behavioral science research is at the core to serve achieve a preventative strategy in managing these networks within the Optical Networking Domain.

Framework People

In this section, I'll be listing entities responsible for drafting, enforcing, executing, and monitoring the framework. Drafting the 'Optical Networks Management Prevention Security Oriented Behavio-Realistic Framework Policy' is to be performed by senior Information Security Engineers, Corp Lawyers, as well as field specialists for domain expertise. The Draft Policy is then to be reviewed and approved by Top Level Management. This entity is then responsible for working with Internal Communication teams to lay down a process to raise awareness within the organization with regards to the new policy, open room for questions and feedback and iterate on it or on the policy as required. A well-defined maintenance process should be in place, to ensure the policy stays up to date and accommodate underlying standards or business strategy change should that emerge in the future. Personnel training should also be put in place. This is a moment to recall the study referred to in section 1, by the Journal of Consumer Research, which explains the behavior of Prevention and Promotion mindset oriented individuals from a consumption point of view. In that research, studies showed how subjects were willing to pay more at a restaurant based on how the menu was either organized in a big picture category for the Promotion Oriented subjects, vs. in a list based detailed manner for the Prevention oriented subjects [106]. Applying those insight in the design of this framework, I advise to train top management on the big picture by drawing the line back, for instance, to the organization risk appetite and competition strategy when presenting the legal and financial risks the organization could face should it have not adopted the proposed prevention framework. That was the Behavio-Realistic inspired methodology in advising top management to adopt the prevention mindset in managing optical networks. For Network Administrators, Engineers, and Technicians, a different strategy is advised, a training model where details matter, as they directly feed the prevention mindset. For any other stakeholder, a lighter version of the training is to be developed and shared with them on an FYI basis only. As part of the monitoring aspect of the framework, it is also important to form a business continuity and disaster recovery team internal to the company, with the possibility to outsource parts of the process to external vendors if needed. While this is good, an internal quality process should be rigorously put in place and monitored for excellence, with a defined action plan to address quality issues.

Framework Processes

For this framework to work, it is essential to nurture the prevention mindset within the organization by having it as one of its core values. This way, the organization, management and employees will have a reference point against which to judge any decision to be made within the organization. This behavior should govern, to name a few, the acquisition process of new infrastructure, taking into account backup plans in case of failures, to the design of the network with a prevention mindset assuming worst case scenarios, while still being realistic about the organization risk appetite and available resources, to the HR process of hiring the right skill set of network engineers, architects, and technicians, training them to adopt prevention as a core principle in their strategic and day to day work. With Prevention being a core value, comes the need to also define supportive processes in the following areas:

Governance

Simply put, it is the ability to evaluate, measure, and direct resources (optical networks systems and subsystems in our case) in support of achieving strategic goals. It should focus on 5 main areas:

- *Strategic Alignment*

This area takes care of ensuring there is a transparent link between the business and the networks operations department. Elements such as costs and impact should be clearly communicated between Business and Asset owners within the organization.

- *Value Delivery:*

This area's focus is on ensuring whatever was agreed on in the previous area gets actually delivered. Monitoring and Reporting are two keywords to note here.

- *Risk Management:*

This one is no surprise as it is critical in any organization and business, to define the risk appetite, set applicable thresholds, define the various risks and their probabilities, prioritize them, as well as define reasonable mitigation strategies.

- *Resource Management:*

In nowadays world, resource management doesn't simply mean hardware only. Resource management is to be thought of within the context of the Internet of Things as an inspirational reference. Any resource, be it human (human assets, human skills), physical (hardware assets: cables, switches, repeaters, etc.), virtual (vitalization software, network monitoring software), or symbolic capital (Branding) that contributes to achieving the strategic goals, any such resource is to be evaluated and optimized to ensure high efficiency and effectiveness against the prevention oriented defined business goals.

- *Performance Management:*

This area is concerned with ensuring all the above is well put in a framework that communicates easily the status of organization's score against its defined goals. It is very important to manage this in a central manner. For instance, the function responsible for Performance management should coordinate with various functions owners within the organization and connect the dots between the various departments, while planning the performance management reporting as a whole. This way, it will be possible to draw links and derive insights from a fault that happened at point x in the network, and that resource y that was been purchased in month m, with the associated risk profile and mitigation strategies put in place back then. This will help prevent from similar events from a holistic perspective rather than a patchy approach.

Regulations Compliance

This Process should ensure the organization is compliant with currently enforced standards in the domains where it operates, both in the core optical networks domain, as well as the applications domains targeted by the technology. This process owners should identify all functions affected by these regulations, then put together IPO (Input-Process-Output) tables and work with representatives from each function, to ensure a plan is put in place, defining review process, maintenance, and change management well ahead of any change in regulation. This way, whenever there is an upcoming standard or a regulation to comply with, it will be a matter of execution rather than planning it on the spot. This ahead of time preparation could benefit from studying the space to form educated opinions on potential timings of these changes and the nature of those. It also very important to keep up with the latest industrial, political, and technological trends, as they generally have a good weight within the regulatory space, and being familiar with those, would help prevent from any sudden surprises to the organization or disruption to its services due to a lack of readiness to comply within the required time frames, should any follow up regulation emerge.

Framework Technologies

While Internet Control Message Protocol (ICMP) and its 'ping' famous command create a low-level request and response verifying connectivity between two network endpoints, the feature itself does not go beyond this. SNMP comes to enable devices to share their basic configuration and onboard metrics elevating by that the work of ICMP one step further [230]. SNMPv3 has been around for 16 years now and although there is a wide gap between interest in SNMPv3 and the two older versions, as per Google Trends past 10 years results, as can be seen from Figure 3.8 [231], SNMPv1 and SNMPv2 are still alive and used.

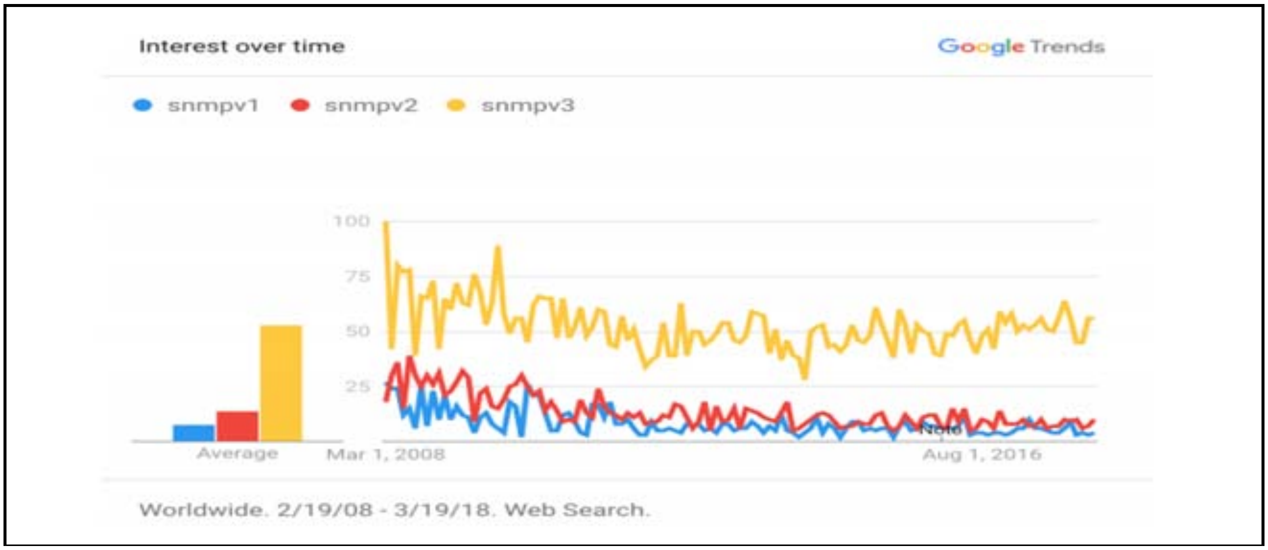


Figure 3.8 Google Trends Results Comparing SNMPv1, SNMPv2, and SNMPv3 over the past 10 years [231]

This poses a security issue and should be paid attention to. I suggest using SNMPv3 as it supports authenticated and encrypted passwords, it doesn't poll devices unless it is absolutely necessary. This behavior leads to an efficient usage of resources and processing power. It does also have a dedicated separate network so that managing traffic could be carried 'out of bound' without impeding the transmission of business data. With SNMPv3, three new elements get introduced: SNMP View, SNMP Group, and SNMP User. Network administrators can define views and specify what users can see to a granular level that can be something like: allow access to a group to only specific interfaces of a device. Now at the stage of defining the groups, the administrators will be asked to define a security model. Though v1 and v2 could be chosen, the v3 is also among the options and it is of course the one recommended to be chosen. After choosing that, the user is prompted to select a security level. Currently SNMPv3 comes with three possibilities: authNoPriv Security Level (auth), noAuthNoPriv Security Level (noauth), or the authPriv Security Model (priv). The last one is of course the best as it will require both authentication and encryption. Now network administrators can give a group x Read or Write Access or both access types to a view v previously defined. The administrators continues next by adding users to the defined group, then selecting SNMPv3 as the security model that the user uses, in order to match the view security model previously defined. The configuration also requires choosing an authentication algorithm: choosing between MD5 and SHA. I recommend selecting SHA, as it has been shown that it takes longer to break using brute force as shown in paper [232]. Upon selecting the authentication algorithm, a strong password should be selected next. Next, comes the encryption question and here SNMPv3 by design allows for only DES, as other encryption algorithms such as 3DES or AES are more resource heavy. This is problematic though as recent papers have been proposing innovative ways [233] of cracking DES 56 bit encryption using FPGA with 1 GHz in just 9 Hours for exhaustive search and 18 minutes for alphabets only.

Conclusion

It is important to keep in mind that while the technological domain continues to advance, pushing The Shannon limit further and further, laying more submarines cables in the ocean, and competing in keeping error rates down to negligible values, it is important to notice, that without a well-established framework with best practices and recommendations for both the technology, the processes, and the people and their motivational fits, the organization could prepare itself for failure. It's become nowadays critical more than ever before, to ensure the big picture is obtained right and the vital areas of the organization are run by strong independent yet collaborative processes, connected thanks to an effective governance that recognizes and enforces prevention as a core value and where each entity is clear on their responsibilities and where the flow is determined, communicated, and customized to fit as much as possible, to ensure successful operations strategically aligned with business vision and mission as well as the higher goals of the prevention oriented mindset framework to achieve organization goals and respond to users need in the domain of operation, safely and securely.

Applying Security-Aware Traffic Policing and shaping strategies with Dynamic Routing and Wavelength Assignment Attack Aware Algorithm in WDM Optical Networks

Optical Transport Equipment Market expected to reach the $16 Billion by 2022, projected DELL'ORO GROUP, an independent research firm in the United States of America, founded since 1995 in their 2018 released "Optical Transport 5-Year Forecast Report". The same report projects a 95% contribution of WDM Systems in Optical Transport Revenue. The Vice President of the research Group foresees demand and use of optical equipment and WDM systems to continue rising as service providers continue to expand their fiber footprint by installing more optical transport capacity between their global data centers. In light of this, this chapter section presents a novel approach applying Security-Aware Traffic Policing and Shaping strategies with Dynamic Routing and Wavelength Assignment Attack Aware Algorithm in WDM Optical Networks.

Introduction

Optical Technology has been gaining a lot of momentum in the past decades. Yet, it actually dates back in history to the 1790s with the invention of the first "optical telegraph" by the French Chappe brothers [234]. The idea back then was to build a system made of a set of lights installed on towers allowing network operators to relay messages between towers [234]. One might probably be aware of the Alexander Graham Bell's invention of the telephone, patented in 1876 [235], however one might or might know, that this scientist had a series of sonic devices, namely the optical telephone system (a.k.a photophone) that Graham Bell invented in 1880 [235][236]. In the mid-90s, Van Heel later developed a cladded fiber system that significantly decreased crosstalk and signal interference between fibers [234]. A couple years only after introducing laser in 1958, a serviceable laser, using an artificial pink ruby crystal as the medium, was invented, and was able to produce a pulse of light [234]. Only a year following that, a theoretical description of single mode fibers with a core so small that it could carry light with only one waveguide mode, was presented by Elias Snitzer [234]. This discovery was good enough for medical applications at the time, but not as much for communication, and that was due to the associated light loss [234]. Four years was the extra time necessary before Corning Glass Works scientists were able to make single mode fibers with attenuation < 20 dB/km by doping silica glass with titanium [234]. Three years following that, Bell Laboratories engineered a modified chemical vapor deposition process, currently still in use as a standard, where chemical vapors and oxygen get heated to form ultra-transparent glass that can be mass-manufactured into the low-loss fiber optic cable [234]. The United Kingdom Police was the first to install an operational fiber-optic in 1975 [234]. Two years later, California was able to transmit the first live telephone traffic through fiber optics [234]. By the late 70s early 80s, firms begun to incorporate fiber optics technologies in their communication infrastructure. That's all great, but I guess it'll be even more impressive if it had to do with long haul communications. Correctly so, the year 1986 was marked by Bell Laboratories inventing the erbium-doped fiber amplifier to reduce the cost of long-distance fiber systems while cutting the need for optical-electrical-optical repeaters [234]. Thanks to this invention, the world was able to witness the operationalization of the first transatlantic telephone cable in 1988 [234]. Getting closer and closer to WDM, where there's an operational single mode WDM devices, a simple definition, as provided by lasercomponents refers to such devices as "Single mode WDM are mainly used for telecom applications. If only one fiber is available, the transmission capacity can be doubled by using WDM. The components can be terminated with all common connectors. Depending on the application, WDMs are available in fusion technology (FSM) or with thin optical filters (TFF)" [237]. WDM, or Wavelength Division Multiplexing (WDM) simply means dividing bandwidth among independent sets of wavelengths, where each wavelength supports one channel of communication, and where each wavelength is independently modulated. With WDM, concurrent multiplexing and transmission occur over the same fiber as illustrated in Figure 8.1 Even if it might seem like a novel topic, given the attention that it's now getting, the reality is quite different. WDM is actually a concept that dates back to the 90s, where the optical amplifier first appeared. With that, was the beginning of wide-area optical networking era [238]. In 1991, optical amplifiers got actually fitted into the optical cable itself [234]. Compared to electronic amplifiers cables, the optical amplifiers cables were able to transfer up to 100 times more information [234]. Also in 1991, photonic crystal fiber was developed. This fiber guides light by means of diffraction from a periodic structure rather than total internal reflection which allows power to be carried more efficiently then with conventional fibers therefore improving performance [234]. Five years following that, TPC-5, the first of its kind all-optic fiber cable was buried down the Pacific Ocean. Only a year post that, Fiber Optic Link Around the Globe (FLAG) became the world's longest single-cable network to provide the infrastructure for the next generation of Internet applications.

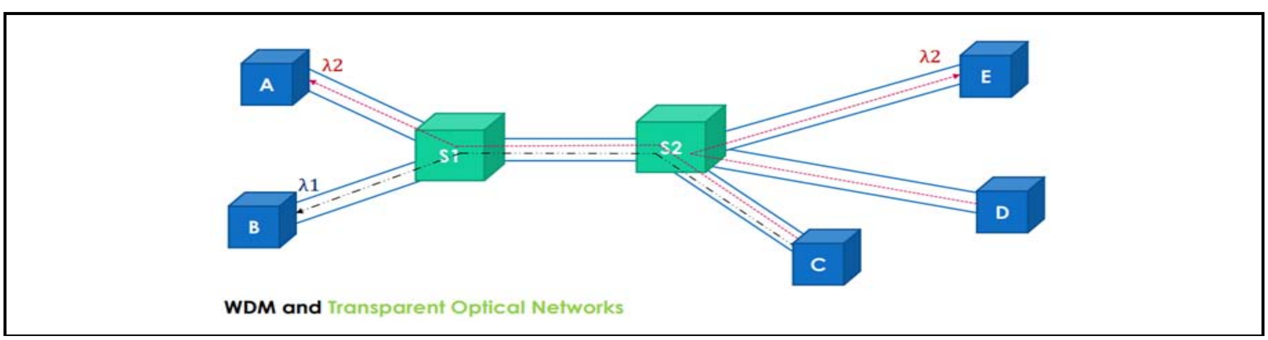


Figure 3.9 Multi-wavelengths transmission on one fiber (between nodes S2 and C) in a WDM Network

After looking at a brief history of fiber optics, it's time to present Optical Networks. In this study, in particular, I focus on Transparent Optical Networks, where such networks are named so due to the lack of opto-electro-conversion devices in them. With such networks, one could request lightpaths between any nodes on the network, fulfilling such requests takes into account both the physical and virtual topology of the network. One shouldn't talk about a virtual network topology, but rather about n potential virtual topologies over the same one physical topology of the network. These virtual topologies all share the same network resources such as nodes and links, but have unique signatures and design criteria, QoS Requirements, and use cases. It's important to note here that virtualizing optical networks has historically been based on Wavelength Division Multiplexing (WDM). The virtual networks resulting from this process are referred to as Virtual Optical Networks (VON) and are anticipated to handle the bursting traffic demands in ISP network infrastructure in the future. Unfortunately while transparent optical networks are known for accommodating multi-protocol format data and multi-services on single infrastructure, they're also known for being prone to erroneous/malicious signals propagating through the network without being detected.

Motivation

They say an image is worth a thousand words. The figures below depict this:

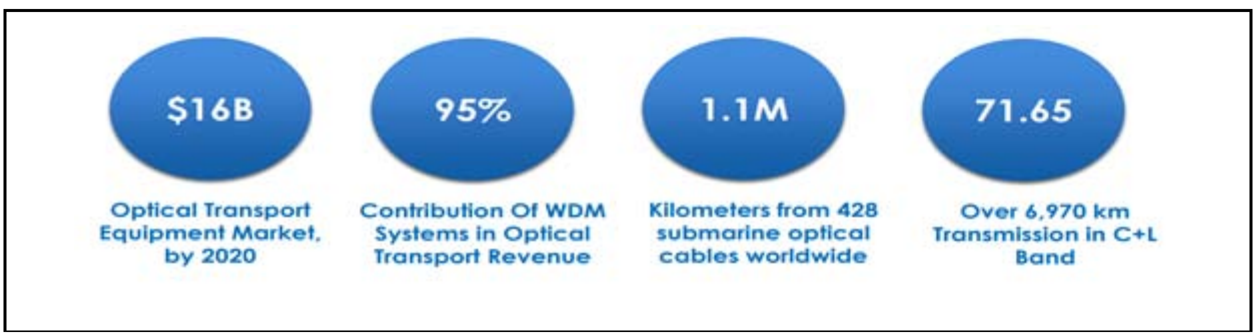


Figure 3.10 Optical Networks and WDM System motivational supporting pointers [239]

Researchers from Emory and the Baylor University College of Medicine published in 2001 a study in the April 15 issue of the Journal of Neuroscience which showed that most people not only love surprises, but actually crave the unexpected! [240]. Very recently this year, an entire country's Internet went down for 48 hours following the African Coast to Europe (ACE) submarine cable break, propagating the effect to a total of 10 countries, including Mauritania where the incident happened [241]. According to Internet performance firm Dyn, Mauritania relies exclusively on ACE to remain connected [242]. This could explain the 2 days down time following the incident, as well as the domino effect on the neighboring connected countries. As seen in Figure 3.11, research firm Dyn published the unfortunate news on April 5th, few days later:

Figure 3.11 Firm Dyn publishing new about ACE Submarine Cable Cut on April 5th, 2018 [139]

Figure 3.12 Online Newspaper reporting the ACE News shortly after [243]

Putting Media coverage aside, checking CISCO's VNI Forecasts [278] gives us a different perspective to understand the motivation behind interest in WDM Network, being a key technology for Internet:

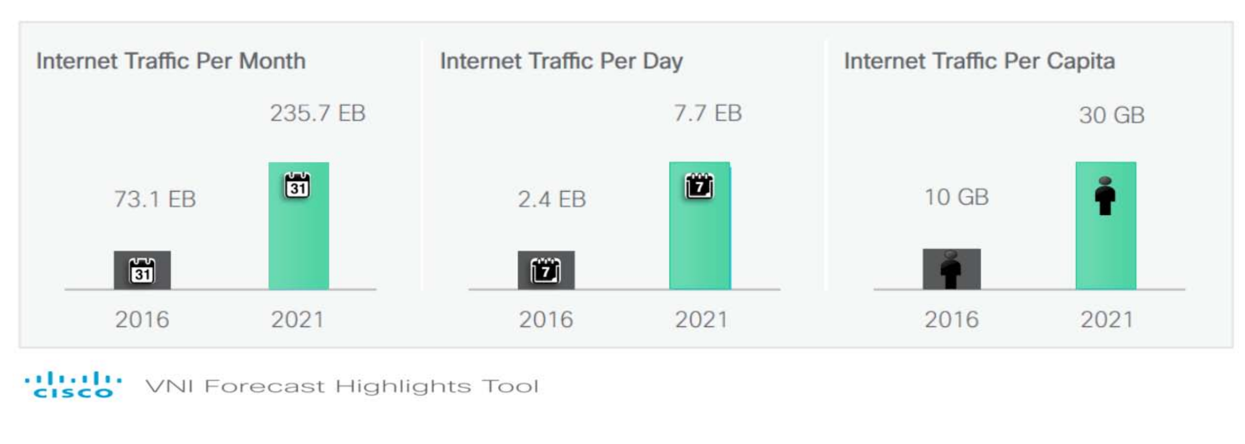


Figure 3.13 Cisco VNI Forecast Highlights Tool [278]

Foundation

WDM

The carrier wave belongs to the classical optical domain, the wave modulation permits transmission of either analog or digital signals up to a few GHz or Gbits/s on a carrier's pretty high frequency, ranging usually between 192 and 196 THz [245]. The bit rate can be enhanced by using multiple carrier waves that are propagating without much interaction on the same cable [245]. One have probably already noted that each frequency corresponds to a wavelength. This process is either Frequency Division Multiplexing (FDM) or Wavelength Division Multiplexing (WDM). In another definition, WDM is the mechanism by which multiple light wavelengths (a.k.a colors) are used to simultaneously send data over the same medium that is the optical fiber. A multi-transmission of signals through the fiber is achieved using different wavelengths [244]. Figure 8.6 below illustrates a WDM System, while Figure 8.7 goes a little deeper and shows what happens at key components of this system:

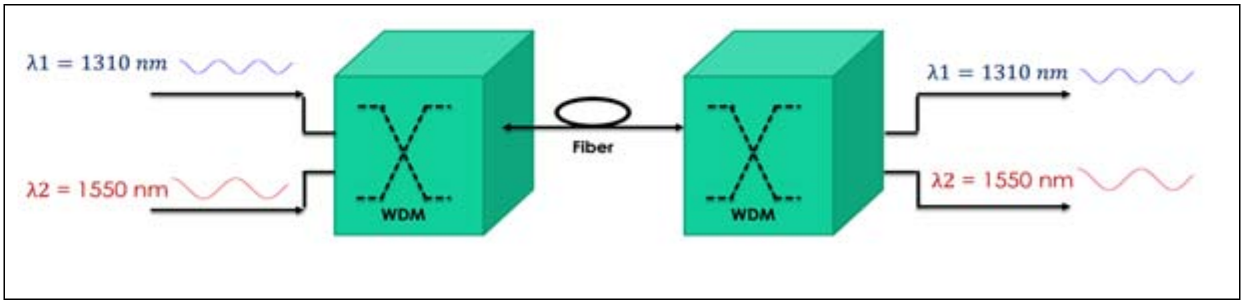


Figure 3.14 Illustration of a WDM System

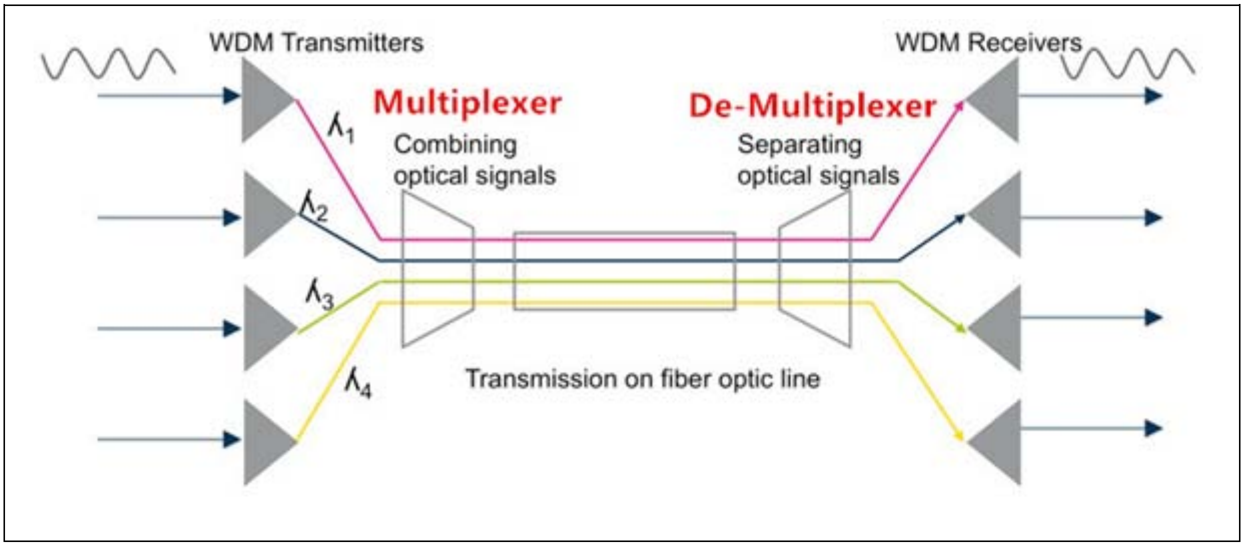


Figure 3.15 WDM System, a deeper view [246]

The light battle...Attack vectors

It's fairly common knowledge now how easy it is to sniff LAN, and WAN networks data, and exploit some common vulnerabilities (e.g. in the lack of strong WPA/WPA2 keys, dictionary attacks are still effective). It's also the case for Optical networks [247][248][249], where attacks are also possible and using simple means (available hardware and software). I present a few attacks targeting Transparent Optical Networks in particular. EDFAs attack, Low power QoS attack, Crosstalk in Optical Switching nodes attack, Correlated jamming attack, Cutting the fiber attack, as well as the famous Tapping attack.

In general, one can distinguish between types of attack origins, those that can be performed by internal attackers accessing a legitimate network nodes, and those performed by external attackers accessing a part of the fiber. Component faults, on the other hand, can result from fiber cut or nodes malfunction. Attacks are harder to locate than components faults, although it doesn't have to be the case, if the right mindset of attack prevention is in place, which should manifest in the form of attack-aware networks and incident response processes. Going back to our topic, the table below illustrates for each selected attack type three elements: the attack name, its strategy, as well as a potential remedy.

TABLE 3.1 Selected TON Physical Layer Attacks, their strategies and potential remedies

TON Physical Layer Attack	Strategy	Security Control
EDFA Attacks	Exploiting Erbium Doped Fiber Amplifiers' gain competition, depriving other signals of power, while increasing its own power.	Automatic Gain Control Amplifiers as they have power monitoring functionality, The functionality sends an alarm when detecting abnormal high power.
Low Power QoS Attacks	Attacking a splitter at the head of a link to attenuate propagation power to a certain amount. This also results in degrading the performance metrics (QoS) of attacked lightpaths and may result in attack propagation If there is optical cross connect (OXC) equalization at network nodes.	QoS degradation monitoring Systems. Paper X proposed a QoS degradation monitoring System based on OOF signaling, monitoring the following criteria: BER level, time during which that BER level was sustained, FP and FN [165].
Correlated Jamming Attack	Bending the fiber to tap part of the signal, injecting noise at the tapping point, resulting in eavesdropping or degradation of the SNR on the attacked signal.	There are a few options to note such as: 1) Threshold power detector systems to detect the jamming attack, 2) Optical Spectrum Analyzers (OSAs) as they can detect jamming attacks that severely impact the optical spectrum, 3) Optical time domain reflectometers (OTDR) detecting the jamming signal

		superimposed on the OTDR probe signal [148].
Cross talk based Attack	Intra-channel crosstalk: In Wavelength-selective switches, channels on the same wavelength can interfere and cause intra-channel crosstalk. Inter-channel crosstalk: Long distances and high-power signals can introduce nonlinearities in fiber and cause inter-channel crosstalk, High power jamming signal injected on a link can interact with other channels via nonlinear effects. Figure 8.8 below does a good job illustrative a few types of crosstalk.	Any system that can detect the change in signal power would do. Such system should be able to detect and monitor power levels at multiplexers, demultiplexers, as well as on switch plane, monitoring if power at any of these exceeds the expected value [166].
Tapping Attack	The attacker requests a channel and does not send on it, cross talk occurs between neighboring channels, the attacker's wavelength carries leaked data from this cross talk, the leakage signal is then amplified, resulting in a strong tapped signal of data which gets delivered directly to the attacker via their channel.	One simple method to prevent from this is encryption. Even if the attacker tries tapping the fiber, there will be no readable data as it would have been encrypted!
Cutting the Fiber Attack	Unambiguously means what it says, resulting in a Denial of Service, if there are no backup fibers.	Secure premises, surveillance, and defense in depth mechanisms should prevent intruders from getting onsite

		and tampering with the fiber infrastructure.

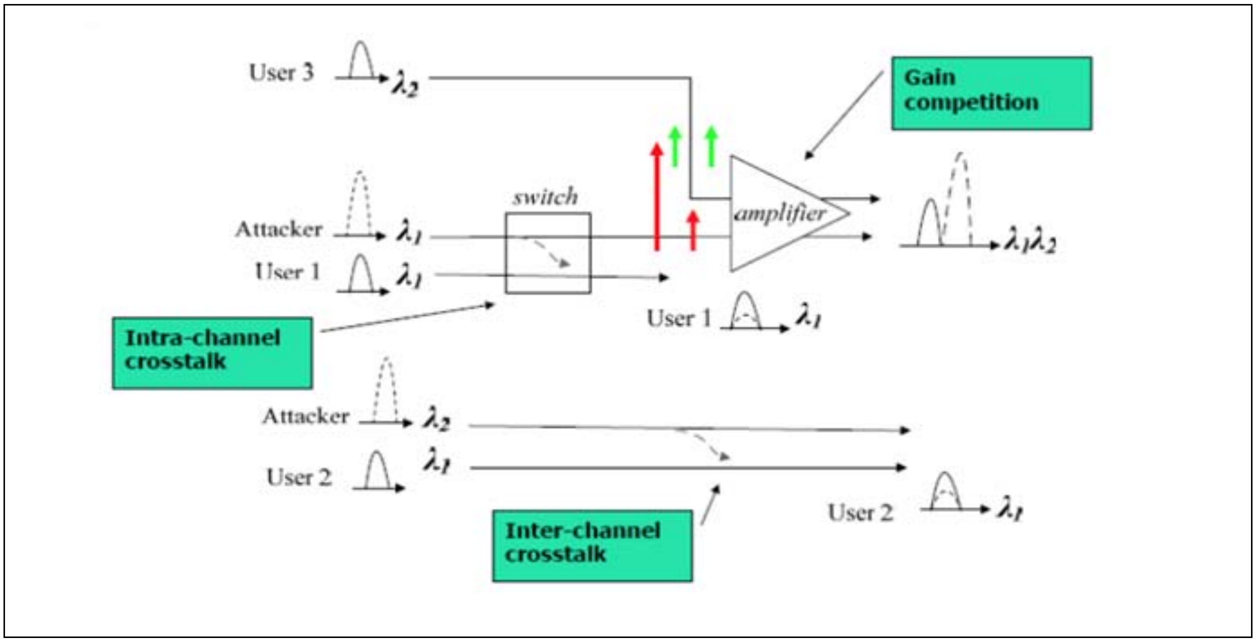


Figure 3.16 Crosstalk types, illustrated

RWA

Routing & Wavelength Assignment Algorithm aims at selecting of a suitable route and wavelength from possible choices for establishing call. RWA algorithms differ in the traffic assumptions and the performance metric used probability. Traffic assumptions fall into two categories: Static traffic, Dynamic traffic. With static traffic, a set of call requests is given and routes and wavelengths have to be assigned to calls such that some metric is optimized. With dynamic traffic, on the other hand, calls arrive to and depart from the network one by one in a random manner. The performance metric in this latter case is typically the call blocking probability.

Shaping & Policing

Shaping & Policing are two QoS traffic regulation mechanisms. Figure 8.9 illustrates QoS in a nutshell, before starting discussion in the topic, let’s present some key concepts first:

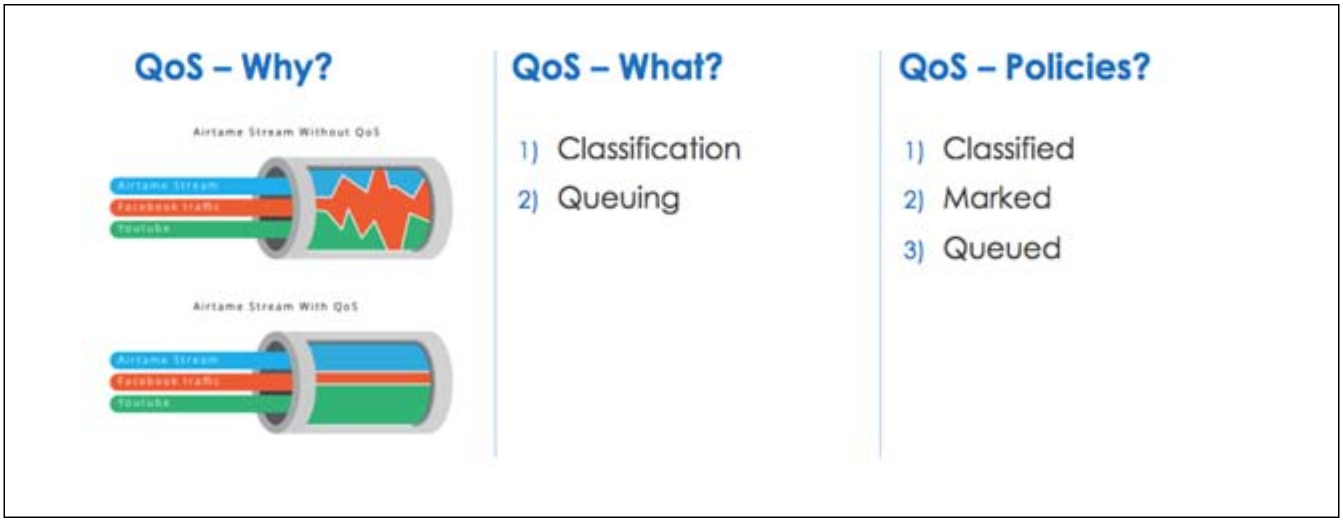


Figure 3.17 Introductory overview to QoS

Leaky Bucket Concept: This concept is used in jointly with resource reservation to police the host's reservation [250]. At the host-network interface, grant packets into the network at a steady rate. These packets may be generated in a bursty mode, but after they go through the leaky bucket, they get into the network evenly spaced [250]. The leaky bucket is a traffic shaper as it changes the characteristics of packet streams, making traffic generation more manageable and more predictable [250]. In some cases, it may be acceptable to permit short bursts of packets to get into the network without adjusting them, in such circumstance, a token bucket, which is a modified leaky bucket, could be used [250]. The bucket keeps tokens that are produced and put into the token bucket at a steady rate [250]. When a packet make it at the token bucket, it is sent if there is a token on hand. Otherwise, it is queued pending next token's availability, the token bucket size is set, and so when it gets full, successively generated tokens are discarded [250].

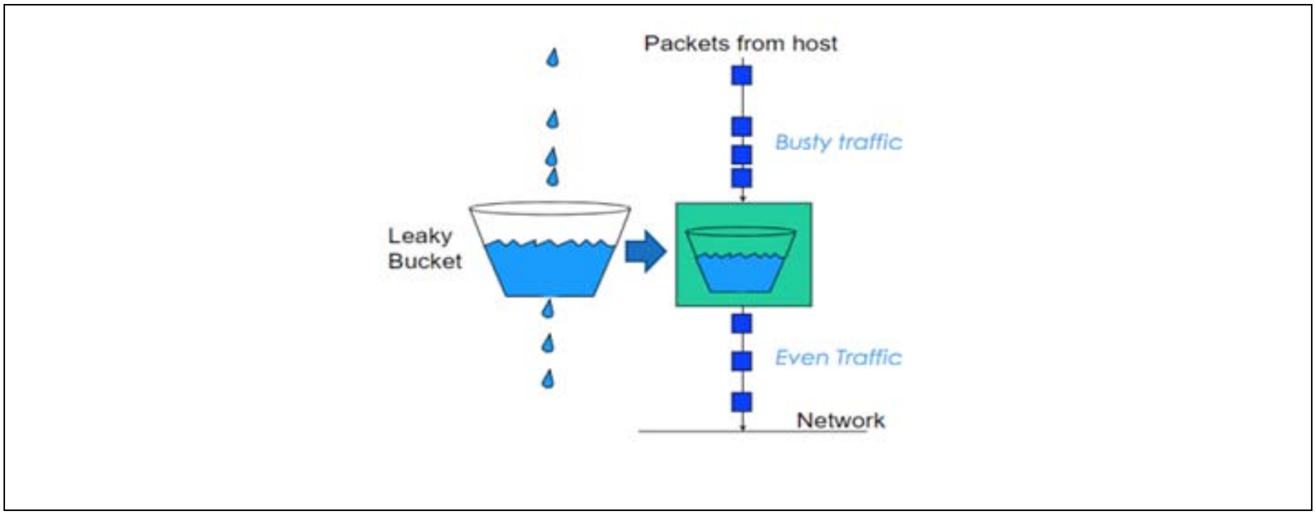


Figure 3.18 Leaky bucket concept

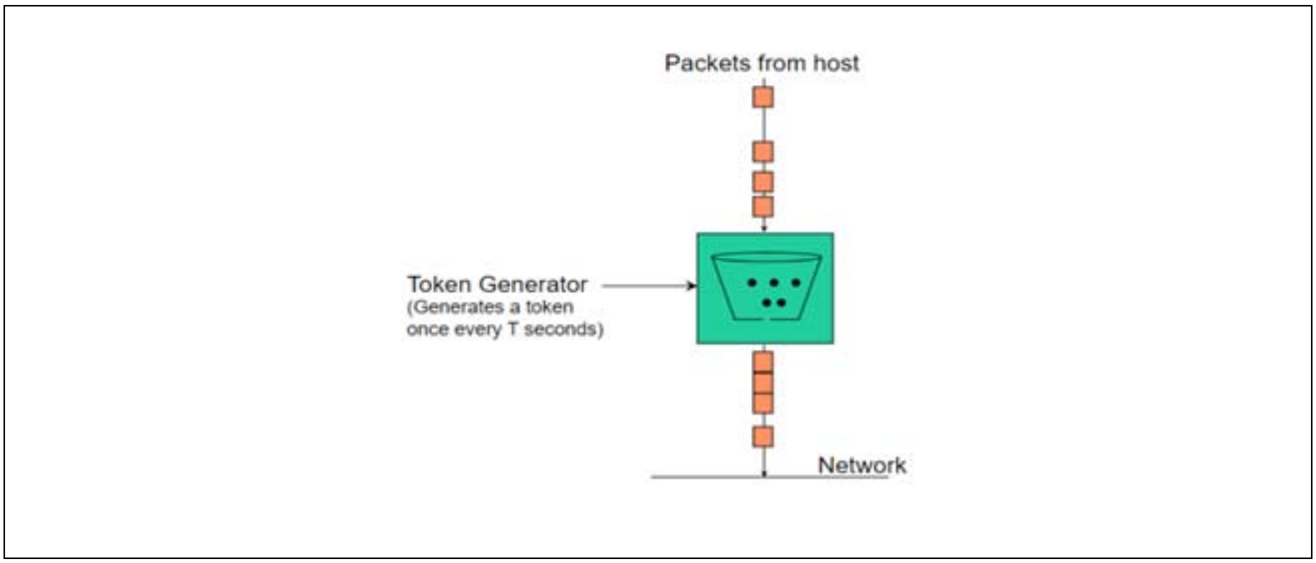


Figure 3.19 Token bucket concept

As the leaky bucket and the token bucket concepts have been presented, one shouldn't forget that this has been brought up within the context of policing and shaping, the two bandwidth management algorithms focus of this study. Policing process is especially recognized for its bandwidth savings and transmission delay prevention at the expense of potential data dropout. In recent literature, Time based traffic policing and shaping (TBPS) with Weibull model (TBPSW) were used to control traffic burst over Committed Access Rate at selected times [251]. Real internet traffic was accumulated and examined on both inbound and outbound internet flows [251].

Anderson Darling (AD) on Goodness of Fit (GoF) test was utilized to forecast the best parameter characterization and pinpoint the best traffic model [252]. Shaping traffic is a bandwidth management strategy that uses multiple correlated token buckets to buffer packet flow, which holds high bandwidth rates. Additional bandwidth management tactics like traffic policing or filtering dropped packets also moderate high packet rates but they utilize leaky buckets. The shortcoming of traffic policing and traffic shaping is that they can only decrement data rates, but don't have as high of an impact when it comes to aggregate burst traffic behavior, but rather do result in a degradation of quality of service in aggregate traffic [253]. While both shaping and policing strategies both control the output rate and both utilize a token bucket to measure packets rate, they are functionally different as will be seen in the next sections.

Policing

The main point to keep in mind when bringing out Traffic policing, is that this method propagates bursts. It doesn't necessitate any buffer for delayed packets. with Policing, when the traffic rate attain the designed maximum rate, any surplus traffic gets simply dropped or remarked, making it unnecessary to use any queues/buffers for that regard. This results in a saw-tooth shaped traffic rate graph as illustrated in figure 8.12 below.

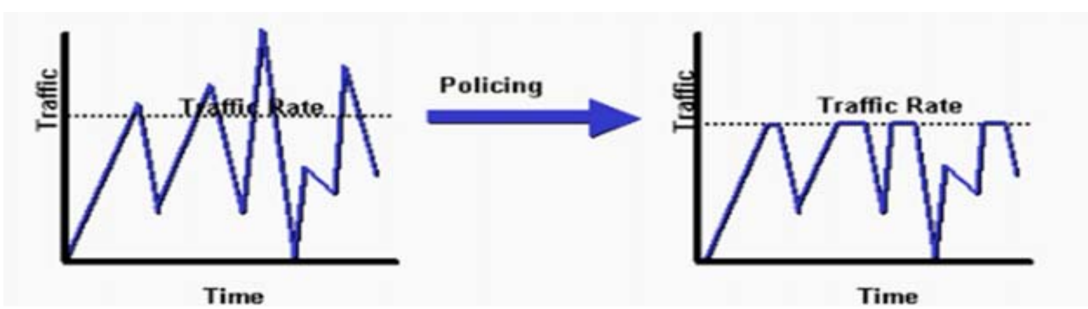


Figure 3.20 Traffic Policing effects on Traffic Rate

Shaping

The Shaping discussion is not complete without reviewing Generalized Processor Sharing (GPS) Algorithm. To give a closer look at GPS, imagine that all traffic that is transferred over the network is split into traffic classes, which can either be single or numerous flows sharing analogous QoS requirements [254]. Let us take a node A in a network. When GPS is utilized, each traffic class that travels this node is assigned a positive weight, specifying the warranted minimum capacity for a class [254]. If a traffic class does not utilize its capacity in full, the surplus capacity becomes then available for other traffic classes traversing this node, above their minimum available capacity. GPS is affiliated with the fair-queuing principle. In process scheduling, for instance, GPS is deemed to be an ideal scheduling algorithm to achieve perfect fairness [255]. Generalized processor sharing assumes that traffic has infinitesimal packet sizes [256], and can be indiscriminately split. Tracking GPS performance could be achieved relying on weighted fair queuing (WFQ) Algorithm. Also referred to as packet-by-packet generalized processor sharing (PGPS), WFQ is a network scheduling algorithm, that is both a packet-based implementation of the generalized processor sharing (GPS) policy, as well as a generalization of fair queuing (FQ) Algorithm which equally shares link's capacity [254]. WFQ is considered a generalization of FQ as it enables schedulers to decide on the % of link capacity to be shared. The PGPS synonym of WFQ comes from the fact that the algorithm estimates GPS to within one packet transmission time, irrespective of the packet arrival behaviors [257][258].

One might be wondering why I presented GPS and WFQ. This is because the latest is a shaping mechanism. Wrapping things up, Shaping is a traffic management strategy to control the available bandwidth, set the traffic priority as prescribed in the policy, controls traffic throughput for a given period or rate, while retaining excess packets in a queue, then scheduling them for later transmission incrementally over time, to finally result is a smoothed packet output rate as shown in figure below.

Figure 3.21 Traffic Shaping effects on Traffic Rate.

Design & Implementation

In this work, I've designed and implemented the Shaping strategy, Weighted Fair Queuing algorithm, Figure 8.14 showcases the algorithm in action. With WFQ, packets get sorted based on their weights, with weights being proportional to the importance of the class to which the packets belong. For instance, a priority queue would have an 80% associated weight compared to the remaining 2 queues/classes who would share the remaining 20%. It is key to note here that WFQ scheduler serves classes in a circular manner and that each class (i) gets a weight that represents its relative share of bandwidth (w_i), and hence its priority. In any time interval, at least one fraction of bandwidth (service) is secured for the class (i):

$$R(i) = R.\frac{W_i}{\sum W_j} \qquad (3)$$

To put this into practice, now imagine the WFQ scheduling policy is applied to a buffer supporting three classes c_1, c_2, and c_3, with the following respective weights: w_1: 0.5, w_2: 0.25, and w_3: 0.25 where each class has a large number of packets in the buffer. Below are a couple possibilities of the sequence in which these classes will be served to comply with their WFQ weights:

- Possibility$_1$: $c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3 \rightarrow c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3 \rightarrow c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3 \rightarrow$ ...
- Possibility$_2$: $c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_3 \rightarrow c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_3 \rightarrow c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_3 \rightarrow$ ...

Now imagine there are no c_3 packets in the buffer. The sequence to serve the classes to achieve their WFQ weights would be: $c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow c_1 \rightarrow c_1 \rightarrow c_2 \rightarrow \ldots$

Moving to the implementation, below is the figure that shows my package structure in Java

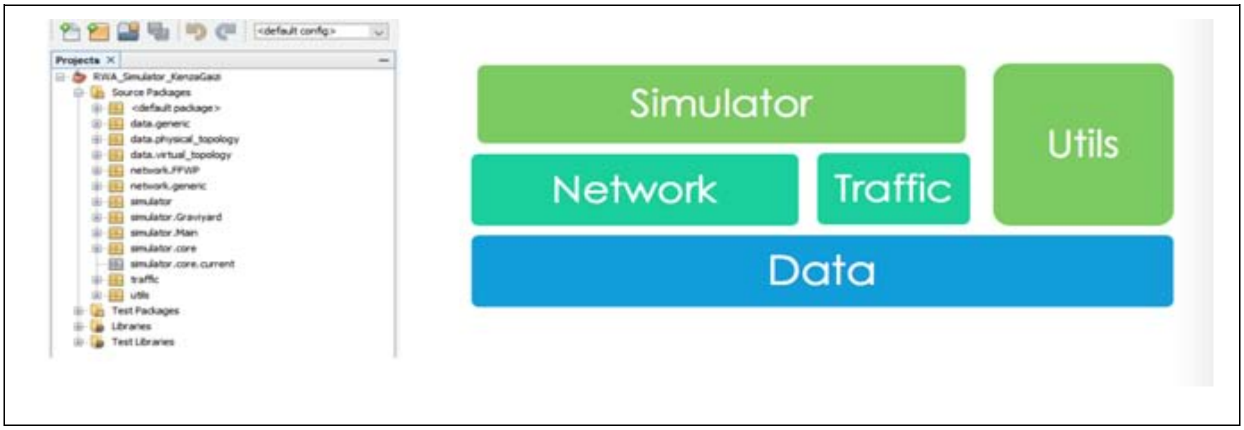
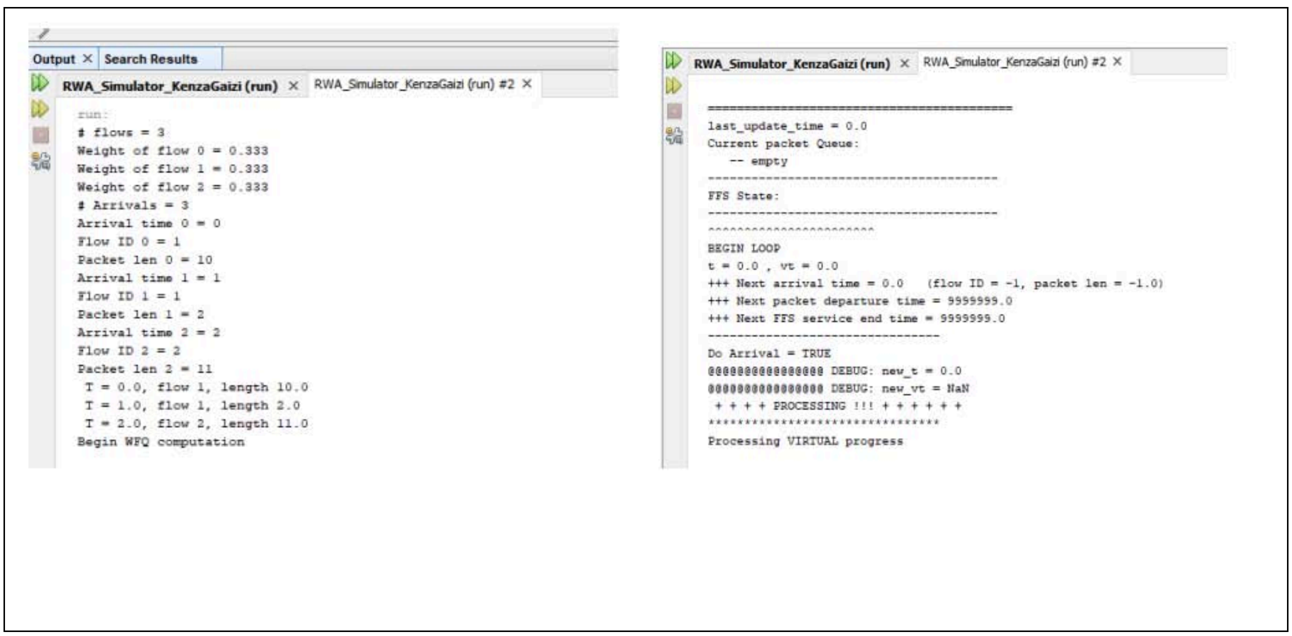


Figure 3.22 An illustration of the Java Package structure for the Project Implementation

Results & Discussion

Below are screenshots from selected parts of the experimental Weighted Fair Queuing Simulation:



```
********************************
Processing VIRTUAL progress

********************************
vt_rate= Infinity
********************************
Processing REAL progress

********************************
***** Processing packet arrival
nextArrIndex = 0
nextArrTime = 0.0
vvvvvvvvvvvvvvvvvvvvvvvvvvvvvvv
END OF LOOP:
t = 0.0
vt = 0.0
Current packet Queue:
   >>> (ID= 0 , packet Length=10.0 , Remaining Transmission Time=10.0 , Remaining Virtual Length=10.0 , virtual End Time=NaN)
----------------------------------------
FFS State:
Q[0].get(0).remaining_Virt_len = 10.0
----------------------------------------
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^



===========================================
last_update_time = 0.0
Current packet Queue:
   >>> (ID= 0 , packet Length=10.0 , Remaining Transmission Time=10.0 , Remaining Virtual Length=10.0 , virtual End Time=NaN)
----------------------------------------
FFS State:
Q[0].get(0).remaining_Virt_len = 10.0
----------------------------------------
^^^^^^^^^^^^^^^^^^^^^^
BEGIN LOOP
t = 0.0 , vt = 0.0
Flow 0 Rem. virt len = 10.0
Flow 0 Rem. virtual transmit time = 30.03003003003003
+++ Next arrival time = 1.0   (flow ID = 0, packet len = 10.0)
+++ Next packet departure time = 10.0
+++ Next FFS service end time = 30.03003003003003
--------------------------------
Do Arrival = TRUE
@@@@@@@@@@@@@@@@ DEBUG: new_t = 1.0
@@@@@@@@@@@@@@@@ DEBUG: new_vt = 3.003003003003003
 + + + + PROCESSING !!! + + + + + +
********************************
Processing VIRTUAL progress

********************************
vt_rate= 3.003003003003003
w[0] = 0.333
Flow 0 remaining_Virt_len = 9.0
Flow 0 remaining_Virt_len/w = 27.027027027027025
********************************


********************************
Processing REAL progress

********************************
!!!! Packet Q, remaining trans time = 9.0
***** Processing packet arrival
nextArrIndex = 1
nextArrTime = 1.0
vvvvvvvvvvvvvvvvvvvvvvvvvvvvvvv
END OF LOOP:
t = 1.0
vt = 3.003003003003003
Current packet Queue:
   >>> (ID= 0 , packet Length=10.0 , Remaining Transmission Time=9.0 , Remaining Virtual Length=9.0 , virtual End Time=NaN)
    -- (ID= 0 , packet Length=2.0 , Remaining Transmission Time=2.0 , Remaining Virtual Length=2.0 , virtual End Time=9.00900900900901)
----------------------------------------
FFS State:
Q[0].get(0).remaining_Virt_len = 9.0
----------------------------------------
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

```
============================================
last_update_time = 27.879849413572327
Current packet Queue:
   -- empty
-----------------------------------------
FFS State:
-----------------------------------------
^^^^^^^^^^^^^^^^^^^^^^^
BEGIN LOOP
t = 27.879849413572327 , vt = Infinity
+++ Next arrival time = 9999999.0    (flow ID = 1, packet len = 11.0)
+++ Next packet departure time = 9999999.0
+++ Next FFS service end time = 1.0000026879849413E7
--------------------------------
@@@@@@@@@@@@@@@@ DEBUG: new_t = 27.879849413572327
@@@@@@@@@@@@@@@@ DEBUG: new_vt = NaN
 + + + + PROCESSING !!! + + + + + +
********************************
Processing VIRTUAL progress

********************************
vt_rate= Infinity
********************************
Processing REAL progress

********************************
t = 27.879849413572327 ----- END
BUILD SUCCESSFUL (total time: 1 minute 18 seconds)


********************************
Processing VIRTUAL progress

********************************
vt_rate= 3.003003003003003
w[0] = 0.333
Flow 0 remaining_Virt_len = 8.0
Flow 0 remaining_Virt_len/w = 24.024024024024023
********************************
Processing REAL progress

********************************
!!!! Packet Q, remaining trans time = 8.0
***** Processing packet arrival
nextArrIndex = 2
nextArrTime = 2.0
vvvvvvvvvvvvvvvvvvvvvvvvvvvvvvvv
END OF LOOP:
t = 2.0
vt = 4.504504504504505
Current packet Queue:
   >>> (ID= 0 , packet Length=10.0 , Remaining Transmission Time=8.0 , Remaining Virtual Length=8.0 , virtual End Time=NaN)
    -- (ID= 0 , packet Length=2.0 , Remaining Transmission Time=2.0 , Remaining Virtual Length=2.0 , virtual End Time=9.00900900900901)
    -- (ID= 1 , packet Length=11.0 , Remaining Transmission Time=11.0 , Remaining Virtual Length=11.0 , virtual End Time=39.0390390390
----------------------------------------
FFS State:
Q[0].get(0).remaining_Virt_len = 8.0
Q[1].get(0).remaining_Virt_len = 11.0
----------------------------------------
^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
```

Figure 3.23 Experimental Weighted Fair Queueing Simulation

The above screenshots of WFQ in action is only one side of the coin. The other side here is Routing and Wavelength Assignment (RWA) Algorithms. In this work, the focus was on dynamic RWA, and choose fixed routing, where lightpath requests between the same end nodes are routed in the same fashion. With this approach, I pre-compute the shortest paths using Dijkstra's algorithm. For wavelength assignment, I select First Fit, where wavelengths are indexed in a successive order, with each lightpath request getting assigned to the least indexed wavelength available which then continues being assigned for the entirety of the physical link. This approach is used for its simplicity, and minimum communication overhead, with a complexity of O(w), where w is the number of available wavelengths.

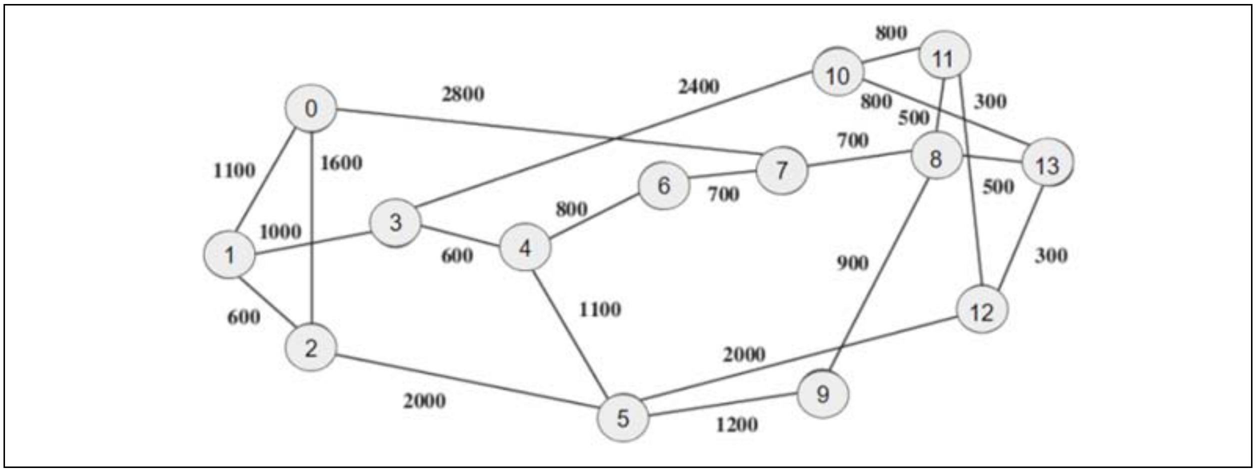


Figure 3.23 An illustration of the NSFNET 14 Nodes 21 Links network

Below figures show the illustrations and testing results of the algorithm above on NSF Network.

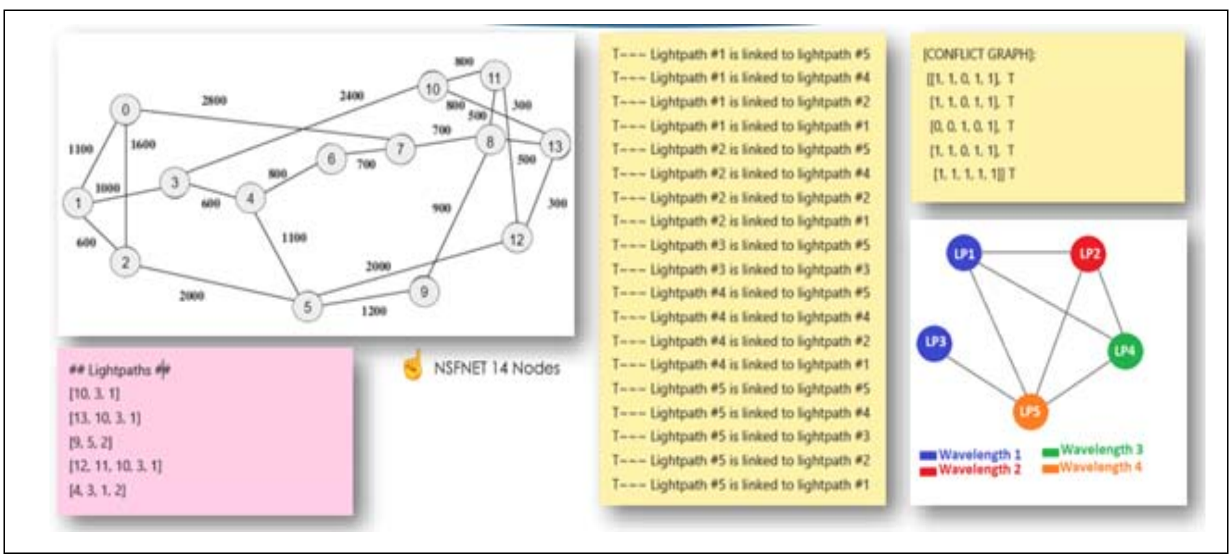


Figure 3.24 Testing Results of the NSFNET 14 Nodes 21 Links network

Figure 3.25 The developed simulator for dynamic RWA algorithm - NSFNET 14 Nodes 21 Links

Conclusion

WDM Market is big and bandwidth demand is increasing, WDM Transparent Optical Networks are prone to attacks, Attack awareness could be planned at design phase. This study shows how QoS Shaping & Policing techniques can be used for WDM Networks as well as how Bandwidth utilization fairness could be achieved with WFQ.

Realistic Dynamic Traffic Generation for WDM Optical Networks

This section presents a realistic approach on tackling the dynamic traffic generation problem for Wavelength Division Multiplexing Optical Networks. Given the relatively novel aspect of these networks, most research in this area was mainly focusing on the problems of routing and wavelength assignment while using fairly simplistic memoryless models for traffic generation in the simulated networks. The Internet of the very early days is way simpler than today's Internet. Although that itself is controversial, what is at least quite evident in today's Internet is its repeating-trends, long-term memory process. This alone makes the old Markov Chain, Poisson, and the rest of the memoryless models that continue to be observed used in simulations, actually stale and out of context. This fact makes any results based on such simulations highly questionable in terms of how close they are to reality and thus how practical to use those results in any applications at all. This chapter section is to address this controversial topic and present the Self-similar Pareto Process as a realistic convenient traffic generation model to simulate today's Internet traffic on its Wavelength Division Multiplexing Optical Networks Backbone.

Introduction

Optical Network is a topic of increasing interest by many professionals and Academicians in the Telecommunication domain. In the 70s, More's Law had been known for predicting that CPU power would double every two years, or more precisely for the computer scientists out there, the number of transistors would actually double every couple years [259].

WORLD INTERNET USAGE AND POPULATION STATISTICS NOVEMBER 30, 2015 - Update						
World Regions	Population (2015 Est.)	Population % of World	Internet Users 30 Nov 2015	Penetration (% Population)	Growth 2000-2015	Users % of Table
Africa	1,158,355,663	16.0 %	330,965,359	28.6 %	7,231.3%	9.8 %
Asia	4,032,466,882	55.5 %	1,622,084,293	40.2 %	1,319.1%	48.2 %
Europe	821,555,904	11.3 %	604,147,280	73.5 %	474.9%	18.0 %
Middle East	236,137,235	3.3 %	123,172,132	52.2 %	3,649.8%	3.7 %
North America	357,178,284	4.9 %	313,867,363	87.9 %	190.4%	9.3 %
Latin America / Caribbean	617,049,712	8.5 %	344,824,199	55.9 %	1,808.4%	10.2 %
Oceania / Australia	37,158,563	0.5 %	27,200,530	73.2 %	256.9%	0.8 %
WORLD TOTAL	7,259,902,243	100.0 %	3,366,261,156	46.4 %	832.5%	100.0 %

Figure 3.26 World Internet Usage and Population Statistics 30-11-2015

This concept didn't take long before it was borrowed in other domains, namely the telecommunication and broadband areas. In 1998, Jacob Neilsen presented a law stating that user's bandwidth doubles on an annual basis. Nelson named this law Nelson's Law of Internet Bandwidth [260]. According to the same reference, the law fits data from 1983 to 2014. According to the Internet World Stats website, about half of the world's population is online [261]. Check out Figure 3.26 for details on the distribution of the online Internet user around the world.

To design adequate networks able to adapt to the increasing demand on bandwidth by the growing number of users who get online every single second, there must be various considerations. One of them falls within the virtual design phase. Before acquiring fiber links and deciding on where and how to install them, it's very important to first do that in a simulation environment. This would allow for a thorough testing of how the network will behave in various scenarios and validate that against business requirements when it comes to QoS or Priority Handling and the like. Assume that the design part is relatively simple and that the concerned entity has either its own virtual network simulator or a licensed or open source third party software. To be able to simulate the network correctly, the concerned entity must either configure a static setup of data requests and configure the available number of channels and the threshold blocking probability, or use a dynamic traffic generator. This is the part that I'm concerned about. This Dynamic traffic generator should not be using any traffic generation model. Especially not the memoryless ones such as Poisson and Markov Chain Models. I suggest using the Pareto Process which is a self-similar process. The use of this process has been studied carefully as it will be shown in the coming sections. But before going further, let's go over the next section to see what has been done in the literature with this regards.

Literature Review

Validating current business requirements and predicting network reliability, survivability, and load balancing capabilities in the future are equally important. This is because that'll mean allowing to report accurate insight that the network owner/user management entity can use to make valid business decisions. More practically, if the network simulator is based on an accurate, close to reality, then the predictions would be more likely accurate, allowing for accurate business decisions such as an ISP deciding to acquire state agreements to introduce more fiber links to connect between different sites redundantly should there be a risk of single point of failure or to cut down costs by eliminating some links if they're no longer needed or could be replaced by other short paths, or simply to face a growing market where demand is high and expansion is cost effective for the entity, thus requiring to add more links or re-engineer the design to cope with the demand using existing links through optimization mechanisms.

During Network design, network designers generally assume that past experience about the network would enable to predict its performance for future requirements [262]. To understand this better let's talk about some of the main usages of traffic models. They could basically be either used within analytical models or used to drive a Discrete Event Simulations [262]. I am interested here in their usage in analytical models.

Memoryless Process

The usage of the memoryless Poisson distribution if traffic generation models could be traced back to the early 90s. According to [263], this distribution was at the heart of traditional telephony networks, analytical models. In theory, this also relates to Operations Management when customers or users arrival times are modeled as a Poisson distribution model. Taking a concrete example: In a store, the management had specified till agents checkout time to be from 16:30 to 16:45. On average, 10 customers enter the checkout line in this time interval. Figure 3.27 below:

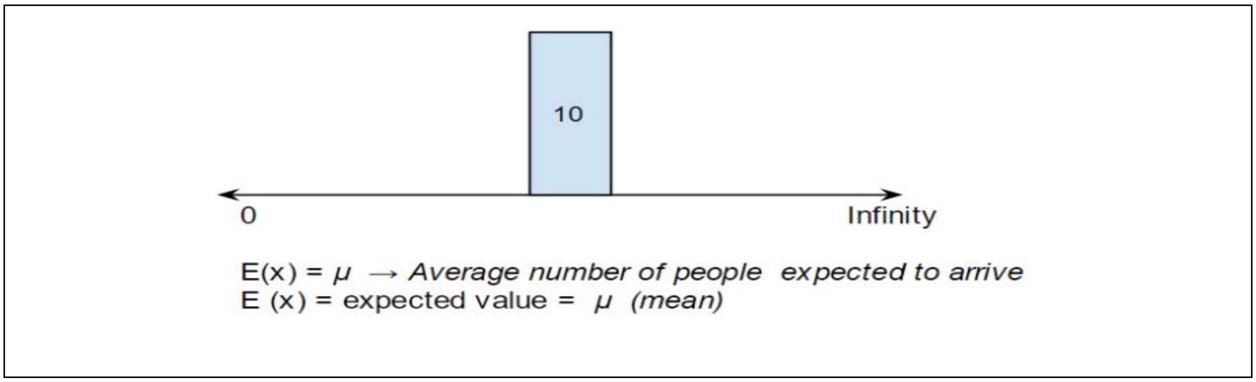


Figure 3.27 Poisson Distribution Parameters, 10 customers average example

Poisson defines its expected value or mean μ as follows:

$$\mu = \lambda = \frac{number\ of\ occurences\ or\ arrivals}{Specified\ interval} \tag{4}$$

With an average of 10 customers entering the checkout line between 4:30 and 4:45, there are 10 customers per 15 minutes. That is λ = 10 $customer$s / 15 $minutes$ = 10

The expected value is the mean (μ) of a discrete probability distribution. Poisson distribution focuses on the number of discrete events or occurrences over a specified interval or continuum (time, length, distance).

Since the Poisson formula is:

$$P(x) = \frac{\mu^x e^{-\lambda}}{x!} \tag{5}$$

And since:

$$\mu = \lambda = \frac{number\ of\ occurences\ or\ arrivals}{Specified\ interval} \tag{6}$$

The Poisson formula can be then written as:

$$P(x) = \frac{\mu^x e^{-\lambda}}{x!} \tag{7}$$

where:

x = 0, 1, 2 … Number of occurrences of interest

$\mu = \lambda = \frac{\text{number of occurrences or arrivals}}{\text{soecified interval}}$ = long-run average

e = 2.118282 (base of natural logs)

Sample questions that an operations manager would like to answer would be something like: What's the probability that exactly 7 customers enter the line between 16:30 and 16:45?

To answer this question, it is known that:

$$\lambda = \frac{10\ customers}{15\ minutes} = 10 \tag{8}$$

And from the question it is inferred that x = 7 customers. It is also known that:

$$P(x) = \frac{\mu^x e^{-\lambda}}{x!} \quad \text{Therefore: } P(x) = \frac{\mu^7 e^{-10}}{7!} = 0.09007922571 \tag{9}$$

This is then the probability that exactly 7 customers would enter the checkout line between 16:30 and 16:45. Another question would be to ask about the probability of more than 10 customers coming to the checkout line.

To answer this question, it know that:

$$\lambda = \frac{10\ customers}{15\ minutes} = 10 \tag{10}$$

And it inferred that x > 10 customers, so $x \notin [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]$. It is also known that:

$$P(> x) = 1 - PoissonCdf(x, x) \tag{11}$$

Thus:

$$P(> 10) = 1 - PoissonCdf(10, 10) = 1 - \text{PoissonCdf}(10, 10) = 1 - \sum_{i}^{10} P(i) \tag{12}$$

Replacing $P(i)$ with its value $P(i) = \frac{\lambda^{i} e^{-\lambda}}{i!}$ results in:

$$P(> 10) = 1 - P(1) - P(2) - \cdots P(10) \tag{13}$$

Though these questions can be answered with Poisson Model for the context of operations management, mapping customers' arrivals to internet packets arrivals or lightpaths requests is not going to lead accurate answers. Poisson is not a realistic model for packets arrivals since discrete events are not real. A realistic model would be one that considers packets arrivals as continuous and sharing of a common trend over time, which is referred to as the long-memory processes in the next section.

Long Memory Process

Long memory processes could be identified by the persistence of a correlation over time that takes far long to decay [264]. It's been an interesting topic for economists since the late 80s. However, this phenomenon itself has been identified earlier than that in different data sets by Hurst (1951, 1957), Mandelbrot and Wallis (1968), Mandelbrot (1972), and Mcleod and Hipel (1978) among others [264].

Self-similar or Fractal Processes are examples of long-memory processes. A variable x is exactly self-similar with scaling parameter H (Hurst Parameter), if for all levels of aggregation m, xm=mH-1x where xm=average of m consecutive values of variable x. In Self-similar traffic, there is no natural length of a "burst" which is a critical characteristic in such traffic. At any scale, small (milliseconds) or big (hours), similar-looking traffic bursts are evident [265]. "Besides, we find that aggregating streams of such traffic typically intensifies the self-similarity ("burstiness") instead of smoothing it." [265].

Analysis & Simulations

There have been some attempts in the literature to study Memoryless and Long-Memory Processes in the context of Optical Networks, such as [82]. On the other hand, there is still some recent work in the Optical networks field, where Poisson is still being considered at the heart of the traffic generation model, [267] as an example. Our research proposes using Pareto Process as a Traffic Generation process and fixing the variables: Routing Policy and wavelength assignment and comparing the results with a quite recent paper [267] that had been cited by 30 papers already. In Figure 3.28, 3.29, 3.30, and 3.31, I plotted Pareto distribution for several shape parameters over multiple ranges up to 100; up to 1,000; up to 10,000 and 10000 and finally up to 100,000. Each time I call the Pareto function on the iteration counter referring to the shape variable, each output of the Pareto function corresponds to a lightpath request within the WDM Optical Network. I plot the results below to show the self-similarity aspect:

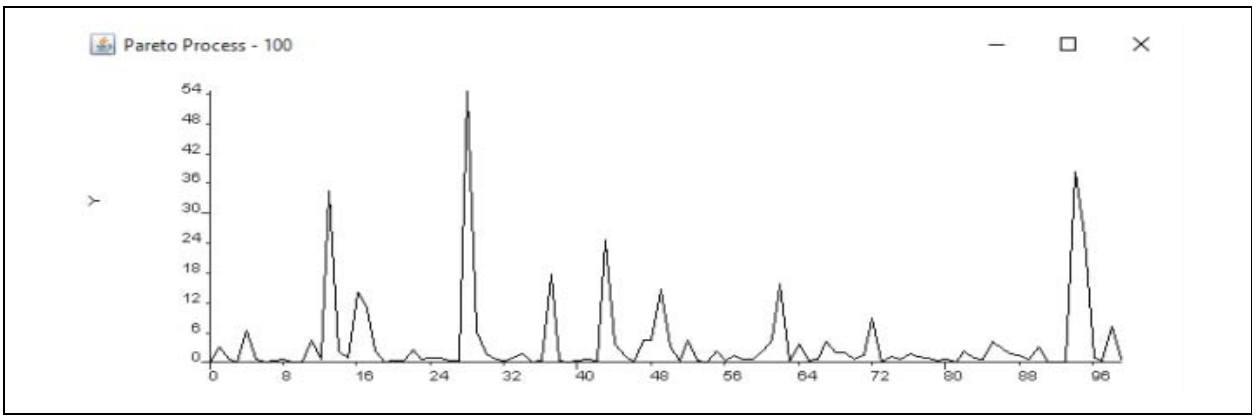


Figure 3.28 Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 100 iterations

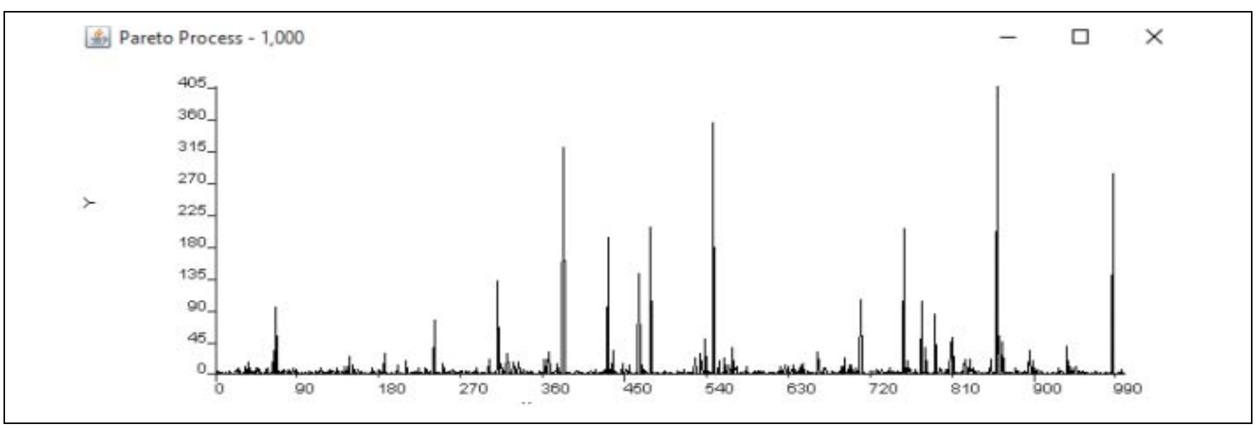


Figure 3.29 Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 1000 iterations

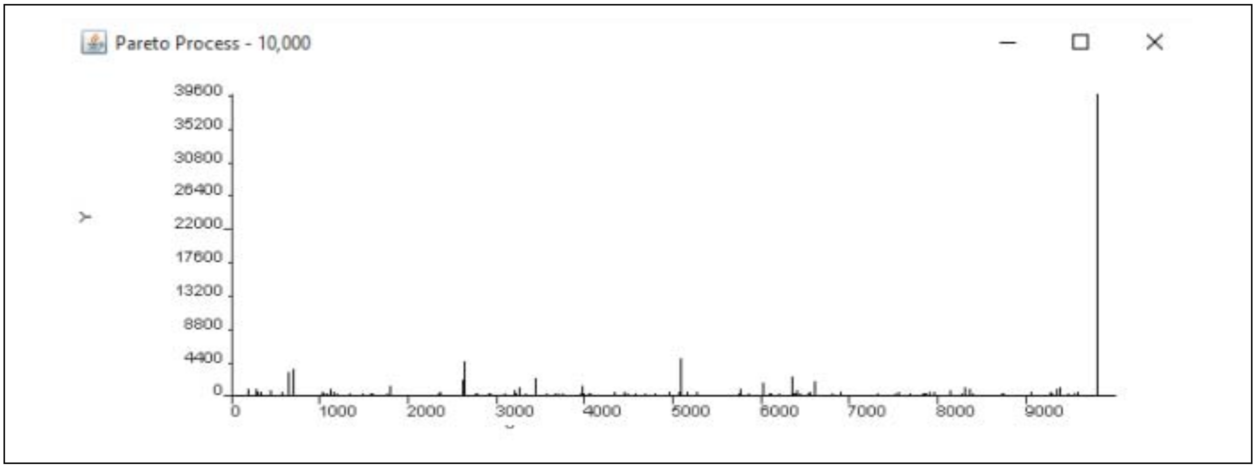


Figure 3.30 Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 10000 iterations

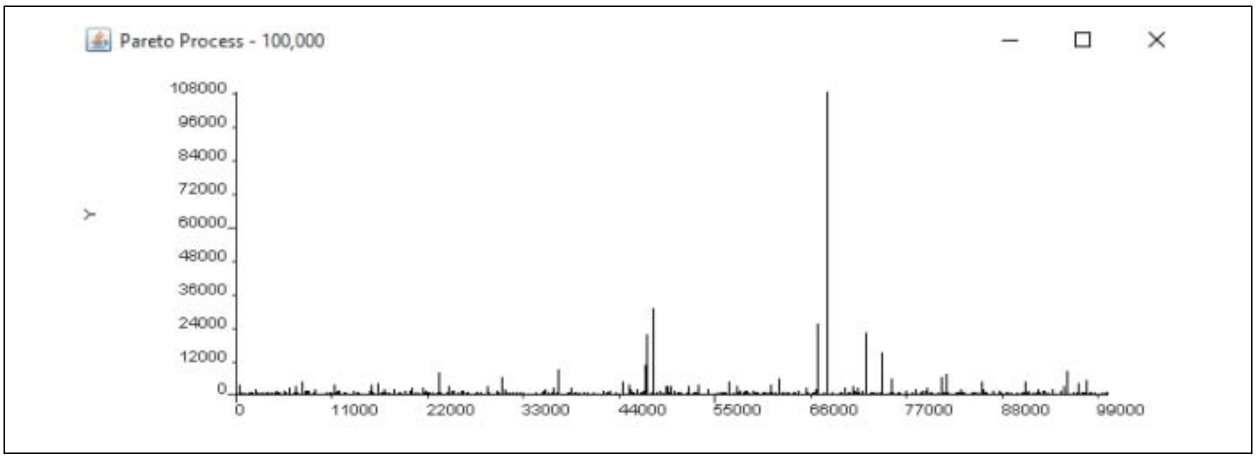


Figure 3.31 Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 100000 iterations

Conclusion

From figures 3.28 through 3.31, I have presented a self-similar simulation of WDM lightpaths requests within Optical Networks. I also showed that our Implementation of Pareto model simulation for WDM Traffic Generation is consistent over multiple iterations and shape variables, making it a realistic model, practical to be used for Traffic Generation Modules for Optical Networks Simulators.

Chapter 4: Static RWA

A Novel Attack and Throughput-Aware Routing and Wavelength Assignment Algorithm in Transparent Optical Networks

The transparency feature of All-Optical Wavelength Division Multiplexing (WDM) Networks makes it an interesting topic of study. Although characterized by the high throughput, low bit error rate, and low noise, Transparent Optical Networks are still considered prone to attacks. The transparency of the network and the lack of optoelectronic conversion allow malicious signals to propagate without being detected. This unnoticeable propagation results in performance degradation and damages the throughput of the network. While several approaches have been focusing on detective measures, this chapter proposes a preventive throughput and attack aware algorithm based on secure topology design. This approach gives enough flexibility to the customer to choose the level of security and throughput that they want to achieve in the network. Namely, the algorithm aims at routing lightpaths in such a way as to minimize the worst case possible damage that can result from different physical-layer attacks. At the same time, the routes have to be selected in such a way as to ensure the desired throughput level. Consequently, two objective criteria for the Routing and Wavelength Assignment (RWA) problem are defined. The first one is referred to as the Maximum Lightpath Attack Radius (maxLAR), while the second is referred to as minimizing the blocking probability. Based on this, the routing sub-problem is formulated as a mixed integer linear program (MILP). Tests are performed on small networks at the time being. When simulating attacks, results indicate that the formulation achieves significantly better results for the Maximum Lightpath Attack Radius and Minimum Blocking Probability.

Introduction

All Based on Wavelength Division Multiplexing (WDM) technology, Transparent Optical Networks (TON) ensure high data rates on one hand and low bit error rates on the other. Given this, such networks represent today's Internet backbone infrastructure. Data is transmitted using signal carriers corresponding to different wavelengths.

Before transmission, lightpaths must be established between the various network nodes. The physical setup of nodes in the network is referred to as the physical topology, while the setup of these lightpaths over the network is known as the virtual topology. Upon establishing lightpaths, they are transmitted transparently to the network without undergoing any opto-electronic conversion at intermediate nodes. This transparency represents a vulnerability for the network.

Security issues and attack management in transparent WDM optical networks has become of prime importance to network operators due to the high data rates involved and the vulnerabilities associated with transparency. Deliberate physical layer attacks, such as high-powered jamming, can seriously degrade network performance and must be dealt with efficiently.

While most approaches are focused on the developing fast detection and reaction mechanisms triggered in case of an attack, we propose a novel approach to help deal with these issues in the network planning and provisioning process as a prevention mechanism.

The RWA Problem

Linked to the physical and virtual topologies of transparent optical network, the Routing and Wavelength Assignment problem (RWA) stands up as a challenge. This challenge is itself divided into two sub-challenges, the routing sub-problem, and the wavelength assignment sub-problem. In the routing sub-problem, the challenge is to find a route for each lightpath over the network's physical topology. On the other hand, the wavelength assignment sub-problem requires assigning a wavelength to each route. Talking about wavelength assignment, there are three different types static, scheduled, and dynamic. Static wavelength assignment implies that the network lightpaths requests are known in advance. The scheduled assignment implies that lightpath setup is based on some sort of schedules. Finally, the dynamic assignment means that lightpath request arrive randomly with random holding times.

Discussing RWA requires highlighting three main axes that are: RWA wavelength assignment constraints, RWA variations, and RWA optimization objectives. The first axis states that there are two RWA wavelength Assignment constraints. The first constraint is the wavelength continuity constraint, requiring each lightpath to be established on one wavelength. The second constraint is the wavelength clash constraint requiring that no two lightpaths sharing at least on common link are assigned the same wavelength.

The second axis related to RWA variation states that the problem can be solved given different configurations and design parameters. The first configuration concerns the number of wavelengths that can be either limited or unlimited. The second configuration concerns conversion in the network, which can be at the level of all nodes, some nodes, or none of them.

The third axis concerns RWA objectives, where minimizing the blocking probability is the most common objective for dynamic wavelength assignment. For the static and scheduled assignment, minimizing congestion is more common as an objective.

With different constraints, variations, and objectives, RWA is considered one of the hard NP-complete problems [268][269]. There have been different methods proposed in the literature to solve each of the sub-problem elements of RWA. Examples of these methods for static, dynamic, and scheduled assignments are explained in [270][271][272][273][274][275][276]. For instance, according to [271] RWA problem in TON is solved through a Genetic Algorithm (GA) by searching for the most convenient set of paths from possible ones. The GA approach in has been evaluated for NSF network and compared with similar topologies. Within the same context, paper [276] proposes a simple, robust and efficient genetic algorithm for RWA in WDM optical networks. Extending Skorin-Kapov heuristic [270] by embedding it into an evolutionary framework, the proposed algorithm increases the performance of one of Skorin-Kapov heuristic multi-start variants by 24.3%. Paper [272] presents an alternate routing approach, based route-wavelength pair and the minimum cost criteria. The proposed approach is used to solve the RWA problem in optical WDM networks with dynamic traffic demands. Paper [273] proposes a new approach for solving RWA, referred to as GDWA (Graph Decomposition based Wavelength Assignment). The approach concerns static Wavelength Assignment for a special type of WDM networks based on de Bruijn graph. The paper [273] also describes a novel request routing strategy abbreviated as LBR (Load Balanced Routing). This, together with GDWA results in a static polynomial time and an enhanced blocking performance compared to other RWA strategies. Paper [181] proposes the use of an Ant Colony Optimization (ACO) algorithm in order to solve the problem of RWA. The work tackles wavelength continuity constraint optical networks. Based on distribution, the protocol presented in [274] allows for higher survivability to network failures or traffic congestion. Applying the protocol of NSFNET like networks provided with promising results in terms of blocking probability.

Paper [275] proposes a novel approach for modelling RWA problem in wavelength-routed Dense Wavelength Division Multiplexing optical networks. Using Artificial Bee Colony (ABC) algorithm, every food source denotes a possible and practical lightpath between each original and destination node pair. According to [275], some artificial bees in the population modify food sources' positions. The aim of these bees is to discover food sources' places. The solution to their search is the food source with the highest nectar value as evaluated by the fitness function. The paper also indicates the possibility of extending the algorithm for dynamic RWA schemes in real-time applications and employed by network resilience architectures.

In this chapter, a detailed analysis of RWA objective criteria, mainly focusing on both Maximum Lightpath Attack Radius and Minimum Blocking Probability. Furthermore, the corresponding necessary algorithms are presented.

Problem Definition

The transparent optical networks attack and Throughput-Aware RWA problem is defined by outlining a physical and virtual network. Modeling the physical topology as a graph with bidirectional edges where each edge direction refers to one optical fiber for a total of two optical fibers per link. Based on a set of lightpath requests, statically established (already known), the RWA aims at finding the suitable routes for each of the virtual/logical topology lightpaths. This is only restricted by WDM constraints over wavelength assignment. Mainly, we talk about the wavelength continuity and clash constraints. The scope of the research assumes that there are no restrictions on the number of used wavelengths, assuming the presence a sufficient number of wavelengths, able to satisfy the network's traffic demands given WDM constraints and for any routing strategy. On the other hand, the number of hops is assumed to be limited in order to prevent from transmission delays resulting from long distances (multiple hops traversed by the lightpath). This limit on the number of hops has another benefit as it allows to prevent from unacceptable physical impairments [277]. The problem definition also assumes that there is an acceptable blocking probability that forms a threshold not to be exceeded by the network.

Having modeled the physical and virtual topology of the network, modeling the mapping of one on the other is also important. This mapping is nothing but the assignment of wavelengths over the network links. Based on [74], WA, which is a sub-problem of the RWA can be modeled as a graph coloring problem where each node refers to one of the network's lightpaths. The graph edges represent the link-sharing concept where two lightpaths are linked using an edge if there is indeed at least a common link between the two. This coloring problem graph is known as the conflict graph where its chromatic number is the minimum number of colors to color the graph. This number is also referred to as the maximum degree of the graph (G). This value is an upper bound for the MaxLAR value, where:

$$MaxLAR = \Delta(G) + 1 \qquad (1)$$

The First RWA Objective: Minimizing the Maximum Lightpath Attack Radius (MaxLAR)

According to the paper [277], a new objective criterion for the RWA problem, known as the Maximum Lightpath Attack Radius (MaxLAR) has been defined as the maximum number of lightpaths that any other lightpath is link-sharing with [277]. In this context, link-sharing indicates if two lightpaths traverse at least one common physical link [277]. The idea behind maxLAR objective is to provide with a preventive solution to physical layer attacks thanks to careful and secure network virtual topology planning. In fact, if an attack, be it low power QoS attack, high power jamming attack, or any variation of cross talk nonlinearities, if one lightpath on a specific link l is damaged, then all the lightpaths sharing that link l will also be damaged by that attack.

The objective is to minimize this MaxLAR value in the network to ensure by this a better prevention against attacks effects. Linked to this, congestion will also be minimized since we will be minimizing the number of lightpaths sharing the same link. Moreover, the MaxLAR is also considered as an upper bound on the number of wavelengths required for effective wavelength assignment independently on the presence or lack of wavelength converters in the network [277].

Based on the 14 nodes NSF Network, Figure 4.1 below illustrates two different virtual topologies setups or routing schemes of four lightpath requests.

We notice that the first virtual topology setup results in a MaxLAR value of 4. This means that there is a possibility that a maximum of four lightpaths will be disturbed or damaged if an attack occurs in the network. On the other hand, the virtual topology setup on the right results in a MaxLAR of 3, meaning that the maximum number of possible damaged lightpaths is 3. Obviously, the second setup is more secure than the first one.

To compute the MaxLAR, we took note of the number of link-sharing lightpaths. This will result in obtaining a list of lightpaths satisfying the link-sharing condition. After that, we remove duplicate lightpaths from that list and compute its size afterwards. That size represents the network MaxLAR value.

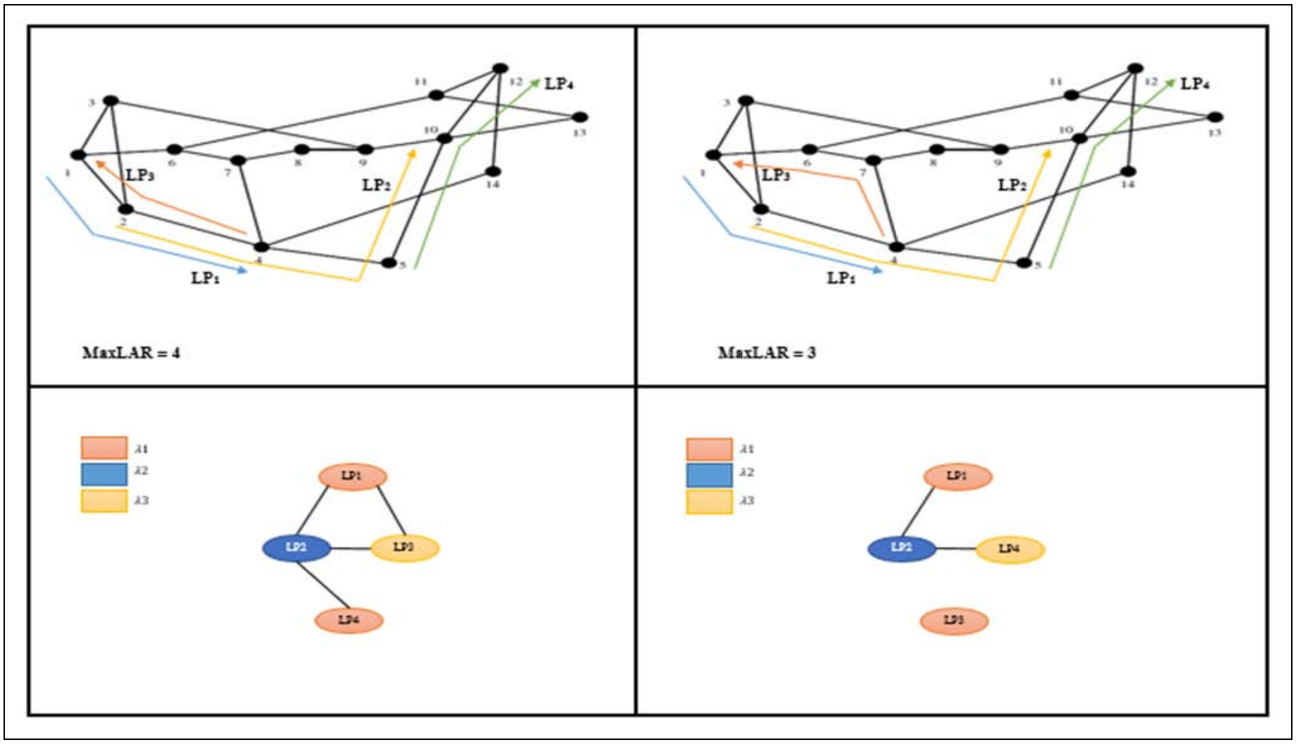


Figure 4.1 Example of two RWA schemes (virtual topologies) on 14 nodes NSF Network with different MaxLAR and throughput values NSF Network with the same number of wavelengths but different MaxLAR values.

The algorithm below describes the steps of obtaining the Network's MaxLAR value:

```
Get optimumVirtualTopologies_list
// Generate the network list of optimum virtual topologies
Define networkMaxLAR_list
// List of the network virtual topologies' MaxLAR values
Define networkMinimumMaxLAR
// Minimum MaxLAR: Attack Radius of the network

For each virtualTopology in optimumVirtualTopologies_list do:
        Define virtualTopologyMaxLAR
        Define virtualTopologyLinks_list
       // List whose elements are lists of lightpaths per link
    For each link, do:
            Get lightpaths_list
           // List of lightpaths that traverse the link
           Get lightpaths_list_size
           // Size of the list of lightpaths that traverse the link
                If lightpath_list_size > 1 Then
                        For each element in lightpaths_list do:
                                If virtualTopologyLinks_list does NOT contain element Then
                                        virtualTopologyLinks_list ← virtualTopologyLinks_list + element
                                End If
                        End For
                End If
    End For
    Get virtualTopologyLinks_list_size
    virtualTopologyMaxLAR ← virtualTopologyLinks_list_size
    networkMaxLAR_list ← networkMaxLAR_list + virtualTopologyMaxLAR
End For
networkMinimumMaxLAR ← MinimumOf (networkMaxLAR_list)
```

Figure 4.2 Algorithm describing the steps of obtaining the Network's MaxLAR

The Second RWA Objective: Minimizing Blocking Probability (BP)

In addition to the MaxLAR minimization objective, this chapter proposes another objective criterion for the RWA problem, referred to as minimizing the blocking probability (BP). The chapter also assumes that there is a threshold or acceptable blocking probability that the network must not exceed. This value is referred to as $\mathrm{Acceptable}_{\mathrm{BP}}$, while the blocking probability being minimized is referred to as $Current_{BP}$.The objective is to satisfy the following constraint:

$$Current_{BP} \leq Acceptable_{BP} \tag{2}$$

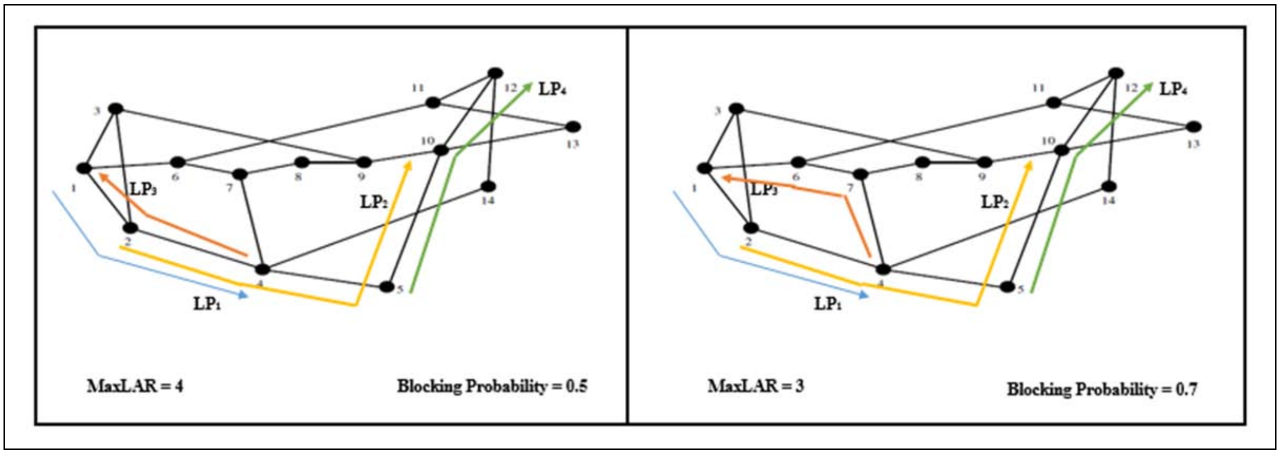


Figure 4.3 An example of two RWA schemes (virtual topologies) on the 14 nodes NSF Network with different MaxLAR and throughput values.

```
Get optimumVirtualTopologies_list
// Generate the network list of optimum virtual topologies

Get networkMinimumMaxLAR
// Minimum MaxLAR: Attack Radius of the network
Get networkMaximumMaxLAR
// Maximum MaxLAR: Attack Radius of the network
Get networkMaxLARdifference
// Difference between Max and Min MaxLAR

Get networkMinimumThroughput
// Minimum Throughput of the network: Maximum blocking probability
```

```
Get networkMaximumThroughput
// Maximum Throughput of the network: Minimum blocking probability
Get networkThroughputDifference
// Difference between Max and Min Throughput

Define desiredSecurityPercentage
// Desired level of security of the network with a value from 0 to 100
Define desiredThroughputPercentage
// Desired level of Throughput of the network with a value from 0 to 100
 Define ThroughputSet
 // Desired level of Throughput of the network with a value from 0 to 100
 Define TS_element
 // This value refers to the elements of the ThroughputSet

 Define MaxLARSet
 // This set contains the possible MaxLARs that can be achieved in the network
 Define ML_element
 // This value refers to the elements of the MaxLARSet

 Define t_selectedMaxLAR
 // This is a temporary value that is determined based on desiredSecurityPercentage
 Define t_selectedThroughput
 // This is a temporary value that is based on desiredThroughputPercentage
 Define selectedMaxLAR
 // This value is the first element of the set MaxLARSet, that is greater than t_selectedMaxLAR
 Define selectedThroughput
 // This value is the first element of the set of Throughputs: ThroughputSet, that is greater
// than t_selectedThroughput

 networkMaxLARdifference ← networkMaximumMaxLAR - networkMinimumMaxLAR
```

```
networkThroughputDifference←networkMaximumThroughput - networkMinimumThroughput

t_selectedMaxLAR ← (desiredSecurityPercentage x networkMaximumMaxLAR) / 100
t_selectedThroughput← (desiredThroughputPercentage x networkMaximumThroughput)/100
For each ML_element, do:
    If ML_element ≥ t_selectedMaxLAR Then:
        selectedMaxLAR ← ML_element
        Break
    End If
End For

For each TS_elements, do:
    If TS_elements ≥ t_selectedThroughput Then:
        selectedThroughput ← TS_element
        Break
    End If
End For
```

Figure 4.4. Algorithm to achieve X% of Security and X% of Throughput

```
GetVirtualTopologyWithOptimumValuesOf(selectedMaxLAR, selectedThroughput)
// The following algorithm refers to the implementation of this function

Define bestMaxLARThroughputSum
// The sum of the selected MaxLAR and throughput based on the security and throughput
// percentage as shown in the code above
Define MaxLARThroughputSum_List
// The list of the sum of MaxLAR and throughput in each optimum virtual topology
Define MTL_element
// Refers to MaxLAR Throughput List element of the MaxLARThroughputSum_List
```

```
Define selectedVirtualTopology
// Refers the selected virtual topology based on the best sum of MaxLAR and Throughput that
// is the closest to the bestMaxLARThroughputSum

Define temp
// Temporary auxiliary variable
Define tempMin
// Temporary auxiliary variable

bestMaxLARThroughputSum ← selectedMaxLAR + selectedThroughput
For each virtualTopology in optimumVirtualTopologies_list do:
        Temp ← getVTopologyMaxLAR() + getVTopologyThroughput()
                MTL_element ← | bestMaxLARThroughputSum - temp |
                MaxLARThroughputSum_List + = MTL_element
End For

temp_Min ← getMinimum(MaxLARThroughputSum_List)
selectedVirtualTopology ← GetVirtualTopology(temp_Min)
// Loop over the list of optimum virtual topologies and returns the one whose sum of MaxLAR
// and throughput is equal to temp_min
```

Figure 4.5 Algorithm to get the virtual topology having the optimum throughput and MaxLAR values

Combining RWA Objectives: MaxLAR and BP

After explaining this, this section suggest a model of incorporating both objectives together. In fact, the idea here is to choose one of the virtual network topologies based on two factors selection: Security Strength, where MaxLAR is the metric. Throughput Quality, where the Blocking Probability is the metric. This approach does not favor one on the other, but it is flexible enough to allow choosing the setup that satisfies a certain level of each of these selection factors. Figure 4.3 above illustrates scenarios of both the MaxLAR and the blocking probability of each virtual topology. Suppose we are during the process of selecting between these different setups to solve our routing and wavelength assignment problem. Some may want to favor security

100% over the throughput, others may decide to favor throughput 100% over security, while others may decide to find a compromise between the two by choosing a percentage of security to be ensured and another one for throughput. The only condition is that the sum of the two percentages is equal to 100%. In order to allow for this, our research proposes a flexible algorithm that allows to select the best network virtual topologies in the light of security and throughput demands. The decision will be made according to the desire of the network administrator, thus, he/she will be fully responsible for the chosen decision. In reality, it is important to notice that the proposed security and throughput percentages must be based on a set of factors that can differ based on the environment of operation and the needs of the business of organization in question. Suppose that we have a set $T = \{th1, th2, th3\}$ corresponding the possible throughputs that can be achieved in a network. Suppose, that the different optimal virtual network topologies of that network have different values of MaxLAR as in the following set $T = \{1, 2, 3, 4, 5\}$. A network administrator may want to choose the network virtual topology that will allow achieving 60% security and 40% throughput. Figure 4.4 depicts the steps needed to satisfy such a requirement. Now that the selected MaxLAR and throughput have been determined, the algorithm must specify the virtual topology setup that satisfies such values as much as possible. Differently said, the sum of the selected topology's MaxLAR and Throughput values must be as close as possible to the sum of the chosen virtual topology's MaxLAR and Throughput. Figure 4.5 depicts the algorithm implementing this.

Mixed Integer Linear Programming (MILP) Formulation: MILP LAR

This section presents the formulation of the routing sub problem as Mixed Integer Linear Program (MILP). The reason behind choosing MILP instead of ILP is due to the fact that this research defines two main RWA objectives where the first objective's variable is an integer (the MaxLAR) and the other is a double (the blocking probability). The Wavelength assignment sub-problem is solved using Greedy Graph Coloring algorithm where each color denotes a wavelength. The purpose of such algorithm is to minimize the number of colors used in the network. The next sections provide a formulation for the routing sub-problem:

Notation

TABLE 4.1 MILP – Problem Notations

Notation	Meaning
s, d	Denotes the lightpath source and destination nodes where s, d belong to the set {1, 2, 3, …, N} E.g. 1, 4 stands for lightpath (LP1) starting at node 1 and ending at node 4.
s', d'	Denotes the lightpath source and destination nodes where s', d' belong to the set {1, 2, 3, …, N} E.g. 1, 4 stands for lightpath (LP1) starting at node 1 and ending at node 4.
p, q	Denotes the physical link's source and destination nodes that belong to the set {1, 2, 3, …, N}

Parameters

TABLE 4.2 MILP – Parameters

Parameter	Meaning
N	The number of nodes in the network
$Phy_{p,q}$	The network's physical topology, where: • $Phy_{p,q} = 1$ If there's a link between p & q • $Phy_{p,q} = 0$ If there isn't
Hop	The maximum possible number of physical hops of a lightpath
$Vir_{s,d}$	The network's virtual topology, where: • $Vir_{s,d} = 1$ If there's a lightpath request between p & q • $Vir_{s,d} = 0$ If there isn't

Variables

TABLE 4.3 MILP – Variables

Variable	Meaning
$Phy_{p,q}^{s,d}$	Physical routing variable, indicating if a lightpath corresponding to the virtual $Vir_{s,d}$ is routed on physical link $Phy_{p,q}^{s,d}$ where: • $Phy_{p,q}^{s,d} = 1$ if the above is True • $Phy_{p,q}^{s,d} = 0$ if the above is False
$Phy_{p,q}$	The network's physical topology, where: • $Phy_{p,q}$, q=1 if there's a link between p and q • $Phy_{p,q}$, q=1 otherwise
$Lsh^{(s,d)(s',d')}$	Link sharing variables indicating if two lightpaths corresponding to virtual links: $Vir_{s,d}$ and $Vir_{s\prime,d\prime}$ are sharing at least one common link, where: • $Lsh^{(s,d)(s',d')} = 1$ if this is True • $Lsh^{(s,d)(s',d')} = 0$ otherwise
$Lsh_{p,q}^{(s,d)(s',d')}$	Link-sharing variable indicating if two lightpaths corresponding to virtual links $Vir_{s,d}$ and $Vir_{s\prime,d\prime}$ are routed over the physical link $Phy_{p,q}$ where: • $Lsh_{p,q}^{(s,d)(s',d')} = 1$ if True • $Lsh_{p,q}^{(s,d)(s',d')} = 0$ otherwise
LAR	Denotes the attack radius of the lightpath corresponding to virtual links. This value stands for the number of lightpaths that share links with including itself.
maxLAR	Denotes the maximum LAR of lightpaths in the network
Thr_list	Denotes the list of possible throughputs that can be achieved in the network, given its virtual topologies
$Current_{BP}$	Denotes a specific blocking probability
$Acceptable_{BP}$	Denotes the acceptable blocking probability or threshold

Objectives

- Minimize maxLAR

- Minimize BP

Constraints

Constraints linked to Physical routing:

$$Phy_{p,q}^{s,d} \leq Phy_{p,q} \quad \forall\, s, d, p, q \tag{3}$$

The constraint above ensures that lightpaths are routed only on existing network physical links.

$$Phy_{p,q}^{s,d} \leq Vir_{p,q} \quad \forall\, s, d, p, q \tag{4}$$

The constraint above ensures that only requested lightpaths are routed over the physical topology.

Constraints linked to Flow conversation over physical links:

$$\sum\nolimits_{n} Phy_{k,n}^{s,d} - \sum\nolimits_{n} Phy_{n,k}^{s,d} = \begin{cases} Vir_{s,d}, & s = k \\ -Vir_{s,d}, & d = k \ \ \forall s, d, k \\ 0, & k \neq s, d \end{cases} \tag{5}$$

$$Phy_{n,d}^{s,d} \in \{0, 1\} \tag{6}$$

Constraints linked to lightpath Cycling:

$$\sum p Phy_{p,q}^{s,d} \leq 1 \quad \forall\, s, d, p, q \tag{7}$$

$$\sum q Phy_{p,q}^{s,d} \leq 1 \quad \forall\, s, d, p, q \tag{8}$$

$$Phy_{p,q}^{s,d} + Phy_{q,p}^{s,d} \leq 1 \quad \forall\, s, d, p, q \tag{9}$$

Constraints linked to lightpaths link-sharing:

$$Lsh^{(s,d)(s',d')} \leq \sum\nolimits_{p,q} Lsh_{(p,q)}^{(s,d)(s',d')} \quad \forall\, s, d, s', d' \tag{10}$$

$$Lsh^{(s,d)(s',d')} \geq \sum Lsh_{(p,q)}^{(s,d)(s',d')} \quad \forall\, s, d, s', d', p, q \tag{11}$$

$$Lsh^{(s,d)(s',d')} \in \{0, 1\} \tag{12}$$

These constraints denote that lightpaths $Vir_{s,d}$, $Vir_{s',d'}$ are marked link-sharing if they share at least one common link:

$$Lsh_{p,q}^{(s,d)(s',d')} \geq Phy_{p,q}^{s,d} + Phy_{p,q}^{s',d'} - 1 \quad \forall\, s,d,s',d',p,q \tag{13}$$

$$Lsh_{p,q}^{(s,d)(s',d')} \leq Phy_{p,q}^{s,d} \quad \forall\, s,d,s',d',p,q \tag{14}$$

$$Lsh_{p,q}^{(s,d)(s',d')} \leq Phy_{p,q}^{s',d'} \quad \forall\, s,d,s',d',p,q \tag{15}$$

$$Lsh^{(s,d)(s',d')} \in \{0,1\} \tag{16}$$

These constraints denote that lightpaths $Vir_{s,d}$, $Vir_{s',d'}$ are marked link-sharing if they share a common link $Phy_{p,q}$.

MaxLAR Constraints:

$$LAR^{(s,d)} = \sum\nolimits_{s',d'} Lsh^{(s,d)(s',d')} \quad \forall\, s,d \tag{17}$$

$$LAR^{(s,d)} \geq 0,\ \ LAR^{(s,d)}\ is\ an\ integer \tag{18}$$

$$\max LAR \geq LAR^{(s,d)} \ \ \forall\, s,d \tag{19}$$

The constraints above specify that the lightpath attack radii must not exceed the network MaxLAR.

Lightpath Hop bound related Constraints:

$$\sum\nolimits_{p,q} Phy_{p,q}^{s,d} \leq Hop \tag{20}$$

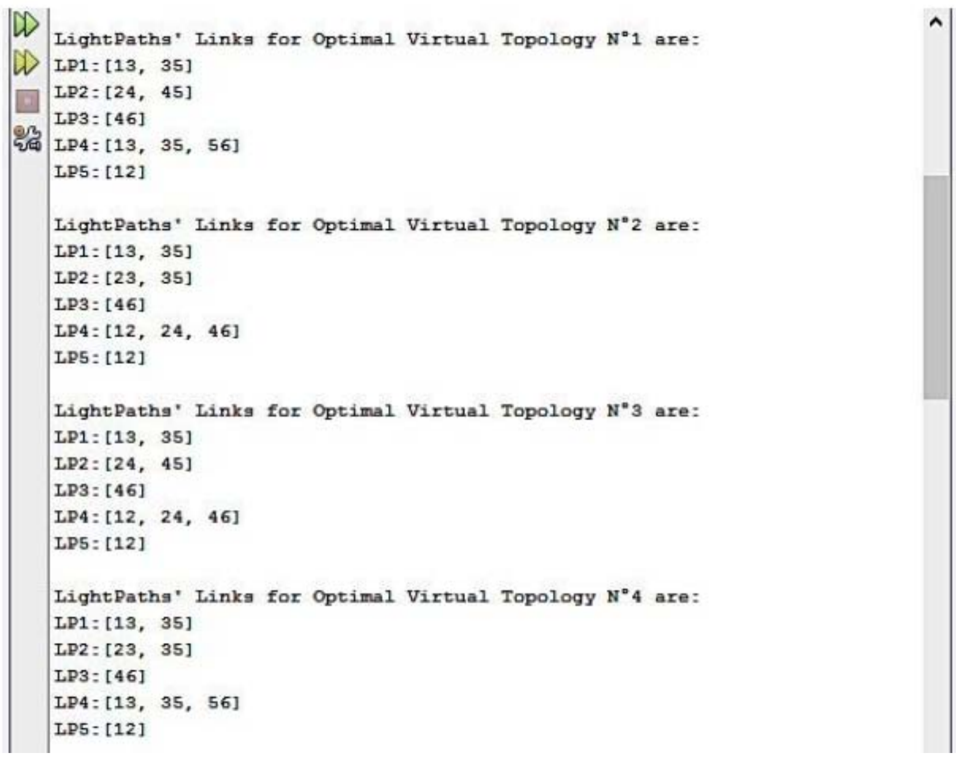
Blocking Probability related Constraints (BP):

$$Current_{BP} \leq Acceptable_{BP} \tag{21}$$

Given these parameters, variables, and constraints, the next step is to solve this MILP formulation to get the optimal routing or virtual topology setup.

Simulation and results

Focusing on the two objective functions presented in the MILP, the presented algorithms have been simulated in Java. The output presented below show that the model does not favor security only. It allows even for cases when the network administrator does not care about security at all. The figure below illustrates this case:



```
the MaxLAR for Optimal Virtual Topology N°1 is: 2

the MaxLAR for Optimal Virtual Topology N°2 is: 5

the MaxLAR for Optimal Virtual Topology N°3 is: 4

the MaxLAR for Optimal Virtual Topology N°4 is: 3

The Lightpaths Adjacency matrix for Optimal Virtual Topology N°4 is:
    0  1  2  3  4  5
  --------------------
0 | 0  0  0  0  0  0
1 | 0  0  1  0  1  0
2 | 0  0  0  0  1  0
3 | 0  0  0  0  0  0
4 | 0  0  0  0  0  0
5 | 0  0  0  0  0  0
```

```
Optimal Virtual Topology N°1
Attacking one of the links of lightpath 1 ...

Attack on lightpath 1 will disrupt a total of 2 lightpaths
This is because lightpath 1 shares links with 1 other lightpaths

Optimal Virtual Topology N°2
Attacking one of the links of lightpath 1 ...

Attack on lightpath 1 will disrupt a total of 2 lightpaths
This is because lightpath 1 shares links with 1 other lightpaths

Optimal Virtual Topology N°3
Attacking one of the links of lightpath 1 ...

Attack on lightpath 1 will disrupt a total of 1 lightpaths
This is because lightpath 1 shares links with 0 other lightpaths

Optimal Virtual Topology N°4
Attacking one of the links of lightpath 1 ...

Attack on lightpath 1 will disrupt a total of 3 lightpaths
This is because lightpath 1 shares links with 2 other lightpaths
```

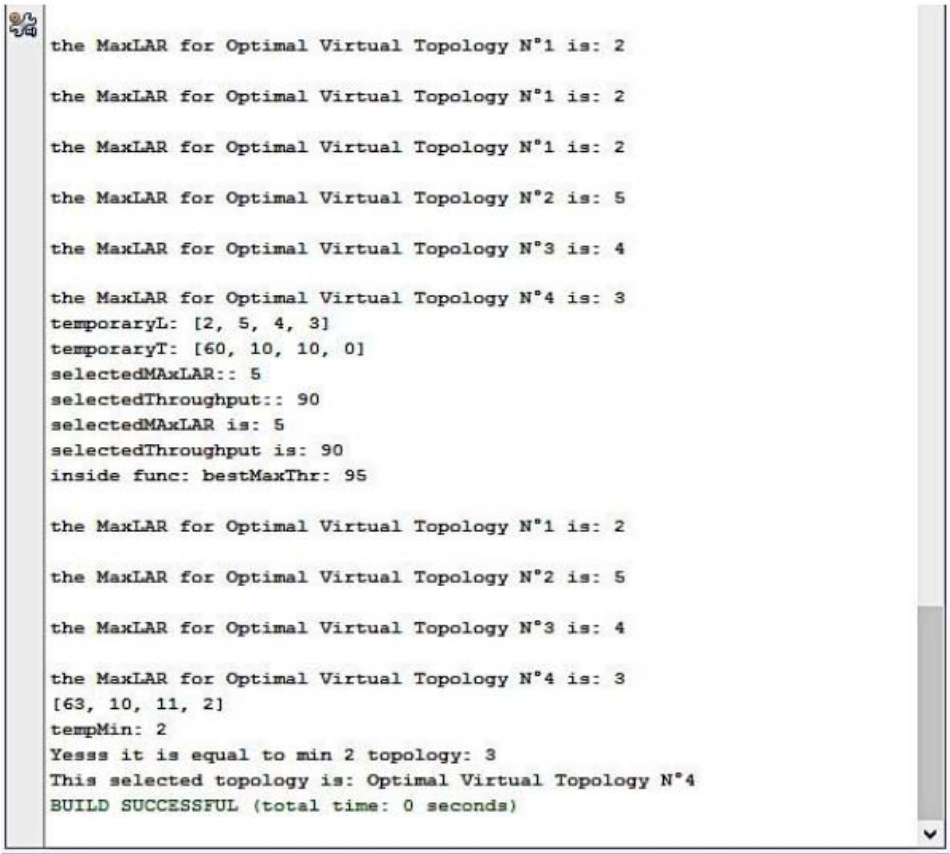


Figure 4.6 Simulation example results: physical topology and optimal virtual topologies with MaxLAR values

Conclusion

In this chapter, we have studied how to represent the Static WDM Routing and Wavelength assignment algorithm as an Integer Linear Program, with two objective functions, one to maximize the throughput, and the other to minimize the attackability in the network. A set of constraints were taken into account, such as clash and wavelength continuity constraints. This chapter also proposed a preventive throughput and attack aware algorithm based on secure topology design, giving enough flexibility to the customer to choose the level of security and throughput that they want to achieve in the network.

Chapter 5 Extended Static RWA

Introduction

This chapter extends the work in the previous chapters in two parts; In Part 1: by making the wavelength assignment algorithm also attack and blocking probability aware, optimizing for attack awareness and blocking probability for Wavelength Assignment. Then, in Part 2: by bringing the various building blocks from the previous chapters into a proposed Comprehensive Security Framework for WDM Optical Networks (CSF-WDM).

Part I: An attack and Blocking Probability Aware Wavelength Assignment Algorithm for Optical Networks

Methodology

Following on from the previous chapter, we got the best virtual topology of the 6 nodes network and selected the one with the lowest MaxLAR = 2. The selected topology prevents Attacks (As min MaxLAR means the number of lightpaths sharing links is minimized).

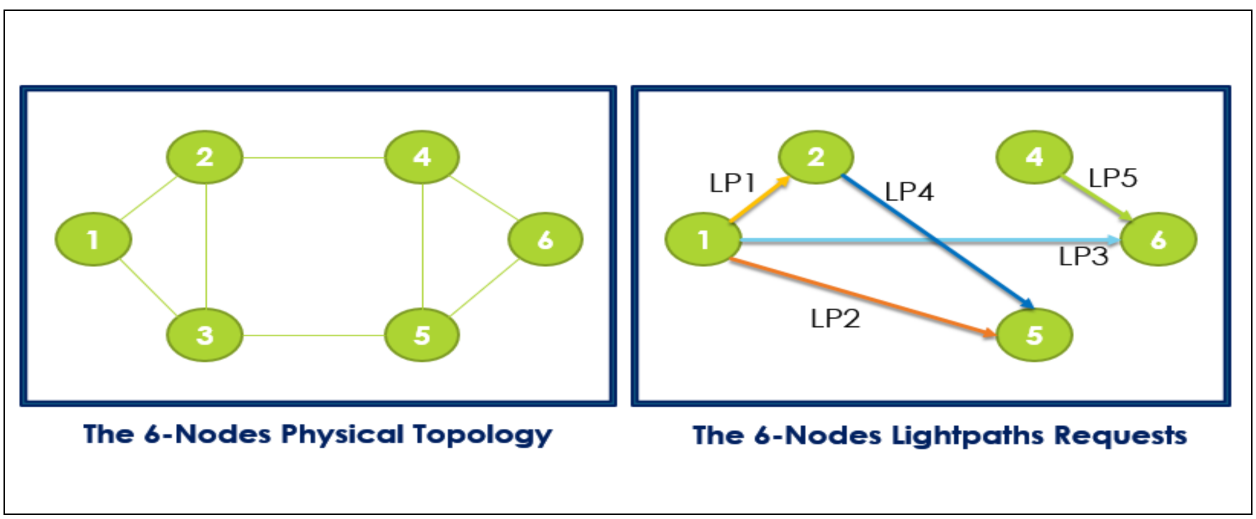


Figure 5.1 Physical Network Topology and Virtual Topology

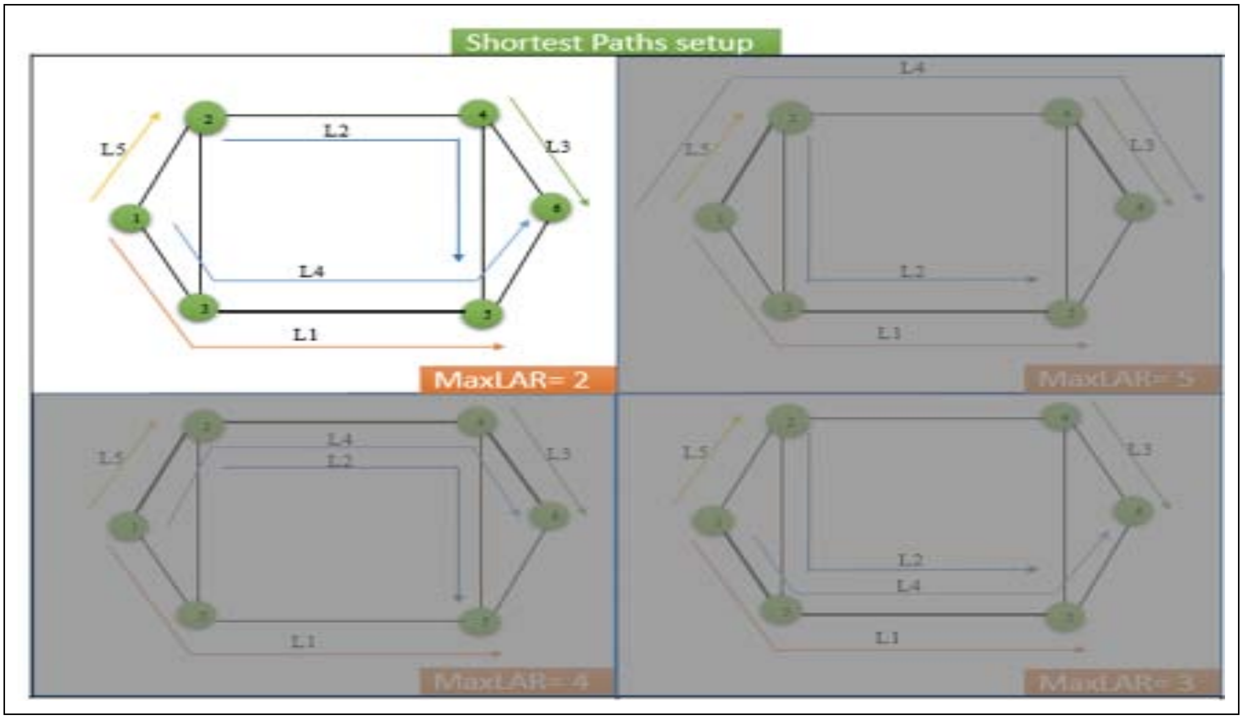


Figure 5.2 Selected Virtual Topology based on the minimum MaxLAR

From the above figure, we see that the lightpaths that would lead the best virtual topology design from an attack awareness point of view go through a specific number of nodes. We map theses nodes in the next table:

TABLE 5.1 The lightpaths to lead the best virtual topology design from an attack awareness point of view

Optimal Minimum Attackability Lightpath	Number of nodes
LP1 (1-3-5)	3
LP2 (2-4-5)	3
LP3 (4-6)	2
LP4 (1-3-5-6)	4
LP5 (1-2)	2

Now that we have the list of nodes associated with the optimal minimum attackability lightpaths (LP1 to LP5), this list of nodes looks as follows: {3, 3, 2, 4, 2}. If we take the unique nodes out of this list, we will end up with {2, 3, 4} as depicts Figure 5.3 below.

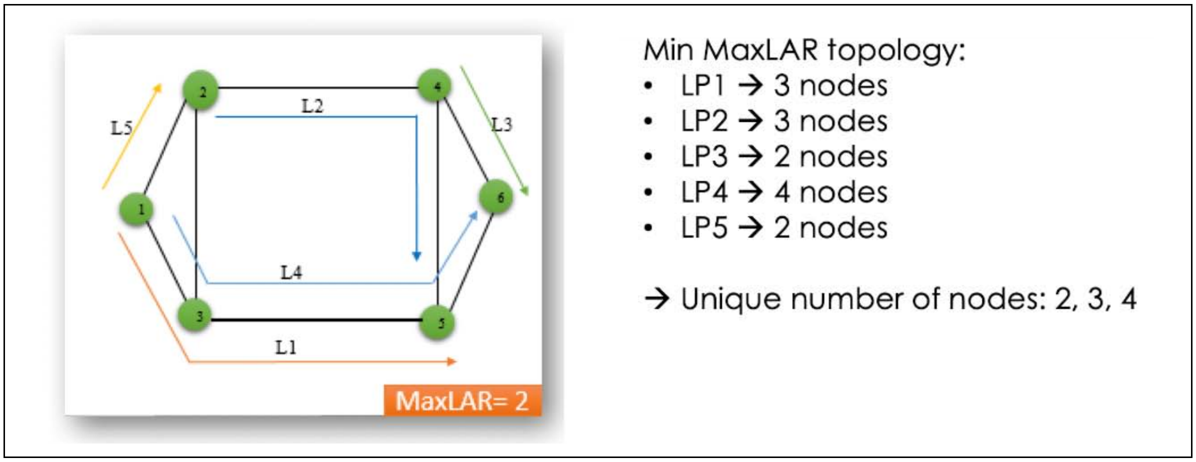


Figure 5.3 unique number of nodes associated with the optimal minimum attackability lightpaths

The 3 unique nodes values 2, 3, and 4 are the ones of interest to us in the study of the 6 nodes network above. The next section focuses on computing the blocking probability at these nodes, using 4 Wavelength Assignment algorithms: First Fit / First Channel (FC), Middle Channel (MC), Random Channel (RC), and Last Channel (LC).

Simulations

To select the best Wavelength Assignment algorithm, we now need to check the blocking probability for each of the unique number of nodes obtained from the MaxLAR. We start by looking at the case of 2, 3, and finally 4 nodes. The numbers 2, 3, and 4 correspond to the unique numbers of nodes corresponding to the optimal minimum attackability lightpaths in TABLE 5.1.

Figure 5.4 focuses on the case of 2 nodes (obtained from MaxLAR optimum lightpath topology) that we obtained during the design phase (prevention), comparing the blocking probability using 4 Wavelength Assignment algorithms: First Fit / First Channel (FC), Middle Channel (MC), Random Channel (RC), and Last Channel (LC).

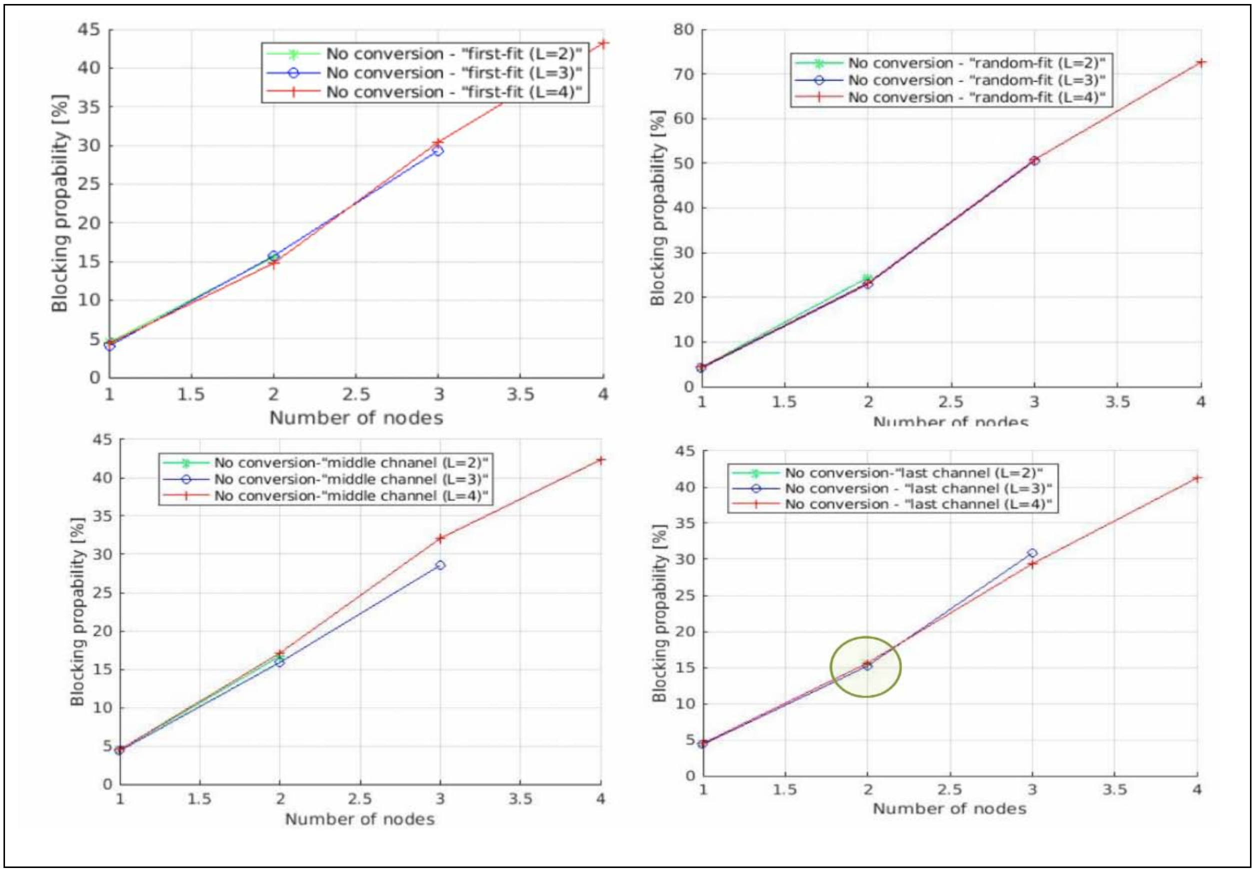


Figure 5.4 Comparing First Fit, Random Fit, Middle Channel, and Random Channel Wavelength Assignment Algorithms' blocking probability for 2 nodes to select the optimum one (Last Channel from the figures)

From Figure 5.4, the optimal WA Algorithm for 2 nodes lightpath is **Last Channel.**

Next, Figure 5.5 focuses on the case of 3 nodes (obtained from MaxLAR optimum lightpath topology) that we obtained during the design phase (prevention), comparing the blocking probability using 4 Wavelength Assignment algorithms: First Fit / First Channel (FC), Middle Channel (MC), Random Channel (RC), and Last Channel (LC).

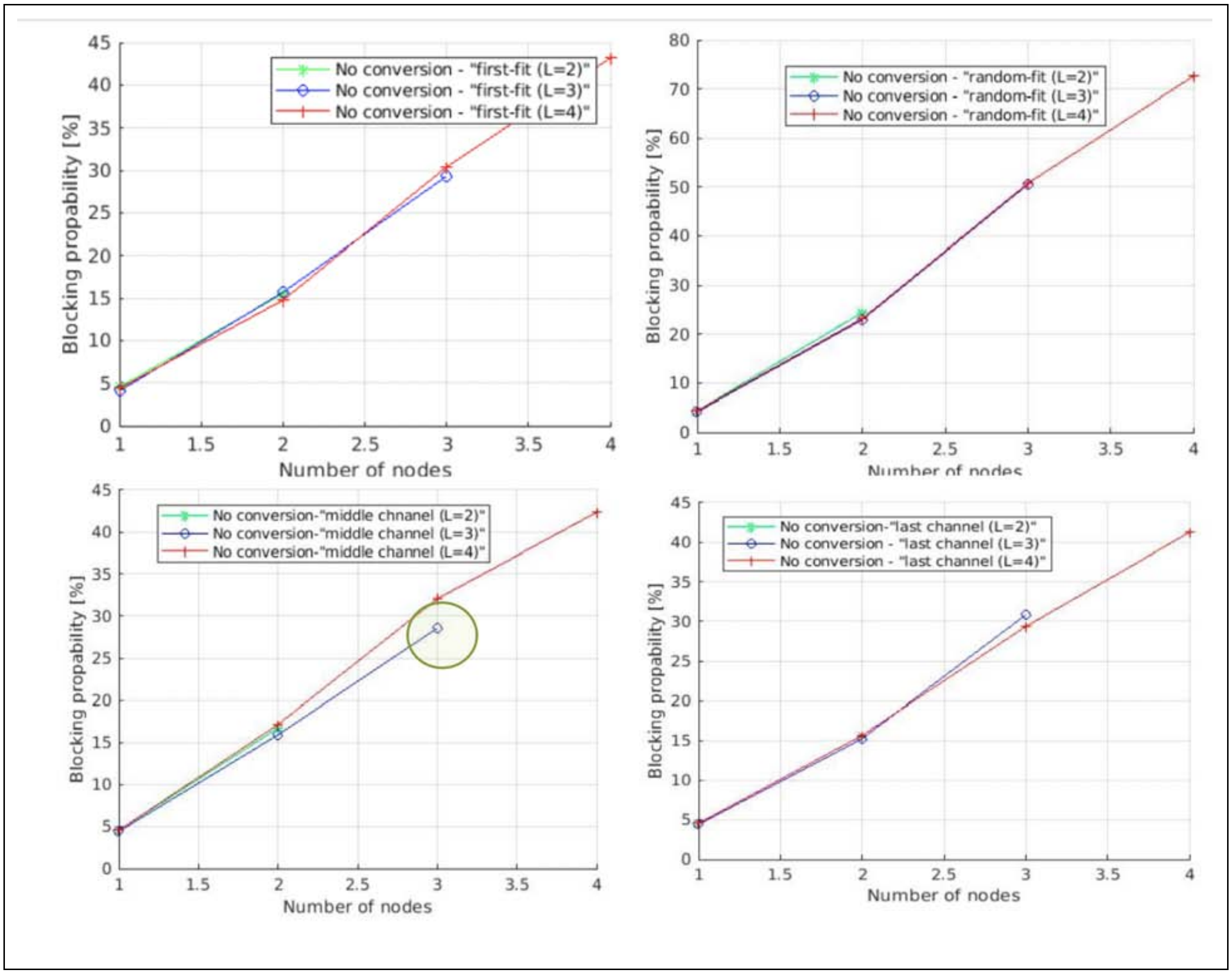


Figure 5.5 Comparing First Fit, Random Fit, Middle Channel, and Random Channel Wavelength Assignment Algorithms' blocking probability for 3 nodes to select the optimum one (Middle Channel from the figures)

From Figure 5.5, the optimal WA Algorithm for 3 nodes lightpath is **Middle Channel.**

Finally, Figure 5.6 focuses on the case of 4 nodes (obtained from MaxLAR optimum lightpath topology) that we obtained during the design phase (prevention), comparing the blocking probability using 4 Wavelength Assignment algorithms: First Fit / First Channel (FC), Middle Channel (MC), Random Channel (RC), and Last Channel (LC).

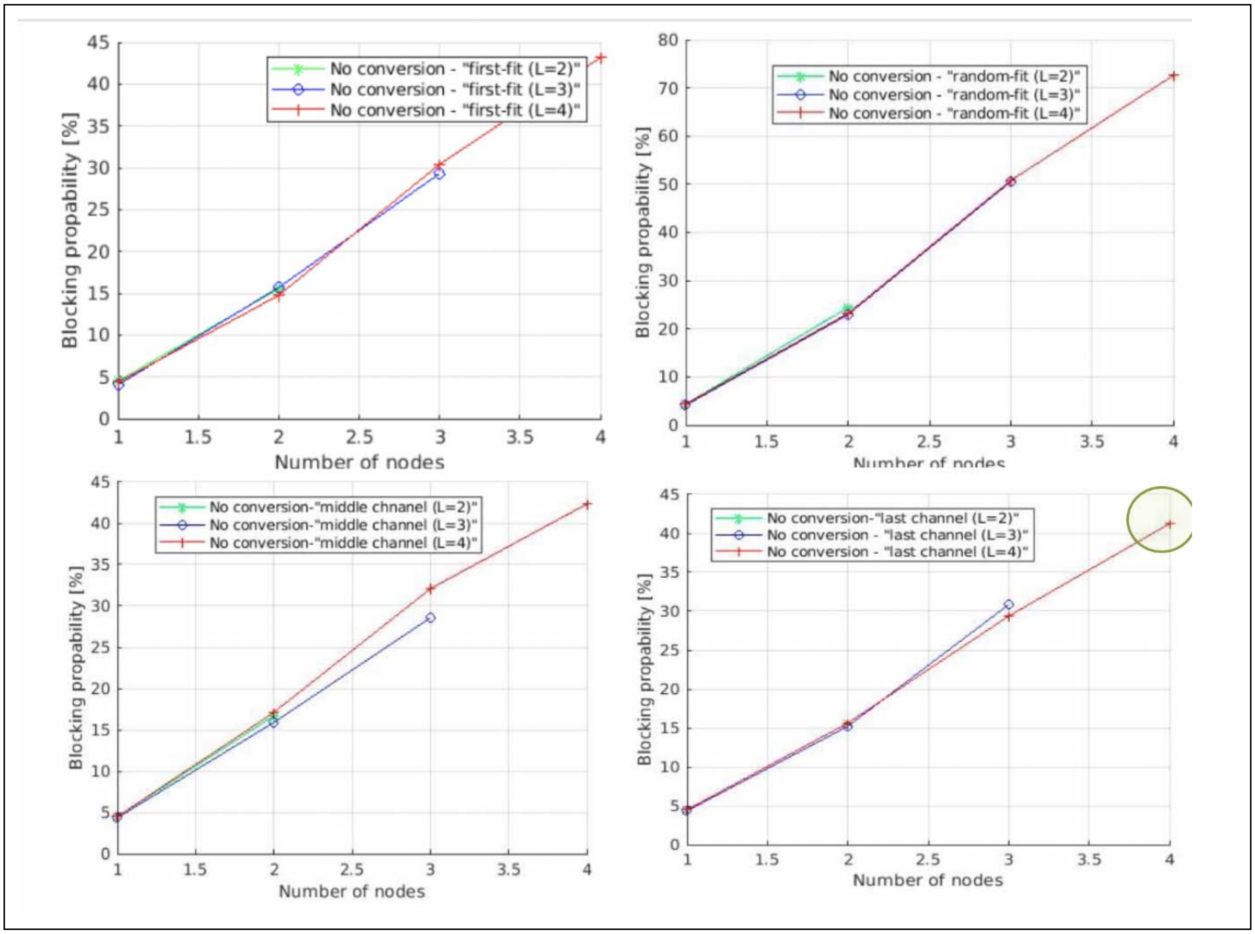


Figure 5.6 Comparing First Fit, Random Fit, Middle Channel, and Random Channel Wavelength Assignment Algorithms' blocking probability for 4 nodes to select the optimum one (Middle Channel from the figures)

From Figure 5.6, the optimal WA Algorithm for 4 nodes lightpath is **Last Channel.**

Nodes per optimal lightpath	Weight (#lightpaths having this number of nodes)
2	2
3	2
4	1

Mapping of nodes vs. weights:
- 3 nodes → Weight 2 (2 Lightpaths: L1 + LP2)
- 2 nodes → Weight 2 (2 Lightpaths: LP3 + LP5)
- 4 nodes → Weight 1 (1 Lightpath) → LP4

Figure 5.7 Defining nodes weights in terms of lightpaths having that number of nodes

As seen in Figure 5.3 earlier, we started by running the Min MaxLAR algorithm where we get the virtual topology having the optimum throughput and MaxLAR values (Refer to Figure 5.5) and obtain the virtual topology with the smallest MaxLAR = 2 as depicts the top left corner of the figure. Next, for each of the lightpath requests, we computed the number of nodes the lightpath traverses (e.g. LP1 (request from 1 to 5 via 3 → 3 nodes: 1, 5, and 3). From that we saw that LP1 and LP2 are both mapped to 3 nodes each, LP3 and LP5 mapped to 2 nodes, and LP4 mapped to 4 nodes. Hence, the unique number of nodes from these mappings are: 2, 3, and 4.

With these three unique nodes, Figure 5.7 above defines the weight, which stands for the number of lightpaths having this number of nodes, where 2 nodes correspond to a weight of 2 (as there are two lightpaths going through 2 nodes, and these lightpaths are: LP3 and LP5), then for 3 nodes, we have a weight of 2 (as there are two lightpaths going through 3 nodes, and these are: LP1 and LP2), while for 4 nodes we have a weight of 1 since there's only 1 lightpath going through 4 nodes, and that is LP4.

Based on the MaxLAR Prevention and throughput design topology of the lightpaths, and the performance simulations of blocking probability in the case of the unique number of nodes in the optimal lightpath topology design, I have been able to identify the best WA algorithm for the 6 nodes network for various number of nodes per lightpath:

- For 2 nodes lightpath requests: Last Channel Wavelength Assignment Algorithm (1/3)
- For 3 nodes lightpath requests: Middle Channel Wavelength Assignment Algorithm (1/3)
- For 4 nodes lightpath requests: Last Channel Wavelength Assignment Algorithm (2/3)

Based on the ***weightedWA_map*** defined in Figure 5.11 (The Algorithm), we notice that the Wavelength Assignment Algorithm selected the most as yielding minimum blocking probability for the various unique lightpath nodes 2, 3, and 4, is **Last Channel Wavelength Assignment Algorithm** as also visibly seen from the graph below:

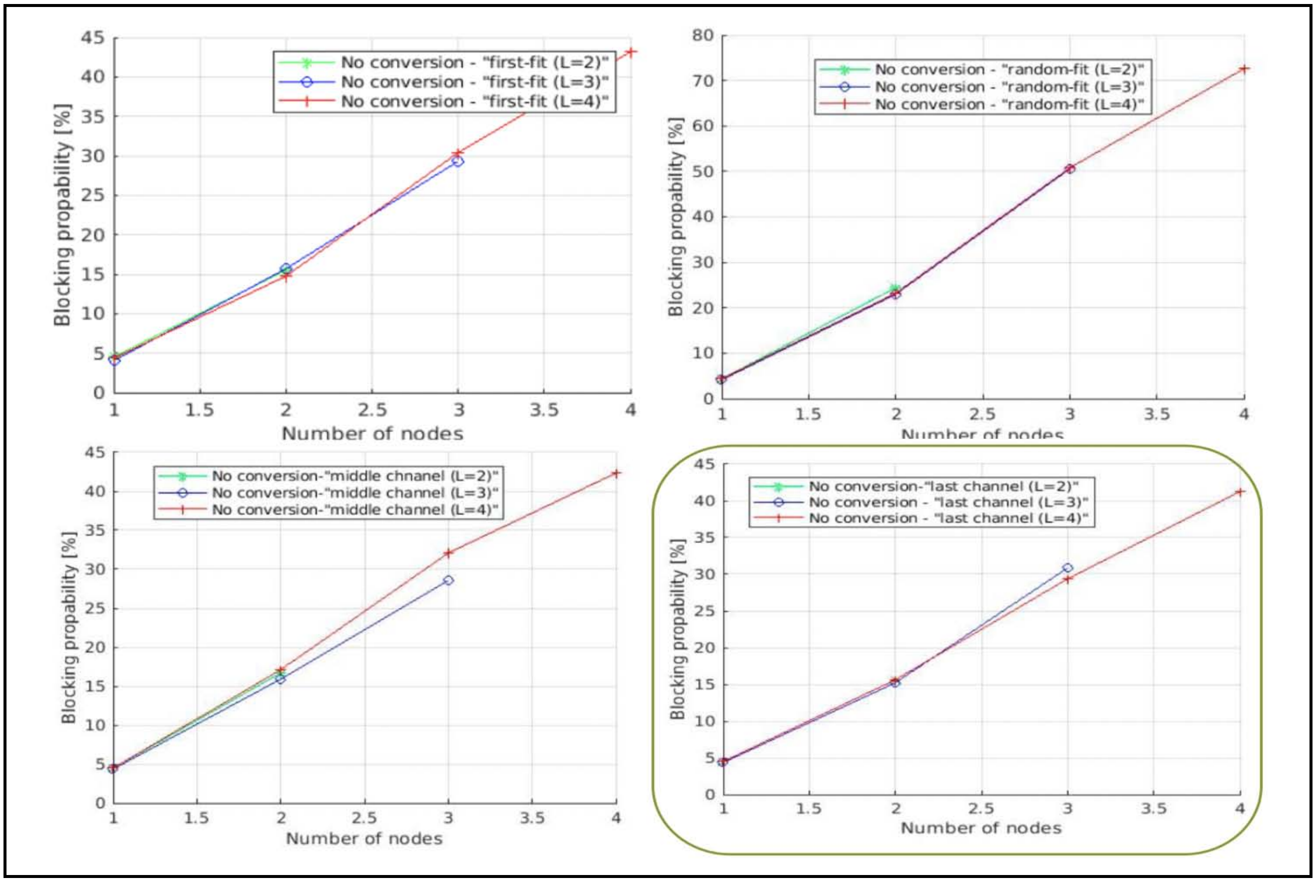


Figure 5.8 Comparing 4 Wavelength Assignment Algorithm to select the one yielding the minimum overall blocking probability of the 6 nodes network.

From the above simulations, we can select Last Channel as the best Wavelength Assignment Algorithm for routing the 6 nodes network topology requests listed above.

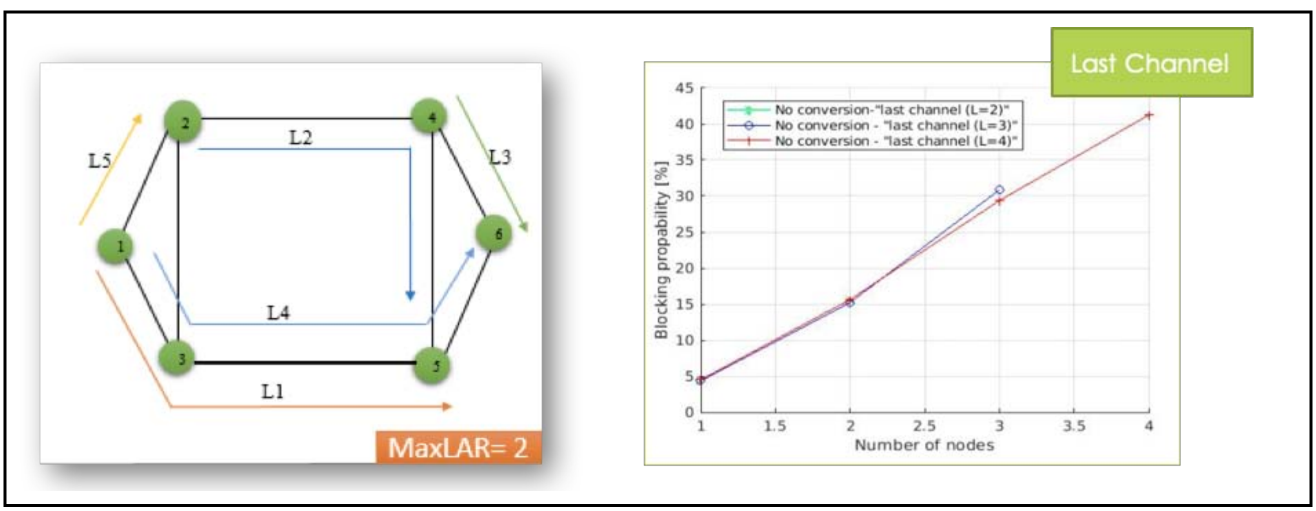


Figure 5.9 The selected Last Channel Wavelength Assignment Algorithm yielding the minimum overall blocking probability of the 6 nodes network.

This has also been validated by checking the results for more lightpath nodes in the network:

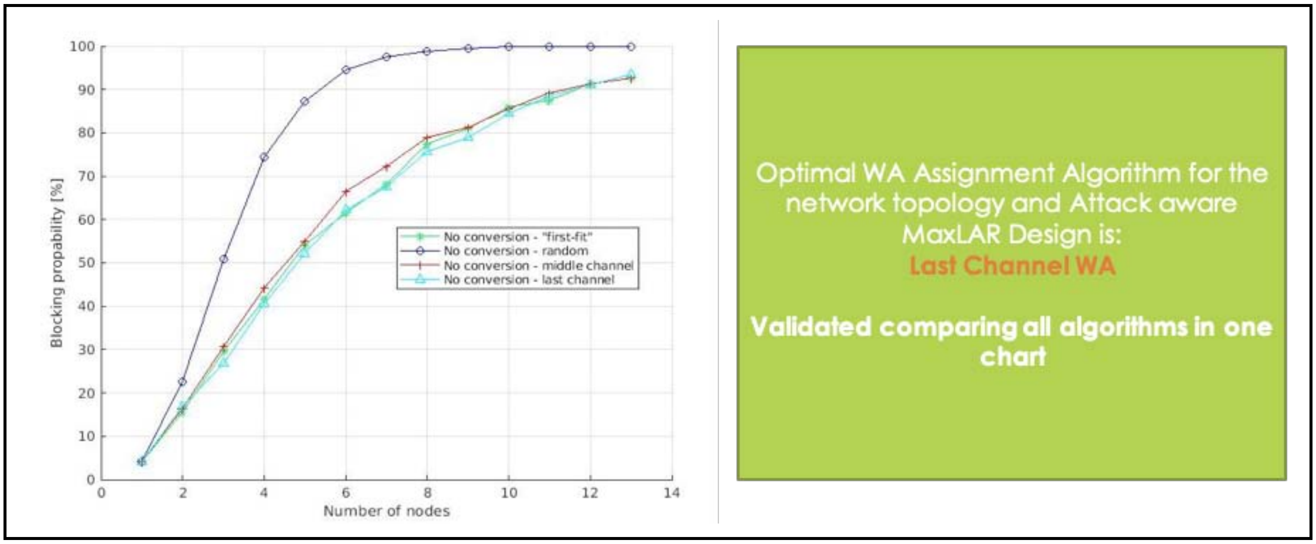


Figure 5.10 Last Channel WA Algorithm resulting in lowest blocking probability compared to First Channel, Middle Channel, Random Channel, and Last Channel, for multiple Nodes variations.

Algorithms

The next two figures depict the Algorithms used above:

GetVirtualTopologyWithOptimumValuesOf(selectedMaxLAR, selectedThroughput)

// The following algorithm refers to the implementation of this function

Define ***bestMaxLARThroughputSum***

// The sum of the selected MaxLAR and throughput based on the security and throughput

// percentage as shown in the code above

Define ***MaxLARThroughputSum_List***

// The list of the sum of MaxLAR and throughput in each optimum virtual topology

Define ***MTL_element***

// Refers to MaxLAR Throughput List element of the MaxLARThroughputSum_List

Define ***selectedVirtualTopology***

// Refers the selected virtual topology based on the best sum of MaxLAR and Throughput that

// is the closest to the bestMaxLARThroughputSum

Define ***temp***

```
// Temporary auxiliary variable
Define tempMin
// Temporary auxiliary variable

bestMaxLARThroughputSum ← selectedMaxLAR + selectedThroughput
For each virtualTopology in optimumVirtualTopologies_list do:
        Temp ← getVTopologyMaxLAR() + getVTopologyThroughput()
                MTL_element ← | bestMaxLARThroughputSum - temp |
                MaxLARThroughputSum_List + = MTL_element
End For

temp_Min ← getMinimum(MaxLARThroughputSum_List)
selectedVirtualTopology ← GetVirtualTopology(temp_Min)
// Loop over the list of optimum virtual topologies and returns the one whose sum of MaxLAR
// and throughput is equal to temp_min

//Map the number of nodes per lightpath requests from: selectedVirtualTopology
//Define an Array structure to store selectedVirtualTopology lightpaths nodes.
selectedVirtualTopologyLightpaths = GetLightpaths(selectedVirtualTopology)
For each lightpath in selectedVirtualTopologyLightpaths:
    lightpathNodes[lightpath] = GetNodesCount(selectedVirtualTopologyLightpaths[lightpath])

//Get the unique number of nodes from lightpathNodes
uniqueLightpathNodes_list = GetListOfUniqueValues(lightpathNodes)

// Sort the uniqueLightpathNodes_list in an ascending order (as the values will correspond to the x axis of the
// graph plotting blocking probability against number of nodes, later

// For each of the wavelength Assignment Algorithm studied: First Channel (FC), Last Channel (LC),
// Middle Channel (MC), and Random Channel (RC), we compute the blocking probability associated with
// The unique lightpath nodes stored in uniqueLightpathNodes_list variable above.
// We define some variables first: C (Number of Channel), L2 = 2 nodes, L3 = 3 nodes, L4  = 4 nodes
C=10 // Number of channels
```

```
load=6 // Total load in Erlangs
number_generations=10000 // Number of generations for holding times

// Get the number of nodes from the uniqueLightpathNodes_list sorted in ascending order:
uniqueLightpathNodes_list_sorted_asc = GetListOfUniqueValuesSortedAsc(lightpathNodes)

L2= uniqueLightpathNodes_list_sorted_asc[0];  // This corresponds to number of nodes = 2
L3= uniqueLightpathNodes_list_sorted_asc[1];  // This corresponds to number of nodes = 3
L4= uniqueLightpathNodes_list_sorted_asc[2];  // This corresponds to number of nodes = 4

// Get the blocking probability per each element from uniqueLightpathNodes_list_sorted_asc

// The Wavelength Assignment Algorithms are given as parameters: FC, MC, RC, LC
// In the case of First Channel (FC) Wavelength Assignment Algorithm:
blockingProbability_fc_L2 = getBlockingProbabilityNoConversion(C, L2,number_generations, FC )
blockingProbability_fc_L3 = getBlockingProbabilityNoConversion(C, L3,number_generations, FC)
blockingProbability_fc_L4 = getBlockingProbabilityNoConversion(C, L4,number_generations, FC)

// In the case of Middle Channel (MC) Wavelength Assignment Algorithm:
blockingProbability_mc_L2 = getBlockingProbabilityNoConversion(C, L2,number_generations, MC)
blockingProbability_mc_L3 = getBlockingProbabilityNoConversion(C, L3,number_generations, MC)
blockingProbability_mc_L4 = getBlockingProbabilityNoConversion(C, L4,number_generations, MC)

// In the case of Radom Channel (RC) Wavelength Assignment Algorithm:
blockingProbability_rc_L2 = getBlockingProbabilityNoConversion(C, L2,number_generations, RC)
blockingProbability_rc_L3 = getBlockingProbabilityNoConversion(C, L3,number_generations, RC)
blockingProbability_rc_L4 = getBlockingProbabilityNoConversion(C, L4,number_generations, RC)

// In the case of Last Channel (LC) Wavelength Assignment Algorithm:
blockingProbability_lc_L2 = getBlockingProbabilityNoConversion(C, L2,number_generations, LC)
blockingProbability_lc_L3 = getBlockingProbabilityNoConversion(C, L3,number_generations, LC)
blockingProbability_lc_L4 = getBlockingProbabilityNoConversion(C, L4,number_generations, LC)
```

```
// Plotting blocking probability graphs for each wavelength assignment algorithm, against the x Axis composed of the unique number of nodes in the uniqueLightPathNode_list

// Plotting Blocking probability in the case of First Channel WA:
xAxis = uniqueLightPathNode_list // L2, L3, L4
yAxis = [0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100] // Blocking probability possible values
fc_data = { blockingProbability_fc_L2, blockingProbability_fc_L3, blockingProbability_fc_L4}
PlotGraph(xAxis, yAxis, fc_data}

// Plotting Blocking probability in the case of Middle Channel WA:
xAxis = uniqueLightPathNode_list // L2, L3, L4
yAxis = [0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100] // Blocking probability possible values
mc_data = { blockingProbability_mc_L2, blockingProbability_mc_L3, blockingProbability_mc_L4}
PlotGraph(xAxis, yAxis, mc_data}

// Plotting Blocking probability in the case of Random Channel WA:
xAxis = uniqueLightPathNode_list // L2, L3, L4
yAxis = [0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100] // Blocking probability possible values
rc_data = { blockingProbability_rc_L2, blockingProbability_rc_L3, blockingProbability_rc_L4}
PlotGraph(xAxis, yAxis, rc_data}

// Plotting Blocking probability in the case of Last Channel WA:
xAxis = uniqueLightPathNode_list // L2, L3, L4
yAxis = [0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100] // Blocking probability possible values
lc_data = { blockingProbability_lc_L2, blockingProbability_lc_L3, blockingProbability_lc_L4}
PlotGraph(xAxis, yAxis, lc_data}

// For each unique number of nodes from uniqueLightPathNode_list, we compare the blocking probabilities of
// the 4 Wavelength Assignment Algorithms plotted (FC, MC, RC, and LC) and select the one yielding the
// minimum blocking probability
```

```
// We iterate based on L2, L3, and L4 (as they correspond to 2, 3, and 4 nodes, which correspond to the unique
// number of nodes from the lightpaths matching the optimized minimum Attackability Radius Virtual Topology
// Design.

// We begin with the case of a lightpath with 2 nodes:
min_blockingProbability_L2 = getMin(blockingProbability_fc_L2,
                                    blockingProbability_mc_L2,
                                    blockingProbability_rc_L2,
                                    blockingProbability_lc_L2)

// Then move to the case of a lightpath with 3 nodes:
min_blockingProbability_L3 = getMin(blockingProbability_fc_L3,
                                    blockingProbability_mc_L3,
                                    blockingProbability_rc_L3,
                                    blockingProbability_lc_L3)

// We finish with the case of a lightpath with 4 nodes:
min_blockingProbability_L4 = getMin(blockingProbability_fc_L4,
                                    blockingProbability_mc_L4,
                                    blockingProbability_rc_L4,
                                    blockingProbability_lc_L4)

// Now that we have 3 minimum blocking probabilities for each of the unique lightpath nodes: L2, L3, and L4
// We  identify which of the WA algorithms yield that lowest minimum blocking probability for L2, L3, and L4
L2_minBlockingProbabilityWA= getWavelengthAssignmentAlgorithm(min_blockingProbability_L2, L2)
L3_minBlockingProbabilityWA= getWavelengthAssignmentAlgorithm(min_blockingProbability_L3, L3)
L4_minBlockingProbabilityWA= getWavelengthAssignmentAlgorithm(min_blockingProbability_L4, L4)

 // In order to select the best WA for the network's attack aware virtual topology as a whole, we pick the one
// that's yields the maximum number of minimum blocking probabilities per number of unique lightpaths nodes
weightedWA_map = getUniqueValuesAndWeights(L2_minBlockingProbabilityWA,
                                           L3_minBlockingProbabilityWA,
                                           L4_minBlockingProbabilityWA
```

```
// The best (blocking probability wise) WA for the network's attack aware virtual topology as a whole
min_blocking_probability_attack_aware _wa = getHighestWeightWA(weightedWA_map)
```

Figure 5.11 Attack Prevention Design Based Routing and Wavelength Assignment Algorithm for WDM Networks

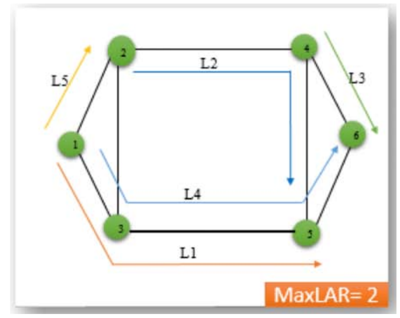
```
// Defining the function used in Figure 5.11 to return the blocking probability per WA Algorithm and
// node
Function getBlockingProbabilityNoConversion(C, Ln, number_generations, WA)
// Ln = Unique number of nodes in a lightpath, where n = Ln
// WA: Wavelength Assignment Algorithm, we have four choices: FC (First Channel), MC (Middle
// Channel), RC (Random Channel) and LC (Last Channel)

C=10 // Number of channels
load=6 // Total load in Erlangs
number_generations=10000 // Number of generations for holding times

for each g in number_generations

  for each t in link

     until_next(t) = -log(1-rand)/Load  // exponential distribution of time till next call

     holding_time{t} = -log(1-rand)  // exponential holding time

     proper_place{t}(1:C) = 0

    check_free{t} = find(connections_vector{t} = = 0)

  if length(check_free{t})~=0

    // Wavelength Assignment Algorithm = First Fit / First Channel (FC)

    If WA = FC

       reserved_place = 1; // Reserve the first channel

    End
```

```
// Wavelength Assignment Algorithm = Random Fit / Random Channel (RC)

If WA = RC

    reserved_place = ceil(rand*length(check_free{t})) // Reserve a random channel

End

// Wavelength Assignment Algorithm = Middle Fit / Middle Channel (MC)

If WA = MC

    reserved_place = ceil(length(check_free{t})/2) // Reserve middle channel

End

// Wavelength Assignment Algorithm = Last Fit / Last Channel (LC)

If WA = LC

    reserved_place = length(check_free{t}) // Reserve middle channel

End

proper_place{t}(check_free{t}(reserved_place)) = proper_place{t}(check_free{t}(place))+1

connections_vector{t}(check_free{t}(reserved_place))=holding_time(t)

End
```

Figure 5.12 Wavelength Assignment Aware, No conversion, Blocking Probability Algorithm for WDM Networks, modified and extended based on Mathworks WDM Toolbox.

The next table illustrates the summary of the algorithms above in action:

TABLE 5.2 The wavelength Assignment Security Aware Algorithm, explained, in action, step by step

<table>
<tr><th>Algorithm (in a nutshell)</th><th>Network State</th></tr>
<tr><td>Get the lightpath design topology from the MaxLAR Prevention and throughput Algorithm (Figure 4.5) from the previous chapter.</td><td>
</td></tr>
<tr><td>Map the number of nodes per lightpath requests (from the above attack aware topology) (Figure 5.11)</td><td>Min MaxLAR topology:
• LP1 → 3 nodes
• LP2 → 3 nodes
• LP3 → 2 nodes
• LP4 → 4 nodes
• LP5 → 2 nodes</td></tr>
<tr><td>Get the unique number of nodes from the above mapping (Figure 5.11)</td><td>→ Unique number of nodes: 2, 3, 4</td></tr>
<tr><td>Based on the performance simulations of blocking probability (Figure 5.11, and Figure 5.12) in the case of the unique number of nodes in the optimal lightpath topology design.

Map the number of nodes per lightpath request against the Optimal WA algorithms that can be selected</td><td><table><tr><th>Lightpath Nodes</th><th>Optimal WA Algorithm</th></tr><tr><td>2</td><td>Last Channel</td></tr><tr><td>3</td><td>Middle Channel</td></tr><tr><td>4</td><td>Last Channel</td></tr></table></td></tr>
<tr><td>Select the WA algorithm with the max weight, meaning more lightpaths could be established with minimum blocking probability if the WA algorithm was chosen for the given lightpath requests. See (Figure 5.11) and the dark green on the right table.</td><td><table><tr><th>Optimal WA Algorithm</th><th>Lightpath nodes</th><th>Weight (number node buckets)</th></tr><tr><td>Last Channel</td><td>2, 4</td><td>2</td></tr><tr><td>Middle Channel</td><td>3</td><td>1</td></tr></table></td></tr>
</table>

Summary

The Last Channel Wavelength Assignment Algorithm has been shown to be the best in allowing to achieve the minimum blocking probability of the lightpath requests on the 6 nodes network while attack prevention (MaxLAR design) is taken into account.

Part II: A Comprehensive Security Framework for WDM Optical Networks (CSF-WDM)

Introduction

This part concludes the previous chapters in this thesis as it presents a comprehensive Security Framework for WDM Optical Networks. The comprehensiveness comes from the focus on three key security controls: Physical, Technical, and Administrative or Managerial. I list each of these controls and references to where it's been presented in the thesis while presenting my proposed Optical Networks Arena's model of security controls:

Optical Networks Arena's Security Controls

As part of the CSF-WDM proposed framework, I define "Optical Networks Arena" as an arena of technical, physical, and managerial security controls spanning across various entities: People, Processes, Devices, Links, and Algorithms:

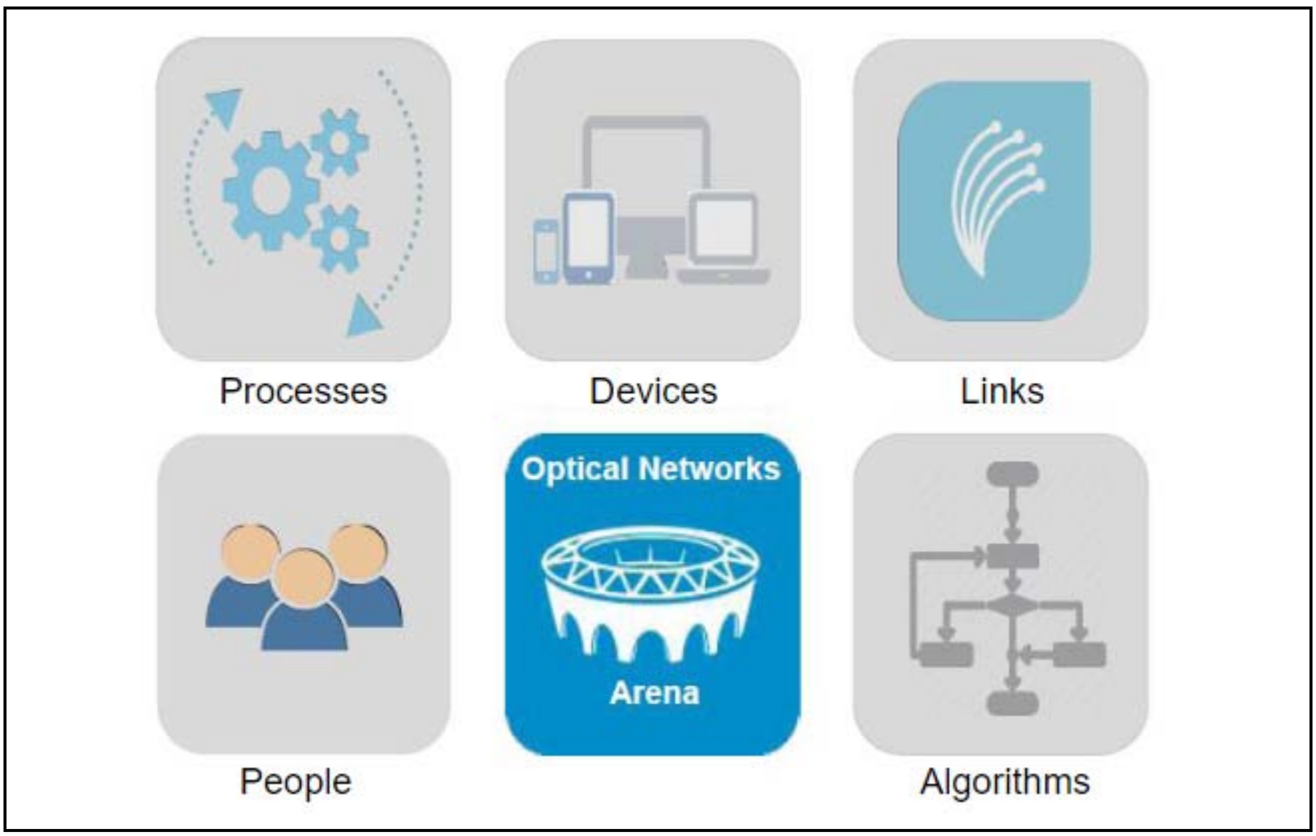


Figure 5.13 My proposed CSF Optical Networks Arena of Security Controls entities

People oriented security controls

This security controls set comprises of 4 areas: the Information Security Awareness Program; Information Security Policies; Information Security Procedures; and Accountability. These controls concerns the behavioral and compartmental aspects of people involved with optical networks in an organization and establishes guiding principles to ensure adherence with security principles within the organization and protect against attacks on this first line of defense or rather the weak circle of the chain that is of humans. For instance, a social engineering detection training could enable an organization's personnel from the door guards to the networks engineers to be alert against such attacks where intruders might seek to gain confidential information or access by exploiting the personnel's trust, fear, naivety, or even evil motives (in the case of internal staff willing to collaborate with external intruders for money, fame, or power purposes). When there's a well-defined awareness program with clear consequences of breaching the set security controls, this could act both as a preventative security controls (educating staff and hence preventing leakage of information by means of lack of awareness) as well as deterrent control for internal potential intruders (as they'll know up front that any unauthorized behavior will lead to termination).

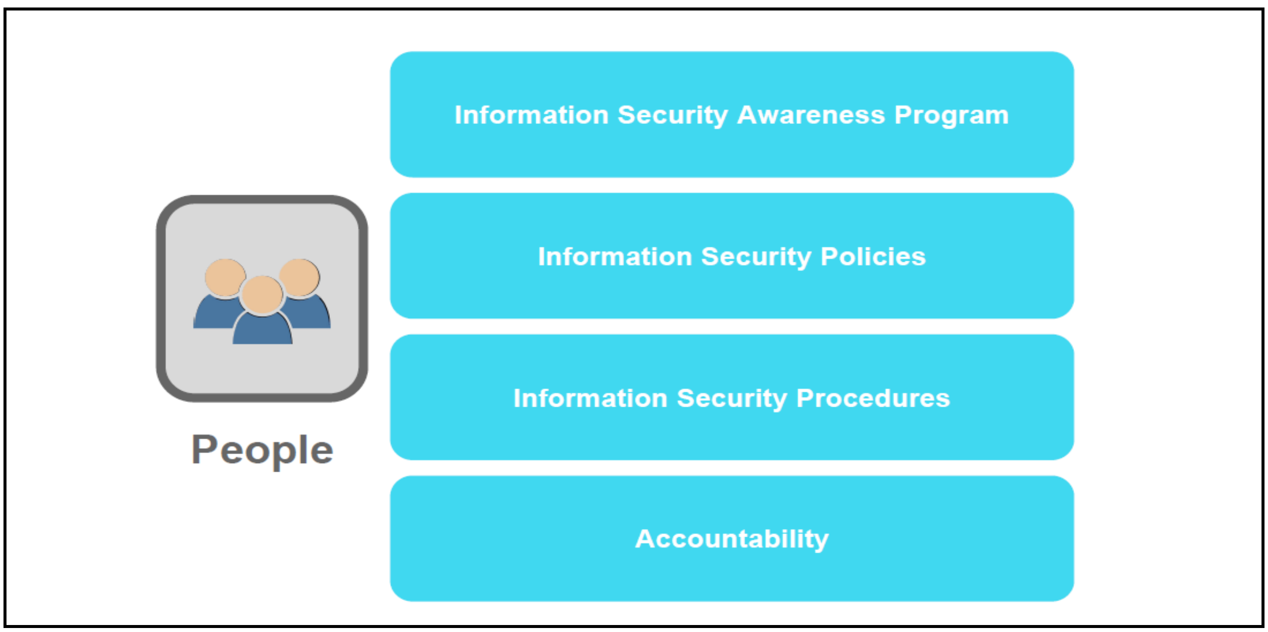


Figure 5.14 CSF Optical Networks Arena's People Security Controls

Process oriented security controls

This security controls set comprises of 4 areas: Incident Response Process; Disaster Recovery Process; Secure Employment Termination; Secure Inter-Process Channels. These areas are concerned with Managerial and administrative security controls aspects of the network.

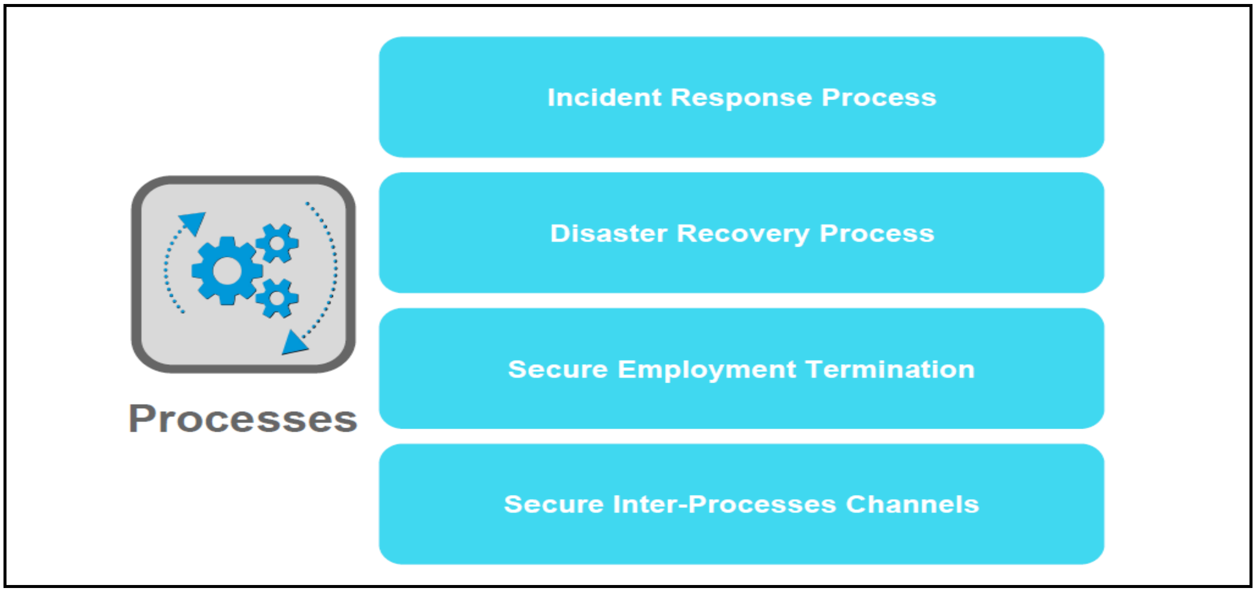


Figure 5.15 CSF Optical Networks Arena's Process Security Controls

Device oriented security controls

This security controls set comprises of 4 areas: Components with lower crosstalk levels; Optical limiting amplifiers; Variable optical attenuators; Secure Premises. These elements aim at addressing the physical security controls aspects of the network.

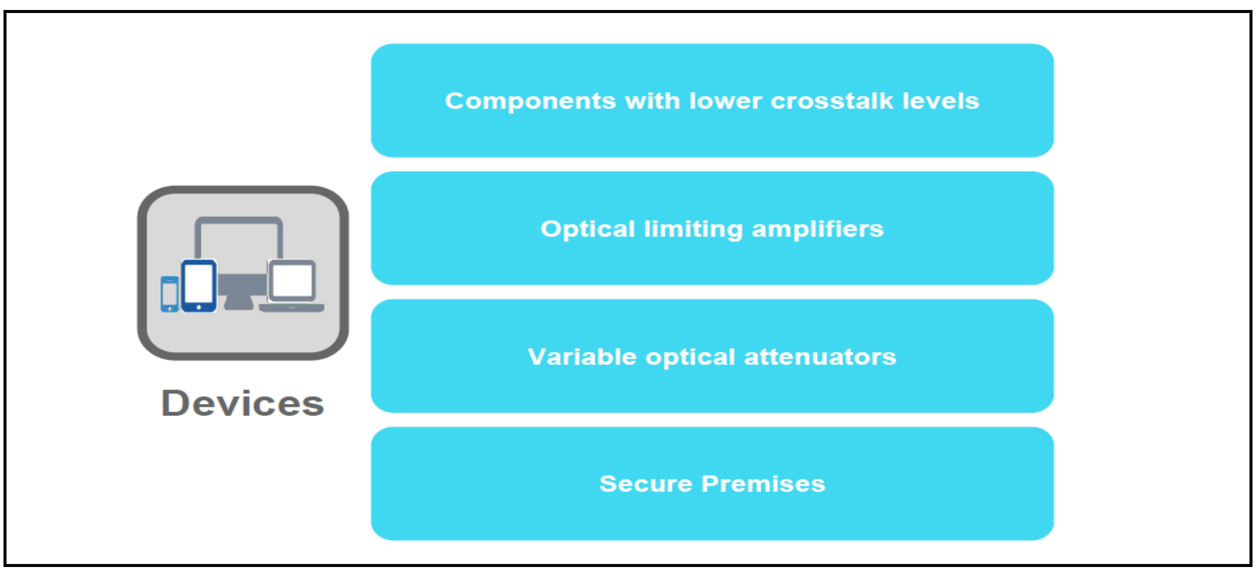


Figure 5.16 CSF Optical Networks Arena's Devices Security Controls

Link oriented security controls

This security controls set comprises of 4 areas: Assessment of link risk; Optical encryption; Optical steganography; and Secure Premises. These elements aim at addressing the physical Security controls aspects of the network.

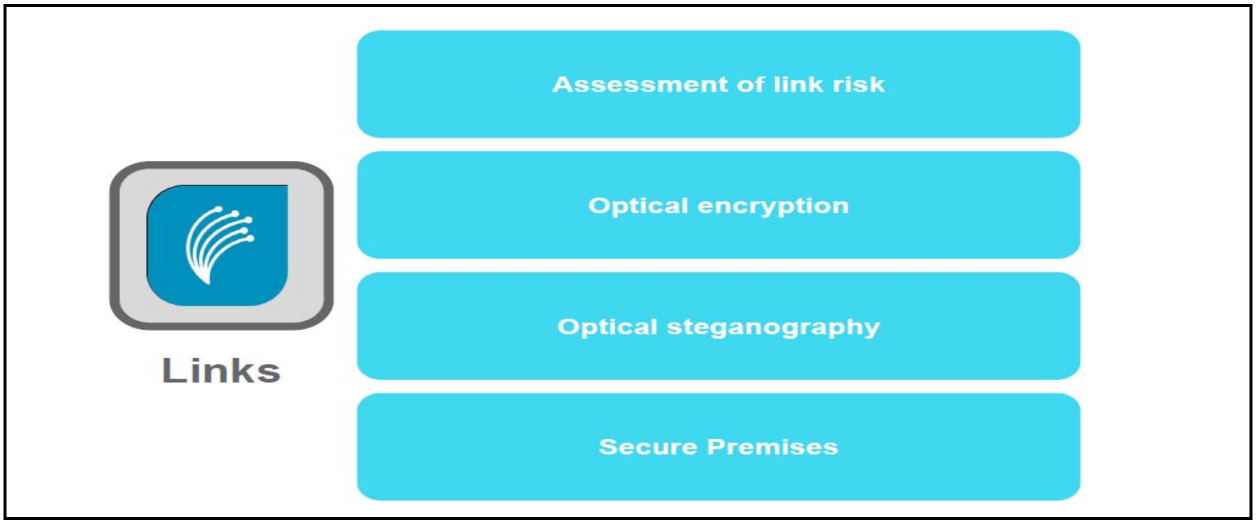


Figure 5.17 CSF Optical Networks Arena's Links Security Controls

Algorithm oriented security controls

This security controls set comprises of 4 areas: Security Design Principles; Realistic Traffic generation simulation module, Attack and throughput aware RWA, and Blocking probability aware wavelength assignment algorithm. These elements aim at addressing the Technical Security Controls aspects of the network.

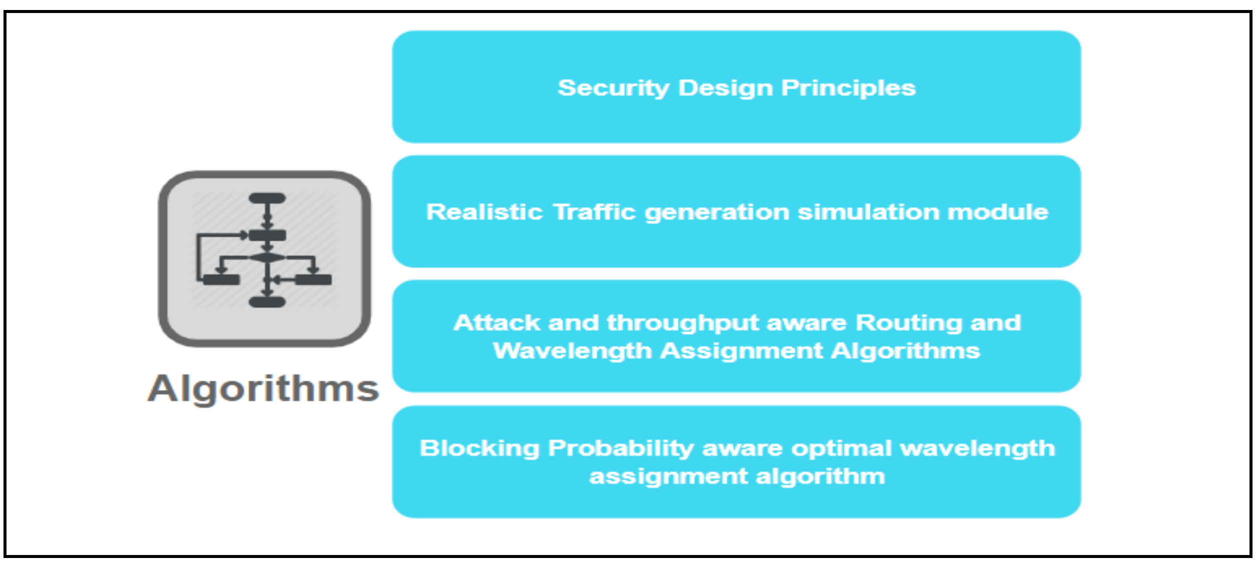


Figure 5.18 CSF Optical Networks Arena's Algorithms Security Controls

Optical networks Physical, Technical, and Administrative Security Controls

Optical Networks Physical Controls

This has been presented in the first chapters (chapter 2 namely) where analytical and experimental studies were conducted on the physical properties of the network focusing on nonlinear effects (SPM, XPM, and FWM), and their impacts on the BER and PER in the network, as well as best practices to reduce such effects in the network.

Optical Networks Technical Security Controls

The next aspect on Technical controls where a set of Routing and Wavelength Assignment Algorithms were proposed taking into account prevention from attack at the network design level, as well as allowing to prioritize throughput vs. security with various weights based on the needs of the organization and the applications, we have also seen proposed algorithms on minimizing blocking probability in the network via a blocking probability and attack aware wavelength assignment algorithm customized for each lightpath request, and then used to select the optimal wavelength assignment algorithm that aims at achieving a collective minimal blocking probability in the network given all the given lightpath requests, for those requests to be routed on the previously selected routes that are deemed to achieve the lowest attackability in the network based on the optimal virtual topology allowing so.

Optical Networks Managerial Security Controls

This aspect was tacked as part of the Security oriented mindset framework in managing optical networks. Chapter 4 presented how with a well-established framework with best practices and recommendations for both the technology, the processes, and the people and their motivational fits, the organization could be successful. Thanks to an effective governance that recognizes and enforces prevention as a core value and where each entity is clear on their roles and responsibilities and where the flow is determined, communicated, and customized to fit as much as possible, to ensure successful operations strategically aligned with business vision and mission as well as the higher goals of the prevention oriented mindset framework to achieve organization goals and respond to users need in the domain of operation, safely and securely.

Conclusion

Security is not a one-off patch. It's an ongoing activity that should be at the heart of Managerial, Physical and Technical Controls.

Future work: Chapter 6 Dynamic RWA, nonlinear effects & security aware algorithm

This chapter presents the conception and design of future works on this thesis. The aim is to develop the previous contributions further into a Dynamic-CSF-WDM based on the modular study and research that was worked on in the previous chapters. This chapter integrates the realistic dynamic traffic generation developed self-similar module for traffic generation, together with security awareness network design based controls, designed for efficiency against nonlinear effects, using Fair Queuing as a methodology for dynamic RWA, and finally integrating these various modules as part of a dynamic RWA, nonlinear effects & security aware algorithm, which I will unveil over the coming sections.

Consolidated Software Architecture & Design

Dynamic-CSF-WDM Architecture:

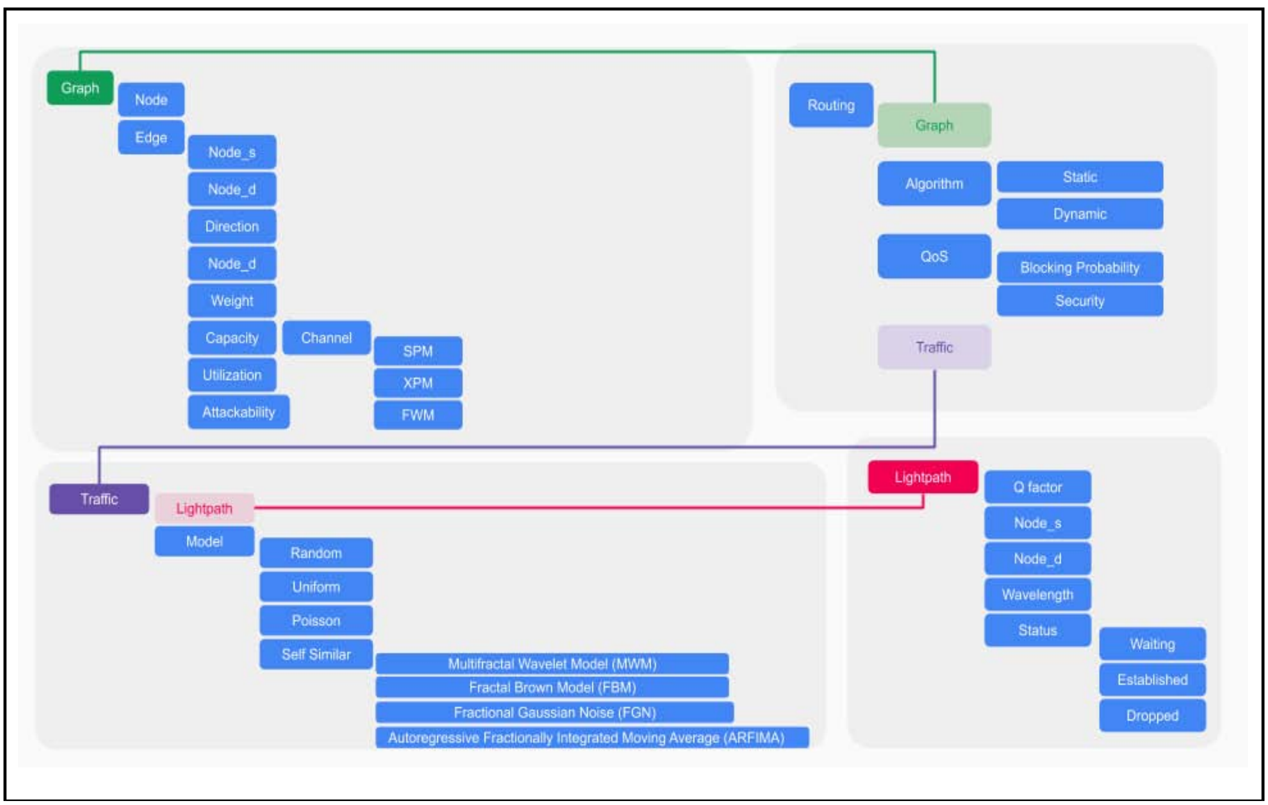


Figure 6.1 Dynamic-CSF-WDM Architecture

Dynamic-CSF-WDM Design:

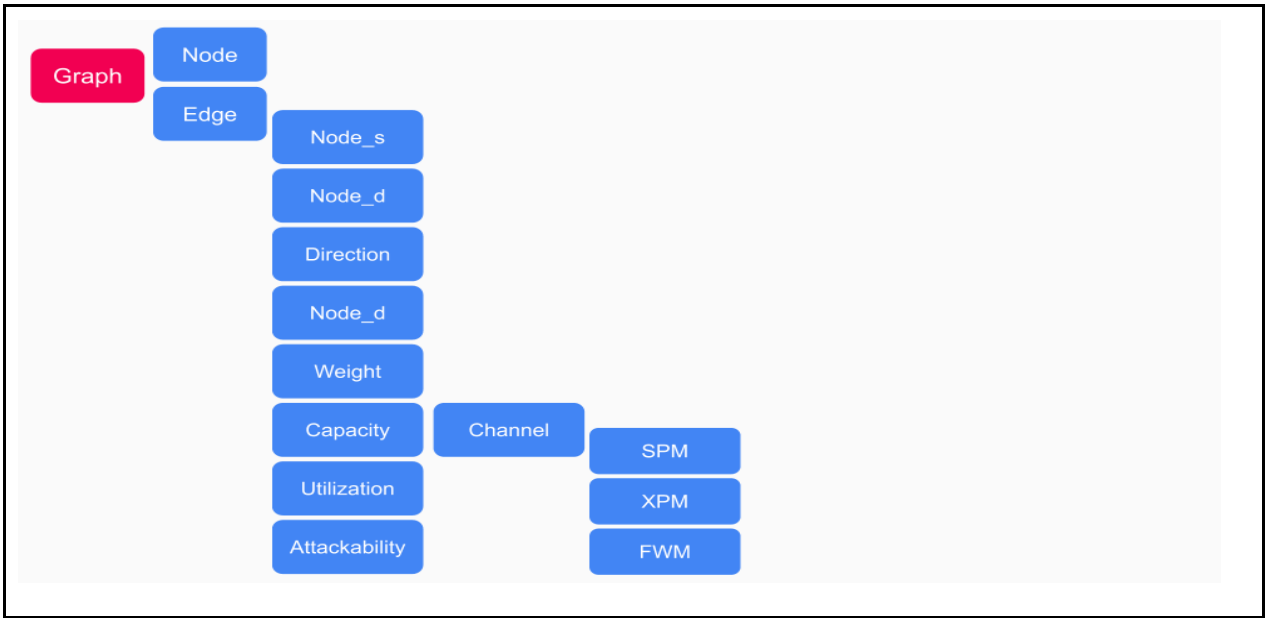


Figure 6.2 Dynamic-CSF-WDM Design - Graph Module

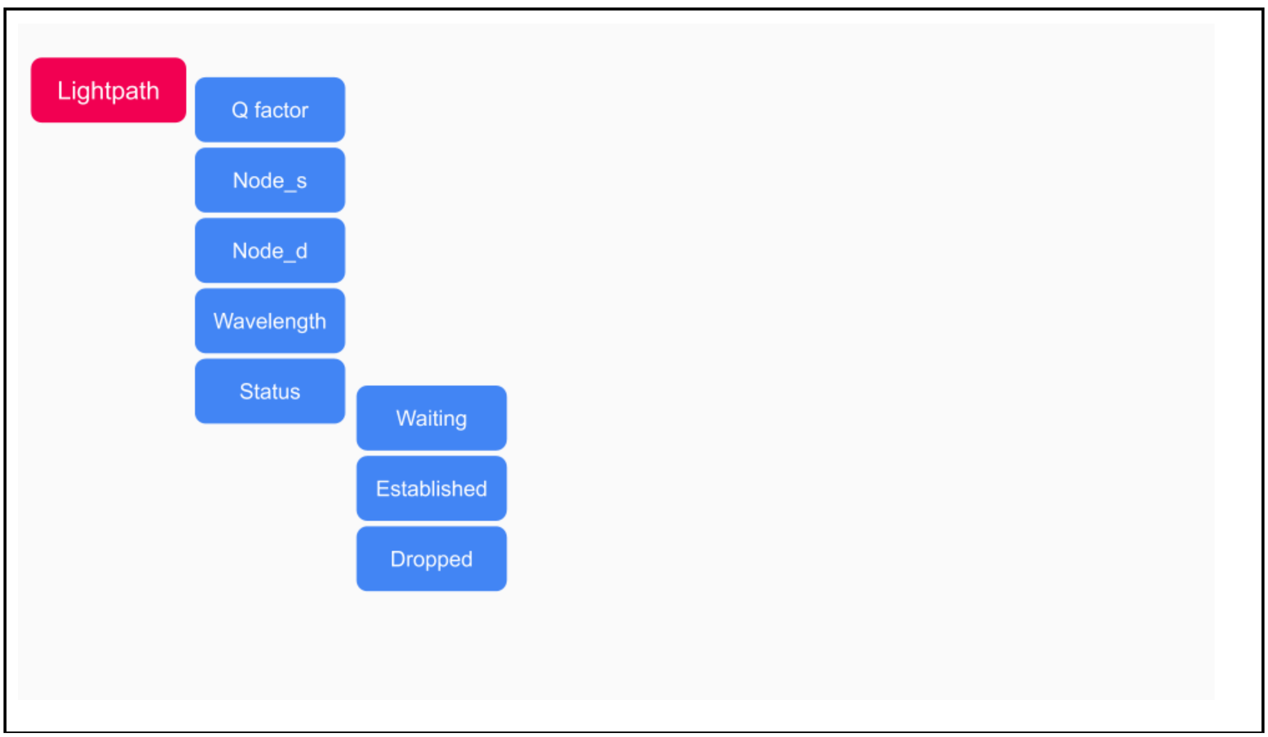


Figure 6.3 Dynamic-CSF-WDM Design - Lightpath Module

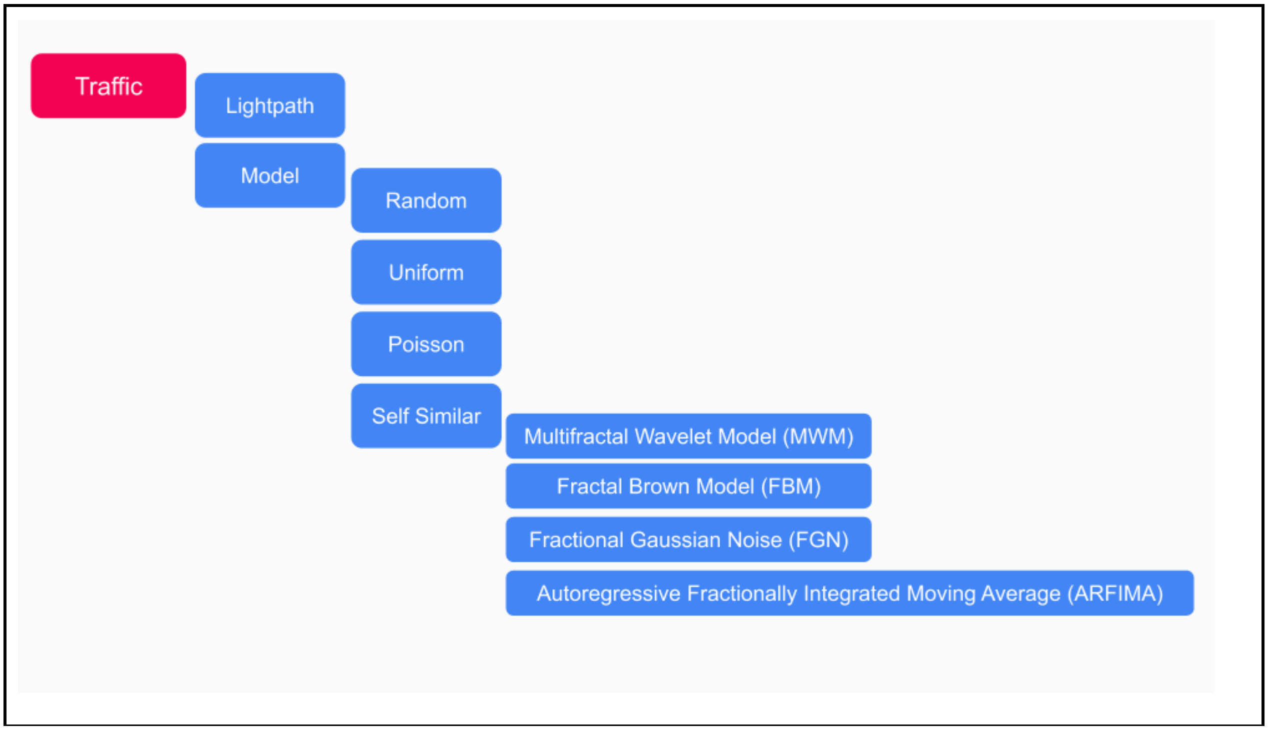


Figure 6.4 Dynamic-CSF-WDM Design - Traffic Module

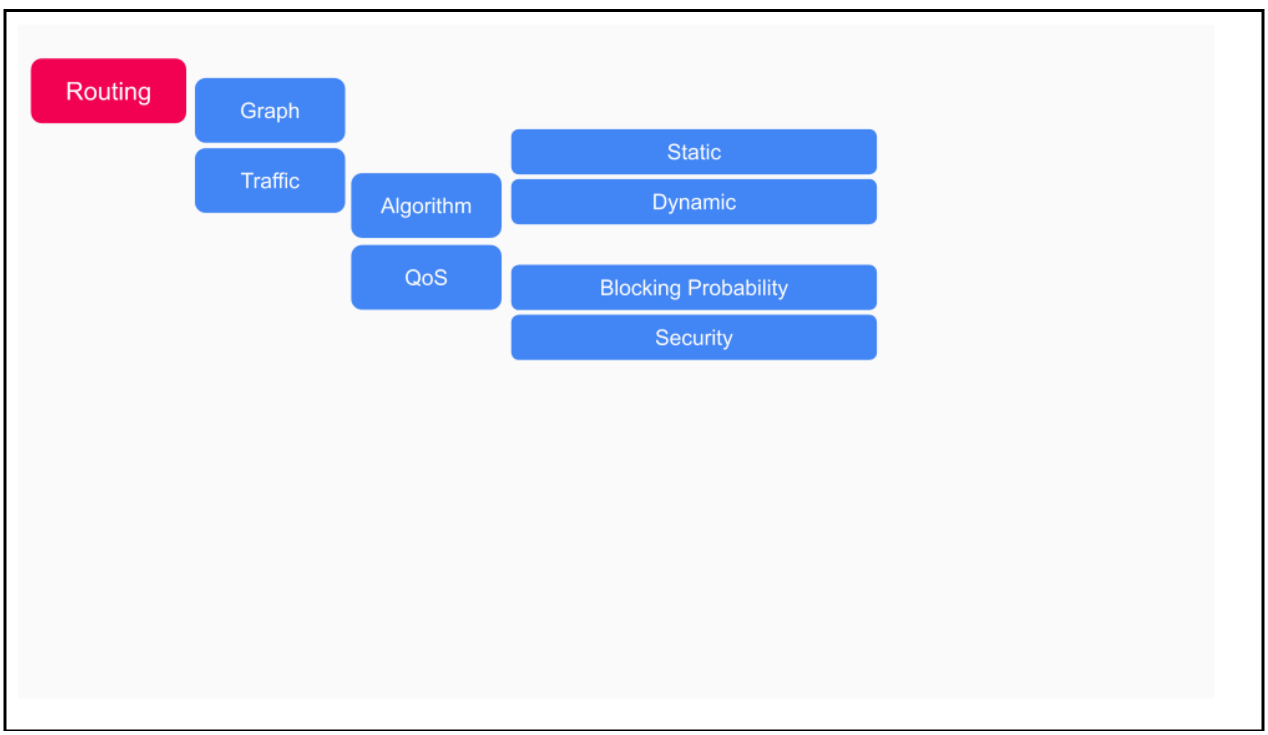


Figure 6.5 Dynamic-CSF-WDM Design - Routing Module

Implementation

The integrated Dynamic-CSF-WDM Solution will be entirely developed in Java, utilizing all modules presented in the various sections of the above (e.g. Realistic Dynamic Traffic Generation in Matlab), (RWA in a Java Module), Nonlinearities (in Java), as well as security Module (in Java). This segregation will be intentional to ensure modularity and effective unit testing of the various elements of the architecture. This will focus on presenting the integrated solution aiming at integrating the above various modules in one compact system and assessing it by simulating dynamic RWA on NSFET Networks and using low, medium, and high number of channels.

To represent the network, an XML file will be used, structured in such a way to indicate edges and vertices, as well as their attackability and nonlinear parameters. The same principle has been used to represent both the physical and virtual topology of the network in the Static RWA presented in earlier chapters.

Simulations & Discussion

This will be continued as part of future works.

Conclusions and Recommendations

This thesis presents 8 contributions. First, is an ILP model to solve the static RWA algorithm, with design built in security controls preventing from worst case attacks. Second, is a realistic traffic generation model to allow to accurately simulate Internet Traffic when testing RWA algorithms. Third, is an analytical and experimental model of nonlinear effects in WDM networks, focusing of SPM, XPM, and FWM. Fourth, is a novel psychology & behavioral science based prevention oriented mindset framework to manage WDM networks from a managerial and technical perspective, linking technical expertise with operational management. Fifth, is the use of Shaping and Policing Traffic Control mechanisms in Dynamic WDM Networks RWA algorithms, Sixth, An attack and throughput aware RWA. Seventh, a Blocking Probability aware wavelength assignment algorithm, and 8^{th} an already started future work section on dynamic attack aware, throughput aware and nonlinear effects aware algorithm.

We have seen in chapter 1 an overview of WDM with its types, Routing & Wavelength Assignment Algorithms Background and Motivation, Literature Review, Definition, Objectives, Categories, Classification as an NP hard problem, as well as a discussion of its sub-problems and some of the main algorithms to implement each. This chapter has also given an overview of 5G and its relation to WDM networks, its main areas of focus and impact, as well as challenges and vision for 6G. Moreover, the chapter reviewed Security challenges and controls in RWA, and finally had given a view of some of the most prevalent nonlinear effects in WDM Networks.

In Chapter 2, we have seen from the experiments above how Self Phase Modulation results in self Spectrum broadening. We have also seen that Cross Phase Modulation causes Mutual Spectrum Broadening, while Four Wave Mixing is responsible for generating new frequencies. We have also observed the thresholds for each of these nonlinear effects in the observed WDM Network. From the WDM Nonlinearities simulations, we have seen that the central channel is the most affected by FWM. The more channels we have and the least spacing between them, the worst is the effect of FWM. The more channels, the worst are the effects of FWM. We also observed that FWM is worst at center channel frequency for Dispersion shifted fiber. Using a NDSF (SMF) decreases the effect of the FWM, and there is a positive correlation between number of channels and FWM.

There is a positive correlation between the BER and the traffic load, as well as positive correlation between the BER and the number of channels - No difference between 80 & 320 Channels. For the same traffic load, the bigger the channel spacing the lower the BER. There was no correlation observed between PER and number of channels. There is a positive correlation between the PER and Packet length (Long Packet → High PER). Moreover PER is ~2 Orders of magnitude lower for short packets when compared with long packets. There is also no correlation between PER and number of channels. We also saw a Positive correlation between PER and packet size (low PER for short packets), a positive correlation between PER and the traffic load, as well as a positive correlation between number of channels and BER. Finally, we could observe a negative correlation between BER and Input power.

Chapter 3 shows how important it is to keep in mind that while the technological domain continues to advance, pushing The Shannon limit further and further, laying more submarines cables in the ocean, and competing in keeping error rates down to negligible values, it is important to notice, that without a well-established framework with best practices and recommendations for both the technology, the processes, and the people and their motivational fits, the organization could prepare itself for failure. It's become nowadays critical more than ever before, to ensure the big picture is obtained right and the vital areas of the organization are run by strong independent yet collaborative processes, connected thanks to an effective governance that recognizes and enforces prevention as a core value and where each entity is clear on their responsibilities and where the flow is determined, communicated, and customized to fit as much as possible, to ensure successful operations strategically aligned with business vision and mission as well as the higher goals of the prevention oriented mindset framework to achieve organization goals and respond to users need in the domain of operation, safely and securely. Always in the same chapter, we have shown how big WDM Market is and how huge is the bandwidth demand. Given WDM Transparent Optical Networks are prone to attacks, Attack awareness should be planned at design phase. The study in that chapter shows how can QoS Shaping & Policing techniques be used for WDM Networks as well as how Bandwidth utilization fairness could be achieved with WFQ. To close it off, the chapter also presented a self-similar simulation of WDM lightpaths requests within Optical Networks. We also showed that our Implementation of Pareto model simulation for WDM Traffic Generation is consistent over multiple iterations and shape variables, making it a realistic model, practical to be used for Traffic Generation Modules for Optical Networks Simulators.

In chapter 4, we have studied how to represent the Static WDM Routing and Wavelength assignment algorithm as an Integer Linear Program, with two objective functions, one to maximize the throughput, and the other to minimize the attackability in the network. A set of constraints were taken into account, such as clash and wavelength continuity constraints. This chapter also proposed a preventive throughput and attack aware algorithm based on secure topology design, giving enough flexibility to the customer to choose the level of security and throughput that they want to achieve in the network.

Chapter 5 is split into two parts; part I extends the work from chapter 4 to design and implement and validate an attack and blocking probability aware Wavelength Assignment Algorithm for Optical Networks. Then, we have Part II which presents the proposed integrated CSF-WDM framework, which is built based on 4 parent components: 1) Realistic Dynamic Traffic Generation, 2) Routing Module, 3) Wavelength Assignment, 4) Nonlinearities Awareness, 5) Security Awareness.

Chapter 6 presents future work on a dynamic RWA algorithm that is attack aware, blocking probability aware and nonlinear effects aware. The chapter already presents the design modules of the future work's algorithm.

Appendix I: Basics of fiber

Basics of Fiber

The very basic model of an optical network would contain a light source, an optical transition medium and a receiver. Let's look at other devices that make it on an optical network. The next sections describe several fundamental elements of optical networks.

Hardware

Active components

We distinguish between active and passive hardware. We refer to devices able to generate electricity as active devices such as Lasers, wavelength shifters, and modulators. While any other optical device unable to generate electricity or light is said to be passive.

Lasers

Laser stands for Light Amplification by Stimulated Emission of Radiation, resulting in a thin ray of light where all of the light waves have very similar wavelengths [15]. This concentrated beam of light can travel long distances. In 1960, Theodore Maiman developed the very first working laser at Hughes Research Lab [16]. The laser works by reflecting light through an optical cavity, so that the stream of photons stimulates atoms that store and release light energy at useful wavelengths. Ytterbium, 70Yb, is the most common lazing atom [17]. Doping the core of an optical fiber with 70Yb controls the refractive index and photon absorption. With 70Yb, a broader spectrum of light can be absorbed at the shorter 915 nm wavelength, while a more efficient absorption can occur at the longer, narrower, 976 nm wavelength. The photon absorbed by the Ytterbium dopant disappears and electrons whizzing around the atomic nucleus move to higher orbitals on account of the absorbed energy. This process is called pumping, to indicate that energy is injected into and stored by the atoms in the fiber. Within about a millisecond, the electrons otherwise unstimulated, drop to their ground state and emit a photon at a wavelength of 1064 nm. The energy efficiency of this absorption and re-emission is known as the quantum efficiency, which is simply the ratio of the pump over the emission wavelength. It's impossible to get a higher optical efficiency than this number. Typically a fiber laser has an absorption length of about 95%

of the pump energy. There are lasers that produce signals at a single frequency and others that produce signals at multitude of frequencies. This second type is referred to a tunable laser and has applications in DWDM for their ability to supply a backup frequency for any signal.

Modulators

In Optical networks, a modulator is a device to manipulate properties of optical beams. Modulators can control a set of properties such as: phase, polarization, spatial light modulations, etc. [18]. The principle behind these modulators is that their constituent material transforms its optical properties under the presence of an electric or magnetic field [19]. The figure below illustrates the types of optical Modulators:

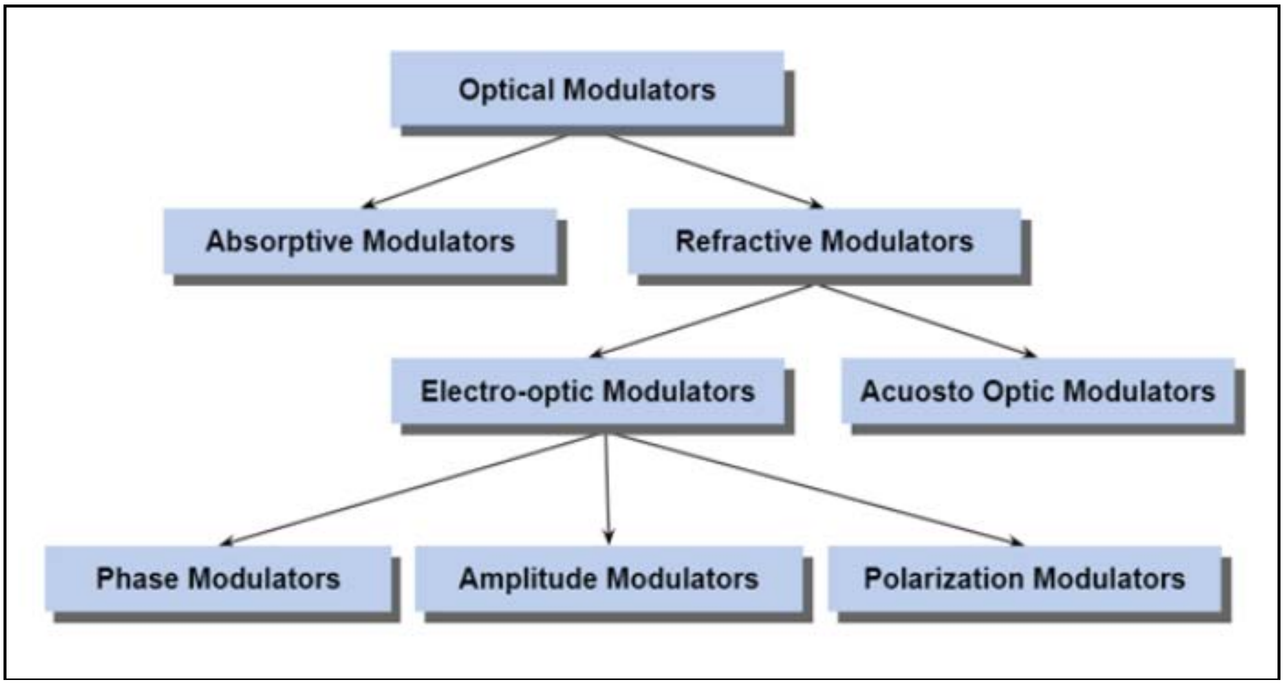


Figure A1.1 Optical Modulators categories. Adapted from [18]

Wavelength shifters (converters)

A wavelength shifter is a photo fluorescent material that absorbs higher frequency photons and emits lower frequency photons. The material absorbs a photon, and emits one or multiple lower-energy photons. The relaxation time of the excited molecule is usually in the order of nanoseconds.

Passive components

Such components cannot produce energy or gain power. We list a few in the next sections.

Fibers

Optical fiber was invented in 1970s [12]. Optical fibers are very thin strands of glass or S_iO_2 almost the same diameter as a human's hair strand. This medium serves as a transmitter of light signals. Optical fibers are made of two basic elements; the core, the cladding. The light is transmitted via the core, the cladding keeps the light inside, preventing it from escaping.

There are two types of fibers: Single mode and Multimode. Single mode fibers have a smaller core diameter and is designed to carry light over a single path over long distances, it has high information carrying capacity and low attenuation and is the most widely deployed optical fiber in the world. Multimode fiber has a larger core, allowing light to travel through multiple paths simultaneously. Typically, this type of fiber is deployed in Data Centers, Local Area Networks, and storage area networks where it's more cost effective than single core fiber.

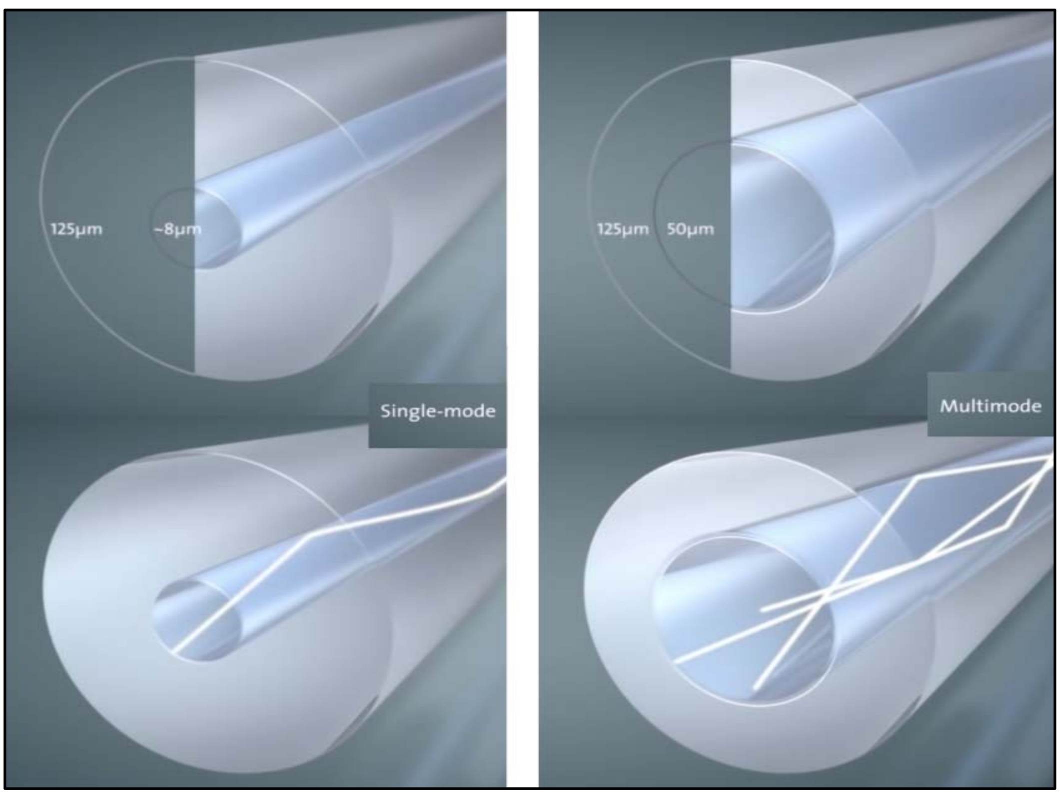


Figure A1.2 Single Mode Fiber vs. Multimode Fiber - Specifications and light propagation [20]

There are three key attributes that can limit the speed or the information carrying capacity of the fiber. They are: 1) Attenuation 2) Dispersion, and 3) Bend induced loss in the form of macrobending and microbending performance. Attenuation refers to signal loss along the length of the fiber. It can be caused by the quality of the glass or induced by bending. Dispersion is the distortion of a signal along the fiber length. This occurs because different spectral components of the optical fiber travel at different speeds. Macrobending and microbending are optical effects that occur when the fiber is bend from a straight access. Microbending is an attenuation increase caused by high frequency small radius bends along the length of the fiber. Macrobending is the attenuation associated with bending or wrapping the fiber. This allows light to leak out of the fiber causing loss of some of the original signal.

Figure A1.3 Microbending [20]

Figure A1.4 Macrobending [20]

Optical fibers operate based on the principle of total internal reflection, which keeps the light within the core and guides on the length of the fiber. Refraction refers to the bending of light as it passes from one substance to another. The glass used in the fiber core has a higher refractive index than the glass used in the cladding. Si that the light can be trapped in the core by reflection at the cladding interface as it propagates down the length of the fiber.

Two additional characteristics of single mode fiber that are important are cut-off wavelength and mode field diameter. The cut-off wavelength is the wavelength above which the fiber will support only a single mode. Wavelength below the cut-off support two or more modes. The cut off wave is determined by the fiber refractive index profile, the length, and bend of the fiber, as well as the cabling process and deployment conditions encountered during use. In a single mode fiber, some of the optical powers are actually guided outside the core, in fact, as much of 30% of the light propagate in the cladding layer of some fibers. The mode field diameter defines the size of the optical power distribution of the fiber. Multimode fiber has two important characteristics: numerical aperture and core size. Numerical aperture is the measure of the angular range of acceptance of light into a fiber. The angle over which the fiber accepts light depends on the refractive indices of the core and cladding glass. Core diameter is a fundamental design parameter of multimode optical fiber. The larger the core, the more modes of light can propagate through the fiber. Multimode fiber has a much larger core size than single mode fiber. Optical fiber is strong, flexible, and reliable. Inch for inch is stronger than steel and more durable than copper. Fiber offers excellent signal performance over a wide range of environmental conditions. Since fiber carries light instead of electricity, it is not susceptible to lightning strikes or electrical faults and unlike copper, it is not corrode or rust, as a result, fiber reduces maintenance cost and has a proven record of reliability in the field. Corning reported it is common for customers to report the cable installed in the late 1970s or early 1980s are still in use today. Optical fiber is cost effective, durable, scalable, has low attenuation and it features the superior transmission quality needed for high speed transmission of voice, data, and video in today's leading applications.

With today's technology, it's possible to transport over a million Gigabit per second, about a Petabit. That'll be like downloading 17K High definition movies from Netflix in 1 second!

Multiplexers/Demultiplexers

Similar to Add-Drop multiplexers (ADMs) in SONET networks to add and remove signal components selectively without demultiplexing the entire stream of signals [21], Optical Multiplexers or Optical Add-Drop Multiplexers (OADMs) are devices that take optical wavelengths from various fibers and converge them into one beam [22][23]. They multiplex a user-defined number of input WDM signal channels. See below an example of a WDM Mux/Demux illustrating these inputs (ports):

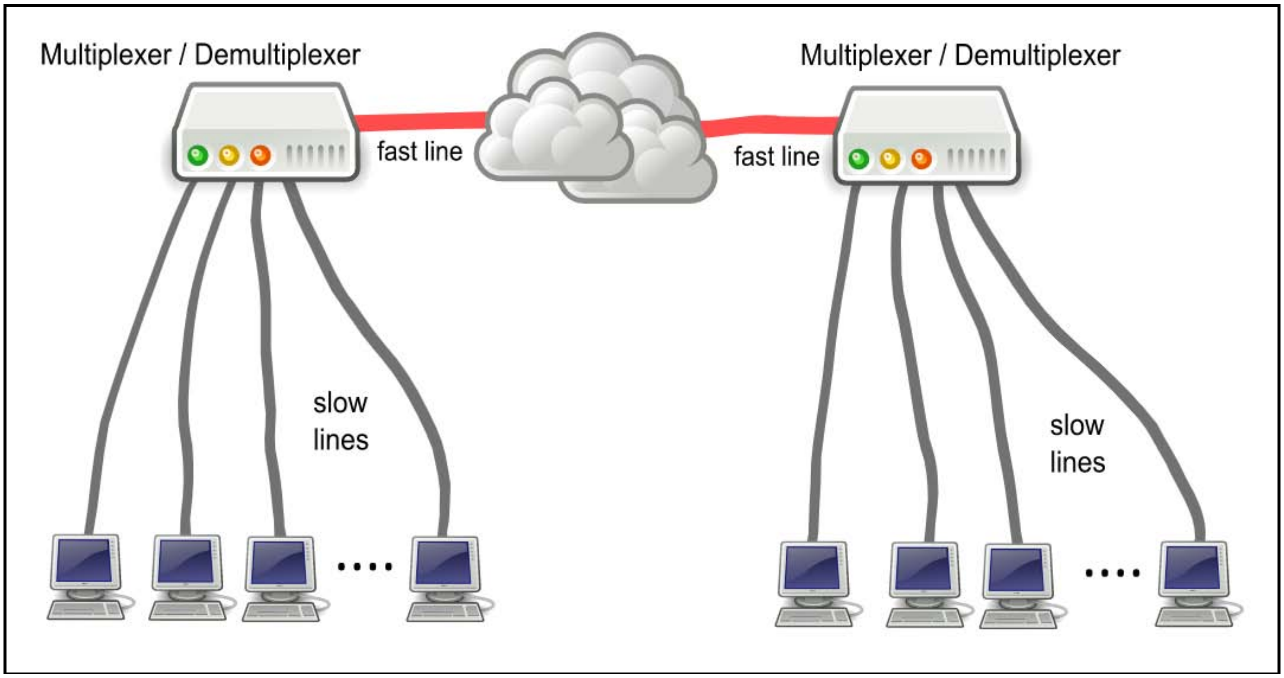


Figure A1.5 Multiplexing demultiplexing scheme [24]

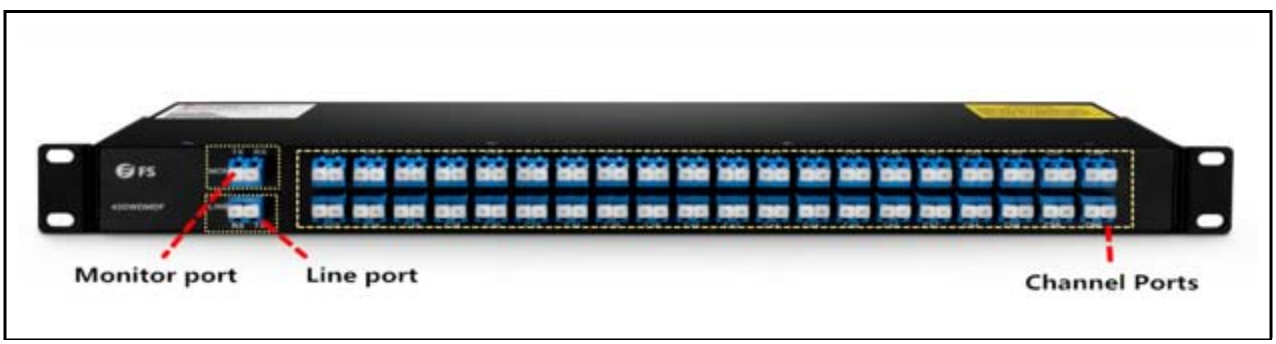


Figure A1.6 Mux/Demux device must have ports [25]

Line Ports (a.k.a common port) are two essential ports on CWDM and DWDM Mux/Demux devices as they connect it to the fast line fibers as demonstrated in Figure A1.5. When zoomed in, as Figure A1.6, we can see that these ports are marked as Tx and Rx. They're especially important since the multiplexing and demultiplexing all WDM channels happens over these ports [27].

Channels Ports Depending on the type of WDM Mux/Demux device in hand, we can distinguish between two categories: CWDM and DWDM. CWDM uses 2-18 wavelengths of the range [1270 nm - 1610 nm] and a channel spacing of 20 nm. You can see the full-channel CWDM Mux/Demux with the 18 wavelengths: 1270 nm, 1290 nm, 1310 nm, 1330 nm, 1350 nm, 1370 nm, 1390 nm, 1410 nm, 1430 nm, 1450 nm, 1470 nm, 1490 nm, 1510 nm, 1530 nm, 1550 nm, 1570 nm, 1590 nm, 1610nm, as illustrates the figure below [27].

Figure A1.7 Full-channel CWDM Mux/Demux with the 18 wavelengths [25]

Monitor Port allows monitoring and troubleshoots the network as it enables to test the signal dB level with no service interruption [25][26].

Figure A1.8 Mux/Demux device nice to have ports [25]

Expansion Port When available on a Mux/Demux device, this port allows increasing the network capacity expanding more wavelengths or channels to the existing network. Let's say, you've got an 8 Channels Mux/Demux, and need to add 8 more channels. For that, you'll need to get a new 8 Channels Mux/Demux device, then connect your original device's expansion port to the new device's line port. Ensure, you're having the same number of channels available at the receiving end. [25][26].

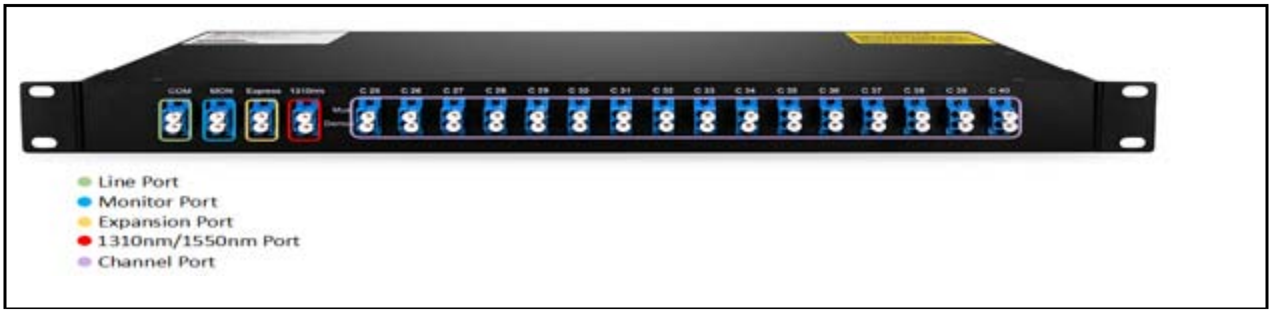


Figure A1.9 Mux/Demux device ports overview [26]

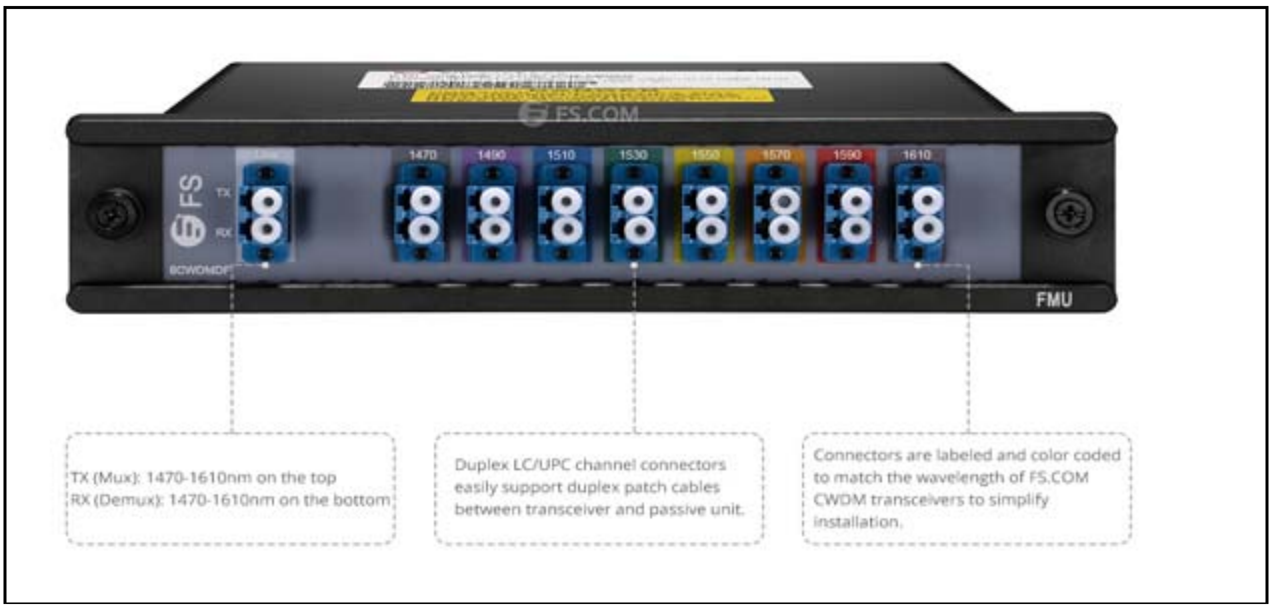


Figure A1.10 Zoomed in view of 8 Channels WDM Mux/Demux Device [28]

Couplers

A fiber optic coupler is a device able of joining multiple fiber ends, allowing the transmission of light signals in multiple paths. The optical coupler can either connect multiple input light signals into a single output or divide a single light signal input into multiple outputs. The issue with couplers though is with attenuation as the input signal can be divided between the output ports. Optical couplers can be categorized as active or passive equipment. As explained earlier, the difference between active and passive devices is in the power supply, where active Optical couplers need power, which is not the case for passive optical couplers. Based on the number of input and output ports, optical couplers could be grouped into different types: X couplers, splitters, combiners, stars and trees. The three major types of manufacturing technologies used in fiber optic couplers are fused-fiber, micro optics and planar waveguide [29].

Isolators

An optical isolator uses a Faraday rotator together with a half-wave plate, between two beam-displacement polarizers, to provide isolation from back reflections. While both series provide excellent isolation from optical feedback, they do so through different geometries [30]. As a result, these two series offer several optimized performance requirements. The IO-H series is optimized for performance at a specific wavelength (Such as 1550 nm for IO-H-1550APC) [30].

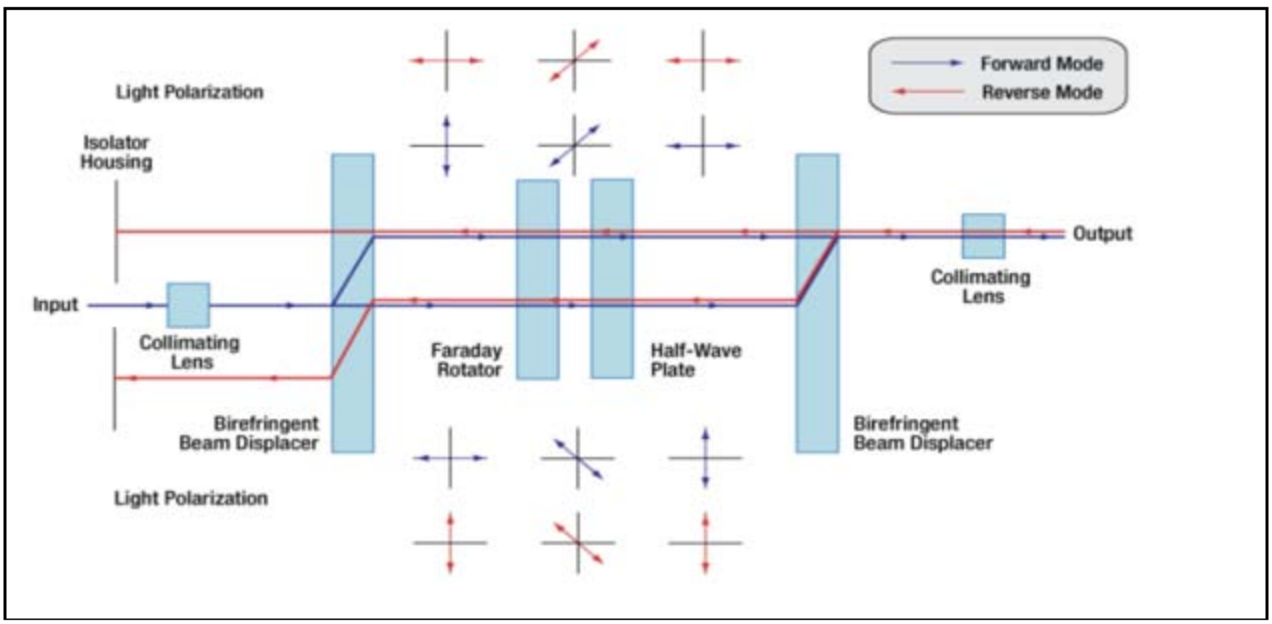


Figure A1.11 Optical Isolator Principle (IO-H-1550APC) [30]

The IO-F series, is designed as a more diverse platform and provides customized performance over several wavelength bands. These bands are defined by the choice of half-wave plate and collimating lenses. Optical isolators play a key role in deterring back reflections from re-entering the light source, protecting, by that, he source from optical feedback and damage [31].

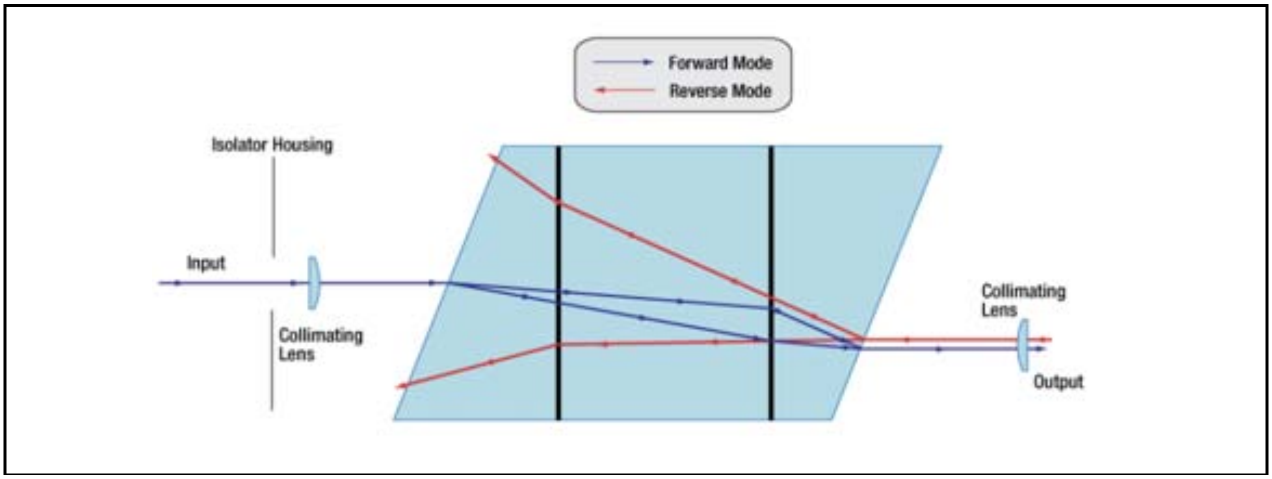


Figure A1.12 Optical Isolator Principle (IO-F-1550APC) [30]

Attenuators

An optical attenuator is a device used to reduce the intensity of a signal. It could either be temporarily used (to test power level margins) or permanently (to meet the transmitter/receiver power levels). Consider the case of a single mode system with laser transmitters where power is quite high, optical attenuators provide with an option to reduce receiver power [32]. An optical attenuation could be achieved by providing an end gap between two fibers (gap loss), by an angular or lateral misalignment, by deliberate poor fusion splicing, by inserting a neutral density filter or even stressing the fiber [32]. Attenuators are available in models with variable attenuation or with fixed values from a few dB to 20 dB or more [32]. There are several categories of optical attenuators. We list: Single mode (SM), multimode (MM), or polarization-maintaining (PM) variable optical attenuators (VOAs) [33].

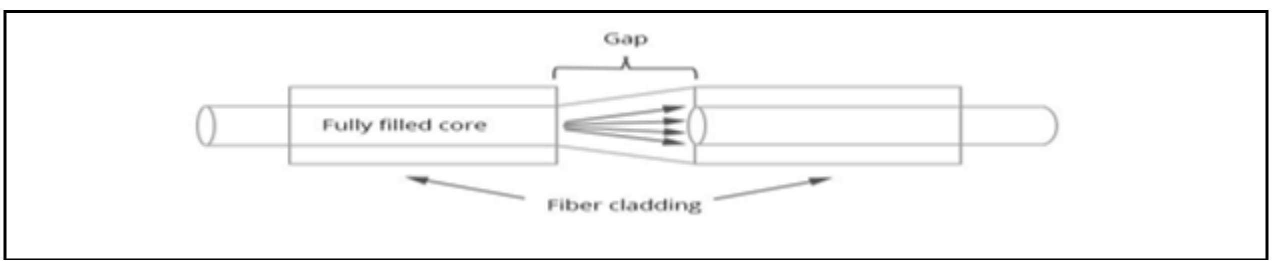


Figure A1.13 Attenuation via gap loss [34]

Circulators

Optical circulators are couplers that have specific couplings based on the propagation direction of light signals. We list two variants: 3-port circulator and 4-port circulator. In a 3-port circulator, light signal enters via port-1 and leaves via port-3, with port-2 being the bidirectional port. On a 4-port circulator, light signals enter via port-1 and leave on port-4, while ports 2 and 3 allow for bi-directional propagation [35].

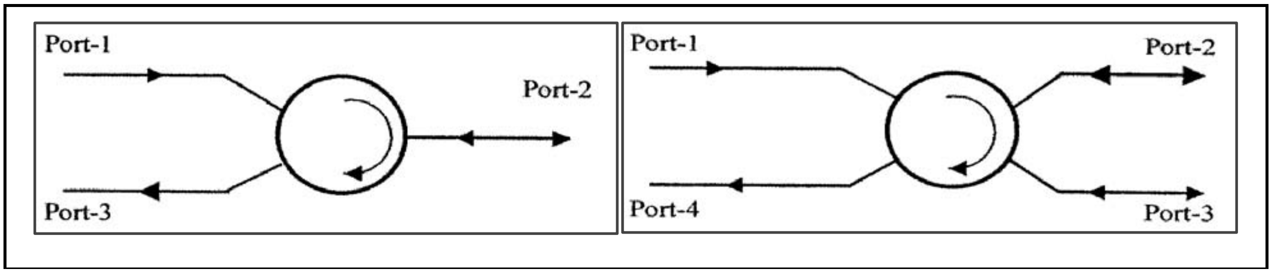


Figure A1.14 3-Port circulator (on the left) vs. 4-Port circulator (on the right) [35]

Circulators can be used to couple different parts of the network, they could make a fiber link bi-directional if 2 of them are placed at one of the fiber ends. They can provide better performance than couplers in an Optical Time Domain Reflectometer, measuring optical fiber length and loss, and they can also be used in the production of Optical Add-Drop Systems [36].

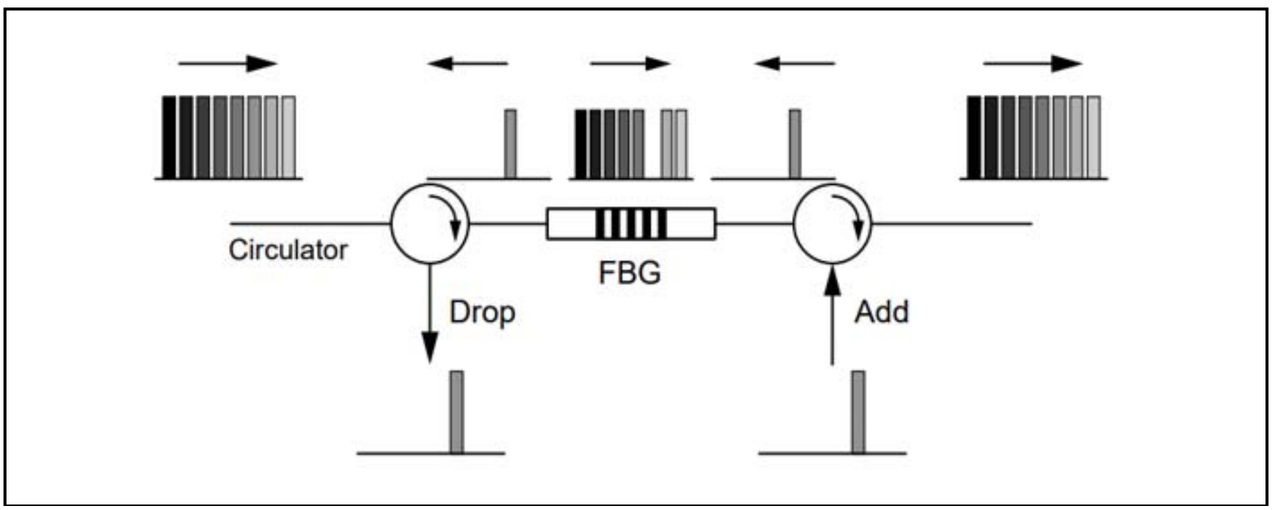


Figure A1.15 Optical Circulators used in an Add-Drop System [36]

Software

Studying software in the context of optical networks, we distinguish between two categories: A) Software as a component of the network, and B) Software as a representation of the network. With category A, we can list three sub-categories: 1) Network management software 2) Software for order management and billing and 3) Operations Support Systems (OSSs).

Network Component

Network Management Software

Network Management comprises of a set of disciplines including fault analysis, performance management, and networks provisioning, as well as maintaining the quality of service. Software that allows to perform network management tasks is referred to as NMS or Network Management System. This category of software helps detecting and locating fiber cable attenuation, faults, and attacks, alerting operators and managers with the details on the incidents and their criticality. Figure below represents the functionalities of an NMS.

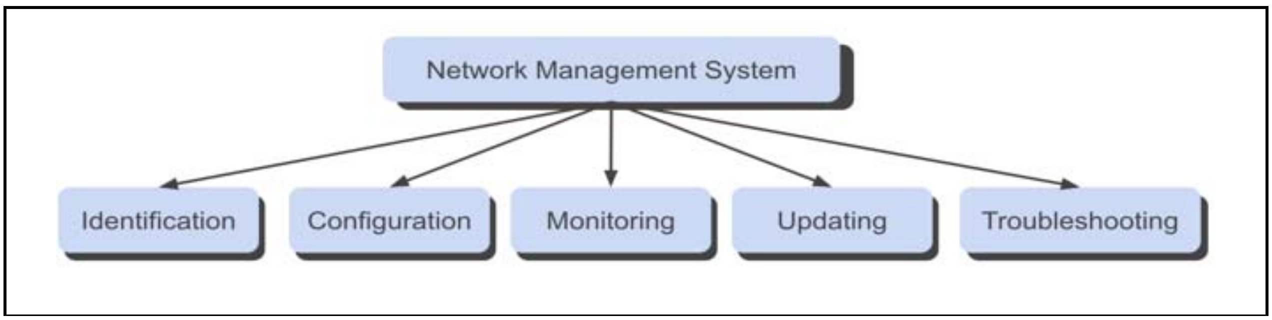


Figure A1.16 Network Management System functional areas

Business Support Systems

Business Support System is a complementary term, abbreviated as BSS, describing "business systems" managing customer support processes such as order management, bill management, and payment collection [37]. This can also be referred to a software responsible for order management and billing.

Operations Support System

The Operations Support System (OSS) is a set of network management software used by Telecom Service Providers comprises to manage their network operations functionalities such as network configuration, network inventory, service provisioning, and fault management [37]. OSS contain four central components: Processes, Data, Applications, and Technology [38].

Combined with BSS, OSS is utilized to support different end-to-end telecommunication services. These two systems have their respective data and service functions. They often are also referred to together as OSS/BSS, BSS/OSS or B/OSS [38].

Network Representation

Software Defined Network:

Software-defined networking (SDN) is the segregation of the control plane from the forwarding plane (Figure A1.17 below) [39]. SDN is an architecture that offers support for virtual machine mobility regardless of the physical network [40]. The idea lies in the central software based network intelligence where SDN controllers retain a holistic view of the network. When compared to traditional data network, we observe that network functionalities are physically implemented in devoted hardware equipment such as routers, switches, application delivery controller, etc. [40]. When the network functionality is not implemented on dedicated equipment, it is found implemented in Application Specific Integrated Circuits (ASICs). This is problematic for a multitude of reasons: The slow evolution of ASICs, the dependency on proprietary vendors for upgrades, security, and functionality improvement, configuration overhead. Now, when an organization following such traditional network management framework, and as part of server virtualization, virtual machines are dynamically moved from a server to another in seconds or minutes. Imagine now, that the mobilization of a VM crosses a Layer 3 boundary. This can take from days to weeks of network reconfiguration before the network is able to support the VM in the new location [40]. This situation puts the network's agility in a questionable state.

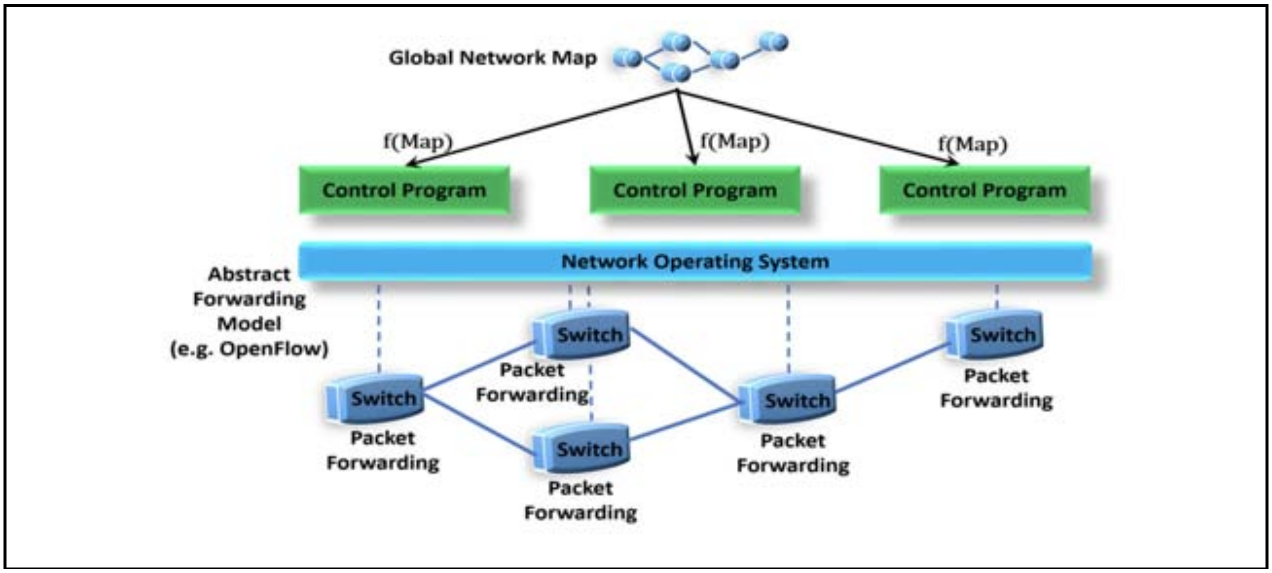


Figure A1.17 Software Defined Network (SDN) [39]

With this information in mind, I've summarized the main points discussed in [40] by creating the graph in Figure A1.18, depicting some of the main use cases that may push concerned organizations to adopt Software Defined Networks Architecture:

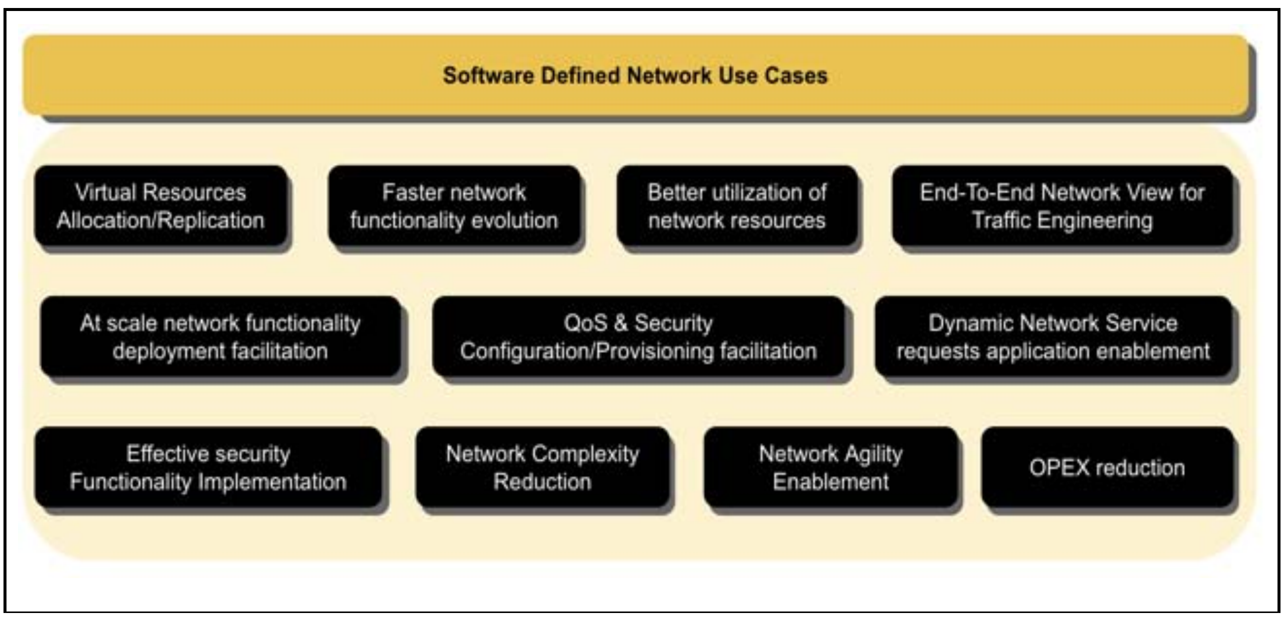


Figure A1.18 Software Defined Network Use Cases. Adapted from [40]

Protocols

A key traits of Optical Networks is their transparency, the ability to transmit various types of data down the same fiber. This is possible thanks to protocols such as Optical Transport Network

(OTN). Also referred to as Digital Wrapper, OTN is the next-generation, industry wide, standard protocol to multiplex different services onto optical light paths, while also allowing to troubleshoot wrapped protocols with minimum or restricted troubleshooting all with OTN troubleshooting capabilities [41]. Recommendation ITU-T G.709/Y.1331 by the International Telecommunication Union clarifies how OTN supports optical networks operation and management, over a set of architecture varieties [42]. Data from a multitude of protocols (SONET, IP, etc.) is then sent via an optical channel (OCh) as simplistically represented in Figure A1.19 below.

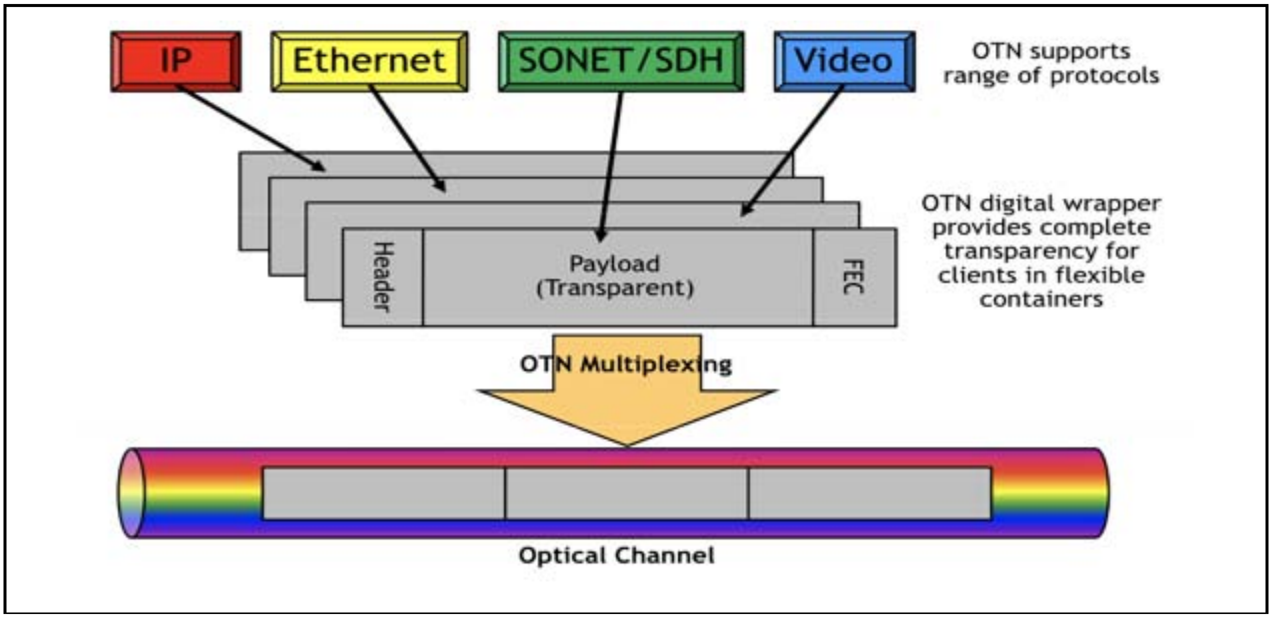


Figure A1.19 Optical Channel Wrapping of multi-Protocol data [43]

Going back to G.709, the recommendation defines an OTN frame as a wrapper of data packets. This OTN frame has 3 overhead sections. The Optical Payload Unit overhead (OPU OH), the Optical Data Unit overhead (ODU OH), and the Optical Transport Unit overhead (OTU OH). These overhead bytes supply section and path performance monitoring, alarm warning communication, and protection switching capabilities [44]. Moreover, each frame benefits from a Forward Error Correction function (FEC), improving the Optical Signal-to-Noise Ratio (OSNR) by 4 to 6 dB, and hence resulting in longer spans and fewer regeneration requirements [44]. Below is a representation of the OTN frame:

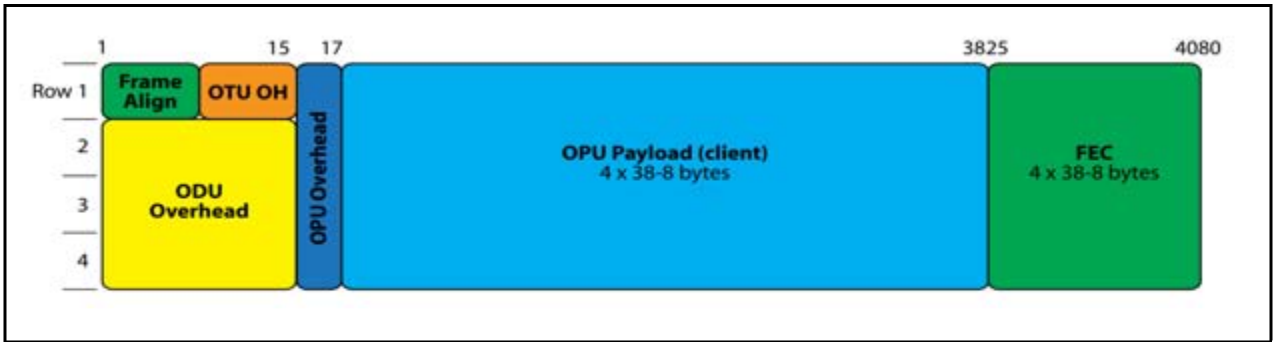
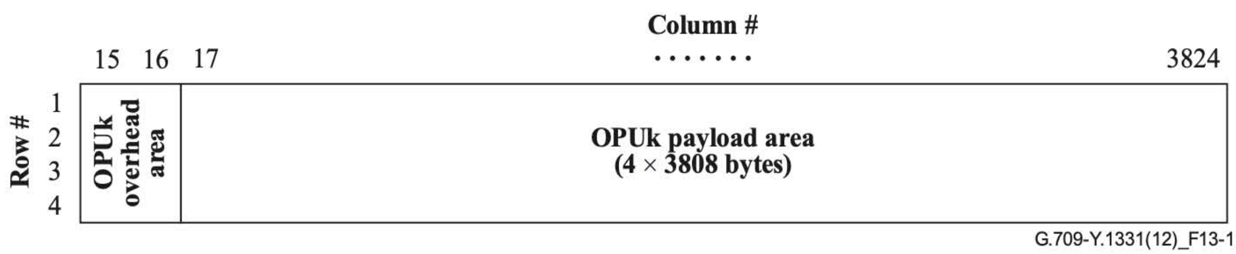


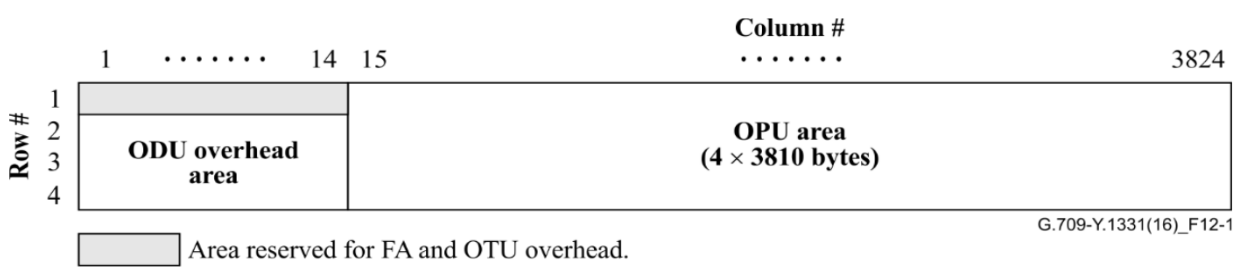
Figure A1.20 OTN frame [44]

Recommendation G.709 defines specifications of the 6 layers of the OTN frame as shown below:

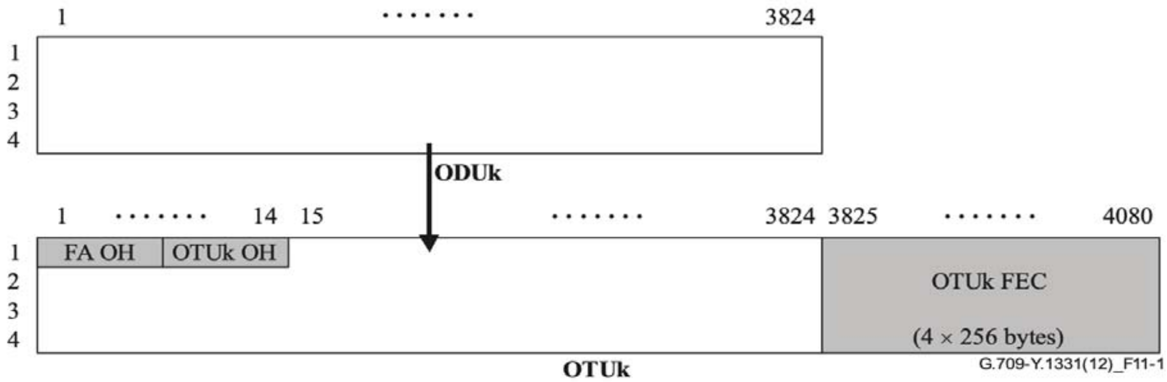
- OPU: Optical Channel Payload Unit. This contains the wrapped client data, together with a header to describe the encapsulated data [45]. Below is an illustration from G.709 [42].



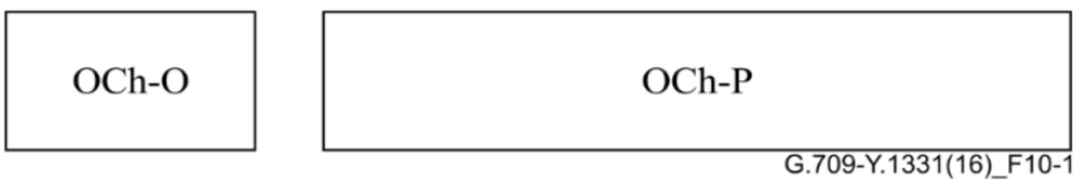
- ODU: Optical Data Unit. This layer adds optical path-level monitoring, alarm indication signals and automatic protection switching [45]. Below is an illustration from G.709 [42].



- OTU: Optical Transport Unit. This stands for a physical optical port (e.g. OTU2 for 10GbE Wide Area Network), and adds performance monitoring (for the optical layer) and the FEC (Forward Error Correction) [45]. Below is an illustration from G.709 [42]



- OCh: Optical Channel. This represents an end-to-end optical path [45]. OCh transports a digital client signal between 3R regeneration points, with the frame composed on an overhead part (OCh-O) and a payload part (OCh-P) illustrated below [42].



- OMS: Optical Multiplex Section. It handles fixed DWDM between OADMs [45].

- OTS: Optical Transport Section. It deals with fixed DWDM between relays [45].

Architecture

A picture is worth a thousand words. The two figures below build nicely from the previous Protocol section and represent the OTN Architecture as the OTN container is built, while the next figure depicts how are Internet protocols fitting together in the big picture of IP over WDM, and where does OTN stand in all of this. Figure A1.21 does present with an overview of that.

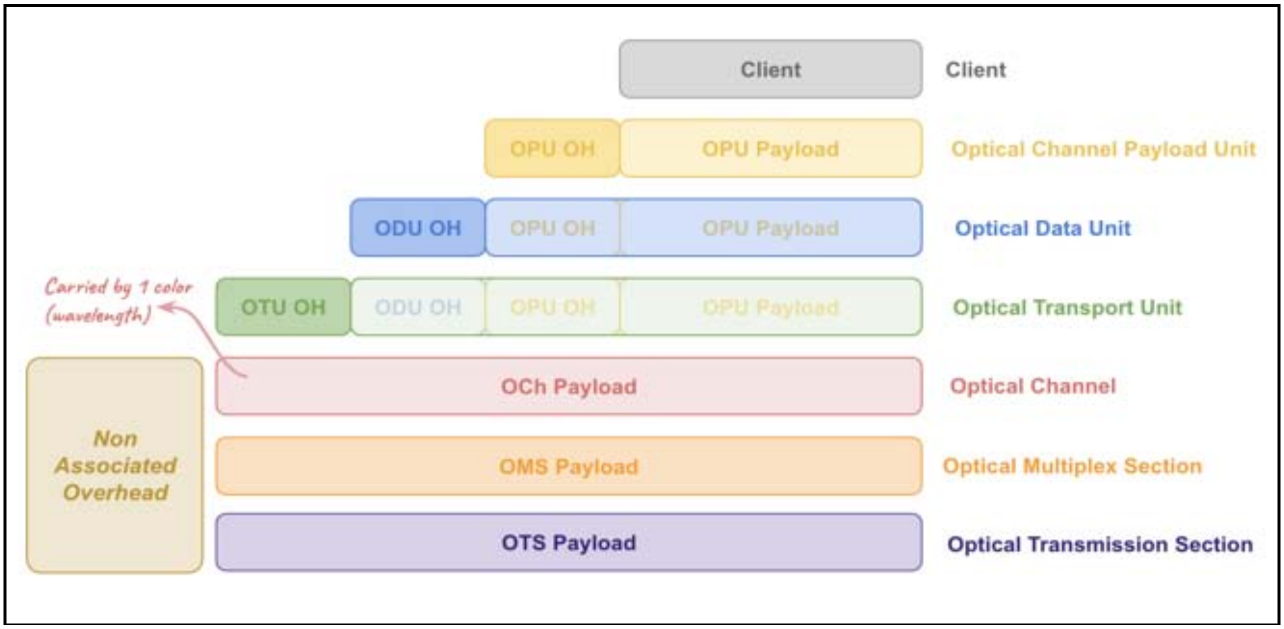


Figure A1.21 Building an OTN Container. Adapted from [46]

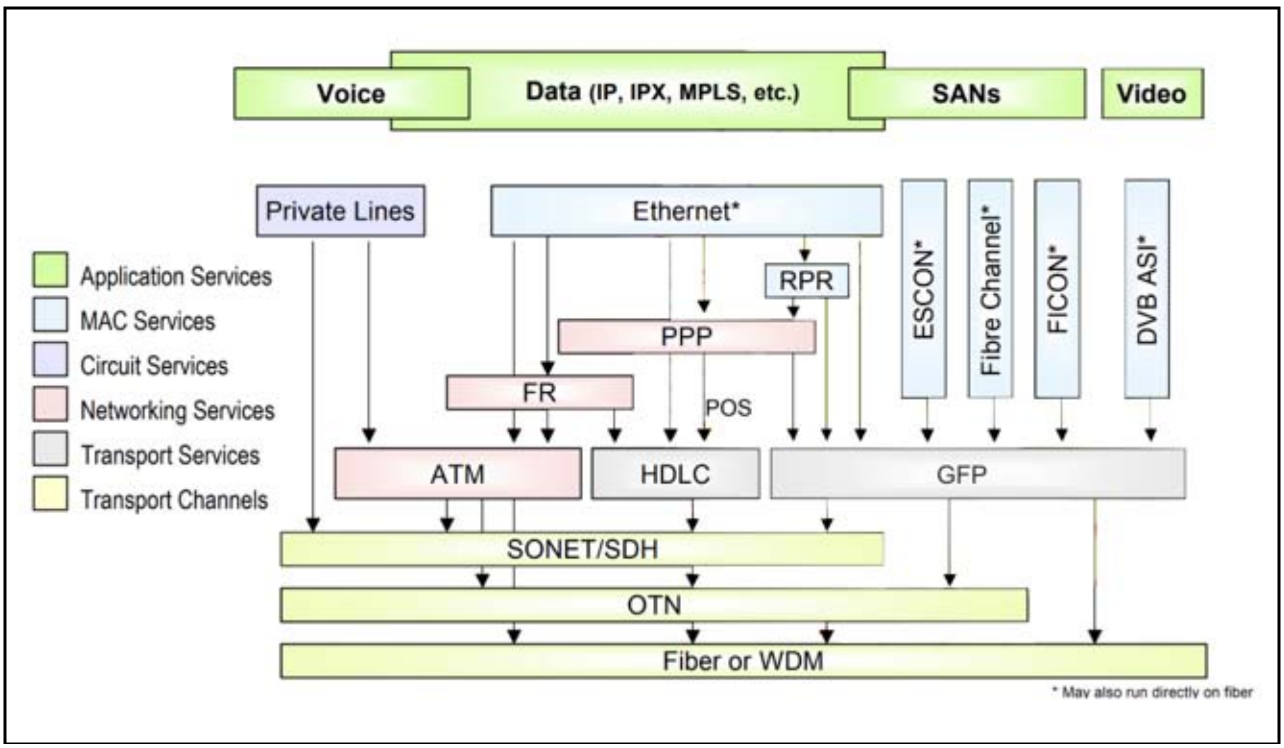


Figure A1.22 IP over WDM. Adapted from. Adapted from [47]

Security

With ITU G.709 describing communication over optical networks, I've looked for OTN Security recommendations or baseline on the same portal, to be surprised with the following:

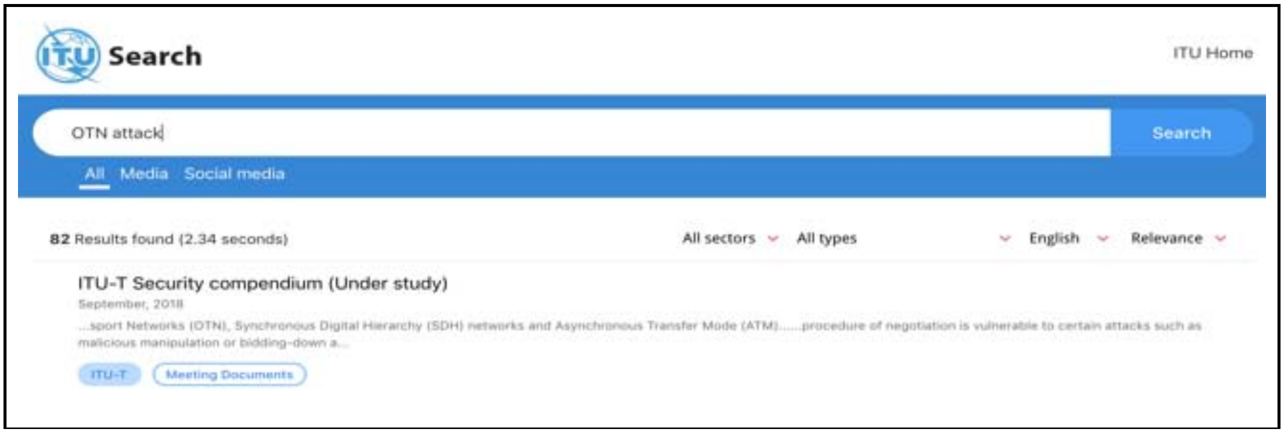


Figure A1.23 Looking up "OTN attack" on Internationalization Telecommunication Union portal [48]

The returned result is still under study, with the last edit made in September, 2018. Clicking on it for more details, led to the following page:

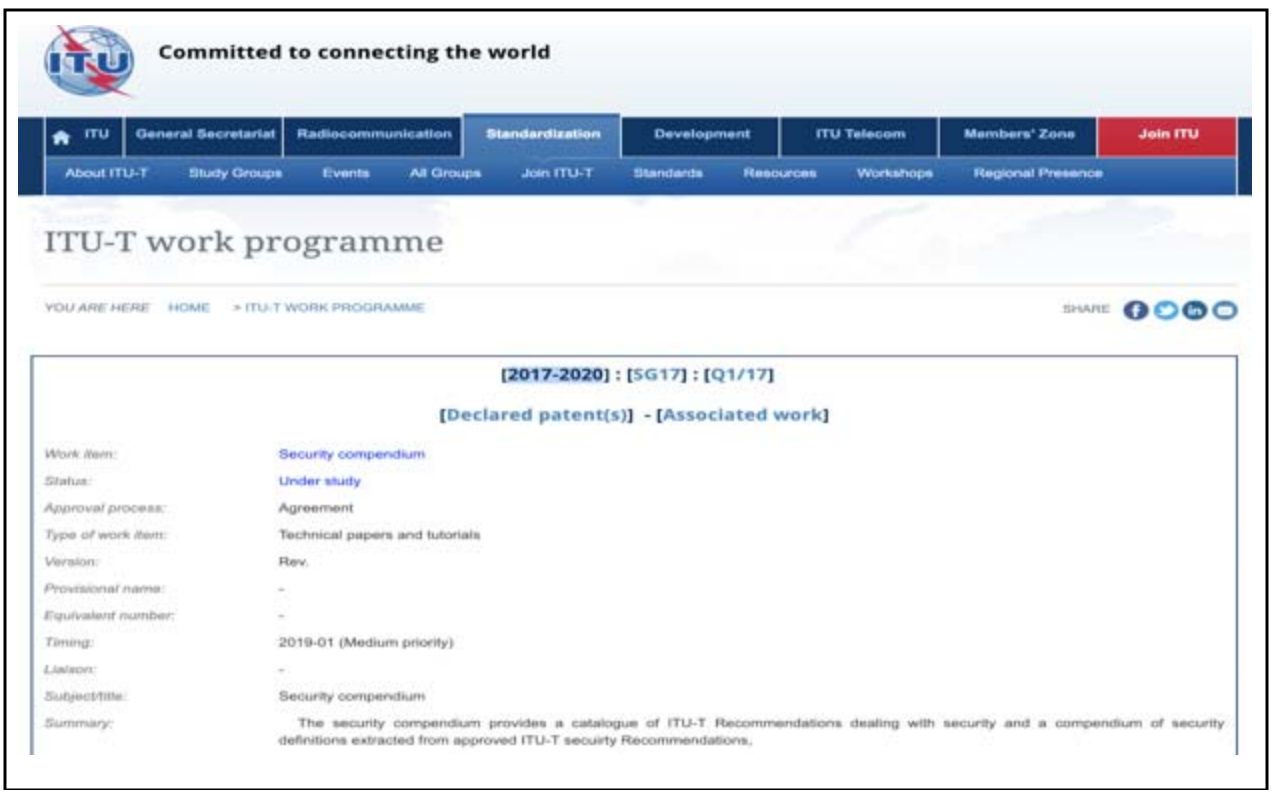


Figure A1.24 Clicking on search result "ITU-T security Compendium" on "OTN attack" on ITU [49]

Now this page shows the planned time span for completing this Security Compendium, listed between 2017 and 2020. Slighting altering the search query, the results were still quite similar:

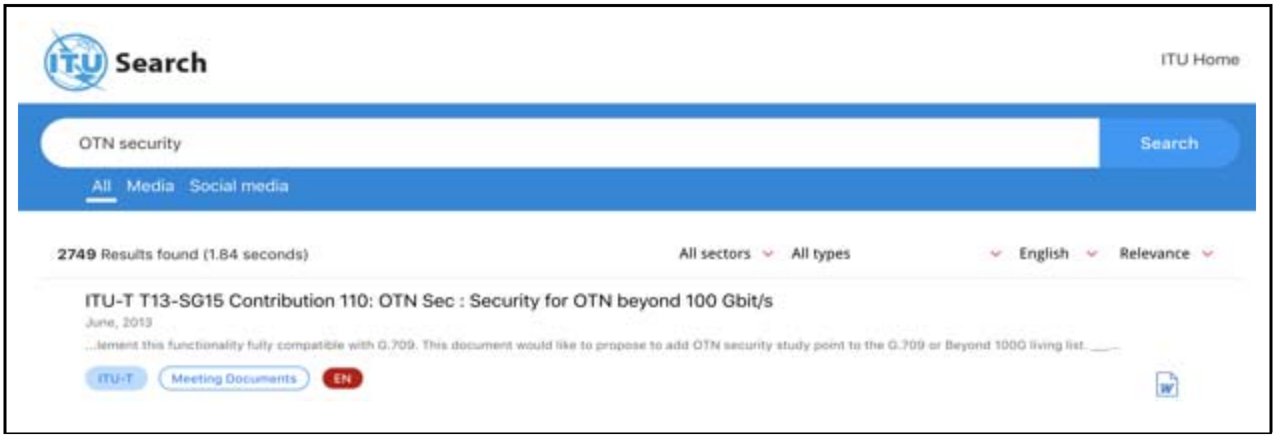


Figure A1.25 Looking up "OTN Security" on ITU Portal [50]

I've gone ahead and tried accessing the link, to only find that it's restricted to ITU members only and that it's still in the works.

Figure A1.26 Clicking on result "Security for OTN beyond 100 Gbps" on "OTN security" on ITU [51]

Now what? Did I give up? Of course not! This just made me even more motivated as this, through 4 years since I signed up for my PhD, this topic is still in the work by big standardization bodies, not any body, those are Internet Regulators, these are entities that approve protocols used worldwide by billions of people, using various Telecommunication means, including Optical.

Leaving OTN aside for a moment, I've been thinking about the big picture of things, namely the OTN Elements, also known as Optical Networking Elements. The main one of course is the fiber. As simple as a strand of glass, this medium is of great interest to attackers, looking to intercept, or alter the transmitted data, for a range a malicious intents. One easy way to study this is by studying how would a network administrator monitors (a.k.a) intercept the network for quality assurance purposes? It's no different right: :) Believe it or not, but the tools used by hackers are not all different from tools used by the IT/Network Operations department technicians, architects, and engineers. Besides, such tools (hardware: e.g. couplers, or software: e.g. Wireshark) are easily available at an affordable price, or even for free (Wireshark).

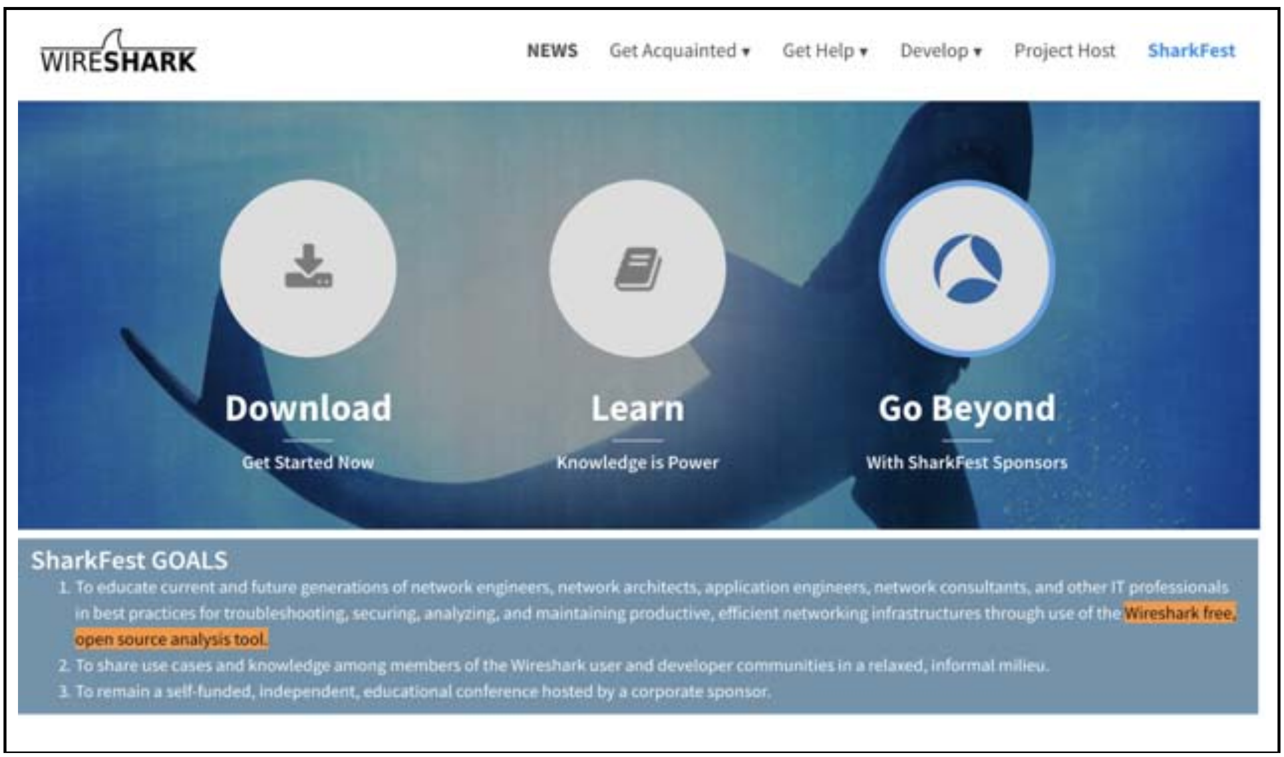


Figure A1.27 Wireshark network sniffing software is a free analysis tool available for the public [52]

As for devices, though these are not for free, but they're still quite affordable, given the impact of the operation, making the cost justifiable. Below is a close-up on a clip-on-coupler:

Figure A1.28 Close-up for an optical clip-on coupler. Adapted from [53]

As we've just seen the clip-on-coupler, let's now see how this device is put into action by attackers. To gain access to the end of the fiber, the attacker needs to bypass all the physical security measures of the premises, which is not an easy task to do, given the amount of security controls generally placed there (e.g. monitoring devices, guards, cameras, etc.). A less tricky situation would be to try to access the fiber along the way, or what's referred to as mid-span access. To carry out this mid-span fiber access, the attacker should polish away at least 30-60 cm of the fiber jacket to gain access to the fibers inside the cable [54]. Let's take a 24-Fiber OFNP MIC® Cable) as an example. OFNP Stands for Optical Fiber Nonconductive Plenum, as it only contains class fibers, and no copper (conductive elements) [55]. This type of cable is intended for horizontal runs within an air handling conduct. The cable complies with the Underwriters Laboratories Fire safety test Plenum/910 [55].

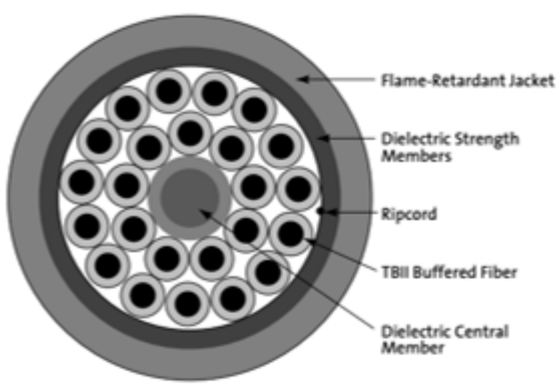


Figure A1.29 A 24-Fiber OFNP MIC® Cable [56]

Reviewing a research paper [54] by two researchers from Corning Inc., the paper describes various ways through which optical networks tapping is possible, such as Fiber bending, Optical Splitting, Evanescent Coupling, V-Groove Cut, and Optical Scattering [54].

1) Fiber bending: Starting with Fiber bending, the idea leverages that fiber bend loss tap is considered to be one of the easiest field tapping [54]. It would suffice for it to strip one fiber strand down to the cladding, then to bend it in order to compromise the Total Internal Reflection, which results in coupling out a fraction of the optical signal [54]. The tapped signal power varies according to the radius (R) and angle (Θ) of the bend (See Figure below). The goal of an attacker in this setting is to use the minimum bend loss necessary to tap a discernable data signal without interrupting the optical signal in its entirety or damaging the fiber, as doing so, would result in security alarms detecting the signal interruption, which will draw security guards eyes to the premises and impede the intrusion operation [54]. With an optimal fiber bend tap, though, the degradation of the signal will be minimal enough, hopefully, to not make it to the alarming threshold, and would rather be only detectable through ongoing monitoring and testing, which could or could not happen around the same timeframe of the intrusion operation, the thing that would help make it successful.

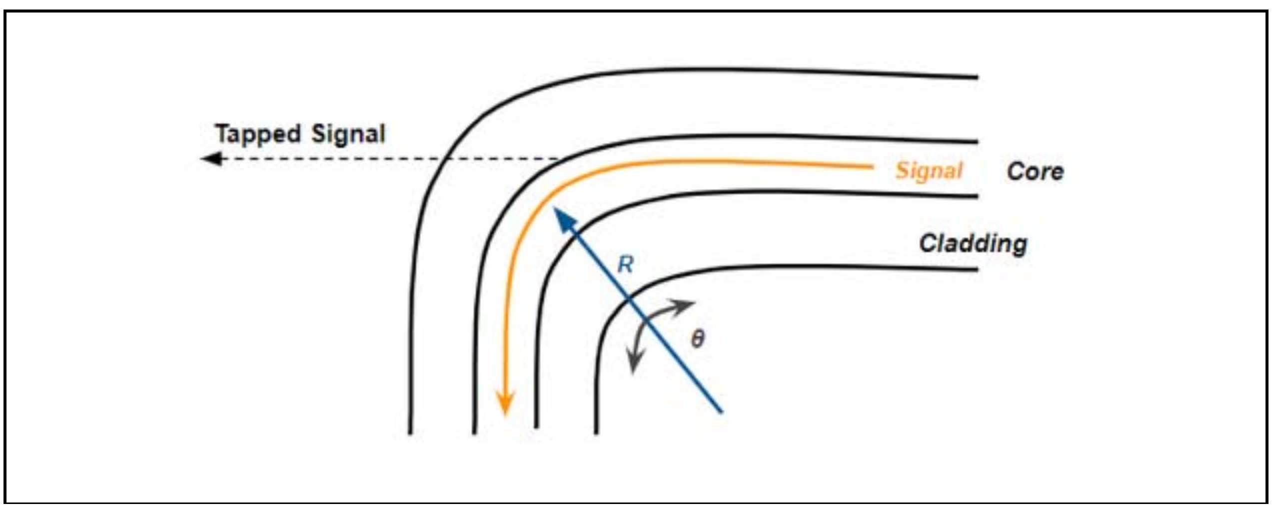


Figure A1.30 Fiber Bend Mechanics. Adapted from [54]

2) Optical Splitting: As its name indicates, this technology consists of 'splitting' an optical signal into two similar signals. However, for the device to be installed, the targeted fiber should be first cut with its both ends getting spliced onto the optical splitter [54]. As soon as the fibers are accessed within the cable, splicing the fibers onto the optical splitter would only take about 2-3 minutes depending on the splicing method used [54], and Bam! You've got your identical copy of the original signal! The biggest downside to using an optical splitter is that the potential ease of detectability, the installation of such device would very likely cause an interruption of service, which would in turn, trigger a security response [54]. Using a lossless splitter might not be the best idea either. This is due to its dependency on a source of energy, thing that makes it detectable attractive by monitoring systems [54]. If the splitter is mounted where the optical power in the fiber is more or less high, all it will be needed would be to tap a few percent of the signal with less than 1 dB loss so that the splitter loss is not that high [54].

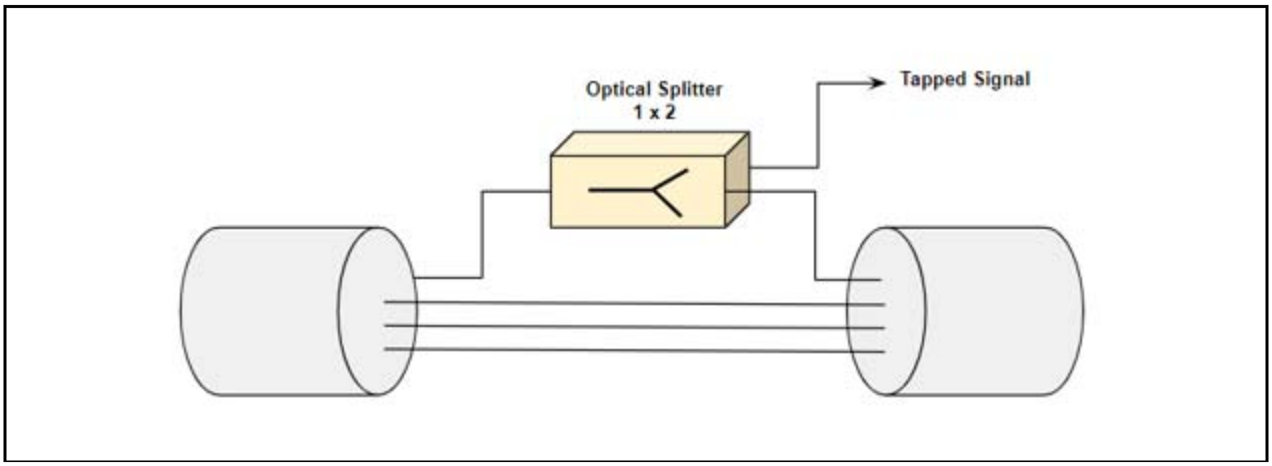


Figure A1.31 Optical Splitter Installation. Adapted from [54]

3) Evanescent Coupling: Not very different from the Optical splitting strategy, this utilizes the same process except that it does not require the targeted fiber to be cut [54]. Instead, Evanescent Coupling field-constructs a 1x2 optical splitter by shaving the cladding very close to the fiber core on both the targeted and capture fibers [54]. By doing so, it limits the reflectivity of the core-cladding boundary while allowing part of the optical signal to be seized by the tap fiber [54]. There are few challenges for this approach: 1) The difficulty of its implementation in the field, without specialized high precision equipment to polish a fiber that's thinner than a human hair, and whose core is 1/8 of that 2) Assuming the attacker has the required skill for that, they would still need to

have enough unnoticeable time in the field to do it 3) This approach results in a significant loss ranging between 1 and 2dB, making it easier to detect and trigger the security response procedures in the premises.

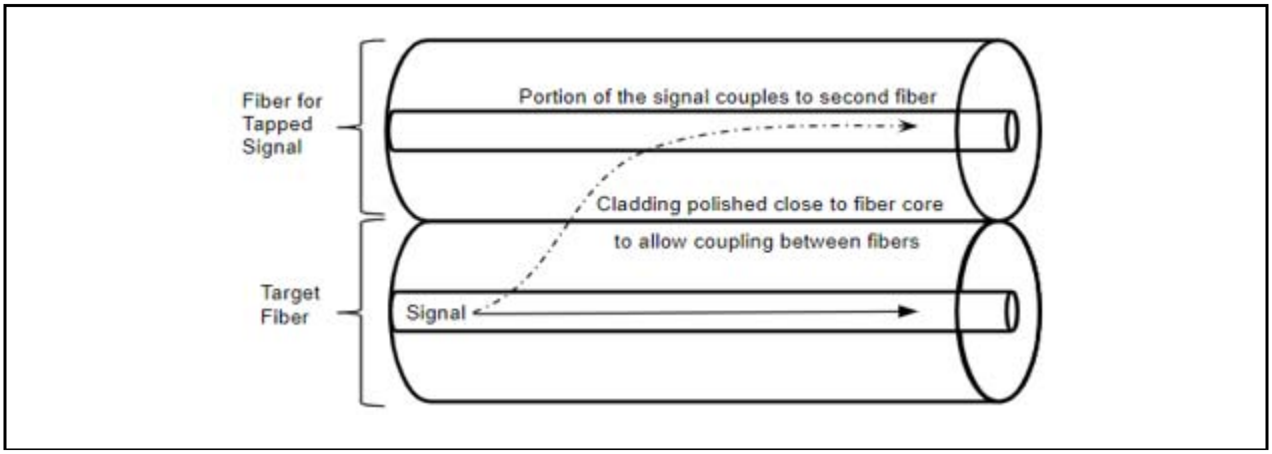


Figure A1.32 Evanescent Coupling. Adapted from [54]

4) V-Groove Cut: With this method, a V-groove is cut in the optical fiber cladding, very close to the fiber core, in such a way where the angle between the signal propagating in the fiber and the face of the V-groove is greater than the critical angle for total internal reflection [54]. If this is put in place, the portion of the signal traversing the fiber cladding and intersecting with the V-Groove cut will undertake total internal reflection and get coupled out through the side of the fiber [54]. Similar to Evanescent Coupling, as there are fiber cuts involved in this method, except for the loss part, all the previously listed challenges apply However. V-Groove cut would actually result in very little optical loss and would hence be quite difficult to discover [54].

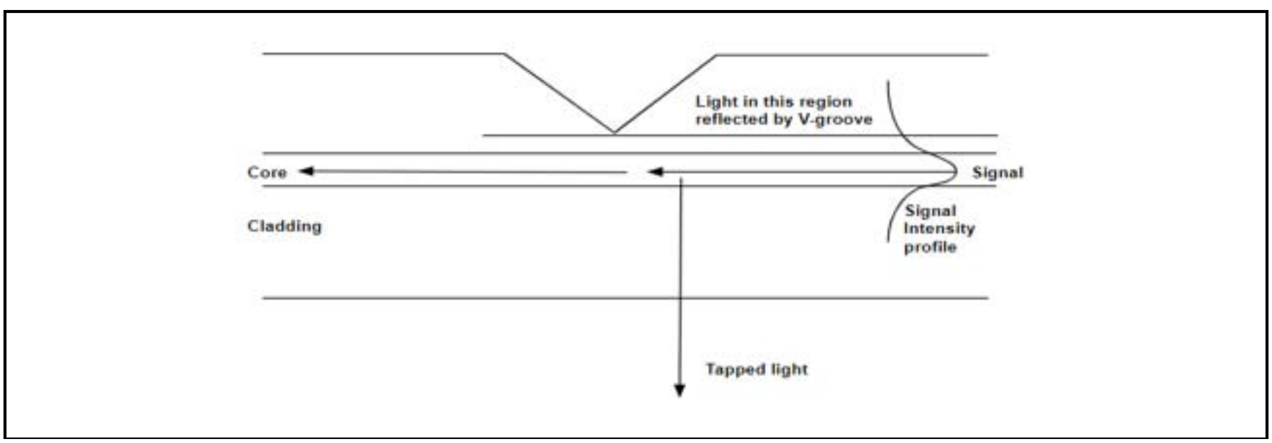


Figure A1.33 V-Groove Cut. Adapted from [54]

5) Scattering: This is the most advanced, but also the hardest to detect, field tapping technique in this discussion set [54]. This strategy consists of using Fiber Bragg Grating (FBG), a simple cheap filter built into the core of a wavelength-specific fiber cable. FBGs are used as inline optical filters to block certain wavelengths, or as wavelength-specific reflectors. to achieve a fiber tap: using an Excimer UV Laser to create an overlapping and interfering field of UV rays that subsequently 'etches' a Bragg Grating onto the fiber core [54]. This grating causes a portion of the signal to reflect out of the targeted fiber into the attacker's fiber [54].

Deployment

In order to deploy the fiber, it is important to have a justified cost-benefit analysis of the business case to deploy the fiber at the first place, then to understand the application, the functional, and nonfunctional requirements. Starting with the inventory, both industrial and non-industrial devices should be listed. There should also be a plan stating the system and subsystem security requirements for availability, integrity, and confidentiality. Documenting communication patterns, topology, and resiliency requirements is also part of this. Finally, understanding the types of traffic: information, control, safety, time synchronization, motion control, voice, and video [57].

Once the requirements are studied, there comes the need to develop a logical framework (roadmap): defining segmentation and zones (e.g. VLANs) before inserting both devices and applications in the logical framework based on the identified functional and nonfunctional requirements [57]. Designing the physical framework is the following logical step, taking into account design security practices of redundancy, defense in depth, self-recovery, and robustness against physical, technical, and administrative attacks, all while observing the bounding IT requirements, following industry best practices and standards, reference models, and reference architectures [57].

Monitoring

As part of its functionality, OTN Standard compliant optical networking equipment supports an extensive set of connection monitoring functionality [58]. Three sets of monitoring overhead are supplied: Section monitoring overhead, providing Optical Transport Unit segments monitoring, the path monitoring overhead which supports monitoring of Optical Data Unit end-to-end paths, as well as Tandem Connection Monitoring (TCM) overhead which facilitates arbitrary subnetwork connections monitoring [58]. These monitoring capabilities may be utilized to monitor segments of an end-to-end OTN path and to support unprotected or protected connections [58].

ITU-T Rec. G.805 defines a tandem connection as a random set of adjacent "link connections" or "subnetwork connections" which represents the part of a trail that necessitate monitoring separately from the monitoring of the full trail [58]. There are six levels of Tandem Connection Monitoring with different modes of operation. These Tandem Connection Monitoring (TCM) levels permit simultaneous use of monitoring applications (service monitoring, administrative domain monitoring, fault localization, segment protection, verification of delivered quality of service, delay/latency measurements and adjacency discovery) along all Optical Data Unit trails [58].

Rec. G.805 also describes numerous TCM applications based on the concept of a monitoring domain [58]. Listing below 3 general tandem connection domain applications:

- Protected domain: In this domain, protection switching operations are controlled, by having special tandem connection monitors monitor the failure state and error performance status of both working and protection type connections.
- Serving operator administrative domain: In this one, service providers use tandem connection monitors to monitor the status of customer delivered connections.
- Service requesting administrative domain: here, customers use tandem connection monitors to monitor the status of service provider received connections [58]

ITU-T Rec. G.872 discusses Optical Channel Data Unit connection monitoring including tandem connection monitoring discusses the concept of nested connections up to the maximum number of levels defined by the requirements of the specific technology (ITU-T Rec. G.709) [58]. ITU-T Rec. G.872 also describes a typical optical channel data unit connection with 5 levels of nested connection monitoring, where each color represent a level of nested monitoring [58].

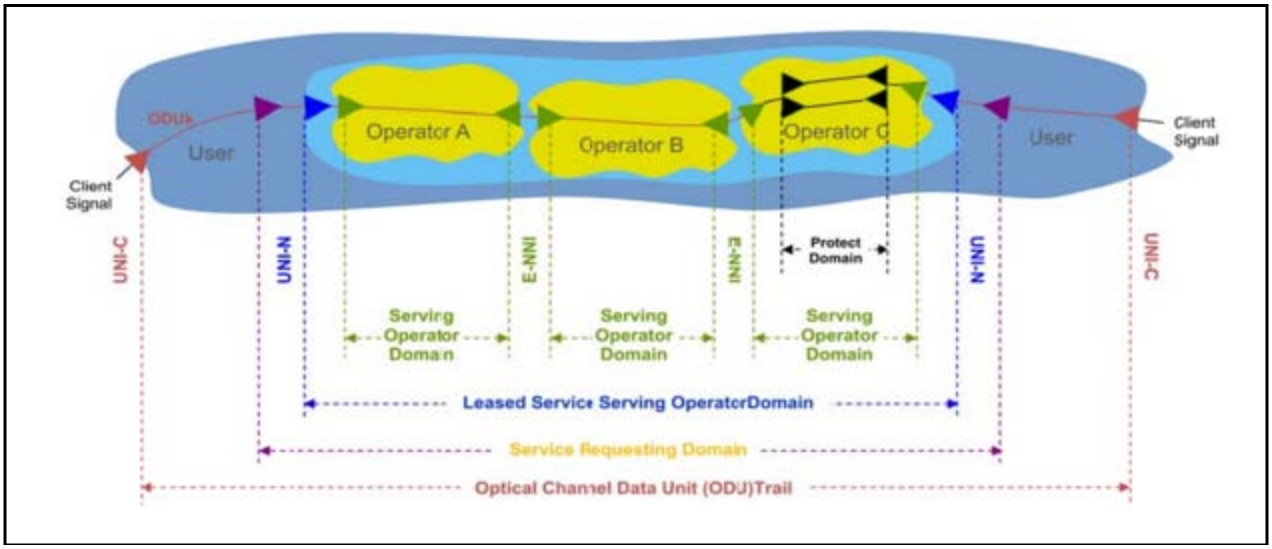


Figure A1.34 TCM Application example [58]

In a nutshell, the interest of studying optical networks lies in its industry attractiveness, its high transmission rate, and its multidisciplinary applications, including the Internet backbone!

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