

# Physical Layer Impairments in the Optimization of the Next-Generation of All-Optical Networks

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## 1. Introduction

The Internet traffic is constantly growth and the applications of type unicast/multicast with different Quality of Service (QoS) requirements. The increase of internet traffic over the last couple of years is well known (the rate of increase is reported to be 60% to 100% per year (Malik, 2011). Applications like multicast are used more frequently than ever (for example HDTV, videoconferencing, IPTV, interactive games among others)(Kamat, 2006).

For this reason, the Optical Transport Networks (OTN) must continue the evolution towards All-optical networks (without optical-to-electrical-to-optical conversion). OTN employ Wavelength Division Multiplexing (WDM) in order to transmit great deals of information. WDM allows the multiplexing of different wavelengths along the same fiber, each one can transmit at speeds of around 40 Gbps and can achieve speeds in the range of Tbps along a single fiber. Currently, the equipment needed to carry out the transmission (including routing) of information functions in an optical environment between two nodes and at each one of these an optical-electronic-optical (OEO) conversion is carried out when it is needed in order to add or drop traffic. Optical Cross Connects (OXC) are systems that allow for the commutation of traffic at each of these nodes.

New applications (both unicast and multicast) do not yet have the capacity provided by a wavelength, therefore, by allotting a wavelength in the range of Gbps to an application of a couple of Mbps one is underutilizing the full bandwidth available in one wavelength. To solve the underutilization problem researchers have proposed the concept of Traffic Grooming (TG). TG came about in order to improve the utilization of bandwidth and optimize OTN systems (Solano et al., 2007). TG is the ability given to a WDM network to combine several slow speed traffics (in the range of Mbps or a few Gbps, example: OC-1, OC-3) into one of greater speed (OC-192 or greater). To accomplish TG all of the nodes must have some special characteristics, more so if it is needed for multicast traffic. The network design problem that support TG efficiently is not an insignificant one and the solution may have a great impact on the cost of the network. TG is ability to support unicast traffic has been widely researched (Bermond et al., 2006).

The routing of unicast traffic is accomplished using the concept of the lightpath, which is a virtual channel in a completely optical environment between two nodes (Zhang et al., 2008). The intermediate nodes do not carry out OEO conversions for routing. The concept of the light-tree is employed in order to support Multicasting Traffic Grooming (MTG). The transport of traffic point-multipoint is achieved in an entirely optical medium (without OEO

conversions). This kind of transmission is called transparent and it is possible to carry it out using optical cross-connect (OXC). The architecture for the support of light-trees is presented by Khalil et al. (2006). When light trees perform grooming of unicast and multicast traffic they can use a lot of bandwidth in routing unicast sessions toward unwanted destinations. This is done in order to avoid OEO conversions in information transmission which, from a transparency point of view, are very expensive (Sreenath et al., 2006). With the purpose of improving on the resources available (wavelength and available capacity) in an optical transport network and to accomplish this in a completely optical medium, Sierra et al. (2008) have proposed the Stop and Go (S/G) Light-tree architecture. S/G light-tree allow optimal routing and grooming of unicast and multicast sessions.

Currently, there are different architectures for optical transport nodes that allow the optimal routing and/or traffic management unicast/multicast using the concept of Traffic Grooming in optical networks. However, grooming techniques and the assignment and routing algorithms proposed do not account for phenomena that can be provided in the optical fiber (Bastos-Filho et al., 2011), which mitigate or added interference between the different wavelengths in WDM Networks.

The chapter of the book describe various optical transport architectures that performs unicast/multicast traffic grooming. Routing and wavelength assignment are analyzed taking into account the effects of linear and nonlinear optical fiber. The model presented optimizes network resources taking into account the blocking probability in all-optical transport networks. Traffic has different levels of service quality. The work presented shows different optimization models and algorithms.

### 1.1 Background multicast traffic grooming

There is a tendency in telecommunications toward an increase in multicast traffic, for this reason many researchers have been interested in examining and providing better solutions. In the design of optical networks WDM mesh that are used by Billah et al. (2003) a heuristic algorithm for the efficient use of bandwidth and improvement of the throughput of the network is proposed. It is divided into two steps: *i*) find the light-tree and *ii*) assign the wavelength. They apply an algorithm for a WDM mesh network with sparse splitter capacity. They show that the heuristic algorithm accomplishes a significant reduction in the number of wavelengths needed in a connection and in the total wavelengths required. The nodal architecture used is Multicast Grooming Capable Wavelength Router. The node has wavelength conversion (efficient in the optical domain), splitting, grooming, and amplifiers. The heuristic algorithm takes into account the amount of hops, used by Dijkstra to determine the Shortest Path and the assigning of wavelengths are accomplished through the First Fit strategy.

The term light-tree is often used to refer to the design on multicast networks with grooming capabilities. It was introduced in *wavelength-routed optical networks* by Sahasrabudde & Mukherjee (1999). In their article they focus on unicast and broadcast traffic. They present the light-tree as an optimization problem, given a virtual topology, how to find a traffic matrix with the following functions: limit packet delay, average in the jump distance for a wide area network and, limit the number of total transceivers in the network. They explain that a light-tree supports as much unicast traffic as it does multicast, although it has better performance for multicast by using splitting light.

Vishwanath & Liang (2005) examine the problem of online multicast routing in mesh transport networks without the capability for conversion of wavelengths, by dividing wavelengths in multiple time slots and multiplexing the traffic. The goal is to route the multicast traffic efficiently by using grooming while balancing the connection loads. Likewise in Sahasrabudde & Mukherjee (1999), they point out that multicast applications can be efficiently routed using light-tree (this improves throughput and network performance).

Sreenath et al. (2006) address the problem of routing and the assigning of wavelengths in multicast sessions with low capacity demands in WDM networks with sparse splitting capacity. For this reason only a few nodes on the network are able to split traffic. Nevertheless those nodes not able to split can do so with OEO conversions. They point out that the splitting of traffic is more expensive at the electronic level than at the optic level because of the delays caused by OEO conversion.

Liao et al. (2006) explore the dynamic problem of WDM mesh networks with MTG to analyze and improve the blocking probability, by proposing an algorithm based on light-tree integrated with grooming. The results after using it show its usefulness. The blocking probability is reduced while taking advantage of the resources of the network under low restrictions of non conversion of wavelength and a limited number of wavelengths and transceivers. They divide the problem into three sub-sections: *i*) defining the virtual topology using light tree, *ii*) routing the connection applications across the physical topology and optimally assigning the wavelengths for the multicast tree and, *iii*) grooming low speed traffic in the virtual topology.

Khalil et al. (2006) explore the problem of providing dynamic low speed connections unicast and multicast in mesh WDM networks. They focus on the dynamic construction of the logic topology, where the lightpath and the light-tree are configured according to the traffic demands. They also propose using all resources efficiently in order to decrease the blocking probability. This is how they propose several heuristic sequential techniques, by breaking down the problem into four parts:

1. Routing problem
2. Logic topology design
3. Problem of providing wavelengths
4. TG problem

Huang et al. (2005) also analyze the blocking probability. Nevertheless, they also analyze when there are sparse splitting capacities. The algorithm that they proposed is based on light-tree dynamics that support multihop. The algorithm can be dropped and branched and can establish a new path when an application is received or alter itself when there are existing path free of traffic.

The components mentioned carry out the process of grooming by using OEO conversions when multicast and unicast traffics are jointly multiplexed.

## 1.2 Routing unicast and multicast traffic together

In WDM networks, there are two typical all-optical communication channels, lightpaths and light-trees (Kamat (2006)). A lightpath is an all-optical communication channel that passes through all intermediate nodes between a source and a single destination without

OEO conversion. A light-tree is an all-optical channel between a single source and multiple destinations. Like the lightpath, there is no OEO conversion at any intermediate node on a light-tree.

Using a light-tree to carry multicast traffic is a natural choice in WDM mesh networks. Many researches have addressed the very fundamental multicast routing and wavelength-assignment problem, such as in (Liao et al., 2006; Singhal et al., 2006; Sreenath et al., 2006; Ul-Mustafa & Kamal, 2006). In these studies, proposals for handling static and dynamic traffic has been made. Proposals have focused on mathematical models based on ILP (Integer Linear Programming) and heuristic techniques based on minimum-cost steiner tree. All these studies used a node architecture similar to that employed in Singhal et al. (2006), which employs Optical Splitters for the duplication of traffic. However, these proposals do not take into account the optimal routing of unicast and multicast traffic together.

Huang et al. (2005) tackled the problem of routing traffic unicast/multicast together. They address the online multicast traffic grooming problem in wavelength-routed WDM mesh networks with sparse grooming capability. The architecture node that employ them provide: optical multicasting and electronic grooming. The basic component of the architecture is a SaD Switch, which has configurable Splitters.

The routing, allocation and grooming problem has been initially resolved with off-line techniques. Sahasrabudde & Mukherjee (1999) presents a mathematical model (MILP) with opaque nodes (OEO conversions) and wavelength continuity constraint for the type broadcast traffic. Billah et al., 2003; Zsigri et al., 2003 employs heuristics that use Shortest path and First Fit for the routing and allocation of wavelengths. Additionally, it must be taken into account that not all nodes have multicast capabilities (sparse splitting).

Recently the work has been focused on the analysis of dynamic traffic. Vishwanath & Liang (2005) proposes an Adaptive Shortest Path Tree (ASPT) using Dijkstra's algorithm that takes into account a function of cost to minimize implementation costs. Khalil et al. (2006) divides the problem into: *i*) routing, *ii*) logical topology, *iii*) provisioning and *iv*) traffic grooming. This makes it possible to minimize the blocking probabilities in transparent networks.

In previous works, different algorithms have been used to handle the traffic unicast and multicast together but taking into account electronical grooming and OEO conversions. Below, we describe the problems of using the architectures mentioned.

### 1.2.1 Problem definitions

In this section, an example is used to explain the disadvantages of the classical methods used for routing unicast and multicast traffic. Let us consider a subset of the *NSFNet* network of 14 nodes interconnected through optical links (Figure 1). Three sessions are considered: *i*)  $S_1$  being a unicast session  $\{N_3\} \rightarrow \{N_6\}$ , where the node  $N_3$  is the source node and the node  $N_6$  is the destination; *ii*)  $S_2$  being a multicast session  $\{N_3\} \rightarrow \{N_6, N_7\}$ , where  $N_6$  and  $N_7$  are the destinations nodes, and *iii*)  $S_3$  being a unicast session  $\{N_5\} \rightarrow \{N_7\}$ , where the node  $N_5$  is the source node and the node  $N_7$  is the destination. Routing these two sessions can be performed in the following ways:

**Light-trees** (Singhal et al. (2006), Figure 2): sessions  $S_1$  and  $S_2$  are both routed through the same wavelength. In this case, no OEO conversions are used but traffic cannot be differentiated. As a consequence, all groomed traffic in a light-tree is routed to all

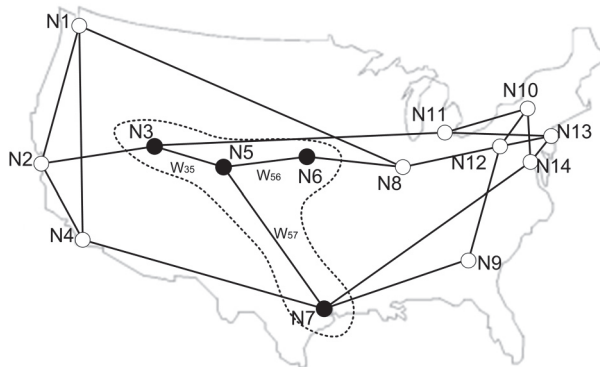


Fig. 1. NSFNet network. Sessions  $S_1$  and  $S_2$  in nodes  $N_3, N_5, N_6$  and  $N_7$

destinations. In this example, since the  $S_1$  traffic should not be sunk at node  $N_7$ , there is bandwidth wastage. When a new request arrives ( $S_3$ ) a new lightpath ( $N_5 \rightarrow N_7$ ) is set up.

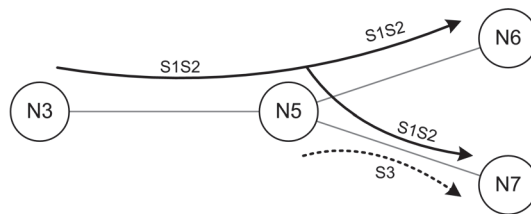


Fig. 2. Example Light-tree, Unicast  $S_1 : \{N_3\} \rightarrow \{N_6\}$ , Multicast  $S_2 : \{N_3\} \rightarrow \{N_6, N_7\}$ , and Unicast  $S_3 : \{N_5\} \rightarrow \{N_7\}$

**Lightpaths** (Solano et al. (2007); Zhu & Mukherjee (2002), Figure 3): two lightpaths are needed for routing both sessions  $S_1$  and  $S_2$ . The first lightpath follows the path  $N_3 \rightarrow N_5 \rightarrow N_6$  routing the sessions  $S_1$  and  $S_2$ . The second lightpath routes session  $S_2$  using the path  $N_6 \rightarrow N_5 \rightarrow N_7$ . It requires an additional wavelength, even though both demands could fit within one wavelength. In this case, there is also a waste of bandwidth, since spare bandwidth cannot be used. As in Light-tree, this scheme requires an additional lightpath to route  $S_3$ .

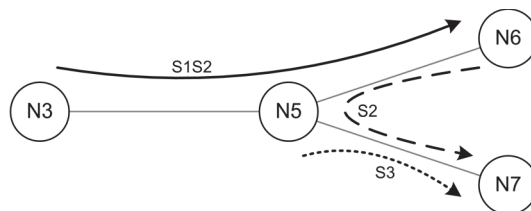


Fig. 3. Example Lightpath, Unicast  $S_1 : \{N_3\} \rightarrow \{N_6\}$ , Multicast  $S_2 : \{N_3\} \rightarrow \{N_6, N_7\}$ , and Unicast  $S_3 : \{N_5\} \rightarrow \{N_7\}$

**Light-trails** (Wu & Yeung (2006), Figure 4): one light-trail is required for routing sessions ( $S_1, S_2, S_3$ ). A light-trail is an unidirectional optical bus. In the example, we can setup one between nodes  $N_3$  and  $N_7$  as  $N_3 \rightarrow N_5 \rightarrow N_6 \rightarrow N_5 \rightarrow N_7$ . The disadvantage of light-trails is that the path may contain repeated nodes and the length of a light-trail is limited. Note that in our example, a wavelength is used in  $N_5 \rightarrow N_6$  and another one in  $N_6 \rightarrow N_5$ .

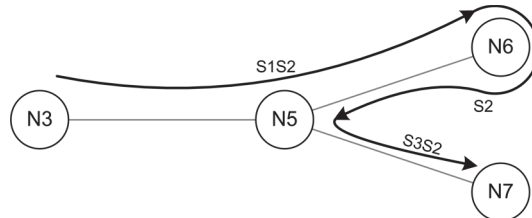


Fig. 4. Example Light-trail, Unicast  $S_1 : \{N_3\} \rightarrow \{N_6\}$ , Multicast  $S_2 : \{N_3\} \rightarrow \{N_6, N_7\}$ , and Unicast  $S_3 : \{N_5\} \rightarrow \{N_7\}$

**Link-by-Link** (Huang et al. (2005), Figure 5): this scheme routes traffic allowing OEO conversions on all nodes. Three lightpaths are used:  $N_3 \rightarrow N_5$ ,  $N_5 \rightarrow N_6$  and  $N_5 \rightarrow N_7$ . A lightpath routes sessions  $S_1$  and  $S_2$  together from node  $N_3$  to node  $N_5$ . Node  $N_5$  processes electronically the traffic and forwards sessions  $S_1$  and  $S_2$  together through the lightpath  $N_5 \rightarrow N_6$  and,  $S_2$  and  $S_3$  through the lightpaths  $N_5 \rightarrow N_7$ . The wavelength bandwidth is efficiently used, however it requires more electronic processing and OEO conversions.

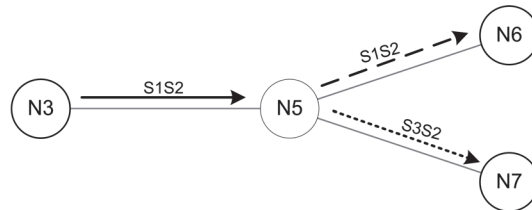


Fig. 5. Example Link-by-Link routing, Unicast  $S_1 : \{N_3\} \rightarrow \{N_6\}$ , Multicast  $S_2 : \{N_3\} \rightarrow \{N_6, N_7\}$ , and Unicast  $S_3 : \{N_5\} \rightarrow \{N_7\}$

In particular, the problem arises when there are two (or more) sessions such as in: *a*) both are originated in the same root node, *b*) the wavelength capacity is enough for both sessions but, *c*) destination nodes of one session is a subset of the other. As we could see by our example, there is no optical architecture that can efficiently route such traffic: either residual bandwidth is wasted, or more OEO conversions are needed. While bandwidth plays an important role in the revenues of any service provider, the cost incurred by OEO conversion is the dominant cost in setting up the OTN. In general, the tendency is to setup a light-tree spanning to all possible destinations of a set of sessions, as shown in Figures 2-5.

Several studies tackle this problem. Huang et al. (2005) proposes an on-line technique called Multicast Dynamic light-tree Grooming Algorithm (MTDGA). MTDGA is an algorithm that performs multicast traffic grooming with the objective of reducing the blocking probability by multiplexing unicast and multicast together. Khalil et al. (2006) also sets out to reduce the blocking probability, however it uses separate schemes for routing and grooming multicast and unicast traffic.

### 1.3 Stop-and-Go Light-tree (S/G Light-tree) architecture

We use *Stop-and-Go Light-tree (S/G Light-tree)* (Sierra et al., 2008). S/G Light-tree allows grooming unicast and multicast traffic together in a light-tree, hence reducing bandwidth wastage. An S/G Light-tree allows a node to optically drop part of the multiplexed traffic in a wavelength without incurring on OEO conversions. Hence, once the traffic is replicated, it prevents or *stops* the replicas from reaching undesirable destinations. Moreover, it enables a node to aggregate traffic in a passing wavelength without incurring on OEO conversions. More detailed information can be found in Sierra et al. (2008).

Figure 6 shows the solution to the previous problem using an S/G Light-tree. Session  $S_1$  is dropped at node  $N_5$  without the need of OEO conversions of the routed traffic in the wavelength. Session  $S_3$  is added on the same wavelength of the S/G Light-tree at node  $N_5$ . While Link-by-link (Figure 5) and S/G Light-tree (Figure 6) efficiently use the bandwidth, the first needs OEO conversions.

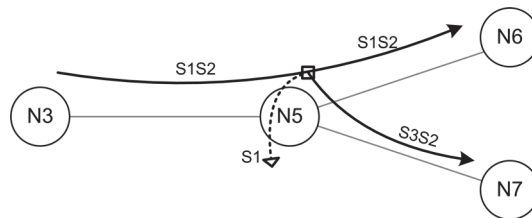


Fig. 6. S/G Light-tree scheme

The Stop-and-Go functionality is supported by optical labels or "Traffic Tags" (TT). Each packet in a wavelength contains a header carrying a TT field. Both unicast and multicast traffic can be marked with a TT. A TT can be inserted orthogonally to the packet data. The label information is FSK modulated on the carrier phase, and the data is modulated on the carrier amplitude. Figure 7 shows this procedure. The architecture has been designed for easy detection and processing of the TT. We assume that the bit pattern interpreter in the architecture has low configuration times. Moreover, the bit pattern has to be configured for the traffic of each multicast tree.

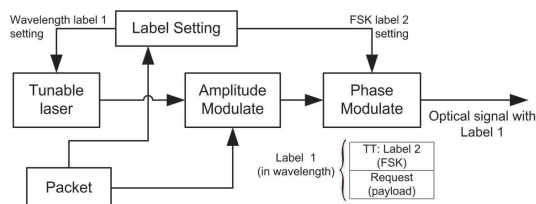


Fig. 7. S/G Light-tree Labels

Figure 8 shows the used node architecture. Initially, the optical fiber traffic flows are demultiplexed in the wavelength channel (Demux).  $\lambda_2$  carries the request  $S_1$  and  $S_2$  multiplexed electronically.  $S_1$  is marked with a TT indicating that it should be stopped from going to  $N_5$ .  $\lambda_2$  is switched (OSW1) in the Splitter and Amplifier Bank. The splitter replicates the incoming traffic to all the node's neighbors, regardless of the TT field. Then, for each packet replica, the TT field is extracted in order to decide whether the packet should be stopped from being forwarded to an undesired destination.

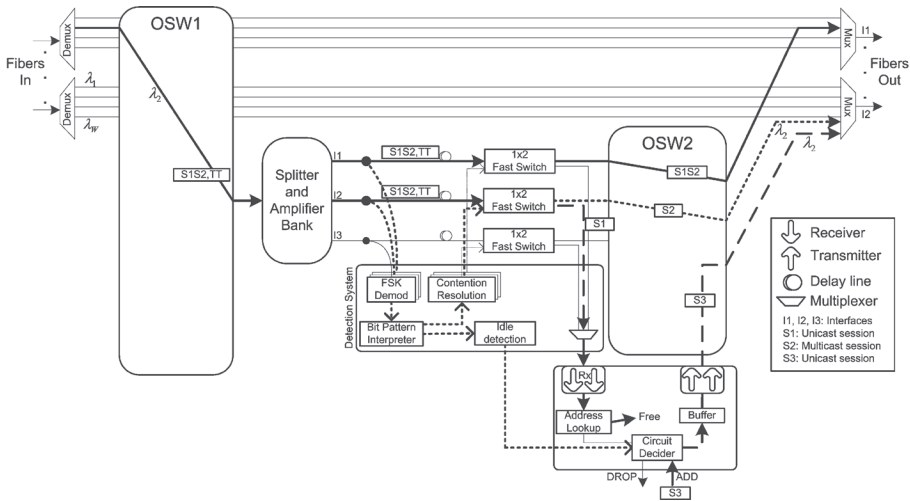


Fig. 8. *Stop-and-Go Light-tree (S/G Light-tree), node  $N_5$*

A detection system consists of FSK Demod, 1x2 Fast Switch, Bit pattern Interpreter, Contention Resolution, Idle detection and fiber delay lines (A similar detection system was proposed in Van Breusegern et al. (2006); Vlachos et al. (2003)). A small amount of power is tapped from the wavelength and redirected to the FSK Demod, where the label gets demodulated and ready for interpretation. FSK Demod sends the TT field to the Bit pattern Interpreter. The TT-field is analyzed by an all-optical correlator in the Bit pattern Interpreter block.

If the interpreter-block identifies that the TT field has stopped, it communicates to its corresponding 1x2 Fast Switch in order to either drop or switch the packet towards the receiver (Rx). A multiplexer is used to reduce the number of receivers. These packets are later analyzed to decide whether they must be dropped (FREE), groomed in another S/G Light-tree or, dropped to the local network.

A S/G Light-tree node allows to add traffic to the wavelength as well, only when free capacity is detected (Idle Detection). In our example, session  $S_3$  can employ wavelength 2 with tunable lasers. S/G Light-tree also allows to add sessions using the traditional way.

## 2. Physical phenomena in optical fibers and the importance in WDM networks

Grooming algorithms, routing and wavelength assignment (GRWA) work with the assumption that all wavelengths in the optical media have the same characteristics of transmission of bits - no bit error (Azodolmolky et al., 2011). However, the optical fiber presents some phenomena that impair the transmission quality of the light-trees. Physical phenomena that may occur in the fiber is divided into two:

1. Linear optical effects: spontaneous amplification, spontaneous emission (ASE), polarization mode dispersion (PMD), chromatic dispersion.
2. Non-linear optical effects: Four-wave mixing (FWM), Selfphase modulation (SPM), Cross-phase modulation (XPM), Stimulated Raman scattering (SRS).



Current work studying PMD, ASE, FWM algorithms applied to routing and wavelength assignment (without grooming), taking into account the effect of power, frequency, wavelength and length of the connection (Ali Ezzahdi et al., 2006).

In this chapter, we propose a predictive model of allocation of wavelengths based on Markov chains. The model takes into account the residual dispersion in WDM networks with traffic grooming and support the applications unicast/multicast with QoS requirements.

## 2.1 Allocation model wavelengths, taking into account chromatic dispersion

Some definitions and/or parameters used:

- We define 3 classes of service (CoS) for different traffic or sessions that will use the transport network. The CoS are: High Priority ( $CoS_A$ ), Medium Priority ( $CoS_M$ ) and Low Priority ( $CoS_B$ ). The CoS of each session to be sent by the network depends on the type of protocol or traffic, for example, if a video session will require a better deal on the network, so their priority is high ( $CoS_A$ ). In case, for example, a data session will be low priority ( $CoS_B$ ).
- $\Lambda$  is the set of wavelengths available to allocate. Where  $\Lambda = \lambda_\alpha, \lambda_\beta, \lambda_\gamma$ .  $\lambda_\alpha$  is the subset of wavelengths with low dispersion,  $\lambda_\beta$  the subset of wavelengths with a mean dispersion,  $\lambda_\gamma$  the subset of wavelengths with high dispersion.

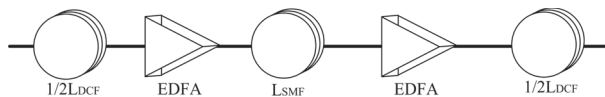


Fig. 9. Standard section

The model is based on the Residual Dispersion (RD), which is defined as the total dispersion in optical fiber transmission in a given fiber compensation. The model takes into account a standard section (Figure 9) and contains the following elements:

- Single Mode Fiber (SMF): optical fiber designed to carry a single ray of light. The fiber may contain different wavelengths. It is used in DWDM.
- Dispersion Compensating Fiber (DCF): Fibers responsible for controlling/improving the chromatic dispersion. It works by preventing excessive temporary widening of the light pulses and signal distortion. The DCF compensates the distortion accumulated in the SMF.
- Length of SMF ( $L_{SMF}$ )
- DCF length ( $L_{DCF}$ )
- EDFA Amplifiers

The model is intended to find the percentage of wavelengths with low ( $\lambda_\alpha$ ), medium ( $\lambda_\beta$ ) and high dispersion ( $\lambda_\gamma$ ), comparing the value of RD with a threshold. The model is defined as follows:

### Inputs:

- $B$ : Compensation Factor (Dispersion Slope) [ $ps/nm^2km$ ].
- $\Lambda$ : set of wavelengths available to allocate.  $\Lambda = \lambda_1, \lambda_2, \dots, \lambda_w$ . Where  $w$  is the number of wavelengths.

- $\lambda_{ref}$ : reference wavelength [nm]. It depends on the bandwidth of the channels. The parameters are available in the Rec G.694.1.
- *Threshold*: threshold of acceptance [ps/nm]. *Threshold* = 1000 ps/nm for speeds of 10 Gbps.
- $D_{smf}$ : Coefficient of dispersion in the SMF for the reference wavelength [ps/nm.Km].
- $D_{dcf}$ : Coefficient of dispersion in the DCF for the reference wavelength [ps/nm.Km].
- $L_{SMF}$ : SMF length [km].
- $L_{DCF}$ : DCF length [km].

### Outputs:

Equations 1,2,3 help to obtain the parameters of RD, as shown in Equation 4.

$$\Delta\lambda_w = \lambda_w - \lambda_{ref} ; \forall w \quad (1)$$

$$\Delta D_w = \Delta\lambda_w \times B ; \forall w \quad (2)$$

$$D_w = D_{\lambda_{ref}} + \Delta D_w ; \forall w \quad (3)$$

$$RD_w = D_w(SMF) \times L_{SMF} + D_w(DCF) \times L_{DCF} \quad (4)$$

The RD parameter will be used for the allocation of wavelengths. The proposal seeks to allocate the wavelengths less DR sessions with higher priority ( $CoS_A$ ). We used the cost function proposed in Ali Ezzahdi et al. (2006) (Threshold = 1000, other parameters were taken from Zulkifli et al. (2006)) to determine the value of RD (Equation 5).

$$d_{ij} \times RD_w \leq threshold \quad (5)$$

Given the analysis performed, we conclude that the first 15% of the wavelengths have less residual dispersion, the dispersion medium below 60%, while the remaining 25% has high dispersion. These parameters will then be used for the assignment.

#### 2.1.1 Proposed allocation model

The WDM network is modeled by a connected directed graph  $G(V, E)$  where  $V$  is the set of nodes in the network with  $N = |V|$  nodes.  $E$  is the set of network links. Each physical link between nodes  $m$  and  $n$  is associated with a  $L_{mn}$  weight, which can represent the cost of fiber length, the number of transceivers, the number of detection systems or other. The total cost of routing sessions unicast/multicast in the physical topology is given by equation 6:

$$TotalCost = \sum_{iek} \sum_{w \in W} \sum_{(m,n) \in N} L_{mn} \cdot f_i \cdot \chi_{mn}^{iw} \quad (6)$$

Where:

- $N$ : Number of nodes in the network.
- $W$ : Maximum number of wavelengths per fiber.
- $bw_i$ : Bandwidth required per session unicast/multicast  $i$ .
- $C_w$ : Capacity of each channel or wavelength. For example,  $C_w = OC-192$  or  $OC-48$ .

- $f_i$ : Fraction of the capacity of a wavelength used for the session  $i$ .  $f_i = bw_i/C_w$ .
- $k$ : a group of unicast or multicast sessions.
- $\chi_{mn}^{iw}$ : Boolean variable, which equals one if the link between nodes  $m$  and  $n$  is occupied by the session  $i$  on wavelength  $w$ . Otherwise  $\chi_{mn}^{iw} = 0$ .

$K$  sessions are considered unicast/multicast denoted by  $R_i(S_i, D_i, \Delta_i) | i = 1, 2, \dots, k$ . Each session  $R_i$  is composed of a source node  $S_i$ , node or set of destination nodes and a parameter  $D_i$  class of service associated  $\Delta_i = CoS_A, CoS_M, CoS_B$ .  $\Delta_i$  be determined by a model presented in the next subsection.

Let  $T_i(S_i, D_i, \Delta_i, \lambda_i)$  tree routing for the session  $R_i$  in  $\lambda_i$  wavelength. When  $R_i$  is multicast, the message source  $S_i$  to  $D_i$  a tree along the  $t_i$  is divided (split) on different nodes to route through the various branches of the tree to wound all nodes  $D_i$ . The architecture of S/G Light-tree allows this operation. Regarding the degree of the node is supposed to be unlimited (bank splitter architecture S/G unlimited). In addition, the wavelength conversion are not considered. The wavelength conversion in all-optical half are expensive and are still under development.

The objective of grooming, routing and allocation algorithm is to minimize the cost of the tree taking into account the dispersions present in the wavelengths. That is, the network has a set  $\Lambda = \lambda_1, \lambda_2, \dots = \lambda_\alpha, \lambda_\beta, \lambda_\gamma$  of wavelengths, which:  $\lambda_\alpha$  is the set of wavelengths of low dispersion,  $\lambda_\beta$  is the set of half wavelength dispersion and  $\lambda_\gamma$  all wavelengths of high dispersion. As obtained in the previous section:  $\lambda_\alpha$  is the first 15%,  $\lambda_\beta$  15% to 75% and  $\lambda_\gamma$  the last 25% of wavelengths. The wavelength is assigned to a particular  $R_i$  depend on the type of service required for that session  $\Delta_i$ . The main objective is given by the equation 7.

$$\text{Minimize} \sum_{iek} \sum_{w \in W} \sum_{(m,n) \in N} L_{mn} \cdot f_i \cdot \chi_{mn}^{iw} \quad (7)$$

The problem of routing unicast/multicast is basically a minimum Steiner Tree problem, which is NP-hard. We propose a heuristic to find the tree predictive routing taking into account QoS (through CoS) and dispersions in all wavelengths. Another feature of the heuristic is trying to keep more spare capacity in the low wavelength dispersion for the sessions  $r_i$  with  $\Delta_i = CoS_A$  are most likely to access this resource.

### 2.1.2 Prediction using Markov chains

Markov chains are a tool to analyze the behavior of some stochastic processes, which evolve in a non-deterministic over time to around a set of states. Using Markov chains to predict in different systems has been tested and validated for their efficiency in different systems of telecommunications. We use Markov chains to predict the possible CoS that come with the next session (in  $t + D_t$ ). The states are defined as class of service (CoS) of a given session. The model applies for  $n$  types of CoS as shown in Figure 10. For the case study (3 CoS), we obtained the transition probabilities ( $P_{xy}$ , where  $x$  and  $y$  are states that define the CoS) taking into account the available data traces of ACM SIGCOMM (Acm, 2000). From this data was obtained the following transition matrix:

$$P_{xy} = \begin{bmatrix} 0.1009 & 0.3082 & 0.5910 \\ 0.1007 & 0.3089 & 0.5905 \\ 0.1009 & 0.3083 & 0.5908 \end{bmatrix} \quad (8)$$

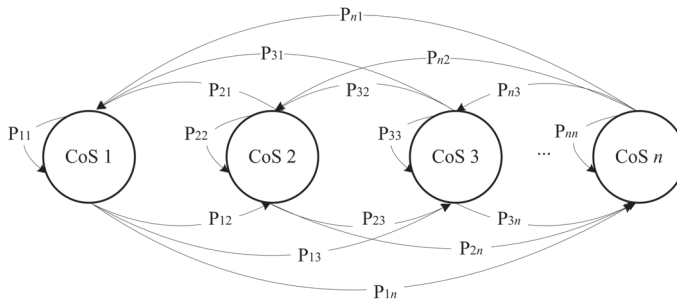


Fig. 10. Markov chain diagram for  $n$  CoS

Markov chain with transition probabilities will be used to determine the type of packet (CoS) that come in the following application (session).

### 2.1.3 Heuristic proposed

We propose a heuristic on-line that deals with the optimal routing, wavelength assignment and grooming, taking into account quality of service for the various sessions and the effects of dispersion in the wavelengths available for allocation. The heuristic aims to probabilistically assign the wavelengths with lower dispersion sessions that have higher priority or CoS. The algorithm is called PredictionTG-QoS and is shown in Figure 11. The algorithm uses Assignmentgrooming function which is shown in Figure 12. The input parameters of the algorithm are:

- $N$ : is the number of nodes in the network.
- $X$ : set of sessions,  $k = |X|$  is the number of sessions.  $k = 1, 2, \dots, i$ .
- Set  $\Lambda = \lambda_1, \lambda_2, \dots = \lambda_\alpha, \lambda_\beta, \lambda_\gamma$  of wavelengths.  $W = |\Lambda|$  is the number of lengths.
- $T_i(S_i, D_i, \Delta_i, \lambda_i)$  is the routing tree for the session  $R_i$  in wavelength  $\lambda_i$ .
- Class of Service (CoS) associated  $\Delta_i = \{Cos_A, Cos_M, Cos_B\}$
- $P_{mn}$ : physical topology, where  $P_{mn} = P_{nm} = 1$  indicates an optical fiber direct link between nodes  $m$  and  $n$ . If no fiber link between nodes  $m$  and  $n$ , then  $P_{mn} = 0$ .
- Each link between nodes  $m$  and  $n$  is an associated weight  $L_{mn}$ .
- $C$ : capacity of each wavelength. Assume  $C = OC - 48$ .
- $S_i$ : source node for session  $i$ .
- $D_i$ : set of destination nodes for each session.  $D_i$  includes unicast and multicast traffic.
- $bw_i$ : bandwidth required for each session.

PredictionTG-QoS algorithm initially with session information  $R_i$  determines the class of service ( $\Delta$ ) and the set of lengths ( $\lambda \in \Delta$ ) in which the session can be routed (including grooming) taking into account the prediction through the Markov chain. With this information we proceed to apply the routing, allocation and grooming algorithm shown in Figure 11. The assignment and grooming algorithm is based on the known minimum steiner tree to determine the routing tree. Once it is determined the tree routing (in this case the time) it is found that the wavelength being tested have the capacity available for the session can

```

Function PredictionTG-QoS( $n,s,D,$  )
1  |  $\Lambda$ = Determine the set of lengths that can be
   | assigned ( ) given Markov chain
2  | If
3  |   T=Assignmentgrooming( $n,s,D,bw,\lambda,$  );
4  |   If Could not allocate
5  |     | Blocking
6  |   end
7  |
8  | Elseif
9  |   T=Assignmentgrooming( $n,s,D,bw,\lambda,$  );
10 |   If Could not allocate
11 |     | Blocking
12 |   end
13 |
14 | If
15 |   T=Assignmentgrooming( $n,s,D,bw,\lambda,$  );
16 |   If Could not allocate
17 |     | Blocking
18 |   end
19 | end

```

Fig. 11. PredictionTG-QoS algorithm

```

Función Assignmentgrooming ( $n,s,D,$  ));
1  |
2  | While Assigned ==false &&
3  |   Search tree set of available lambdas (steiner minimun
   | tree)
4  |   If capacity is available for the whole tree
5  |     | Generated routing tree in the lambda
6  |     | Available capacity decreases lambda:
   |
   | Assigned =true
7  |   Else
8  |     | Assigned =false
9  |   End
10 |   t--;
11 | End

```

Fig. 12. Assignmentgrooming Function

access that resource. In case of available capacity is allocated to that wavelength the session and is included in  $T$ . If it is not possible to assign that wavelength is tested in the next, until you find available capacity or until the wavelengths are exhausted. If it is not possible to

assign any wavelength, we proceed to eliminate this session is marked as blocked traffic. The advantage of the algorithm is to use the CoS cycles are reduced search when looking for that wavelength can be assigned.

## 2.2 Analysis and results of the proposed model

The simulations are performed using NSFnet transport network, in which the physical topology consists of 14 nodes with 21 bidirectional links. In order to obtain results as close to reality, we decided to get a model coming session to the optical transport network as well as their duration. We used traces of data available in ACM SIGCOMM Acn (2000), which contain traffic carried on the transport network with duration of 30 days between the Lawrence Berkeley Laboratory, California and the world. The data used have information about the timing, duration, protocol, bytes transferred, and others.

The proposed allocation model (PredictionTG-QoS) is compared with the case when given the same treatment to the different sessions (regardless of QoS, called in this case standard assignment) and when it does not take into account the QoS (TG-QoS). The article compares the blocking probability (blocking) and the ability to average available bandwidth of each wavelength. The analysis is done taking into account the following simulation parameters:

- Number of wavelengths: 10
- Wavelengths Capacity:  $OC - 48$
- Possible bandwidth:  $bw = \{OC - 1, OC - 3, OC - 12, OC - 48\}$ , generated with a uniform distribution  $OC - 1 : OC - 3, OC - 12, OC - 48 = 1 : 11 : 1$ .
- Maximum number of sessions: 10000
- Group of wavelengths with low dispersion  $\lambda_\alpha = [1:2]$ .
- Group half-wavelength dispersion  $\lambda_\beta = [3:7]$ .
- Group of wavelengths with high dispersion  $\lambda_\gamma = [8:10]$ .
- The arrival rate of session ( $\lambda$ ) and the duration ( $\mu$ ) of these were modeled as  $\mu = 1$  and  $\lambda$  to vary the load in Erlangs. The load in Erlangs is defined as  $\text{Load (Erlang)} = bw \cdot \lambda / \mu$ .

In Figure 13 shows the blocking probability of link sessions with  $CoS_A$ . The proposed heuristic improves by 16% approx. to TG-QoS heuristics and 11% approx. when performing standard assignment for different traffic loads. As noted the allocation taking into account only the QoS does not improve the standard setting, but all traffic is treated the same way leading to the sessions with  $CoS_A$  not routed by half with less dispersion.

In the case when you have sessions with  $CoS_M$  (Figure 14), shows a better performance when using TG-QoS, but PredictionTG-QoS enhancement to the standard assignment. The reason for TG-QoS provides better performance is due to 60% of available wavelengths are to be assigned only to all traffic with  $CoS_M$ . Moreover, the heuristic-QoS PredictionTG you are looking to improve the QoS sessions mainly  $CoS_A$  giving any kind of traffic can access a wavelength less chromatic dispersion. It is noteworthy that the blocking probability for  $CoS_M$  remains at approximately 32% as for  $CoS_A$  sessions.

As expected, the traffic  $CoS_B$  is penalized by both TG-QoS-QoS as PredictionTG (Figure 15). Importantly, however PredictionTG-QoS blocking probability remains in about 40% for this type of traffic, close to  $CoS_A$  and  $CoS_M$  supplied.

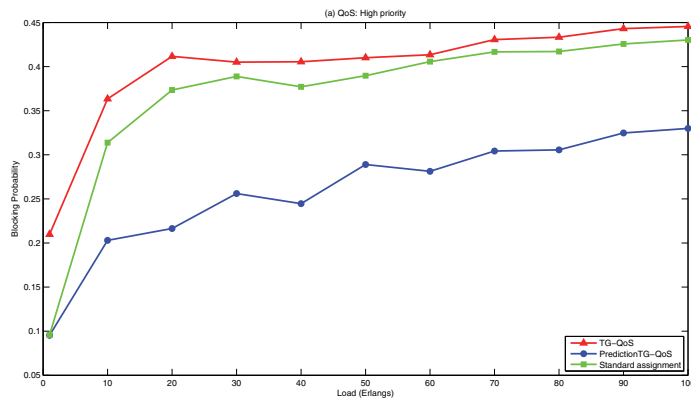


Fig. 13. Blocking Probability for  $CoS_A$ , QoS: High priority

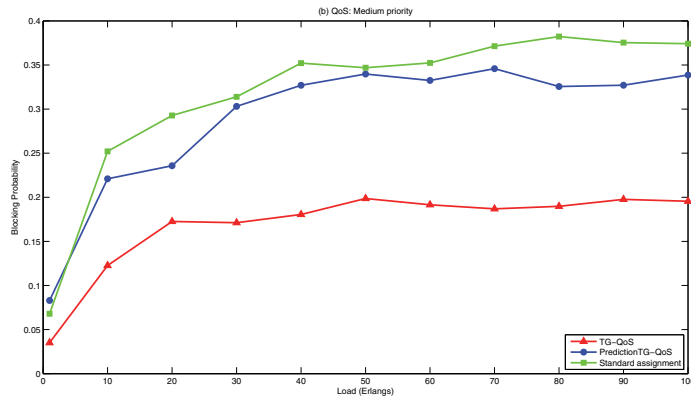


Fig. 14. Blocking Probability for  $CoS_M$ , QoS: Medium priority

Regarding the capacity of available bandwidth in each wavelength, as shown in Figure 16, PredictionTG-QoS on average available capacity remains higher when compared with the other two allocation algorithms. In addition, the algorithm meets its primary objective: to keep the wavelengths with less dispersion available for traffic with  $CoS_A$ . The wavelengths of 3 to 7 are those who remain less available capacity due to more traffic coming into a system is  $CoS_M$ .

### 2.3 Nonlinear model: Four Wave Mixing

Four Wave Mixing (FWM) is one of the main phenomena induced nonlinear crosstalk in WDM networks (Agrawal, 2001). In WDM networks, FWM phenomenon generates a new wave frequency  $w_f = w_i + w_j - w_k$ , where  $w_i, w_j, w_k$  channels are used in the network. For a system with  $M$ -channel  $i, j, k$  range from 1 to  $M$ , which produces up to  $M^2(M-1)/2$  new frequencies.

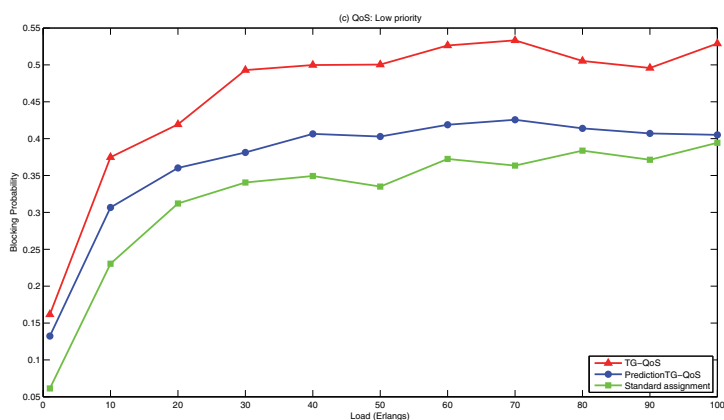


Fig. 15. Blocking Probability for  $CoS_B$ , QoS: Low priority

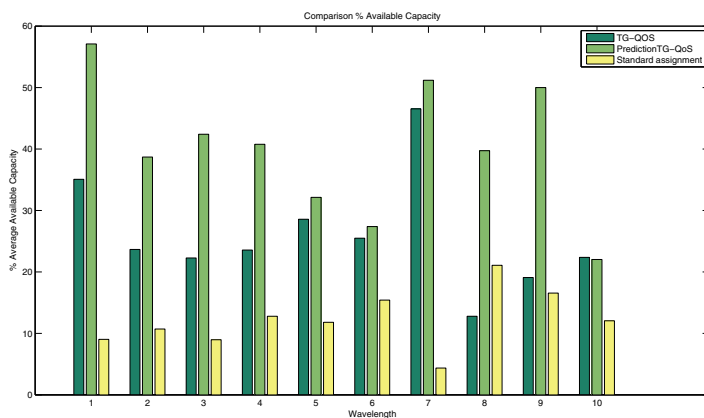


Fig. 16. Average available capacity for each wavelength

In All-Optical Networks (AONS) is important to consider this phenomenon because it does not use OEO conversion at intermediate nodes. This leads to the lightpath and the lighttree signal receives interference by not regenerating (Fonseca et al., 2003; Xin & Rouskas, 2004). When the separation of the channels in the network is the same, it generates new frequencies coincide with frequencies enabled in the system. This leads to the occurrence of interference depends on the bit patterns and the receivers receive different signal fluctuations.

To explain the concept consider a WDM network with 3 channels, with initial wavelength  $\lambda_0 = 1.45\mu$  and channel separation  $0.1\mu$ . Figure 17 shows an example, where in (A) observed the 3 channels used in the system. The phenomenon generates 9 components, however, some matches several times in the channels being used. Figure 17(B) shows the new components.



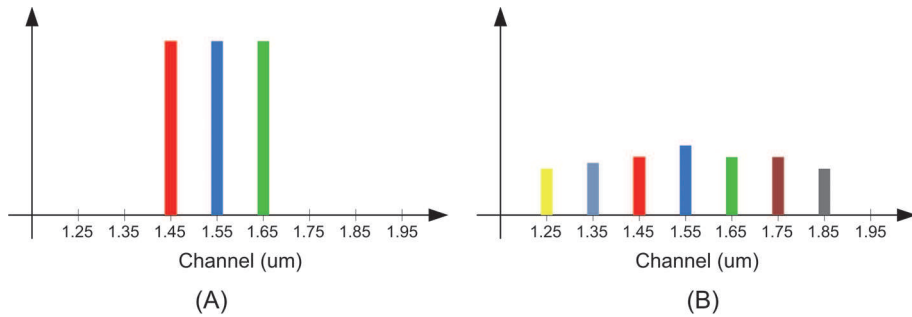


Fig. 17. Example FWM. (A) channels used, (B) signals generated by FWM effect

### 2.3.1 Physical parameters

The system is characterized by the interaction of multiple channels  $w_i, w_j, w_k$  with  $k \neq i, j$ . The new components are generated by  $w_\varphi$  given by equation 9.

$$w_\varphi = w_{ijk} = w_i + w_j - w_k; \forall k \neq i, j \quad (9)$$

The power of the frequency component in the  $w_\varphi$  is calculated using the expression used by Fonseca et al. (2003) and Agrawal (2001), shown in equation 10.

$$P_{w_\varphi}(L) = \frac{\eta}{9} D^2 \gamma^2 P_i P_j P_k e^{-\alpha L} L_{eff}^2 \quad (10)$$

Where:

- $L$ : is the length of optical fiber.
- $P_i, P_j, P_k$ : transmission power of each channel.
- $D$ : deterioration factor.  $D=3$  for  $i = j$ ,  $D= 6$  for  $i \neq j$ .
- $\alpha$ : fiber attenuation.
- $\gamma$ : Nonlinear coefficient.  $\gamma$  can be determined as  $\gamma = 2\pi n_2 / \lambda A_{eff}$ , where  $n_2$  is the nonlinear refractive index of the fiber,  $A_{eff}$  is the effective area of the core of the fiber and  $\lambda$  the wavelength in vacuum.
- $L_{eff}$ : effective length of the fiber.  $L_{eff} = 1 - e^{-\alpha L} / \alpha$ .
- $\eta$ : FWM efficiency.

Considering that in the OTN link has several hops before reaching the destination should be considered that the power is the sum of the components in each hop, so the total power for each component is given by equation 11 ( $h$  is the number of hops).  $P_{TOTAL}$  represents the FWM noise accumulated over the link.

$$P_{TOTAL} = \sum_h \sum_{i,j,k} P_{w_\varphi} \quad (11)$$

The efficiency  $\eta$  depends on the separation of channels, chromatic dispersion  $D_c$  (dispersion slope  $dD_c/d\lambda$ ) and the fiber length and can be determined as shown in equation 12.

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2} \left[ 1 + \frac{4e^{-\alpha L} \sin^2(\Delta\beta \cdot L/2)}{(1 - e^{-\alpha L}/2)} \right] \quad (12)$$

Where:

$$\Delta\beta = \left(\frac{2\pi\lambda_0^2}{c}\right)(w_i - w_k)(w_j - w_k) \quad (13)$$

$$\times \left( \left[ D_c + \frac{\lambda_0^2}{2c} \frac{dD_c}{d\lambda} \right] \left[ (w_i - w_0) + (w_j - w_0) \right] \right)$$

$c$  is the speed of light in vacuum and  $\lambda_0$  is the wavelength on zero dispersion. The term used to determine which wavelength is assigned to certain traffic is Q-factor (Fonseca et al., 2003). To determine taking into account Gaussian noise using On-Off Keying (OOK) and calculating the BER as shown in equation 14.

$$BER = \frac{1}{\sqrt{2\pi}} \int_Q^\infty \exp(-t^2) dt \quad (14)$$

Assuming thermal noise and shot noise can be ruled out in the presence of FWM distortion, Q-factor can be represented as shown in equation 15.

$$Q = \frac{bP_s}{\sqrt{N_{FWM}}} \quad (15)$$

$$N_{FWM} = 2b^2 \frac{P_{FWM}}{8} \quad (16)$$

Where,  $b$  is the responsibility of the receiver,  $P_s = P_i e^{-\alpha L}$  is the received power y  $P_i$  the transmission power of the channel  $i$ .

### 2.3.2 Proposed allocation model

The proposed allocation model is shown in Figure 18. The model is divided into two modules: 1) network layer and 2) physical layer. The network layer is responsible for determining the routing tree (applies to both lighttree to SG). The physical layer is responsible for determining if the routing tree found in certain wavelength can satisfy the QoS requirements of traffic.

The proposed model is called QoSImproved-FWM. QoSImproved-FWM takes into account that a percentage of links to destinations not meet the QoS parameters. In this case if the percentage of links that are acceptable to route the session is over 70, it proceeds to search for those who do not meet again another way. If you do not find the session is blocked. If you are under 70 do not assign that wavelength to the session unicast/multicast (the value 70 is used as an example, this value can be changed).

A variation of QoSImproved-FWM does not take into account the percentage and is called GroomingQoS-FWM. When all branches of lighttree meet the threshold for QoS immediately locks independent of the number of destinations that have good reception.

### 2.4 Simulation and analysis

The analysis was performed for the network NSFnet considering dynamic unicast/multicast traffic with QoS requirements. Was analyzed for 3 classes of service:  $CoS_A$ ,  $CoS_M$ ,  $CoS_B$ .

The physical and network parameters used for the analysis are shown in Tables 1 and 2 respectively. The model is analyzed in terms of blocking probability and average capacity available in the network for each  $CoS$ . Grooming, GroomingQoS-FWM y QoSImproved-FWM are analyzed.

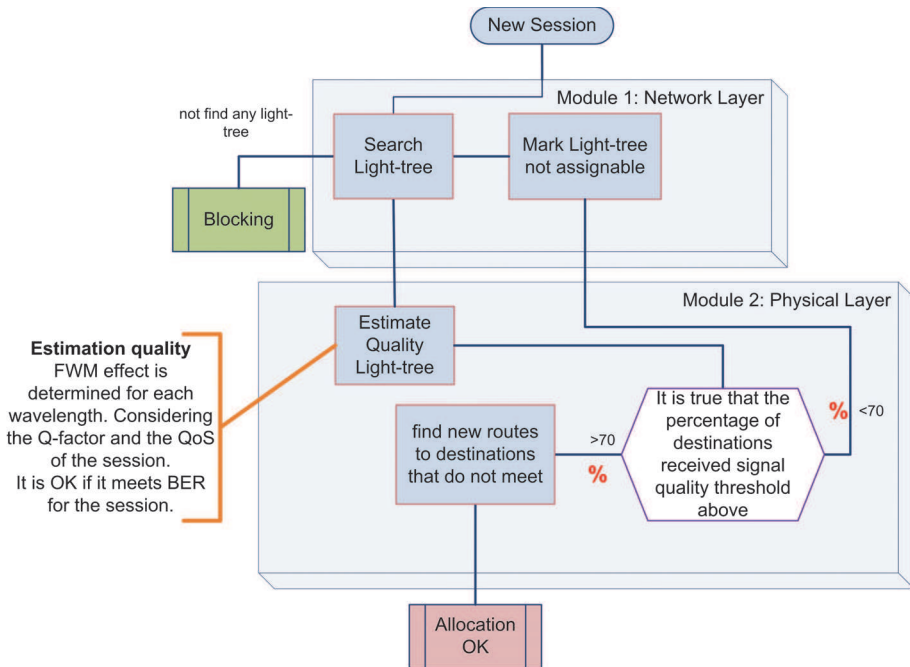


Fig. 18. Flowchart allocation model considering FWM

Parameter	Value
Fiber type	Dispersion Shift Fiber
Zero-dispersion wavelength $\lambda_0$	1549nm
Chromatic dispersion slope	0.67ps / [nm <sup>2</sup> km]
Nonlinear coefficient $\gamma$	2.3(Wkm) <sup>-1</sup>
Fiber attenuation $\alpha$	0.23dB / Km
Transmit power $P_s$	0dBm
Channel Separation	100GHz
BER or threshold for $CoS_A$	10 <sup>-9</sup>
Receptor responsivity	1

Table 1. Physical parameters of simulatio model FWM

parameter	Value
Number of nodes	14
Number of sessions	1000
Number of wavelengths	8
Traffic generation model	Poisson
Duration model	Exponential

Table 2. FWM model simulation parameters

Algorithm y	$\mu$		$\sigma$	
	Min	Max	Min	Max
Grooming, CoS <sub>A</sub>	0,360844	0,489065	0,0666778	0,167471
Grooming, CoS <sub>M</sub>	0,37086	0,49784	0,0610475	0,162028
Grooming, CoS <sub>B</sub>	0,43367	0,484205	0,0199832	0,0615137
GroomingQoS – FWM, CoS <sub>A</sub>	0,540755	0,642445	0,0488886	0,129757
GroomingQoS – FWM, CoS <sub>M</sub>	0,352686	0,506732	0,0801074	0,201202
GroomingQoS – FWM, CoS <sub>B</sub>	0,278883	0,323472	0,019591	0,0555651
QoSImproved – FWM, CoS <sub>A</sub>	0,263923	0,41164	0,0768166	0,192936
QoSImproved – FWM, CoS <sub>M</sub>	0,426429	0,514891	0,0425289	0,112878
QoSImproved – FWM, CoS <sub>B</sub>	0,323474	0,397966	0,0358129	0,0950524

Table 3. Confidence Intervals 95%. FWM

In analyzing the blocking probability for sessions with CoS<sub>A</sub> the proposed allocation model QoSImproved-FWM improvement in more than 12% the algorithm Grooming and 20% to GroomingQoS-FWM. Note that as discussed the analysis seeks to improve the blocking probability for this type of traffic. Figure 19(A) shows the results.

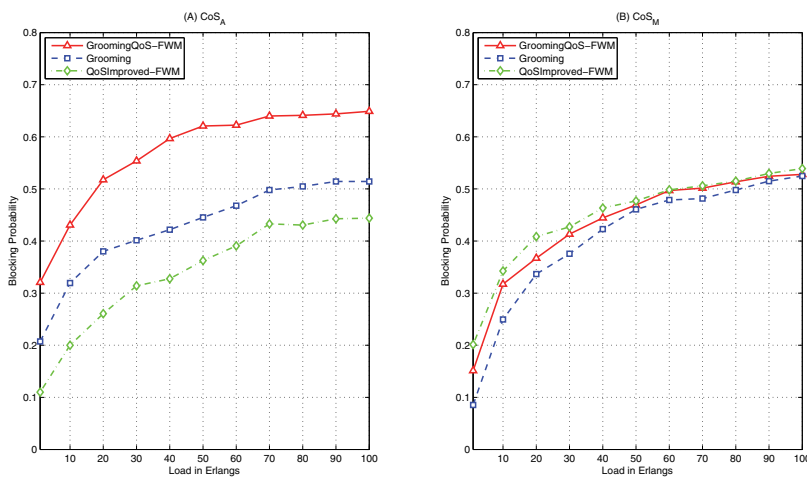


Fig. 19. Blocking probability, (A) CoS<sub>A</sub> and (B) CoS<sub>M</sub>. Parameters: NSFnet, k=1000, c<sub>w</sub> =OC-48, w =8, BW =OC-[1 3 12 48]

The algorithms showed a similar result for trades with CoS<sub>M</sub>. Approximately have a blocking probability of 50% as shown in Figure 19(B).

By using QoSImproved-FWM blocking probability for traffic with CoS<sub>B</sub> was not good compared to GroomingQoS-FWM. It should be noted that the analysis found that the algorithm is enhanced by Grooming proposals for this project.

When analyzing the average available capacity per wavelength, we found that the wavelengths 1 and 8 have more available capacity when using QoSImproved-FWM. These

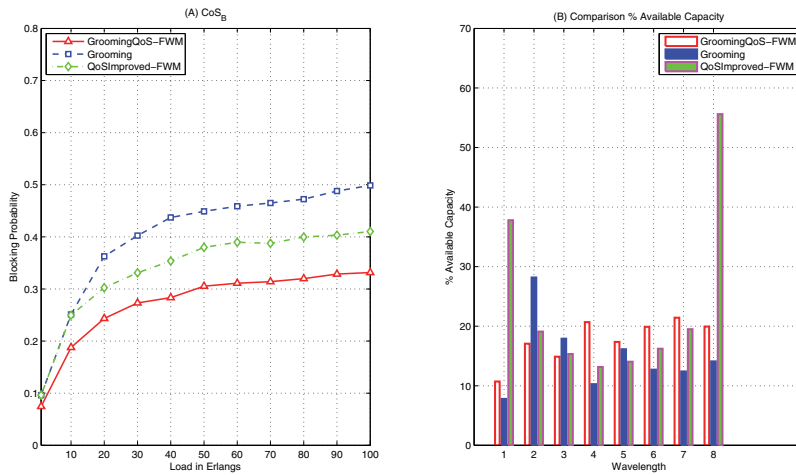


Fig. 20. Blocking probability, (A)  $CoS_A$  and (B) Available capacity. Parameters: NSFnet,  $k=1000$ ,  $c_w = OC-48$ ,  $w = 8$ ,  $BW = OC-[1\ 3\ 12\ 48]$

wavelengths are reserved for traffic requiring QoS improvement. For other wavelengths the average available capacity is similar for all algorithms.

Table 3 summarizes the confidence intervals for the results.

### 3. Conclusions

In this chapter, we propose a predictive model based on Markov chains. The allocation, routing and grooming algorithm takes into account the phenomena occurring in the optical fiber as well as parameters of quality of service (QoS) in traffic of unicast and multicast type.

The proposed allocation model significantly improves the blocking probability for high priority traffic, while maintaining a similar range to other types of traffic. The model also keeps most available capacity in the low wavelength dispersion, which will allow traffic with high quality requirements may be more likely to have access to good resources.

This chapter analyzes dynamic traffic networks using OTN architecture SG. Heuristics are proposed that seek to minimize the blocking probability for these networks. Furthermore it is noted that the traffic have different characteristics related to QoS. Given this, it is proposed to note that the physical environment in AONs has limitations that the systems are evident and alter the signal propagating in different lighttree. Models are proposed that take into account linear and nonlinear distortions. Results show that it is important to analyze the physical effects.

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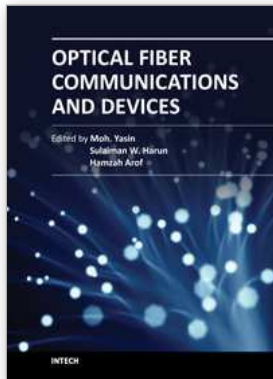
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This book is a collection of works dealing with the important technologies and mathematical concepts behind today's optical fiber communications and devices. It features 17 selected topics such as architecture and topologies of optical networks, secure optical communication, PONs, LANs, and WANs and thus provides an overall view of current research trends and technology on these topics. The book compiles worldwide contributions from many prominent universities and research centers, bringing together leading academics and scientists in the field of photonics and optical communications. This compendium is an invaluable reference edited by three scientists with a wide knowledge of the field and the community. Researchers and practitioners working in photonics and optical communications will find this book a valuable resource.

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