# Greedy Algorithm for Reducing *FWM* Impairments in Dynamic Optical Networks

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***Abstract*— This work presents a study on impact of Four Wave Mixing in dynamic optical networks. A simple algorithm is proposed in order to manage Four Wave Mixing impairments. Numerical results regarding blocking probability suggest that wavelength assignment should favor the wavelength with the smallest amount of noise. The limits for the use a simple greedy algorithm are tested. Although the algorithm clearly fails when network is severely impaired by *FWM*, significant improvements are achieved for low and moderate levels of *FWM*.**

## I. Introduction

Algorithms for routing and wavelength allocation in optical networks, e.g. [1]-[4], have been systematically neglecting physical impairments from the optical layer. Algorithm complexity is, possibly, the main reason for this issue to be avoided. However, there are growing concerns on the actual role played by physical layer in network performance. As quality of service is becoming a important issue in today's optical networks [5], proposals for algorithms with some physical-layer visibility, e.g.[6], are gradually arising. Although at a higher complexity cost, algorithms which include physical layer limitations may bring additional benefits such as reductions in overall system cost [7], [8]. Nevertheless, channel mutual influence due to non-linear effects and transient effects during signal propagation in optical fibers and optical amplifiers, respectively, are yet to be considered. In a static point-to-point optical network, every transmission link can be carefully modelled in order to ensure that the quality of the optical signal is achieved for each of them. Nonetheless, it would be rather complex to have such approach applied to dynamic optical networks due to ever-changing connection states throughout the network. The main contribution of this paper lies in a model for network layer with physical visibility in which only important effect of the physical layer should be chosen in order to avoid excessive computational effort. Considering the present scenario, where a increasing number of channels is being transmitted using narrower spacing between them, Four Wave Mixing (*FWM*) is the dominant nonlinear effect in degrading quality of optical signal [10], [11].

For the sake of simplicity, the algorithm here proposed follows what could be called a *Greedy Allocation* procedure as wavelength assignment just takes into account *FWM* noise over available lightpaths linking source to destination through a single wavelength, in other words, the ones with wavelength continuity. Different metrics are discussed regarding the choosing of a particular wavelength out of a set of *qualified lightpaths*, i.e. available lightpaths with signal-to-noise above a given threshold. Considering that a newly established connection is likely to degrade performance of ongoing connections, the limitations for wavelength assignment based on such limited view of the network need also to be assessed. Results suggest that the proposed algorithm might be used as a means of reducing connection blocking probability caused *FWM* accumulation; especially in cases where optical power and channel spacing produce moderate levels of *FWM*. The remainder of this paper is organized as follows. Section II presents features from physical and network layers that are taken into account by the proposed algorithms. Section III presents a comprehensive study regarding blocking probability for three variations over the greedy technique for wavelength assignment and their limitations. Final remarks are drawn in Section IV along with the conclusions.

## II. Network Model and Algorithms for Wavelength Allocation

### A. Network Model

Dynamics optical network model without wavelength conversion has the wavelength continuity as the only criteria for connections blocking [1]. The network model presented in this work, on the other hand, establishes a relationship between physical and network layers. Despite complying with the wavelength continuity constraint, a connection request across the network might also be blocked on ground of insufficient signal-to-noise ratio. The amount of *FWM* from interactions between currently active connections that are falling on available lightpaths.

*1)* ***Four Wave Mixing at Physical Layer****:* *FWM* is characterized by the interaction among propagating channels [12]. Assuming negligible power depletion at original wavelengths, *FWM* crosstalk power is given by [13] for crosstalk generated at frequencies given by $(i, j \neq k)$ [14]:

$$P_{FWM}(L) = \frac{\eta}{9} D^2 \gamma^2 P_i P_j P_k \exp(-\alpha L)(L_{eff})^2 \quad (1)$$

$$f_{ijk} = f_i + f_j - f_k \quad (2)$$

where $P_i$, $P_j$, and $P_k$ stand for the optical powers channel launched into the fiber. $D$ is the degeneracy factor (either 3 or 6 for degenerate and not degenerate *FWM*, respectively), $\gamma$, and $\alpha$ are, respectively, the nonlinear and the fiber attenuation coefficients, $L$ is the fiber length, $L_{eff}$ is the effective length, $\eta$ is the *FWM* efficiency factor [13], $i, j \neq k$, $1, 2, ..., N$; $N$ is the number of channels.

Dispersion Shift Fiber (*DSF*) is used in the simulations as such fibers present *FWM* as a the most prominent non-linear effect. Dispersion versus wavelength model is given as follows:

$$D_C(\lambda) = S_0(\lambda - \lambda_0) \quad (3)$$

where $\lambda_0$ is the zero-dispersion wavelength and $S_0$ is the chromatic dispersion slope.

For the purpose of investigation of *FWM* effect on network performance, it is reasonable to assume *FWM* as the dominant noise at optical receivers. By using Gaussian approximation, $Q$ factor can be expressed as [15]:

$$Q = \frac{bP_s}{\sqrt{N_{FWM}}} \quad (4)$$

where $N_{FWM}$ is the beat signal-*FWM* noise and is written as:

$$N_{FWM} = 2b^2 \frac{P_{FWM}}{8} \quad (5)$$

In (4) and (5) $b$ is the receiver responsivity, $P_S = P_i \exp(-\alpha L)$ is the channel power in the receiver input.

2) ***Call Admission Control*** *:* The network management call admission control is based on two criteria, namely, wavelength continuity and optical signal quality. A threshold $BER$ (Bit Error Rate) is arbitrated ($BER = 10^{-9}$). A request for a lightpath may meet the wavelength continuity constrain but it is blocked regardless in case $BER$ is below the aforementioned threshold. For an incoming connection request arrives at the network, the routing algorithm is in charge of finding the shortest routes between its origin and respective destination. The wavelength allocation algorithm then searches out available wavelengths in such routes and works out their respective *FWM* noise caused by lightpaths currently in use. It is, therefore, necessary to find out all ongoing connections in the network that share common links with the present connection request. The crosstalk power generated over the available lightpaths can be calculated. The total crosstalk power at the destination is found by adding contributions from each link:

$$P_{RN}(f_m) = \sum_{c=1}^{H} \sum_{f_{kc}} \sum_{f_{jc}} \sum_{f_{ic}} P_{FWM}(f_{ic}, f_{jc}, f_{kc}) \quad (6)$$

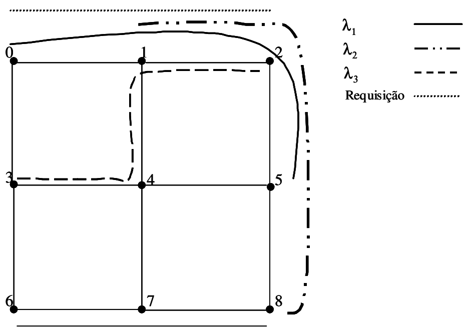


Fig. 1. Network with 9 nodes and 8 wavelengths

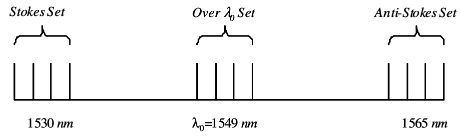


Fig. 2. Wavelength Set Positions

where $P_{RN}(f_m)$ is the total crosstalk power that reaches the receiver; $H$ is the number of hops in a route; $f_m$ is the equivalent optical frequency to the wavelength of the available lightpath; $f_{kc} = f_{ic} + f_{jc} - f_m$. $P_{FWM}$ is calculated using (1).

In order to determine the $Q$ factor for the present connection request, (4) and (5) are used, replacing $P_{FWM}$ by $P_{RN}(f_m)$.

### *B. Algorithms for Wavelength Assignment*

For the *RWA* (*Routing and Wavelength Assignment*) algorithm proposed in this paper, routes are chosen among shortest paths. It takes the path with lowest noise level in case more than one presents the lowest cost. Once a set with *qualified lightpaths* is found, i.e. those simultaneously meeting shortest path with wavelength continuity and *FWM* noise threshold requirements, the wavelength assignment itself may be implemented through:

- *FWM-WA-RD* - (*FWM Wavelenght Assignment Random*)
- *FWM-WA-FF* - (*FWM Wavelenght Assignment First Fit*)
- Minimum *FWM* (*MinFWM*)

If *FWM-WA-RD* algorithm is used, a wavelength is picked randomly. For *FWM-WA-FF* algorithm the well-known *First Fit* technique [16] is applied, while Minimum *FWM* algorithm chooses the wavelenght that presents the lowest *BER* in the set with *qualified lightpaths*.

An illustration for the proposed algorithms is given in Fig. 1, where a hypothetical situation is analyzed. Assuming that at given instant there are four active connections in the network that has eight wavelengths. At this moment, a request for connection from node 0 to 2 arrives. The routing algorithm will choose the route through nodes $0-1-2$ (see Fig. 1) because this is the unique shortest route. The steps will be followed by the algorithm:

1 - Find the available wavelengths in the route $0-2$: $\lambda_4$, $\lambda_5$, $\lambda_6$, $\lambda_7$ and $\lambda_8$.

TABLE I

PHYSICAL LAYER PARAMETERS

| *Parameter* | *Value* |
|---|---|
| Fiber | Dispersion Shift Fiber |
| Zero-dispersion wavelength ($\lambda_0$) | 1549 nm |
| Dispersion Model | see (3) |
| Fiber nonlinear coefficient ($\gamma$) | 2.3 $(\mathrm{W.km})^{-1}$ |
| Fiber attenuation ($\alpha$) | 0.22 dB/Km |
| Channel Power | 0, 4 and 7 dBm |
| Frequency grid | 50, 100 and 200 GHz |
| Threshold *BER* | $10^{-9}$ |
| Receiver responsivity | 1 |

TABLE II

NETWORK LAYER PARAMETERS

| *Parameter* | *Value* |
|---|---|
| Network topology | Partially regulate |
| Number of nodes | 9 |
| Distance between adjacent nodes | 100 km |
| Number of calls | 500000 |
| Number of wavelength | 8 |
| Routing algorithms | Fixed-alternate shortest-path routing |
| Source-destine Distribution | Uniform distribution |
| Model of call generation | Poisson distribution |
| Model of call duration | Exponential distribution with average 1 s |
| Connection Management | Centralized |
| Network load | 10, 15, 20, ..., 100 Erlangs |

2 - Work out *FWM* noise on each wavelength found in step 1 reaching the destination node;

2.1 - the first candidate is $\lambda_4$. In the link $0-1$ there is only one active connection, then no noise will be generated over $\lambda_4$. This analysis is repeated for the link $1-2$. The final value of noise is obtained by adding contributions from links $0-1$ and $1-2$. Notice that the active connection $6-7-8$ has no link in common with the current connection request. Therefore, it is not taken into account in this step.

2.2 - the step 2.1 is repeated for $\lambda_5$, $\lambda_6$, $\lambda_7$, and $\lambda_8$;

3 - find a set with *qualified lightpaths*.

If the set found at step 3 were empty, the connection would be immediately blocked. Otherwise, wavelength assignment takes place. For *Random*, a wavelength is randomly selected from the *qualified lightpaths*. The *First Fit* algorithm always takes the first element from *qualified lightpaths*. Finally, the element that gathers the least *FWM* noise in *qualified lightpaths* would be chosen for wavelength assigned according to *MinFWM*.

## III. NUMERICAL RESULTS

The network simulated in this work is the one shown in Fig. 1, which is a almost regular network with 9 nodes. The eight-wavelength set is placed at three different positions, as it is seen in Fig. 2.

There is an allocation of wavelengths around $\lambda_0$ $(191,6933$ *THz*) with the central channel (*CC*) in the vicinity of $\lambda_0$. Another options is the Stokes Set, which is located around $1530$ *nm* $(196,0784$ *THz*) while Anti-Stokes Set is situated around $1565$ *nm*. Moreover, three different wavelength grids are studied in this paper: 50, 100, and 200 *GHz*. Parameters used at physical and network layers are summarized in Tables I and II, respectively.

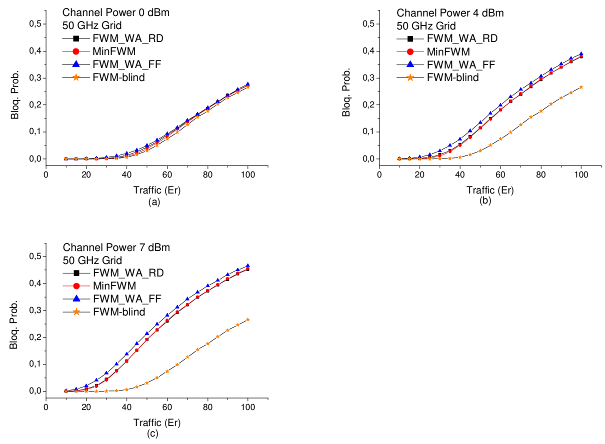


Fig. 3. Comparison between algorithms: 50 *GHz* grid

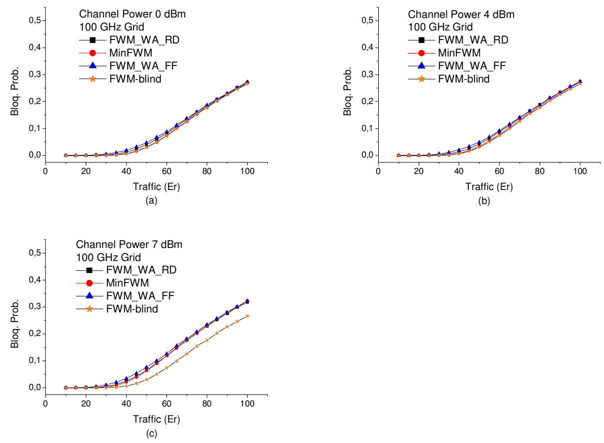


Fig. 4. Comparison between algoritms: 100 *GHz* grid

### A. Blocking Probability

Network performance is measured in terms of average blocking probability (*PB*) experienced by connection requests across network nodes. Simulation for blocking probability is also provided for the case *FWM* Crosstalk is not taken into account. Hence, in such scenario blocking is solely down to the wavelength continuity constraint. This algorithm is called *FWM-blind* and provides an important benchmark for the assessment of *FWM* impairments at network level.

*1) **Wavelength allocation over*** $\lambda_0$ : Results for wavelength set positioned over $\lambda_0$ using a 50 *GHz* grid is shown in Fig. 3. The proposed algorithms produces similar results to *FWM-blind* for reduced optical power levels, e.g. 0 *dBm*, due to the negligible effects of *FWM* on *BER*. In contrast, the additional blocking induced by *FWM* leads to a very different behavior for blocking probability curves as higher optical power is transmitted.

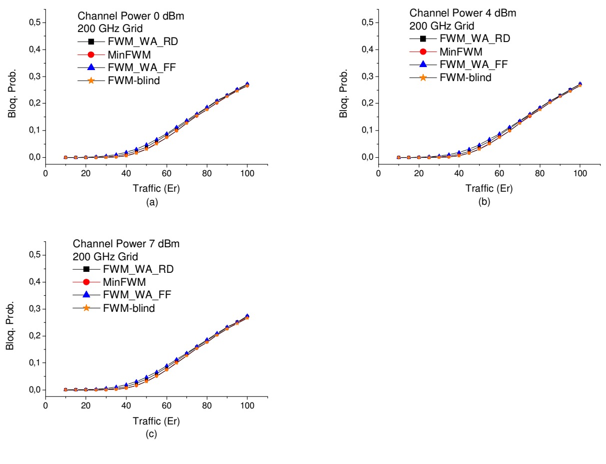


Fig. 5. Comparison between algoritms: 200 *GHz* grid

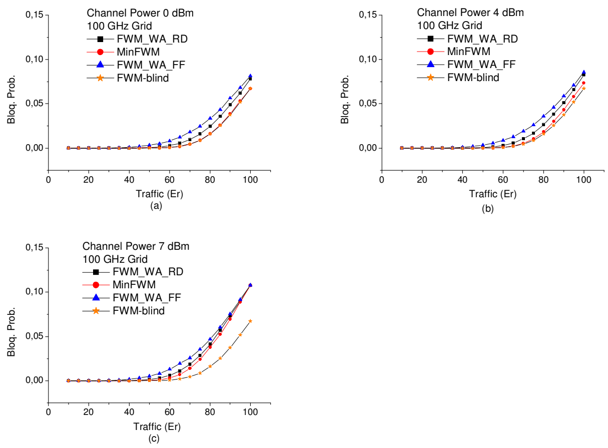


Fig. 7. Comparison between algoritms: 100 *GHz* grid and 12 wavelengths

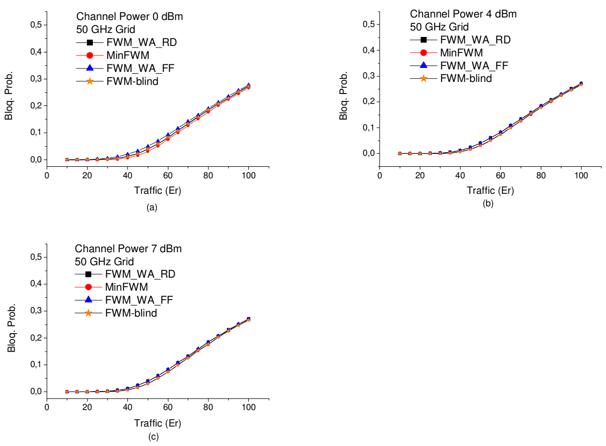


Fig. 6. Comparison between algorithms: 50 *GHz* grid and Anti-Stokes set

Note that the proposed algorithms may be suitable for *FWM* blocking mitigation in the network for moderate levels of crosstalk as results for 100 and 200 *GHz* grid suggest in Figs. 4 and 5.

*2) **Wavelength allocation off** $\lambda_0$ **region**:* Fig. 6 shows the blocking for Anti-Stokes set at 50 *GHz* grid. As it might be expected, wavelength allocation using Anti-Stokes sets, regardless of the wavelength grid used, presents blocking probabilities very similar to *FWM-blind* algorithm, even for high channel power. The same conclusion applies to Stokes set. The channels have chromatic dispersion sufficiently high to preclude phase matching, leading to low efficiency for *FWM* generation. Therefore, in such scenario one may perfectly neglect *FWM* when assigning wavelength.

*3) **Wavelength Assignment Strategy for Greedy Algorithm**:* It is intuitive that the *MinFWM* might be best strategy for wavelength assignment since the wavelength with the smallest amount of noise is chosen out of qualified lightpaths. This is confirmed in results seen in Figs. 3-5. Although no significant difference is noticed so far, results in Fig. 7 are intended to highlight performance benefits of *MinFWM* through simulations of a network with 12 wavelengths.

For moderate *FWM* levels, e.g. optical power 4 *dBm* using 100 *GHz* grid, once again the proposed algorithm proves useful in reducing blocking probability. However, in this case a significant improvement is achieved by employing a proper wavelength assignment strategy. In addition, notice that, differently from works that use just wavelength continuity as constraint on the requests blocking probability evaluation [17], [18], the *FWM-WA-RD* algorithm presents a better performance than the *FWM-WA-FF* one.

### *B. Limits in the use of Greedy Algorithms*

The results presented so far have neglected side effects of newly established connection over lightpaths formerly arranged. This issue is now addressed by assessing a probability for ongoing connection have their *BER* taken below the $10^{-9}$ *BER* threshold by the activation of new lightpaths. A metric called *Threshold Violation Probability* (*TVP*) is proposed as a means of quantifying this influence of new lightpaths on current connections. Fig. 8 shows (*TVP*) for the *MinFWM* algorithm. Notice that for *50 GHz* grid, *TVP* is very severe (close to 1). The same occurs for *100 GHz* grid at high optical power such as 7 *dBm*. This is clear indication that *MinFWM* algorithm should not be used in such circumstances. Nevertheless, *100 GHz* grid for moderate transmitted power and for *200 GHz* grid *TVP* is limited to acceptable levels.

In accordance with results presented in Section III-A, the simulations here suggest that *MinFWM* algorithm should not be used when efficiency *FWM* is high. In these cases, a new wavelength assignment policy must be devised. For instance, the *FWM* noise should be examined at all active connections, instead of limiting this analysis to available lightpaths. This

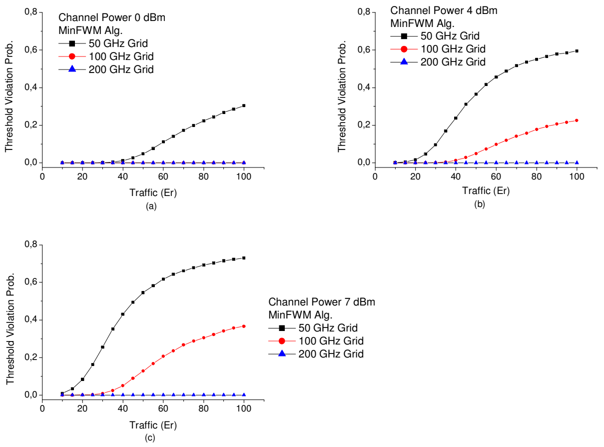


Fig. 8. Degrading Probability: *MinFWM* Algorithm

is, however, an additional complexity burden to be dealt by the algorithm.

## IV. Conclusion

This paper presented a study on the impact of *FWM* in dynamic optical networks addressing the issue *FWM*-aware algorithms. Wavelength assignment on the basis of amount of noise presented the best results. When *FWM* efficiency is not significant, the proposed algorithms presented a good performance as far as connection cloking due to *FWM* crosstalk is concerned. Nevertheless, more complex algorithms have to be used in networks that are under favoring conditions to *FWM* noise. A generalization for the proposed algorithm is straightforward. By examining *FWM* noise over all active connections, the network management reduce the qualified set to lightpaths that do not affect ongoing connections.

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