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

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Abstract*—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 opto-electronic 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 hardware based detective measures, this paper 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 mixed integer liner 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*.

***Index Terms*—Routing and wavelength assignment, transparent optical networks, physical layer attacks, integer linear programming, tabu search, graph coloring.**

I. 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 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.

II. 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 wavelength 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 [1-2]. 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 [3-9]. For instance, according to [4] 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 [9] proposes a simple, robust and efficient genetic algorithm for RWA in WDM optical networks. Extending Skorin-Kapov heuristic [3] 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 [5] 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 [6] 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 [6] 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 [28] 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 [7] 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 [8] 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 [8], 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 paper, 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.

III. Problem Definition

The transparent optical networks attack and throughput-aware RWA problem is defined by outlining a physical and virtual network. Modelling 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 paper 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 [10]. 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 [10], WA, which is a sub-problem of the RWA can be modelled as a graph coloring problem where each nodes 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 *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 $\Delta(G)$. This value is an upper bound for the MaxLAR value, where:

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

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

According to the paper [10], 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 [10]. In this context, *link-sharing* indicates if two lightpaths traverse at least one common physical link [10]. 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 [10].

Based on the 14 nodes NSF Network, Fig. 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.

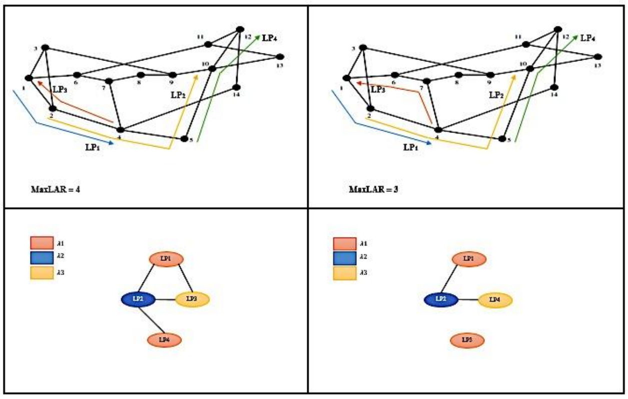


Fig. 1. Example of two RWA schemes (virtual topologies) on the 14 nodes NSF Network with the same number of wavelengths but different *MaxLAR* values.

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   lightpaths_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)
```

Fig. 2. Network *MaxLAR* Algorithm

B. The Second RWA objective: Minimizing Blocking Probability (BP)

In addition to the MaxLAR minimization objective, this paper proposes another objective criterion for the RWA problem, referred to as *minimizing the blocking probability (BP)*. The paper also assumes that there is a threshold or acceptable blocking probability that the network must not exceed. This value is referred to as *Acceptable_BP*, while the blocking probability being minimized is referred to as *Current_BP*. The objective is to satisfy the following constraint:

$$Current\_BP \leq Acceptable\_BP \qquad (2)$$

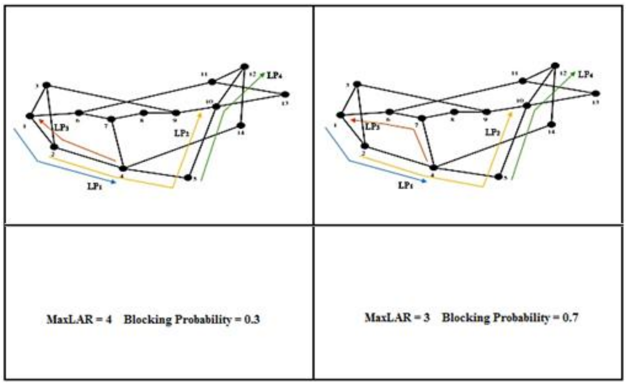


Fig. 3. An example of two RWA schemes (virtual topologies) on the 14 nodes NSF Network with different *MaxLAR* and throughput values

```
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
// This set contains the possible throughputs that can be achieved in the network.
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 × networkMaximumMaxLAR) / 100
t_selectedThroughput ← (desiredThroughputPercentage × networkMaximumThroughput) / 100

For each ML_element, do:
    If ML_element ≥ t_selectedMaxLAR Then:
        selectedMaxLAR ← ML_element
        break
    End If
End For

For each TS_element, do:
    If TS_element ≥ t_selectedThroughput Then:
        selectedThroughput ← TS_element
        break
    End If
End For

GetVirtualTopologyWithOptimumValuesOf (selectedMaxLAR, selectedThroughput)
```

Fig. 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 ← GetVirtualToplogy(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
```

Fig. 5. Algorithm to get the virtual topology having the optimum throughput and MaxLAR values

C. Combining RWA objectives: MaxLAR and BP

After explaining this, this paper 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 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, the paper propose 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 M={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 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 5 depicts the algorithm that implements this.

IV. 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 paper 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:

A. Notation:

TABLE I. MILP – PROBLEM NOTATION

Notation	Meaning
s, d	denote the lightpath's source and destination nodes that 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'	denote the lightpath's source and destination nodes that 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	denote the physical link's source and destination nodes that belong to the set {1, 2, 3, …, N}

B. Parameters:

TABLE II. 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 is a link between p and q $Phy_{p,q} = 0$ otherwise
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 is a lightpath request between s & d $Vir_{s,d} = 0$ otherwise

C. Variables:

TABLE III. MILP – VARIABLES

Variable	Meaning
$Phy_{p,q}^{s,d}$	Physical routing variable, indicating if a lightpath corresponding to the virtual link $Vir_{s,d}$ is routed on physical link $Phy_{p,q}$, where: $Phy_{p,q}^{s,d} = 1$, if it is $Phy_{p,q}^{s,d} = 0$, Otherwise
$Phy_{p,q}$	The network's physical topology, where: $Phy_{p,q} = 1$ if there is a link between p and q $Phy_{p,q} = 0$ otherwise
$Lsh^{(s,d)(s',d')}$	Link-sharing variable indicating if two lightpaths corresponding to virtual links link $Vir_{s,d}$ and $Vir_{s',d'}$ 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 link $Vir_{s,d}$ and $Vir_{s',d'}$ are routed over the physical link $Phy_{p,q}$ where: $Lsh_{(p,q)}^{(s,d)(s',d')} = 1$, if this is 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 shares links with including itself.
$\max\ LAR$	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

D. Objectives

- Minimize maxLAR
- Minimize BP

E. Contraints

1) Constraints linked to Physical routing:

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

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

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

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

2) Constraints linked to Flow conservation over physical links:

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

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

3) Constraints linked to lightpaths Cycling:

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

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

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

4) Constraints linked to lightpaths Link-sharing:

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

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

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

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

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

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

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

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

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

5) Security related Constraints (maxLAR) :

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

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

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

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

6) lightpaths Hop bound related Constraints:

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

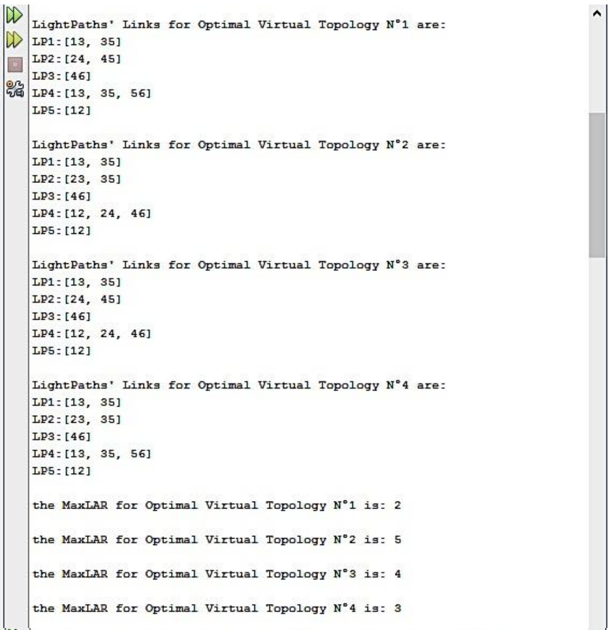
7) Blocking Probability related Constraints (BP):

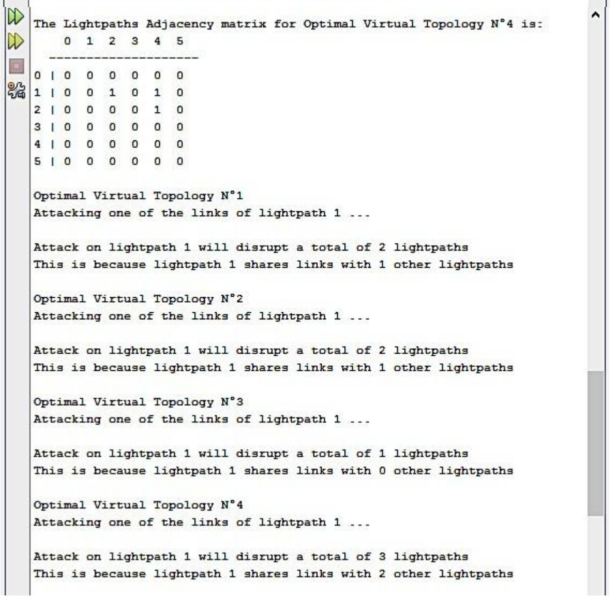
$$Current\_BP \leq Acceptable\_BP \tag{21}$$

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

V. Simulations 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:





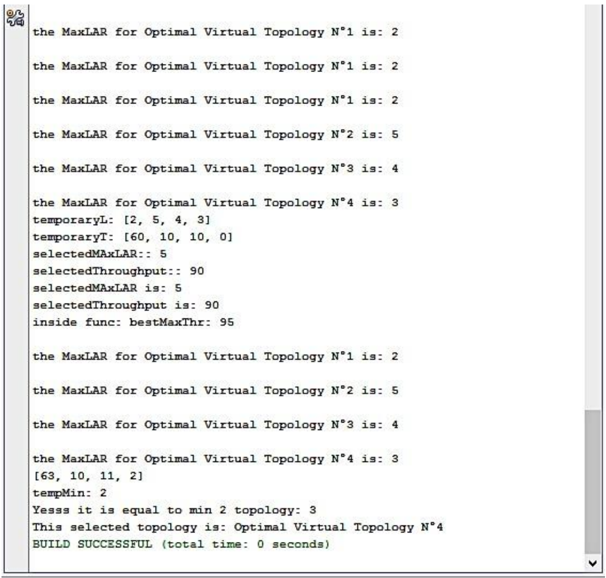


Fig. 6. Simulation example results: physical topology and optimal virtual topologies with MaxLAR values

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Realistic Dynamic Traffic Generation for WDM Optical Networks

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Abstract— **This Paper 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 memoryless models that we see still being 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 paper 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.**

Keywords—**Dynamic Traffic Generation; long term memory; Self-Similar Process; Pareto Process; Optical Networks; Wavelength Division Multiplexing.**

I. 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 each two years, or more precisely for the computer scientists out there, the number of transistors would actually double every couple years [1]. 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 double on an annual basis. Nelson named this law Nelson's Law of Internet Bandwidth [2]. 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 [3]. Check out more details on the distribution of the online Internet user around the world in Figure 1.

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

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 %

Fig. 1. World Internet Usage and Population Statistics 30-11-2015 [3]

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 to use 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.

II. 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

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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 [4]. 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 [4]. We are interested here in their usage in analytical models.

A. Memoryless Processes

The usage of the memoryless Poisson distribution if traffic generation models could be traced back to the early 90s. According to [5], 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. We can take 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. We can represent this in figure 2 below:

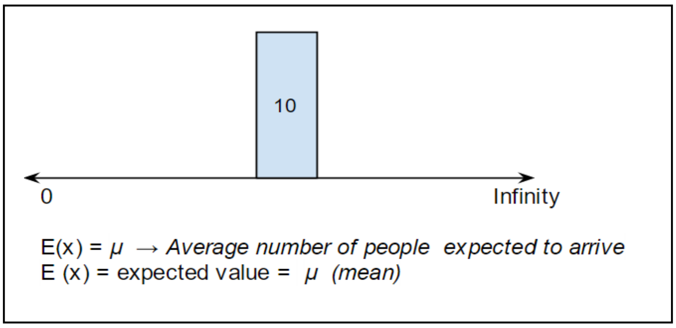

Fig. 2. Poisson Distribution Paramters, 10 customers average example

Poisson defines its expected value or mean value μ as follows:

$$\mu = \lambda = \frac{number\ of\ occurences\ or\ arrivals}{Specified\ interval} \quad (1)$$

We have an average of 10 customers entering the checkout line between 4:30 and 4:45. Thus, we have 10 customers per 15 minutes. That is $\lambda = \frac{10\ customers}{15\ minutes} = 10$

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: $P(x) = \frac{\lambda^x e^{-\lambda}}{x!}$ and since $\mu = \lambda = \frac{number\ of\ occurences\ or\ arrivals}{Specified\ interval}$ we can then also write the Poisson formula as $P(x) = \frac{\mu^x e^{-\mu}}{x!}$

Where:

x= 0, 1, 2, 3... Number of occurrences of interest

$\mu = \lambda = \frac{number\ of\ occurences\ or\ arrivals}{Specified\ interval}$ = long run average

e= 2.1718282 (base of natural logs)

Sample questions that an operations manager would like to ask and answer would be something like:

What is the probability that exactly 7 customers enter the line between 16:30 and 16:45? To answer this question, we know that $\lambda = \frac{10\ customers}{15\ minutes} = 10$ and from the question we are asking about exactly 7 customers, thus x=7. We also know that $P(x) = \frac{\lambda^x e^{-\lambda}}{x!}$ Therefore: $P(7) = \frac{10^7 e^{-10}}{7!} = 0.09007922571$

This is then the probability that exactly 7 customers would enter the checkout line between 16:30 and 16:45.

Another question would be too ask about the probability of more than 10 customers coming to the checkout line.

To answer this question, we know that: $\lambda = \frac{10\ customers}{15\ minutes} = 10$

And we have x > 10 customers, so $x \notin [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]$

We also know that $P(> x) = 1 - PoissonCdf(x, x)$

Thus: $P(> 10) = 1 - PoissonCdf(10, 10) = 1 - \sum_i^{10} P(i)$

Replacing $P(i)$ with its value: $P(i) = \frac{\lambda^i e^{-\lambda}}{i!}$ We'll have:

$$P(> 10) = 1 - P(1) - P(2) - \cdots . P(10)$$

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 we can refer to as the long-memory processes in the following section:

B. Long-Memory Processes:

Long memory processes could be identified by the persistence of a correlation over time that takes far long to decay [6]. 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 [6].

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, $x^m = m^{H-1} x$ where x^m=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 [7]. "Besides, we find that aggregating streams of such traffic typically intensifies the self-similarity ("burstiness") instead of smoothing it." [7].

III. Analysis and Simulations:

There have been a some attempts in the literature to study Memoryless and Long-Memory Processes in the context of Optical Networks, we cite [8]. 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, we cite [9] as an example. Our Paper 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 [9] that had been cited by 30 papers already.

We 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 we call the praetor 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. We plot the results below to show the self-similarity aspect:

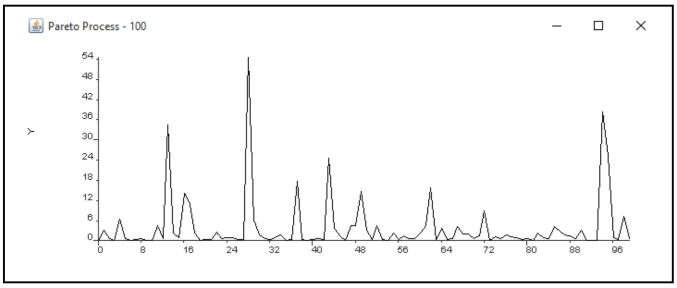

Fig. 3. Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 100 iterations.

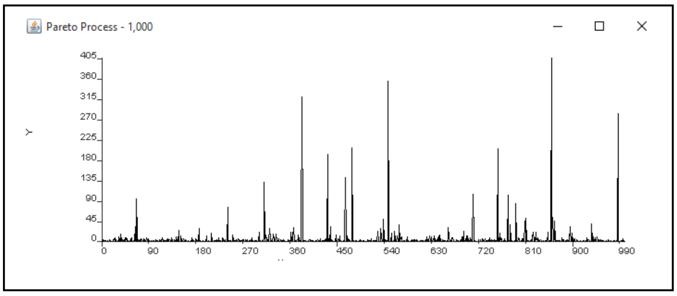

Fig. 4. Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 1000 iterations.

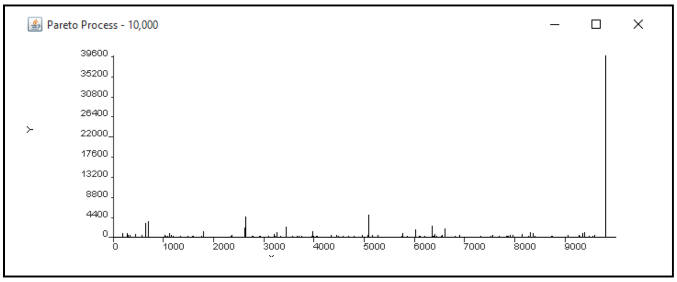

Fig. 5. Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 10,000 iterations

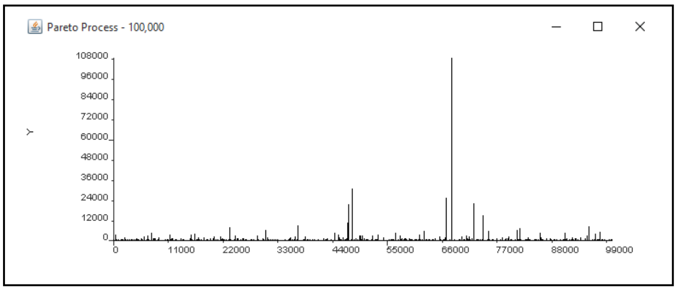

Fig. 6. Poisson Process Simulation for lightpath requests in WDM Optical Networks, up to 100,000 iterations

IV. Conclusion:

From figures 3 through 6, we have 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.

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Research paper

Nonlinear effects in WDM Networks

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Abstract

This paper 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 paper 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.

Keywords: *WDM network; nonlinear effects; Four Wave Mixing; Cross Phase Modulation.*

1. 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 we would then be in the second category of Nonlinear Fiber Optics. In this paper, we will be discussing the propagation of signal in the fiber taking into account nonlinear effects. We would need to answer the following question: If the medium properties change in a fiber due to nonlinear effects, what are the implications on the signal?

2. Signal Propagation within Optical Fibre

2.1. Propagation of One Signal within the Optical Fibre

The 80s was marked as an era during which many researchers were invested in experimental work to establish the equivalence of light and electromagnetic propagation [1]. Marking the beginning of radio telecommunications, in 1887, Heinrich Hertz was able to generate and detect radio waves in the laboratory [2]. This came validating Maxwell's electromagnetic theory [3], 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 [1], [2]. Let's take an example of a pulse that we need to transmit on the optical fibre in the linear domain. The properties of the propagation of such pulse are only decided by the medium properties [4] [5]. We could simply then solve the wave equation without worrying about the amplitude of the pulse, and we can 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 fibre 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 centre 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 centre. If we try to send a continuous signal in the optical fibre, 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) [6], [7], [8]. 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 paper, I will present a simple formulation and we'll answer the question why is nonlinear fibre optics important. We're also going to investigate if it is important to include the effects of nonlinearity into fibre optics communications or not. If the answer is yes, then, we're going to study if we can we make use of these nonlinear effects to improve the signal propagation from the optical communication point of view?

2.1.1. Analytical Model

We're 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' [9]. The induced polarization in the material given by susceptibility of the medium. Normally, we consider only the first order susceptibility 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. We consider a medium nonlinear, if there's a nonlinear relation between the induced polarization P and the applied electric field E [10]. In general, the induced polarization in the material is P, given as:

$$P = \varepsilon_0\{\chi^{(1)}.\overline{E} + \chi^{(2)} : \overline{E}\,\overline{E} + \chi^{(3)} \vdots\, \overline{E}\,\overline{E}\,\overline{E} + \cdots\} \quad (1)$$

$\chi^{(1)}$ is the first order susceptibility, $\chi^{(2)}$ is the second order susceptibility, $\chi^{(3)}$ is the third order susceptibility, and so on. E is the imposed electric field [11]. The dominant term from the Induced Polarization equation is $\chi^{(1)}$ and it contributes to dielectric constant, the second term $\chi^{(2)}$ is small for glass (S_iO_2), and the third term $\chi^{(3)}$, 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 [12].

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

n_2 is the nonlinearity coefficient (a.k.a Kerr nonlinearity) [13]. It is material dependent and also dependent on the third order susceptibility of the medium as shown below:

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

Comparing the nonlinear coefficient of glass to other materials we 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 we really care about the effects of nonlinearities in optical networks at all? To properly answer this question, we need to understand how do nonlinearities manifest in optical fibres compared to the bulk materials and if there's situational difference.

2.1.2. 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 fibre, it travels a long distance during which it keeps interacting with the fibre, resulting in a cumulative nonlinear effect. To compare between the bulk and the fibre material, one can check how much enhancement of nonlinear interaction takes place in fibre material compared to a bulk material. Let's now define a Figure of merit or efficiency parameter for nonlinear interaction, say where:

$$\eta \sim I \times L_{eff} \quad (4)$$

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) [12]. 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, we 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. If we have a Gaussian Light Beam, with a spot radius of ω_0 radius, or a diameter of $2\omega_0$. We can represent the Intensity of Light I as the optical beam power divided by the area of the spot as per the equation:

$$I = \frac{P}{\pi{\omega_0}^2} \quad (5)$$

Where P is the light beam power and ω0 is the light spot radius in the bulk material from this equation, we can see that the length over which the beam focus is related to the size of the spot. So, in a bulk medium, when we try to tightly focus the optical beam, the interaction length gets affected as well [12]. The Interaction length in bulk optics is:

$$L_{eff} = \frac{\pi{\omega_0}^2}{\lambda} \quad (6)$$

Let's now compute the figure of merit:

$$\eta_{bulk} = I \times L_{eff} = \frac{P}{\pi{\omega_0}^2} \times \frac{\pi{\omega_0}^2}{\lambda} = \frac{P}{\lambda} \quad (7)$$

This shows the figure of merit, or the interaction efficiency is independent of the size of the focusing beam. So, in bulk material, if we want to enhance the effect of nonlinearity, and want to do a certain wavelength, the only option we have 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.

2.1.3. Nonlinearities in Bulk Material

Now, let's compare the situation with Optical Fibre. In Optical fibre, 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 fibre is very small, the intensity reduces but very slowly, allowing it to remain almost constant over some tens of kilometres. In the fibre case, let's define the radius of the optical fibre core as a [12]. Hence, the light intensity I would be defined as:

$$I = \frac{P}{\pi a^2} \quad (8)$$

When the light propagates through the optical fibre, it exponentially decreases. Let's define the power attenuation constant as α and the power function as per [12] [14] below:

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

Now, if we take a distance $z_0 = \frac{1}{\alpha}$, we will have:

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

We can then say, in the case of optical fibre, that $L_{eff} \approx 1/\alpha$. Now, let's now compute the figure of merit for the optical fibre:

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

2.1.4. Nonlinearities in Bulk Material and Optical Fiber

We can find how much interaction efficiencies increase in the optical fibre compared to bulk material, we can find out by taking the ratio of η_{bulk} and η_{fiber} as shown below:

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

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

$$a \sim 2\,\mu\mathrm{m}$$
$$\alpha = 0.2\,\mathrm{dB\,km^{-1}} = 0.2\times10^{-3}\,\mathrm{dB\,m^{-1}} \simeq 8\times10^{-5}\,\mathrm{m^{-1}}$$
$$\lambda \sim 1550\,\mathrm{nm} = 1.55\,\mu\mathrm{m}$$

$$\frac{\eta_{fiber}}{\eta_{bulk}} = \frac{\lambda}{\pi a^2 \alpha} \simeq 10^9 \quad (13)$$

So for the same parameters, the nonlinear effects inside optical fibres is enhanced by 1 billion times than those inside of the bulk material. This also means that whatever affects you can see in bulk material with 1 Watt of power, the same effect inside optical fibre can be seen with only 1 nano Watt of power. This means that with the power which we deal with in Optical Fibre in the order of microWatt or milliWatt, the nonlinear effects will certainly be present because once the power will be confined in optical fibre, it will keep interacting with the fibre over long kilometres.
Comparing the Light intensity required to get nonlinear effects in Fibre v.s. in bulk material. We see that in Fibre, such Intensity is at least two orders of magnitude smaller. Now, in fibre optic communications, we aren't working with single fibres, but rather with some complex systems of multi fibre optics such as WDM and DWDM. Assuming we have an intensity of 1 microWatt per meter square induced per fibre. In a 100 channels WDM System that'll already be 100 microWatt/ meter square. WDM systems are using currently way more channels that this example, and the power intensity inside optical fibre 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 analyse ways to make the best use out of them to rather make improvements to the system.

2.1.5. Light Propagation in Optical Fiber with Nonlinearities

To analyse the propagation of light in the optical fibre in the presence of nonlinearity, we'll start from the very basic Maxwell's Equations [3] below:

$$\nabla \times \overline{E} = -\mu_0 \frac{\delta \overline{H}}{\delta t} \quad (14)$$

This is assuming that permeability is not a function of time. Also since we're dealing with dielectric material, we can assume that the permeability is the same as that of free space, hence μ0.

$$\nabla \times \overline{H} = \frac{\delta \overline{D}}{\delta t} \quad (15)$$

$\overline{J} \equiv 0$ Assuming the conduction J of the medium is 0

$$\nabla \cdot \overline{D} = 0 \quad (16)$$

$\delta \equiv 0$ and $\overline{D}$ is the displacement.

$$\nabla \cdot \overline{B} = 0 \quad (17)$$
$$\overline{D} = \epsilon_0 \cdot \overline{E} + \overline{P} \quad (18)$$

And since:

$$P = \epsilon_0\{\chi^{(1)} \cdot \overline{E} + \chi^{(2)}:\ \overline{E}\,\overline{E} + \chi^{(3)}\vdots\ \overline{E}\,\overline{E}\,\overline{E} + \ldots\} \quad (19)$$

Then:

$$\overline{D} = \varepsilon_0\ \overline{E} + \varepsilon_0 \cdot \chi^{(1)}\ E \quad (20)$$

In normal situations, neglecting the other terms:

$$\overline{D} = \varepsilon_0\{1\ \chi^{(1)}\}\ \overline{E} \leftarrow \textit{Linear case.} \quad (21)$$

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.

$$\begin{aligned} \nabla \times \nabla \times \overline{E} &= -\nabla \times \{\mu_0 \frac{\delta \overline{H}}{\delta t}\} \\ &= -\mu_0 \frac{\delta}{\delta t}\{\nabla \times \overline{H}\} \\ &= -\mu_0 \frac{\delta}{\delta t}\{\frac{\delta \overline{D}}{\delta t}\} \\ &= -\mu_0 \frac{\delta^2}{\delta t^2}\{\varepsilon_0 \overline{E} + \overline{P}\} \\ &= -\mu_0 \frac{\delta^2}{\delta t^2}\{\varepsilon_0 \overline{E}\} - \mu_0 \frac{\delta^2 \overline{P}}{\delta t^2} \end{aligned} \quad (22)$$

$$P = \varepsilon_0\{\chi^{(1)} \cdot \overline{E} + \chi^{(2)}: \overline{E}\,\overline{E} + \chi^{(3)}\vdots\ \overline{E}\,\overline{E}\,\overline{E} + \ldots\} \quad (23)$$

Where $\mu_0\{\chi^{(1)} \cdot \overline{E}\}$ is the Linear Polarization P_L. While $\mu_0\{\chi^{(2)}:\ \overline{E}\ \overline{E} + \chi^{(3)}\vdots\ \overline{E}\ \overline{E}\ \overline{E} + \ \ldots\}$ is the Nonlinear Polarization P_N.

$$\nabla(\nabla \cdot \overline{E}) = -\nabla^2 \overline{E} = -\frac{1}{c^2}\frac{\delta^2 E}{\delta t^2} - \mu_0\{\frac{\delta^2 P_L}{\delta t^2} + \frac{\delta^2 P_N}{\delta t^2}\} = 0 \quad (24)$$

The wave equation:

$$\nabla^2 \overline{E} = -\frac{1}{c^2}\frac{\delta^2 \overline{E}}{\delta t^2} = \mu_0 \frac{\delta^2 P}{\delta t^2} + \mu_0 \frac{\delta^2 P_N}{\delta t^2} \quad (25)$$

$\overline{E} = E_0\ e^{j\omega_0 t}$ with ω_0 is the signal frequency. $\overline{E}$ is a function of space (r) and time (t).

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

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

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

$\varepsilon(\omega)$ is given as:

$$\varepsilon(\omega) = 1 + \chi^{(1)}(\omega) + \varepsilon_{NL} \quad (28)$$

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

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

$$-2j\beta_0 \frac{\delta \hat{A}}{\delta z} + (\hat{\beta}^2 - \beta_0^2)\hat{A} = 0 \ \textit{with}\ \frac{\delta^2 \hat{A}}{\delta z^2}\ \textit{negligible} \quad (31)$$

2.1.6. Summary

To summarize, when the light is intense, the induced polarization has high order susceptibility terms also and they cannot be neglected [15]. For a material like glass, the second order susceptibility contribution is negligible because SiO2 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 fibre is very large, the nonlinear effects are very pronounced inside the optical fibre. Compared to the bulk material, the interaction efficiency in optical fibre is a billion time more so this is a strong case to investigate the nonlinear effects inside the optical fibre. We then started with the Maxwell's equations [3] and wrote down the wave equation in terms of the polarization which includes the nonlinear terms.

2.2. Propagation of Multiple Signals within the Optical Fibre

In the previous section, we've studied what happens inside of the optical fibre if there's one signal propagating. In the section below, we'll see what happens inside the optical fibre with multiple signals propagating through it. So, this section will then treat two phenomenon: Cross Phase Modulation and Four Wave Mixing. Both phenomena are related to the term which is due to third order susceptibility.

2.2.1. Cross Phase Modulation

Let's start here with some equations. Let's see we have the electric field which has two frequency components. The first components having an amplitude E1 and a frequency 1 and the second has the amplitude E2 and the frequency 2 and we write the equation:

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

If we substitute this into the polarization expression, we 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.

$$P_{NL} = P_{NL}(\omega_1)e^{j\omega_1 t} + P_{NL}e^{j\omega_2 t} + P_{NL}(2\omega_1 - \omega_2)e^{j(2\omega_1-\omega_2)} + \dots \tag{33}$$

$$P_{NL}(\omega_1) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}E_1 \tag{34}$$

$$P_{NL}(\omega_2) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}E_2 \tag{35}$$

$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\} \tag{36}$$

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 $|E3{-}j|^2 = 0$, 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:

$$\Delta n_j \approx n_2\{|E_j|^2\} \tag{37}$$

When that term $|E3{-}j|^2 \neq 0$, 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):

$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\} \tag{38}$$

In WDM Systems, there will be multiple channel transmissions within the optical fibre and XFM. We know that in WDM Systems, if large number of channels propagate, if there's sufficient power in these channels, there will be 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, we can write the field distribution for the j channel as:

$$E_j = F_j(x,y)A_j(z)e^{-j\beta_{0j}z} \tag{39}$$

Now, if we follow the same steps as were done for the Self Phase Modulation, we'll end up with two equations: One for the field distribution: Fj (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 fibre.
Taking the nonlinear variation of the Schrodinger equation, we're talking about the Nonlinear Schrodinger (NLS) equation, an equation belonging to classical field theory [16]. This equation has, among others, applications related to the propagation of light in nonlinear optical fibres [17]. The NLS equation is given as:

$$\frac{\delta A_j}{\delta z} + \beta_{1j}\frac{\delta A_j}{\delta t} - \frac{j\beta_{2j}}{2}\frac{\delta^2 A_j}{\delta t^2} + \frac{\alpha_j}{2}A_j = -j\frac{n_2\omega_j}{c}\{f_{jj}|A_j|^2 + 2f_{jk}|A_k|^2\} \tag{40}$$

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 attenuation.

f_{jj} is the overlap integral, how much overlap exists between each two signals.

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

The overlap integral f_{jk} is given by:

$$f_{jk} = \frac{\int\int|F_j(x,y)^2||F_k(x,y)^2|dx\ dy}{\int\int|F_j(x,y)^2|dx\ dy\int\int|F_k(x,y)^2|dx\ dy} \tag{41}$$

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.

The nonlinear Schrödinger (NLS) equation will become:

$$\frac{\delta A_1}{\delta z} + \frac{1}{v_{g1}}\frac{\delta A_1}{\delta t} - \frac{j\beta_{21}}{2}\frac{\delta^2 A_1}{\delta t^2} + \frac{\alpha_1}{2}A_1 = \gamma_1\{|A_1|^2 + 2|A_2|^2\}A_1 \tag{42}$$

with $\gamma_1 = \frac{n_2\omega_1}{cA_{eff}}$

In fibre 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 Fibre (DFF), which is a fibre characterized by a smaller mode-field diameter which concentrates optical power in a smaller volume where the increased power density in fibre can cause nonlinear effects [18]. 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 milliWatts, the total power of 128 channels will be easily in the order of 500 milliWatts, 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 milliWatt. 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 if we want channels not to get affected by neighbouring channels due the Cross Phase Modulation, we should get the fibre that has dispersion. You might have read in the literature, that it's desirable to make the dispersion small [19] [20], so that the pulse broadening do not take place. However, now when we are talking about WDM channels, we find that 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, you might get asymmetric spectrum developed because of this phenomenon of Cross Phase Modulation. The same phenomenon gives another phenomenon called Four Wave Mixing, which we'll discover in the following section.

2.2.2. 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 you put two frequencies inside the amplifier, the third frequency is generated because of the nonlinearities. These two frequencies give the product which is sum and difference of frequencies. The same phenomenon is seen in optical fibres because of the third order susceptibility. If we consider a nonlinear polarization with three signals, or three frequencies simultaneously put in the optical fibre:

$$P_{NL} = \varepsilon_0 \chi^{(3)} : E_1 E_2 E_3 \qquad (43)$$

$$\omega_2 = \omega_1 + 2\Delta\omega \qquad (45)$$

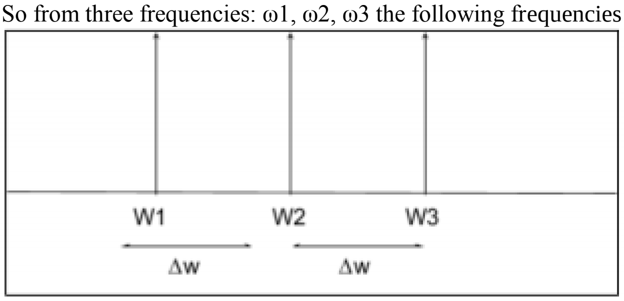
$$\omega_3 = \omega_1 + \Delta\omega \qquad (46)$$

$$\begin{aligned} \omega_4 &= \omega_1 + \omega_2 - \omega_3 \\ &= \omega_1 + \omega_1 + 2\Delta\omega - \omega_1 - \Delta\omega \\ &= \omega_1 + \delta\omega \\ &= \omega_3 \end{aligned} \qquad (47)$$

These three frequencies will produce a fourth frequency ω4 = ω1 ±ω2 ±ω3 and they will be having the wave numbers:

$k = k_1 \pm k_2 \pm k3$ (A)

So from three frequencies: ω1, ω2, ω3 the following frequencies



will be generated:

$\omega_1 + \omega_2 - \omega_3$,
$\omega_1 + \omega_3 - \omega_2$,
$\omega_3 + \omega_2 - \omega_1$,
$2\omega_1 - \omega_2$,
$2\omega_1 - \omega_3$,
$2\omega_2 - \omega_3$,
$2\omega_2 - \omega_3$,
$2\omega_3 - \omega_1$,
$2\omega_3 - \omega_2$ (B)

Fig. 3. Equispaced 3 channels in WDM System

From the previous sections, we have defined a formula P_{NL} where:

From the above, we see that section A's frequency quantities have the same range or lie within the same frequency band while section B's frequency quantities fall in a different band altogether. For instance, ω_4 is almost three times ω_1. We will not be looking into those. The phenomenon that frequencies of section B will lie within the same frequency band is what we call Four Wave Mixing, which is also called the inter modulation. This phenomenon is exactly what you see within an amplifier. Let's consider a WDM system where there are 3 channels and as we know in WDM, m wavelengths 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

$$\begin{aligned} P_{NL} = P_{NL}(\omega_1)e^{j\omega_1 t} \\ + P_{NL}(\omega_2)e^{j\omega 2t} \\ + P_{NL}(2\omega_1 - \omega_2)e^{2\omega_1 - \omega_2} \\ + \cdots \end{aligned} \qquad (44)$$

With:

$$P_{NL}(\omega_1) = \chi^{(3)}\{|E_1|^2 + 2|E_2|^2\}E_1$$
$$P_{NL}(\omega_2) = \chi^{(3)}\{2|E_1|^2 + |E_2|^2\}E_2$$
$$\Delta n_j \approx n_2\{|E_j|^2 + 2|E_{3-j}|^2\}$$

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 we shouldn't propagate channels that are equispaced. Making dispersion 0 on optical fibre is not a good option. We should rather be keeping some residual dispersion to reduce the nonlinear effects in a multichannel transmission.

As a side note, it's worth mentioning that the phenomenon of Four Wave Mixing is not always considered undesirable. It is actually quite beneficial for wavelength conversion. In paper [21], 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.

2.2.3. Simulations

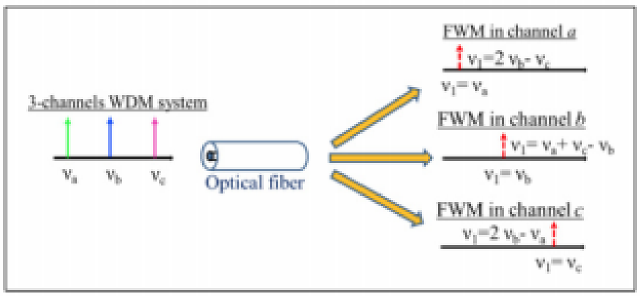


Fig. 1. FWM in a 3 Channels WDM System

The graph in figure 3 represents the number of mixing product terms (M) as a function of number of wavelength where:

$$M = \frac{N^2(N-1)}{2} \qquad (48)$$

As you have seen from the previous section, for a total of 3 input wavelengths, we've obtained a total of 9 mixing product terms.

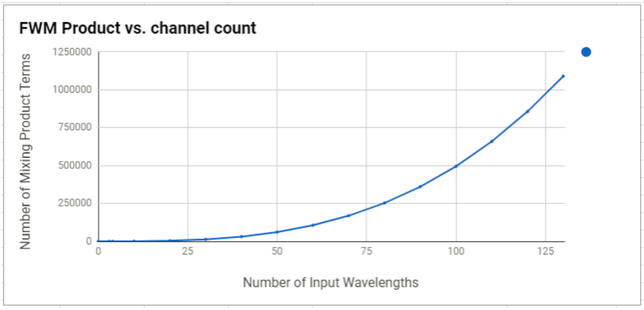


Fig. 4. FWM Product vs. Channel Count

Figure 4 represents how this product is changing as the number of input wavelengths increases. As you can see on the graph, for an input of 10 wavelengths, we obtain 450 mixing product terms. If we triple 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, we see that the FWM product continue to increase very rapidly reaching 1,090,050 terms for only 130 input wavelengths.

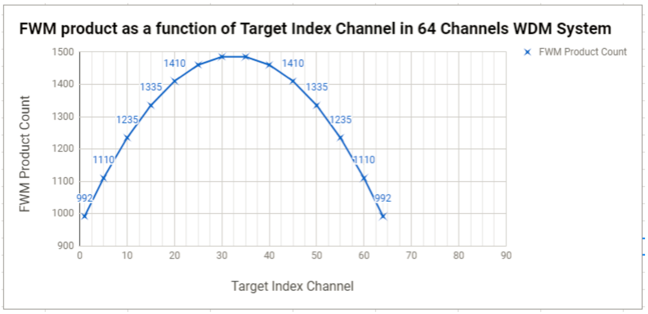


Fig. 5. FWM product as a function of Target Index Channel in 64 Channels WDM System

The next graph in Figure 5 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 1st and the 64th subcarriers have contribution to only approximately 1000 FWM combinations.

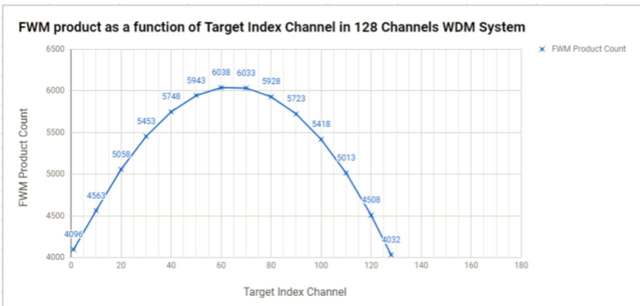


Fig. 6. FWM product as a function of Target Index Channel in 128 Channels WDM System

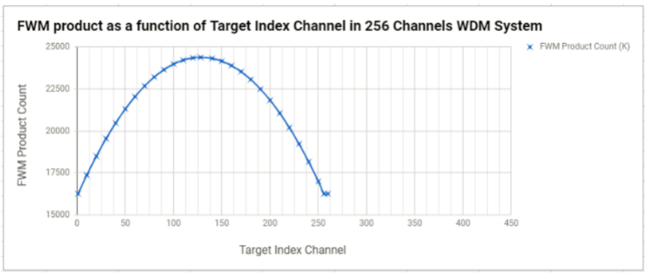


Fig. 7. FWM product as a function of Target Index Channel in 256 Channels WDM System

Figures 6, and 7 represent the same principle but for cases of more subcarriers: 128, and 256 consecutively.

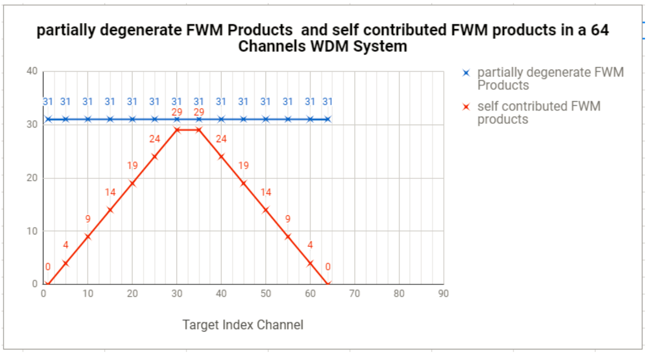


Fig. 8. Partially degenerate FWM Products and self-contributed FWM products in a 64 Channels WDM System

If we look at the next graph in Figure 8, we can see 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 (ω_{pump-1}, ω_{pump-2}, and ω_{signal}) mix in a nonlinear medium, resulting in 2 extra frequencies (a lower frequency ω_{Stokes}, and a higher frequency $\omega_{antiStokes}$) [22] [23]. When $\omega pump-1 = \omega pump-2 = \omega_{pump}$, the process is referred to as Partially Degenerate Four Wave Mixing (PDFWM). We can see from the graph 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 when we studied WDM Systems of 128 and 256 Channels, as illustrated in Figure 9, and 10.

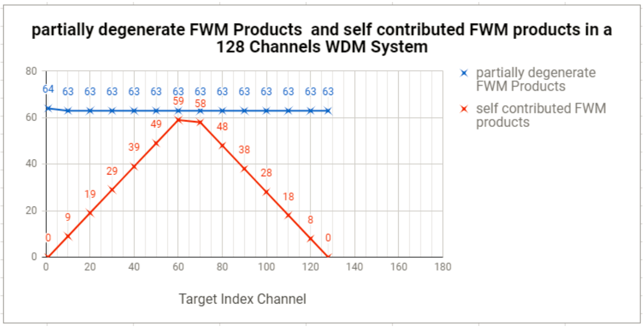


Fig. 9. Partially degenerate FWM Products and self-contributed FWM products in a 128 Channels WDM System

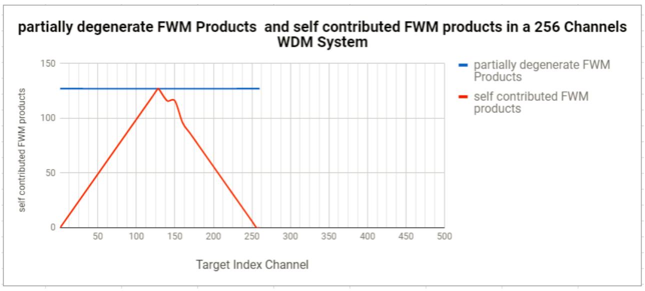


Fig. 10. Partially degenerate FWM Products and self-contributed FWM products in a 256 Channels WDM System

3. Conclusion

In summary, we've begun analysing nonlinear effects in bulk material vs. fibre and found that we've seen that high power is required so that nonlinearities can start getting induced effectively and allow researchers to study their effects. Specifically, you can see in bulk material with 1 Watt of power, the same effect inside optical fibre can be seen with only 1 nano Watt of power. We then moved to study the propagation of light within the optical fibre and saw how very pronounced inside the optical fibre they are, as a result of the very large interaction length inside the optical fibre. We've also seen how fibre 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 we've kept testing with increasing number of channels within the WDM System.

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Towards a Prevention Security Oriented Mindset in Managing Optical Networks

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***Abstract*—Reading the title of this paper, 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 paper aims to address this over four stages. In the first stage, we present a research inventory covering recent studies on preventative mindset characteristics within psychology, and behavioral science domains. In the second stage, we 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, we present the latest optical networks characteristics, applications, and industry trends. While in the last stage, we 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, which we'll be presenting in this work.**

***Index Terms*—Preventative Mindset, Psychology, Behavioral Science, Network Management, Optical Networks.**

I. 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 [1] [2] [3] [4] [5] and many more. You 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 [6]), 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 [7].

As we aim to present a prevention security oriented mindset in managing optical networks, we 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

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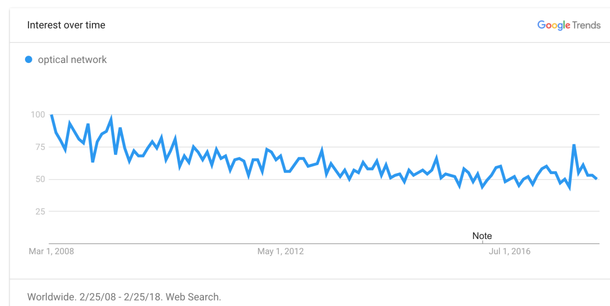

Figure 1. Google Trends Results for "Optical Network" over the past 10 years

current mindset of Internet users in relation to this topic, we 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. We 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 1 [8] depicts results for looking up the term "Optical Network" over the past 10 years. We can clearly see a high popularity of the term in 2008, with fluctuating popularity between the 50 and 75 score.

Figure 2 [9] 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 publications or research in the area is the next step to understand the interest of the research community in these topics. We've looked into the number of publications published on Google Scholar for these two terms, using SCHOLAR PLOTR [10], a public online tool

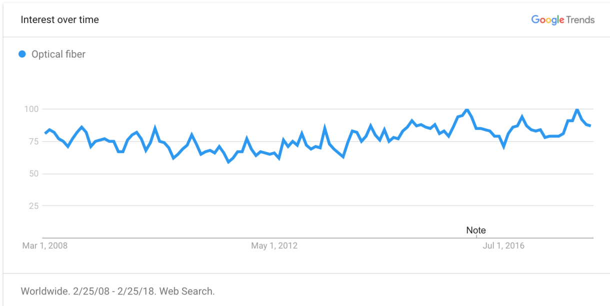

Figure 2. Google Trends Results for "Optical Fiber" over the past 10 years

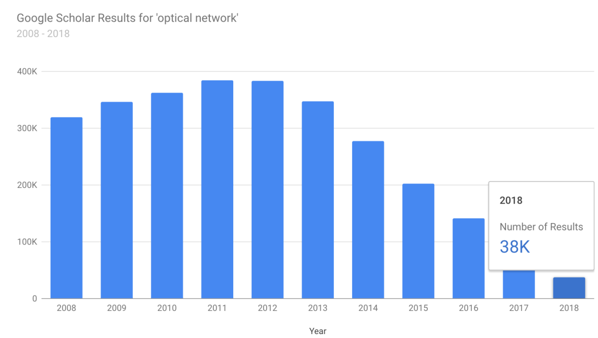

Figure 3. Google Scholar Results for "Optical Network" over the past 10 years

to visualize trends in scholarly research using results from Google Scholar.

Figure 3 [10] depicts the number of Google Scholar publications on "Optical Network" in the last 10 years. This number got near 38K publications in 2018!

Looking at publications on "Optical Fiber" on Google Scholar, Figure 4 [10] depicts that for the last 10 years with near 17K Google Scholar publications in 2018.

Now that we had a look at the popularity and publication volume fore the previous terms "Optical Network", and "Fiber Network", let's look at the Network Management space. 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

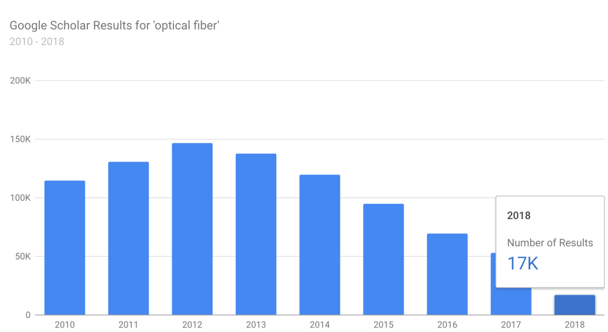

Figure 4. Google Scholar Results for "Optical Fiber" over the past 10 years

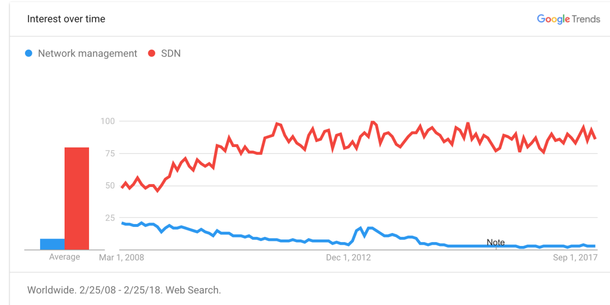

Figure 5. Google Trends Results for "Network Management" vs. "SDN" over the past 10 years

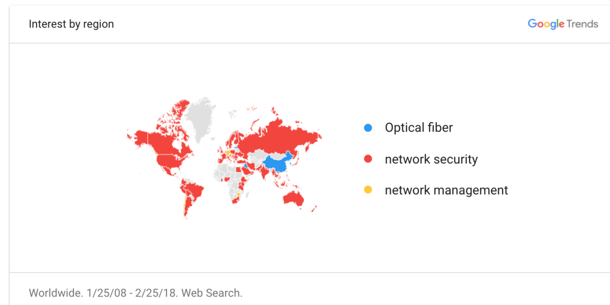

Figure 6. Google Trends Results for "Network Security" vs. "Optical Networks" vs. "Network Management" interest by region over the past 10 years

and visualization in managing networks, the results clearly show a shift toward this later topic as depicted by Figure 5 [11].

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 6 [12] depicts a global interest in these topics, showing an increased popularity of the topic.

II. 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 [13]. According to him, the Promotion Mindset focuses on growth and advancement, while the Prevention Mindset cares about Safety and Security [13]. Now, while some might pose the question, why wouldn't we 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, we'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 [14]. 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 [14]. 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 [15]. Keep that in mind if you're a vendor interested in pitching your prevention product line to your audience to tailor your pitch accordingly, if you're a head of a network operations unit, keep that in mind to motivate your 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 [16].

In this paper we 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.

A. Definitions Terminology

1) Regulatory focus: According to Higgins' definition [13], an individual's regulatory focus is a specific strategic and motivational orientation that they adopt during their goal pursuit.

2) Regulatory Fit: According to research published in [17][18][19] and [20], 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 [21] while at the same time also having a positive effect on increased judgment and avoiding temptation and distraction when pursuing a goal [22]

III. 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 sever network management issues the community was running into following the increased number of vendors, the incredible growth of the connected IP networks (a.k.a Internet), as well as the various non standardized network management protocols designed by each of the vendors [23]. The effort came to limit those effects through a standard protocol where three types of management activities were defined: status monitoring (inc. 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 (inc. status info) [23]. In the same year, the ITU-T Recommendation X.711 entitled 'Information Technology – Open Systems Interconnection – Common Management Information Protocol: Specification' was approved. Simple Gateway Monitoring Protocol (SGMP) was also published that year RFC 1028 [24].

In August 1988, RFC 1067 entitled 'A Simple Network Management Protocol' (SNMP) was published [25]. 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 [25]. 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) [26]. 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 [27]. 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 [26]. Common Management Information Protocol (CMIP) came one year layer to address the long term needs on the networking community [25] [27]. In 1990, SNMP was recognized as a standard protocol with a recommended status (RFC 1157) [28]. 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 [29].

IV. Stage 3: Optical Networks

According to [30], it's estimated that global IP traffic will reach 131.6 exabytes (10^{18} bytes) per month by 2018 which you could think of more than 26 times all of the words ever spoken by mankind [31]. 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 [32], As per 2017 statistics, nearly 428 submarine optical cables of near 1.1 million kilometers are currently in service around the globe.

A. 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 we are 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 [33].

B. 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 [34]. Local exchange carriers (LECs) use it to transmit POTS between central office switches either locally, or to users doors (Fiber To The Home: FTTH) [34]. 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 inline with the business growth and the users base. We should of course not forget about Cable television firms who heavily depend on fiber optics to deliver HDTV telecasts, digital video, and data services [34]. 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 [34]. 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 [35], Military, Space and Industrial sectors [34].

V. Stage 4: Proposed Optical Networks Management Behaviorealistic Framework

The Proposed framework is based on the prevention mindset research of stage II of this paper, as well as the ISO Functional areas of Network Management, also known as FCAPS as it distinguishes 5 main Functional Areas as depicted in the graph below within the context of Optical Networks.

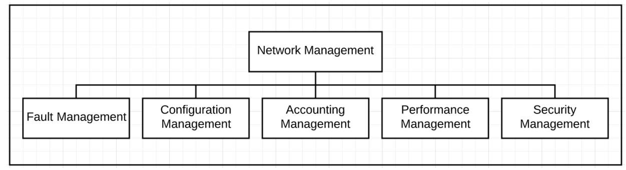

Figure 7. ISO Functional Areas of Network Management

A. Definitions & Terminology

Before we continue, we shall first proceed with a set of definitions.

1) The ISO Functional areas of Network Management:

a) Fault Management Functional Area: The focus here is on identifying and logging abnormal network events, then isolate and deal with such events as appropriate. We distinguish 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). The third is Error Recovery (Including follow up actions of software/hardware replacement).

b) 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.

c) 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.

d) Performance Management Functional Area: This is the area where concepts such as Availability for instance come into play. We define the availability of a subsystem as follows:

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

With MTBF refers to the Mean Time Between Failures, and MTTR refers to the Mean Time To Resolution. Now, the Availability of a System composed of N Subsystems is defined as follows:

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

e) Security Management Functional Area: In this area, the focus is on three subareas: Access Control, Authentication, and Encryption.

B. 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.

C. Framework People

In this section, we'll be listing entities responsible for drafting, enforcing, executing, and monitoring the framework. Drafting the 'Optical Networks Management Prevention Security Oriented Behaviorealistic 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. We should here 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 [15]. Applying those insight in the design of our framework, we 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 behavior-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.

D. 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:

1) Governance: Simply put, we mean by Governance, 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:

a) 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.

b) 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.

c) 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.

d) Resource Management: In this area, and in nowadays world, we no longer simply mean hardware. 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.

e) 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.

2) 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

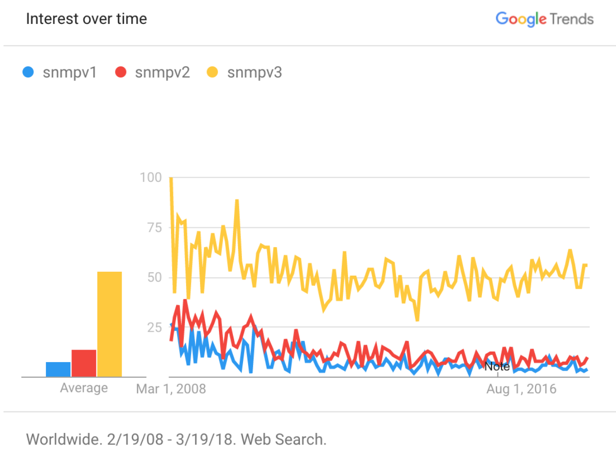

Figure 8. Google Trends Results Comparing SNMPv1, SNMPv2, and SNMPv3 over the past 10 years

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.

E. Framework Technologies

While Internet Control Message Protocol (ISMP) 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 ISMP one step further [36]. As we know, 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 you can see from Figure 8 [37], SNMPv1 and SNMPv2 are still alive and used. This poses a security issue and should be paid attention to. We 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 an 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, you'd be prompted to select a security level. Currently SNMPv3 comes with three possibilities: authNoPriv Security Level (auth), noAuthNoPriv Secuity 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. We recommend selecting SHA, as it has been shown that it takes longer to break using brute force as shown in paper [38]. 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 [39] of cracking DES 56 bit encrypted using FGPA with 1 GHz in just 9 Hours for exhaustive search and 18 minutes for alphabets only.

VI. 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.

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