First Load Priority: A Wavelength Converter Placement Scheme for Optical Networks with Sparse-Partial Wavelength Conversion

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Abstract. *In this paper it is proposed a new wavelength converter placement scheme called First Load Priority - FLP, useful for designing and planning of optical networks with sparse-partial wavelength conversion architecture. A performance evaluation of FLP working in different scenarios is provided. Comparing to others wavelength converter placement schemes like MBPF, TOT, XC and partial wavelength conversion, FLP achieved better performance results in all scenarios studied, very close to that achieved from a full-complete wavelength conversion architecture.*

1. Introduction

WDM (wavelength division multiplexing) allows several optical channels (wavelength) to be allocated simultaneously in an optical fiber, improving its transmission capacity [Murthy and Gurusamy, 2002]. Present status of WDM technology provides transmission rates in the order of terabit per second (Tbps) in one single fiber. Besides, WDM channels can be modulated independently, allowing different rates and transmission formats in the same fiber.

In an optical network, a lightpath interconnects two optical nodes, establishing a communication path formed by one or more concatenated links between them. A lightpath has a specific route and one or more wavelengths through which the information is routed from the source to the destination node.

In WDM networks under dynamic traffic load, lightpath requests arrive upon demand. If there are network resources available, each lightpath will be established and will remain occupying resources during a holding time. Due to the limited number of network resources in this dynamic context, some lightpath requests might not be established, resulting in the blocking of connections [Ramaswami and Sivarajan, 2001].

In typical WDM networks, a lightpath must use the same wavelength in every link of the specified route. This propriety is known as wavelength continuity constraint

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[Zang et al., 2000]. This propriety makes modelling of WDM networks different from that of traditional circuit-switched networks. On the other hand, a wavelength-routed WDM network allows to overcome such restriction by using Wavelength Converters - WC. WCs are devices located at optical network nodes, with the purpose of converting an input wavelength into a different output wavelength. Therefore, using WCs, a lightpath may be formed by different wavelengths, in different links. In WDM networks of this type, a node with wavelength conversion capability is called a Wavelength Convertible Router - WCR [Chu et al., 2003b][Chu et al., 2004].

WCR conversion capability is defined according to the number of WCs implemented at the optical node. One WC converts only one input wavelength into another output wavelength at a time. Thus the number of possible simultaneous conversions in a WCR is determined by the number of WCs it has.

Wavelength-routed WDM networks use to be classified according to their wavelength conversion capability. It is possible to consider the wavelength conversion capability of each node or from the network as a whole. A node can have complete, limited or no wavelength conversion capability. The node has complete conversion capability when it is able to convert any input wavelength to any output wavelength as shown in Figure 1a. A WCR with complete conversion capability has unlimited conversion capability, being able to convert all input wavelengths into others output wavelengths. On the other hand, if the node is able to convert only some wavelengths at a time, it is called WCR with partial conversion capability (Fig. 1b).
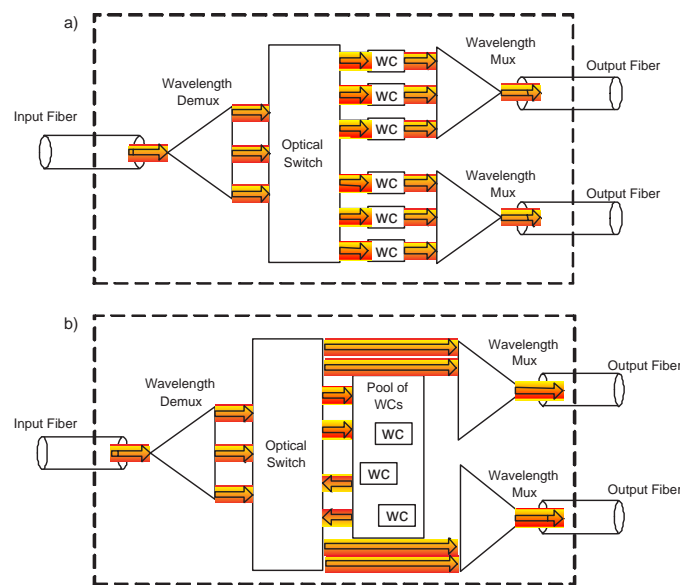

Figura 1: Types of WCR . a) optical node with complete conversion capability. b) optical node with partial conversion capability.

Considering all nodes, an optical network may have one of the following WC/WCR placement architectures: full-complete, partial, sparse or sparse-partial wavelength conversion. A WDM network is said to have full-complete wavelength conversion capacity when any lightpath is allowed to ignore the wavelength continuity constraint along the entire path. Such characteristic achieves the lower limit regarding blocking probability for a WDM network under dynamic traffic load. In a network with partial wavelength conversion, all nodes are WCRs with partial wavelength conversion capability. When only some nodes of the network have complete wavelength conversion capability

there is a sparse wavelength conversion network. If only some nodes of the network have partial wavelength conversion capability the network is said to have Sparse-Partial Wavelength Conversion capability (SPWC).

Although recent improvements in WCs technology , its costs still remain very high. The above architectures were proposed with the goal of achieving performance close to full-complete wavelength conversion using a lower number of WCs, which decreases the equipment costs. Each architecture requires a distribution of WCs or WCRs. Different schemes to place WCs have been proposed for each architecture. This work proposes a new scheme for wavelength converter placement in SPWC optical networks. The rest of this paper is organized as follows: in Section 2, the First Load Priority (FLP) scheme is introduced and some of the main wavelength converter placement schemes are presented. In Section 3, a performance evaluation study comparing the FLP scheme to other wavelength converter placement schemes is presented. Finally, Section 4 presents some conclusions.

2. Wavelength Converter Placement schemes

Many works have proposed and evaluated different wavelength converter placement schemes. Usually, these studies compare theirs proposed schemes with the full-complete wavelength conversion architecture, the lower limit regarding blocking probability. In [Subramaniam et al., 1996] it is shown that using sparse wavelength conversion architecture with some WCs it is possible to achieve a good performance close to the full-complete conversion one. Since this pioneer study, the wavelength converters placement problem started to be taking into consideration in optical network design and planning. Such problem consists in deciding in which nodes the available WCs will be placed, considering the network topology and the expected traffic load characteristics.

Algorithms for optimal position of WCs, in simple topologies, were proposed in [Subramaniam et al., 1998], but in more realistic topologies the placement problem was shown to be more complex. In [Arora, 2000] it was proposed Total Outgoing Traffic - TOT, a wavelength converter placement scheme. The TOT goal is to distribute WCRs between the nodes of the network which have the largest number of routes crossing them. In [Chu et al., 2003a] the wavelength converter placement problem is investigated along with RWA (routing and wavelength assignment) algorithms. Two schemes for wavelength converter placement problem in sparse wavelength conversion network were proposed. The first, called Minimum Blocking Probability First - MBPF, has the ability to place a limited number of WCs in an arbitrary mesh network with FAR-FF (fixed alternative routing-first fit) RWA algorithm; and the second, named Weighted Maximum Segment Length (WMSL), is proposed to work under LLR-FF (least loaded routing-first fit) RWA algorithm. In [Ramamurthy and Mukherjee, 1998], it was proposed an analytical model to incorporate FAR and wavelength conversion. In [Chu et al., 2003a] this analytical model was modified to be used in MBPF algorithm of wavelength converter placement. In [Chu et al., 2004], Xiaowen Chu et al. redefined the wavelength converters placement problem for an SPWC architecture. The goal was to identify which network nodes should be WCRs and how many WCs each WCR should have, based on an specific number of available WCs. They also proposed a new scheme to distribute WCs in an SPWC architecture. Their scheme is based on pre-simulations considering an optical network with full-complete wavelength conversion capability. In our paper, we will be referring to this scheme as XC-scheme.

In this paper it is proposed a new scheme, called First Load Priority - FLP, for placement of wavelength converters in an SPWC optical network that works with any RWA algorithm. Also, it is shown from results based on simulation experiments, that FLP is more flexible and achieves better performance (regarding blocking probability) when compared to the main wavelength converter placement schemes found in the literature.

2.1. Minimal Blocking Probability First (MBPF)

Minimal Blocking Probability First was proposed to work using fixed alternative routing (k-shortest path) and First-Fit wavelength assignment for the sparse wavelength conversion architecture. It is important to remember that in sparse wavelength conversion architecture only some nodes will be WCRs, but they have complete wavelength conversion capability. In this case, a certain number (M) of WCRs with unlimited wavelength conversion capability will be distributed among the nodes of the network.

The MBPF distributes the WCRs one by one. The topology shown in Figure 2 will be used to explain the MBPF scheme. In this example there are $M = 3$ WCRs to be distributed among the 6 nodes of the optical network.
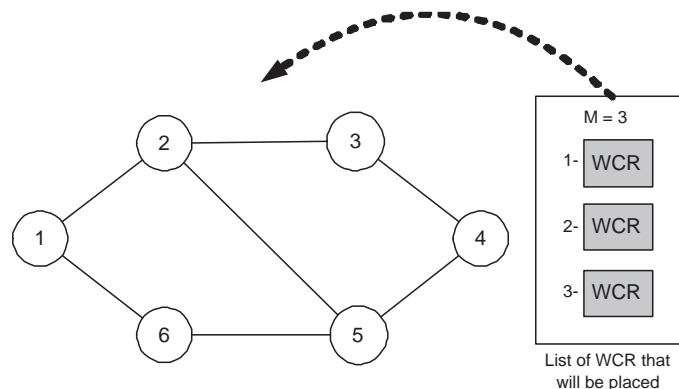

Figura 2: Example of the MBPF scheme.

1. Initially the network does not have WCRs. The first step is to choose the node where the first WCR will be placed. The MBPF calculates the blocking probability (using the analytical model proposed in [Chu et al., 2003a]), taking into account that the network has only one WCR node, and that this first WCR can be placed in any node. Hence, at this first step, six blocking probabilities ($Bp_1, Bp_2, \cdots, Bp_{n=6}$) will be calculated. The Bp_1 assumes that node 1 will be WCR, Bp_2 assumes that node 2 will be WCR, and so on. The first WCR should be placed in the node that results lower blocking probability.
2. Considering that the first WCR was placed, the second will be placed according the same rules used in the first step, but now the network has one WCR already placed. Therefore, the new blocking probabilities ($Bp_1, Bp_2, \cdots, Bp_{n=6}$) should take into consideration the WCR already placed at the previous step.
3. Gradually, this will be done until all WCRs are placed.

2.2. XC Scheme

The XC Scheme was proposed in [Chu et al., 2004] for SPWC architecture. Basically the XC Scheme performs a previous simulation with the optical network in question. It assumes that all network nodes are WCRs with complete conversion capability. Thus,

no connection will be blocked by the absence of WCs, working as a traditional circuit-switched network. At the end of the first simulation it is possible to obtain important information on the use of WCs for each node of the network. The XC scheme analyzes this information from two metrics:

A) A(n): average number of busy converters.
B) P(n): maximum number of busy converters.

The XC scheme defines that the WCRs nodes will be those which have the higher P(n) values. The second step is to determine how M (number of available) WCs will be distributed within the WCRs nodes. This is done using the A(n) measurement. The number of WCs in each node will be proportional to the value of A(n) for each node. The results obtained from the previous simulation for the first scenario studied in [Chu et al., 2004], using the NSFNET topology (Fig. 3) with the availability of 50 converters, are presented in Table 1.
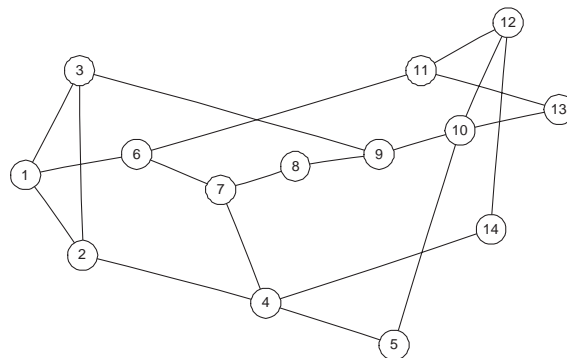

Figura 3: Topology of NSFNET.

Tabela 1: Measures of XC scheme for the NSFNET topology under 200 Erlangs load.

Node n	1	2	3	4	5	6	7
A(n)	0.4	0.7	0.3	2.3	0.4	1.8	1.6
P(n)	9	12	9	22	11	19	16
Node n	8	9	10	11	12	13	14
A(n)	0	0.7	1.4	0.7	0.6	0	0.1
P(n)	0	13	16	12	11	0	6

Applying the XC scheme to the NSFNET, according to [Chu et al., 2004] [Chu, 2003], the results were that nodes 4, 6, 7 and 10 carried out many more conversions than other nodes. The available WCs ($M = 50$) were distributed proportionally to the A(n) values, resulting in 16 WCs for node 4, 13 WCs for node 6, 11 WCs for node 7, and 10 WCs for node 10.

From these results it is possible to make some observations about the XC scheme.

1. A(n) and P(n) are obtained with the hypothetical scenario, that is, they are calculated from previous simulation considering the optical network with full-complete conversion capability. Now, consider the topology and connection status shown in Figure 4a, and try to establish a new lightpath Z between source node 1 and destination node 4 in the hypothetical scenario. For this, it will be necessary to

have WCs at nodes 2 and 3 of the route (1, 2, 3, 4) as there is no continuous wavelength (Fig. 4b). Suppose now that after the placement of all available WCs (in the real scenario), none of them is placed at node 2 (Fig. 4c). We can show that the success in establishing the lightpath Z (in the hypothetical scenario) will have a negative impact on the calculation of A(n) and P(n) for nodes 2 and 3. This latter situation occurs because a wavelength conversion at each node in the hypothetical scenario is taken into account. In the real scenario, however, such alternative would not be possible due to the absence of available WCs at nodes 2 (Fig. 4c). Also in the real scenario, with M WCs distributed, some nodes may not, in fact, be WCRs, and thus all connections established with the help of WCs at those nodes, in the hypothetical scenario, should de discarded to the A(n) e P(n) calculations (see Figure 4c).
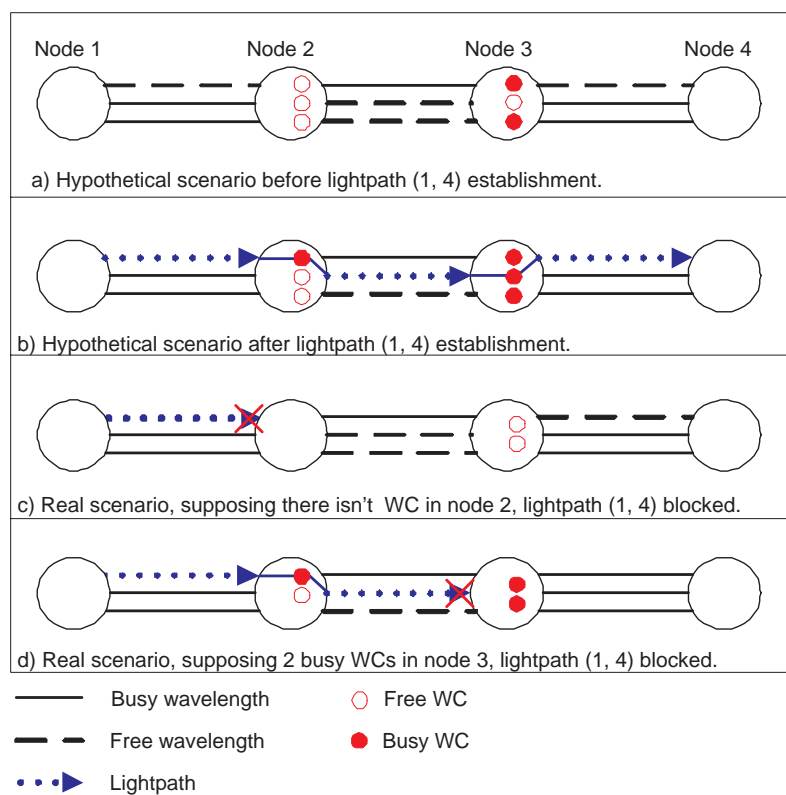

a) Hypothetical scenario before lightpath (1, 4) establishment.

b) Hypothetical scenario after lightpath (1, 4) establishment.

c) Real scenario, supposing there isn't WC in node 2, lightpath (1, 4) blocked.

d) Real scenario, supposing 2 busy WCs in node 3, lightpath (1, 4) blocked.

— Busy wavelength ○ Free WC
– – Free wavelength ● Busy WC
•••▶ Lightpath

Figura 4: Connections in the hypothetical network.

2. Now consider the establishment of the lightpath Z again through of the route (1, 2, 3, 4) (during previous simulation - hypothetical scenario) in the network shown in Figure 4a. The node 3 is using 2 WCs before the establishment of the lightpath Z (Fig. 4a). In the hypothetical scenario the lightpath Z is established successfully (Figure 4b) because there is a third free WC in the node 3 (Figure 4a) before the establishment of lightpath Z. Now suppose that after the placement of the WCs (real scenario), only 2 WCs are placed at node 3 (Fig. 4d). The lightpath Z established in the hypothetical scenario (Fig. 4b) used a third WC at node 3. Nevertheless, in the real scenario the node 3 has only two WCs and they are being used (Fig. 4d). Thus, the establishment of the lightpath Z will have a negative impact for the calculation of A(n) and P(n) for nodes 2 and 3. This occurs because the establishment of the lightpath Z in the hypothetical scenario uses a converter at the nodes 2 and 3, which would not be possible in the real scenario due to the absence of a third WC at node 3 (Fig. 4d).

3. If a WCs placement scheme limits the number of nodes that will become WCRs, in the best case (unlimited WCs, $M = \infty$), the optical network will behave as a sparse conversion optical network one. It is important to observe that the goal of sparse-partial wavelength conversion scheme is to combine the advantages of sparse conversion with those of partial conversion, providing a flexible way to choose which nodes will be WCRs, as well as the number of WCs at each WCR. Therefore, the WCRs placement scheme must have as primary goal the distribution of the M available WCs according to the demand at each node. This aims to achieve performance close to the network with full-complete conversion capability.

2.3. First Load Priority - FLP

Considering the above observations about XC scheme, a new scheme for the placement of converters in an SPWC architecture, called First Load Priority - FLP, was conceived. FLP scheme, as well as XC scheme, requires a previous simulation of the optical network with an unlimited number of WCs in each node. This previous simulation must be carried out under First Load (FL) traffic to distribute M WCs. Such traffic load should be equal to that demanding only M WCs in the whole network.

FL is the traffic load that will require exactly M WCs in the network with full-complete conversion capability. The FLP scheme distributes the M available WCs according to the P(n) values of each node computed at the end of the previous simulation. FL corresponds to the maximum traffic load that can be submitted to the network with M distributed WCs, ensuring that the network has performance identical to a network with unlimited WCs in all the nodes - in terms of blocking probability. This happens because the distribution of WCs is based on the maximum number of WCs demanded at each node, calculated through simulation using a full-complete wavelength conversion scenario under a load equivalent to FL. Figure 5 illustrates the behavior of the curves of blocking probability for the same topology with full-complete wavelength conversion and sparse-partial wavelength conversion using FLP scheme.
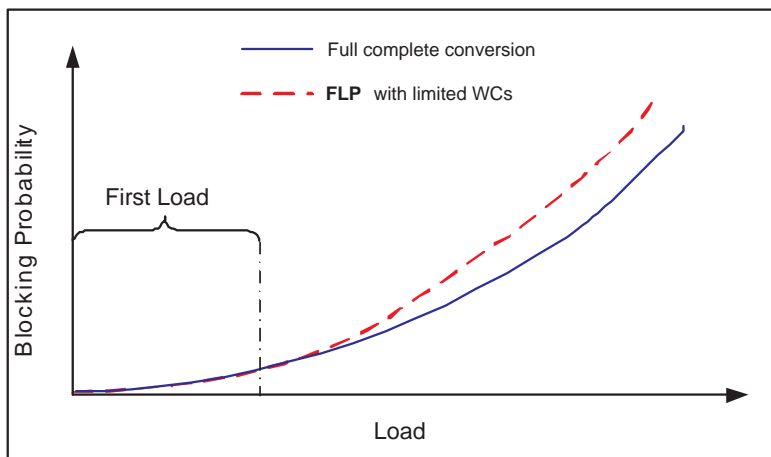

Figura 5: FLP behavior.

Suppose now that there are M=100 available WCs for distribution in a given topology with N nodes. The FLP scheme, initially, must calculate FL through previous simulations under a scenario of full-complete wavelength conversion. Once FL is found, that is, the load with which $\sum_{i=1}^{N} P(i) = 100$, the 100 WCs will be placed according to the values of P(n).

FLP scheme tries to guarantee that all conversions carried out in the hypothetical scenario (network with unlimited capacity of WCs under an FL traffic load) will also be carried out in the real scenario, where the available WCs have already been distributed, avoiding all restrictions pointed out previously from the XC scheme.

3. Numerical Results and Analysis

It is presented in this section a performance evaluation study of the FLP scheme here proposed for WCs placement in an SPWC optical network. Such study is based on simulations of discrete events. FLP performance is compared to the others wavelength converter placement schemes presented in the previous section

3.1. Simulated Model

A dynamic traffic model was used in the simulations, where connection requests arrive at each node following a Poisson process with an average rate λ. The load is distributed uniformly for all nodes. The holding time of connections is distributed exponentially with an average $1/\mu$. All links are bi-directional and each has W wavelengths in both ways. The network load is $\rho = N \cdot \lambda/\mu$, where N is the number of nodes in the network. The wavelength assignment algorithm used was First-Fit.

Simulations for the NSFNET topology were carried out with 14-nodes (Fig. 3) and W = 40. For each simulation, 10 replications with different seeds of random variable were made, and for each replication, 100,000 connections requisitions were generated. All results also show the confidence intervals calculated with 95% confidence level.

Simulations were carried out using SimRWA [Soares et al.,] a simulation tool developed to study RWA algorithms and survivability techniques in all-optical networks. Figure 6 illustrates an example of a SimRWA screenshot.
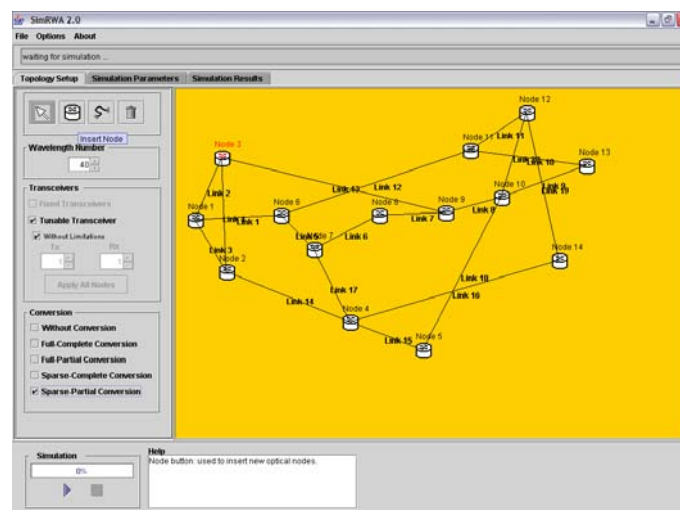

Figura 6: Example of a SimRWA screenshot.

In order to validate the results obtained through simulations with SimRWA working with sparse-partial wavelength conversion capability, it was done a comparison to analytical results using the model presented in [Ramamurthy and Mukherjee, 1998]. It was used network topology of Figure 7 with four nodes with wavelength conversion capability (WCRs). All four WCRs have only three WCs. The RWA algorithms used was
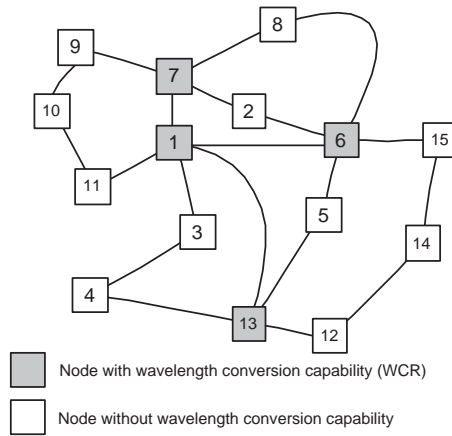
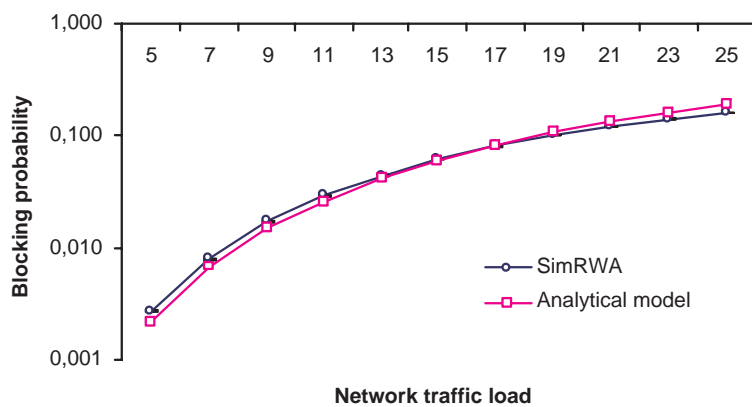**Figura 7: NSFNET configuration used to validate SimRWA modelling.**

Figura 8: SimRWA simulation and analytical modelling performance results.

first-fit and fixed routing with shortest path. Figure 8 shows the results from SimRWA simulation and analytical modelling of the NSFNET configuration studied.

One may observe from the curves in Figure 8 that SimRWA provides performance results very close to the analytical model proposed in [Ramamurthy and Mukherjee, 1998].

3.2. FLP versus MBPF and TOT

Figure 9 presents simulation results for a NSFNET topology after the placement of WCs using FLP, MBPF and TOT wavelength converter placement schemes. First-fit and fixed alternative routing (k=2 disjoint shortest path) were used. Table 2 shows the placement of WCs using MBPF, TOT and FLP schemes. Figure 10 presents the average length of the established connections for FLP, MBPF and TOT schemes and for the network with full-complete wavelength conversion capability.

Tabela 2: WC Placement for MBPF, TOT and FLP schemes.

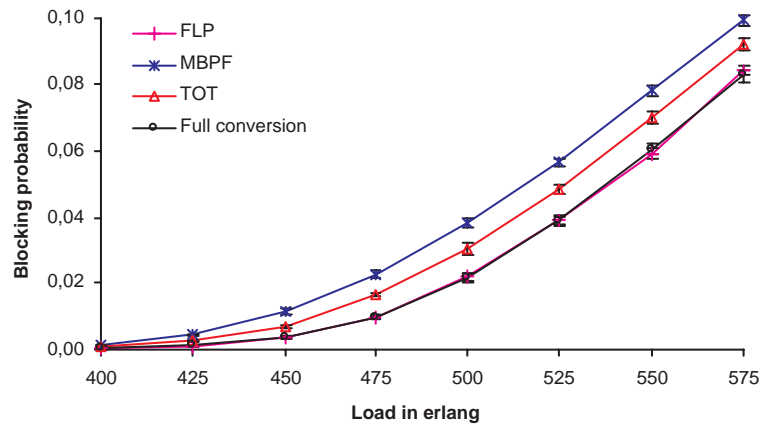| Node	1	2	3	4	5	6	7
MBPF	120	120	0	160	0	0	120
TOT	120	120	0	160	0	120	0
FLP	11	14	12	49	11	40	22
Node	8	9	10	11	12	13	14
MBPF	0	120	0	0	0	0	0
TOT	0	120	0	0	0	0	0
FLP	3	27	36	17	23	1	14

Figura 9: Blocking probability of FLP, MBPF, TOT and Full-Complete Conversion schemes.

From Figures 9 and 10, one observes that FLP scheme presents a lower blocking probability than MBPF and TOT schemes. The blocking probability of FLP is basically the same of the full-complete wavelength conversion scheme. It is important to note that FLP used only 280 WCs while TOT and MBPF used 640 WCs (Table 2). Figure 10 shows that using FLP the average length of the established connections is very close to that one of full-complete wavelength conversion. One can also notice that the average length of the established connections increases when the traffic load increases. This happens because, in this scenario, the fixed alternative routing with shortest path was used. When
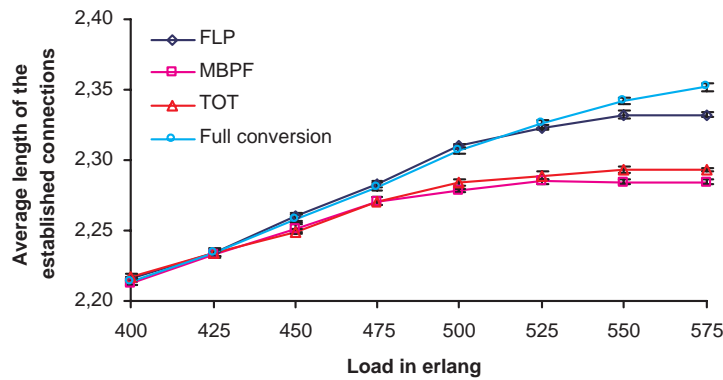
Figura 10: Average length of established connections for FLP, MBPF and TOT schemes.

the first route (k=1) for a given pair of nodes does not have free wavelengths, longer route (k=2) is used. This causes an increase in the average length of the established connections. Besides, achieving better performance than MBPF and TOT, the FLP scheme, in the scenario of Figures 9 and 10, uses a considerably smaller number of WCs and achieves performance results very close to the full-complete wavelength conversion scheme.

In order to compare the FLP scheme in a SPWC network with Partial wavelength converter placement it was carried out another study by simulation. Figure 11 shows FLP performance in a SPWC network versus partial and full-complete wavelength conversion. It was assumed 0, 2, 4, 6, 8 and 10 WCs for each node in a partial wavelength conversion network under a load equal to 500 erlangs. This means respectively, 0, 28, 56, 84, 112 and 140 WCs in the whole network. Therefore, to compare Partial wavelength converter placement with FLP the value of M varied between 0, 28, 56, 84, 112 and 140 WCs.
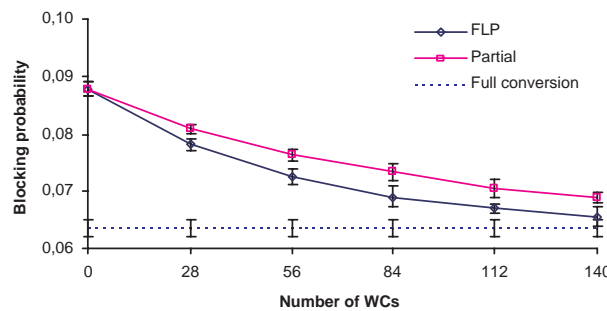

Figura 11: FLP in SPWC architecture versus Partial and Full-Complete wavelength conversion.

One should notice that the SPWC architecture (using FLP) has a performance much better and more flexible than the partial wavelength conversion architecture. FLP had better results in terms of blocking probability and average length of the established connections when compared to Partial wavelength conversion. With 140 WCs, FLP achieved performance results very close to that of the full-complete wavelength conversion architecture.
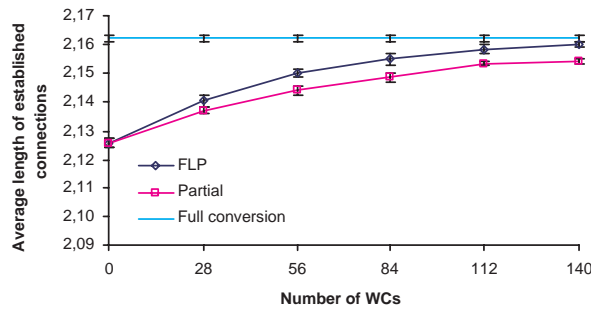
Figura 12: Average length of established connections of FLP in SPWC architecture versus Partial and Full-Complete wavelength conversion.

3.3. FLP versus XC scheme

In this section FLP will be compared with the XC scheme, another wavelength converter placement scheme that also works in SPWC architecture. This scenario is the same as [Chu et al., 2004] [Chu, 2003] and will be used to compare XC and FLP performances - fixed routing with shortest path will be used.

Studies were initially conducted distributing only 50 WCs (M = 50), approximately 3.3% of the number of WCs needed to implement the full conversion network (1,520 WCs). According to [Chu et al., 2004], XC scheme distributes the 50 WCs as shown in Table 3.

Tabela 3: Distribution of M=50 WCs by XC scheme.

Node n	4	6	7	10
Number of WCs	16	13	11	10

Applying the FLP scheme to the NSFNET topology with $M = 50$, it is obtained a WC distribution per node as presented in Table 4. These numbers were obtained for a traffic load of 170 erlangs, First Load - FL. Such WC distribution represents the maximum number of WCs used in each node in the network throughout the previous simulation.

Tabela 4: Distribution of M=50 WCs by FLP scheme.

Node n	1	2	3	4	5	6	7
WCs	1	3	3	11	2	8	3
Node n	8	9	10	11	12	13	14
WCs	0	6	7	3	2	0	1

Figure 13 shows the blocking probability achieved for the NSFNET topology with M = 50, applying XC,FLP, full-complete conversion and no conversion schemes. In Figure 14 the average length of established connections is shown in relation to the network load for the same scenario of Figure 13.

One should notice in Fig. 13 a little difference between FLP and XC in terms of blocking probability, where the former scheme provides a lower probability in comparison to the latter. Besides that, Figure 14 shows that the average length of established connections using FLP was longer than using XC scheme. This indicates a better utilization of the resources by the FLP scheme.
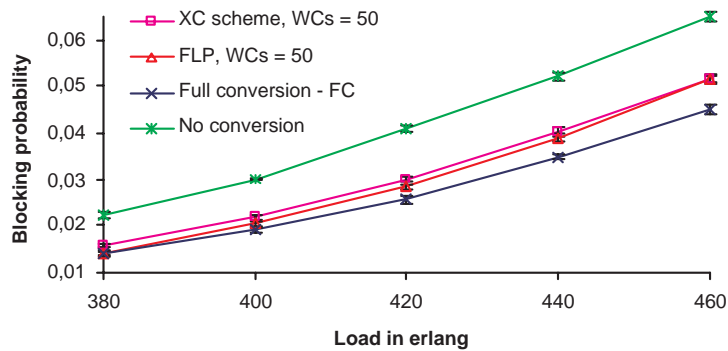
Figura 13: Blocking probability according to wavelength converter distribution scheme, NSFNET topology with M = 50.
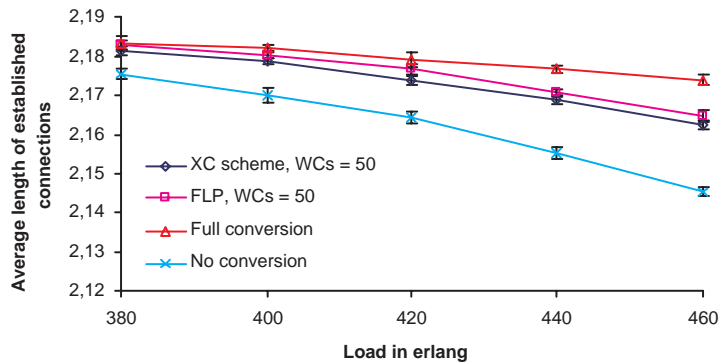

Figura 14: Average length of established connections according to wavelength converter distribution scheme, NSFNET topology with M = 50.

Figure 15 shows the blocking probability for the NSFNET topology with M = 100 (approximately 6.6% of the number of WCs needed for the implementation of full-complete conversion), using schemes XC, FLP, full-complete conversion , no conversion and also with the XC scheme with $M = \infty$. Figure 16 shows the average length of established connections for the same scenario of Figure 15.

Figures 15 and 16 show that with 100 WCs (M = 100), FLP presented a performance very close to that of the architecture with full-complete wavelength conversion capability. This is observed in terms of blocking probability, as well as in terms of established connections average length. The XC performance was again inferior to that of the FLP. It is important to notice that using XC scheme with unlimited number of WCs the results were very close to those obtained with the XC scheme, distributing 50 and 100 WCs. Such behavior was expected for, as indicated previous in this paper, the XC scheme only selects the main nodes according to their statistics for WCs distribution, and thus, although more WCs are made available, the performance of the network will be limited to that of a sparse conversion network. Besides, with the increase in number of WCs, the curves in Figures 15 and 16 show an improvement of the FLP performance.
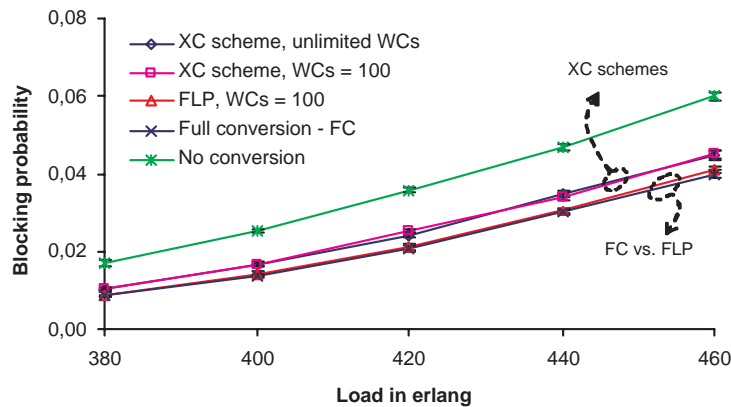
Figura 15: Blocking probability according to wavelength converter distribution scheme, NSFNET topology with M = 100.
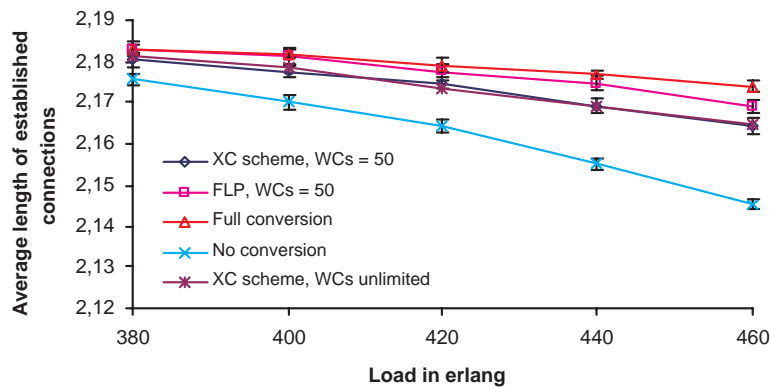

Figura 16: Average length of established connections according to the wavelength converter distribution scheme, NSFNET with M = 100.

4. Conclusion

A new scheme for wavelength converters placement in an optical network with sparse-partial conversion capability, called First Load Priority - FLP, was proposed. The performance of the FLP scheme in terms of blocking probability and resources utilization in different scenarios was studied. FLP performance was shown to be very close to that of the full conversion (limit reference) and superior to schemes like MBPF, TOT and XC for all scenarios studied. Also, FLP when compared to partial wavelength conversion architecture showed better performance.

Other studies are under way, taking into consideration other scenarios of sparse-partial conversion capability network, involving other wavelength assignment algorithms, other routing strategies, and optical networks survivability strategies.

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