# MatPlanWDM: An educational tool for network planning in wavelength-routing networks

P. Pavon-Mariño, R. Aparicio-Pardo, G. Moreno-Muñoz, J. Garcia-Haro, J. Veiga-Gontan

Department of Information Technologies and Communications, Polytechnic University of Cartagena, Plaza del Hospital 1, 30202 Cartagena, Spain
Pablo.Pavon@upct.es, Tlf: +34968325952, Fax: +34 968325973

**Abstract.** This paper presents the MatPlanWDM tool, an educational network planning tool for wavelength-routing WDM networks. It includes a set of heuristic algorithms for solving the virtual topology design, and the routing and grooming of traffic flows on top of it. In addition, an implementation of the linear programming problem to obtain the optimal solution of the complete design is included for comparison. The input parameters to the planning problem are the network physical topology, the traffic matrix, and technological constraints like the number of transmitters, receivers, optical converters and wavelengths available. The tool is implemented as a MATLAB toolbox. The set of heuristic algorithms can be easily extended. A graphical interface is provided to plot the results obtained from different heuristics and compare them with the optimal solution in small-scale topologies.

## 1 Introduction

The tremendous increase of the transmission capacity in optical networks provided by the Wavelength Division Multiplexing (WDM) technology has created a gap between the amount of traffic we can transmit, and the amount of traffic that can be processed electronically in the switching nodes. This is called the "electronic switching bottleneck", and has a more evident impact on backbone networks, which carry the highest volume of traffic.

Several alternatives have been proposed in order to address this bottleneck. They intend to decrease the traffic that has to be switched electronically in the nodes, by allowing a more or less sophisticated switching at the optical layer. Optical Packet Switching (OPS) and Optical Burst Switching (OBS) paradigms are based on switching nodes capable of an optical processing of optical packets/bursts [1]. Both alternatives are still in a research or testing stage [2] because of the non-mature state of the photonic enabling technologies involved. Nowadays, the only commercial

alternative addressing the optical-electronic gap is given by the Wavelength-Routing (WR) switching paradigm. In WR networks, traffic is carried onto transparent lightpaths that may traverse a given number of nodes. This is performed by reconfigurable optical add/drop multiplexers (R-OADM) or reconfigurable wavelength crossconnects (R-WXC), which allow some wavelengths to be dropped or added in a link, while others are optically switched without electronic conversion [1], [3]. Figure 1 sketches a node of this type. Figure 1-(a) identifies the two types of lightpath configurations carrying traffic which is not processed electronically in the node, without (1) or with (2) wavelength conversion. In the first case, the lightpath is called to be the subject of the *wavelength continuity constraint*. Figure 1-(b) shows four lightpaths which carry traffic that is processed electronically in the G-fabric (grooming fabric) of the node. The 100% of the traffic in lightpath (3) is ingress traffic added by the node. The 100% of the traffic in lightpath (4) is egress traffic dropped in the node. Lightpaths (5) and (6) show a much more common situation. Some portion of the traffic in lightpath (5) is dropped in the node. The rest of the traffic is groomed. That is, it is allocated in other lightpaths like (6) which are initiated in this node, sharing the lightpath with other grooming and/or add traffic.

Figure 1 helps us to identify the main functional blocks in the switching nodes and the WR network itself, which impact the overall cost of the network: a) the number of input and output wavelengths, which may be different for each fiber link, b) the number of electro-optic transmitters (T) and opto-electronic receivers (R) in the node, c) the number of tunable wavelength converters (TWC) in the node and d) the electronic switching capacity required, given by the sum of the ingress, egress and grooming traffic.

The equipment required is determined by the network planning decisions taken:

(i) *Virtual Topology (VT) Design*. The VT consists of the lightpaths to be configured in the network, their traversing fibers, and their transmission wavelengths in each hop. A lightpath consumes one transmitter in the initial node, one receiver in the ending node, and one TWC in any intermediate node where a wavelength conversion is required.

(ii) *Routing of the traffic flows on top of the VT*. This decision is related to the way in which the traffic (electronic traffic flows offered to the network) is routed on top of the established lightpaths. This determines the amount of traffic to be carried by each lightpath (which can be used to compose a congestion measure), and where and how the grooming is performed (which determines the electronic switching capacity required in each node).

The combined (i+ii) network planning problem to be solved can be summarized as: "for a given traffic demand and a given network topology (existing fiber links between nodes), determine the VT design and routing of traffic flows on top of it, which optimizes a given cost function". The VT design problem is also denoted as the RWA (Routing and Wavelength Assignment) problem. It is known to be a NP-hard problem ([4], [5], [6]). Obviously, the composed (i+ii) problem is also NP-hard.

In the last decade, several techniques have been presented to solve the aforementioned network planning problems. They can be classified into two categories: mathematical programming approaches, and heuristic methods. The

former, are generally based on a mixed-integer linear programming (MILP) formulation of the planning problem, followed by a search of the optimum or a suboptimum solution by means of conventional optimization algorithms. Unfortunately, the search of the optimum solution is limited to small to medium size topologies because of the exponential complexity growth. The latter approach, is based on faster algorithms, designed specifically to solve problems (i), (i+ii), or some parts of these problems. These algorithms do not search for an optimum solution, but look for a good approximation which can be computed in polynomial time.

Table 1 summarizes some related works in this field.

| Algorithms | (i) | (ii) | Wavelength Conversion | Objective Function | References |
|---|---|---|---|---|---|
| HLDA | YES | NO | NO | Maxim. Single-Hop Traffic, Minim. Congestion | [1] [7] |
| MLDA | YES | NO | NO | Maxim. Single-Hop Traffic, Minim. Message Delay | [1] [7] |
| TILDA | YES | NO | NO | Minim No. Used Physical Links | [7] |
| LPLDA | YES | NO | NO | Minim. Congestion | [7] |
| RLDA | YES | NO | NO | -- (Random Assignment) | [7] |
| SHLDA | YES | NO | NO | Minim. No. of Virtual Hops | [8] |
| LEMA | YES | NO | NO | Minim. Single-Hop Traffic, Minim. Multi-hop Traffic | [1] [9] |
| SHTMH | YES | NO | NO | Maxim. Single Hop Traffic | [1] |
| PDMH (Greedy) | YES | NO | NO | Minim. Propagation Delay | [1] |
| SABH (Sim. Ann.) | YES | NO | NO | Minim. Message Delay | [1] [6] |
| HRWA | YES | NO | NO | Minim. Required No. of Wavelengths | [10] |
| FAR-FF RWA with SWC | YES | NO | YES | Minim. Blocking Probability | [11] |
| LLR-FF RWA with SWC | YES | NO | YES | Minim. Blocking Probability | [11] [12] |
| MBPF under FAR-FF RWA | YES | NO | YES | Minim. Blocking Probability | [11] |
| MBPF under WLCR-FF RWA | YES | NO | YES | Minim. Blocking Probability | [12] |
| WMSL under LLR-FF RWA | YES | NO | YES | Minim. Sum of the maximum segment length | [11] [12] |
| WCA | YES | NO | YES | Minim. Blocking Probability | [13] |
| Flow Deviation Algorithm | NO | YES | NO | Minim. Network-Wide Average Packet Delay | [6] |
| -- | NO | YES | NO | Minim. No. of Transceivers | [14] |

Observations: the acronyms in the table can be found in the included references.

In this paper, an educational network planning tool for WR networks, with and without the wavelength continuity constraint, is presented. It is developed as a set of MATLAB [15] functions, along with a graphical interface. The toolbox can be publicly downloaded at the MATLAB Central site [15]. Its goal is to allow the testing of a set of heuristic algorithms, providing an integrated framework to observe, learn and study the VT planning concepts involved. The user can calculate and evaluate the results obtained when different algorithms are executed (in terms of the items from a)

to d) mentioned above). A MILP optimum search of the (i+ii) problem [1] is also included in the tool, so that their results can be compared to the ones achieved by the heuristic algorithms (except for large topologies). The tool is fully extensible in terms of network topologies, traffic demands and optimization algorithms. These features make MatPlanWDM an adequate teaching tool in the field of network planning in WR networks. As shown in section 2, the focus on the algorithmic issues of the WR network planning is a novel approach not covered by other educational tools.

The rest of the paper is organized as follows. Section 2 summarizes related work. Section 3 describes the structure of the toolbox, and section 4 presents the graphical interface implemented. Finally, section 5 concludes the paper.
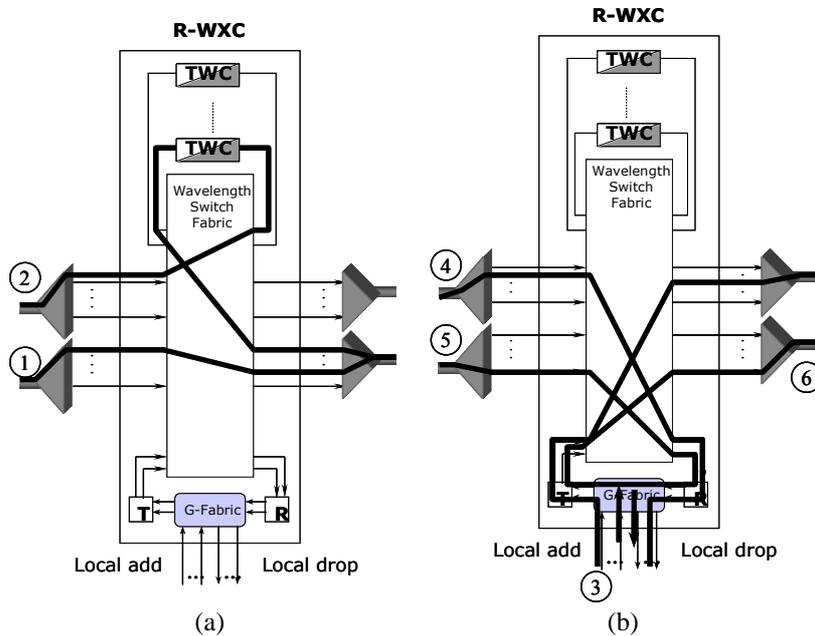


Figure 1. Functional blocks in a switching node in a WR network.

## 2 Related work

This section briefly overviews some relevant educational planning tools, for WR networks. Naturally, a wide range of commercial utilities also exists, for the dimensioning of WDM networks [16-21]. Nevertheless, these tools are not designed for educational purposes (i.e. their underlying algorithmic details are not made public), and are not considered in this paper.

A notable educational tool is the *Optical WDM Network Simulator* (*OWns*) [22], designed as an extension to the well-known network simulator *ns*. The *OWns* facilitates the study of switching and routing schemes in WDM networks. It tries to incorporate the key characteristics of WDM networks in the simulator, such as optical switching nodes, multi-wavelength links, virtual topology constructions, related

switching schemes and routing algorithms. In opposition to the dynamic event-driven *simulator* approach in *OWns*, the MatPlanWDM tool is specifically devoted for *static* or *off-line* network planning, concentrating the focus on the optimization algorithm design. The MATLAB language provides a simpler and more powerful framework than *OWns* for this purpose, which helps to clarify the planning concepts addressed.

Another educational network planning tool that can be employed for the analysis of WDM networks can be found in [23]. It employs the high level programming language Scilab for the user interface and C for computer intensive algorithms. This Scilab code analyses a given fiber plant and traffic requirements and returns the cost of different technological solutions. Unlike MatPlanWDM, the optimization engine in [23] provides little flexibility for testing different planning algorithms. It applies Dijkstra and Suurballe algorithms to obtain the shortest path between each pair of nodes, which further determines the equipment allocation. Therefore, again, this approach does not concentrate on the planning concepts addressed in the MatPlanWDM tool.

Delite [24] is a non-WDM specific educational tool. It follows a similar static philosophy of the MatPlanWDM tool, offering a set of planning algorithms for evaluation and comparison, under different traffic patterns and network topologies. Delite is implemented in C language, it is open source, extensible, and purely designed for academic purposes. Unfortunately, Delite tool does not consider the specifics of the RWA planning problem, or provide any optimum MILP search for comparison. In addition, when compared to MatPlanWDM tool, the advantages of the MATLAB language for the implementation of more complex mathematical operations is made evident.

## 3   Description of the toolbox

The MatPlanWDM tool has been implemented as a MATLAB [15] toolbox, consisting of a set of MATLAB functions. All the functions are documented, and open for free usage. Figure 2 helps us to describe the structure of the toolbox:

- *Input parameters*. The input parameters for the planning problem are: (1) the network topology (including the distances in kilometers between nodes), (2) the traffic matrix, (3) the maximum number of transmitters and receivers in each node, (4) the maximum number of wavelengths in each link, and (5) the maximum number of TWCs in each node. Zero TWCs in all nodes defines a problem restricted by the wavelength continuity constraint. MatPlanWDM provides some sample network topologies (i.e. the NSFNET), and sample traffic matrixes (i.e. sample matrix for NSFNET presented in [7]). In addition, a help function is provided to assist the generation of different types of traffic matrixes: uniform distribution between nodes, composition of heavy loaded and lightly loaded nodes with different proportions, and the method presented in [24] for creating traffic matrixes as a function of node population and inter-node distance.
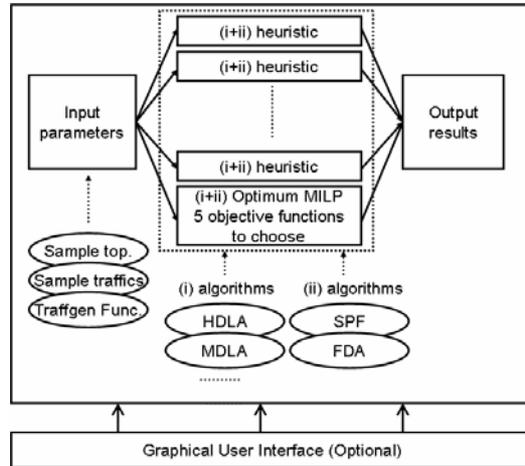
Figure 2. MatPlanWDM toolbox structure.

- *Optimization algorithms*. The optimization algorithms are responsible for calculating a solution to the (i+ii) problem defined by the selected input parameters. These algorithms are implemented as MATLAB functions which follow a fixed signature, establishing the format of the input parameters, and the format of the output results. A broad range of heuristics has been implemented. Many of them result from the combination of one heuristic for the (i) problem, whose output is, in its turn, passed as the input of an algorithm solving the problem (ii). A library of functions of heuristics solving problem (i) is included in the toolbox. These heuristics are: HLDA, MLDA, TILDA and RLDA [7]. In addition, two algorithms for the routing of the flows are also included, an SPF routing (which minimizes the distance of each flow in terms of number of lightpaths traversed), and the Flow Deviation Algorithm (FDA) [6] routing (which minimizes the network-wide average packet delay). This scheme is fully and easily extended with further (i), (ii) or (i+ii) algorithms.

  The MatPlanWDM toolbox developed contains as well a function which implements a MILP programming of the (i+ii) problem as proposed in [1]. MatPlanWDM provides an optimum solution of this program by means of the TOMLAB/CPLEX solver [25]. Optimum solutions have been obtained for topologies of up to 12 nodes, in an Intel© Pentium© M730 processor with 1.6 GHz and 512 MB of RAM. Five different objective functions can be selected, which intend to optimize different metrics: (1) minimization of the average weighted number of hops of the flows on top of the VT, (2) minimization of the network congestion (defined as the utilization of the most loaded lightpath), (3) maximization of the single hop traffic, (4) minimization of the number of used wavelengths and (5) minimization of the maximum number of wavelength channels in any fiber link.

- *Output results*. The results of the (i+ii) optimization problem are the VT design and the routing of the flows on top of the VT. Some relevant measures of the WR network cost and performance can be calculated as a

function of these results. This eases the evaluation and comparison among different solutions. The provided measures belong to the next three categories:

- Cost indicators: number of wavelengths per fiber, number of transmitters/receivers/converters per node, their total number in the network, their maximum value and the percentage of use respecting to the maximum.
- Performance indicators: traffic carried by each lightpath, network congestion (traffic carried by the most loaded lightpath), total traffic carried by the VT, average number of virtual hops, traffic carried by each fiber, total single-hop traffic, total traffic carried by the physical topology, average number of physical hops, average message propagation delay (μs).
- Impairment indicators. These are values that help to give an insight about the signal impairments suffered by the optical signals *in each lightpath*: the number of physical hops, the number of wavelength conversions and the propagation distance in kilometers. Also, the average and maximum of these numbers are provided.

- *Graphical User Interface (GUI).* A user friendly GUI has been developed to ease the use of the MatPlanWDM tool for didactic purposes. Their main functionalities are described in the next section.

## 4  Graphical User Interface

The Graphical User Interface consists of a window workspace, whose configuration changes according to the function mode selected by the user. These modes are:

1) *Design Logical Lightpath Network.* This mode performs the virtual topology design by means of one of the heuristic algorithms or the MILP programming implemented. The user is requested for the design input parameters: the traffic pattern, the physical topology, the number of transmitters (T), receivers (R) and TWCs per node, and the number of wavelengths per fiber. Figure 3 shows the GUI in this operational mode.

2) *Evaluate Optimization Method.* This mode allows evaluating an optimization algorithm under different combinations of input parameters. A comparison metric is computed, such as the network congestion or the average number of virtual hops on the virtual topology, for several combinations of the next design parameters: the number of transceivers (transmitters (T) and receivers (R)) and the number of wavelengths per fiber. The tool displays a comparative graph with the results achieved.

3) *Compare Optimization Method.* This mode compares the results obtained from a set of selected optimization algorithms. The input variables are the number of transceivers (virtual topology maximum degree) for each algorithm. This GUI can be easily extended to compose comparisons modifying other parameters like the number of wavelengths per fiber, or the number of wavelength converters per node.
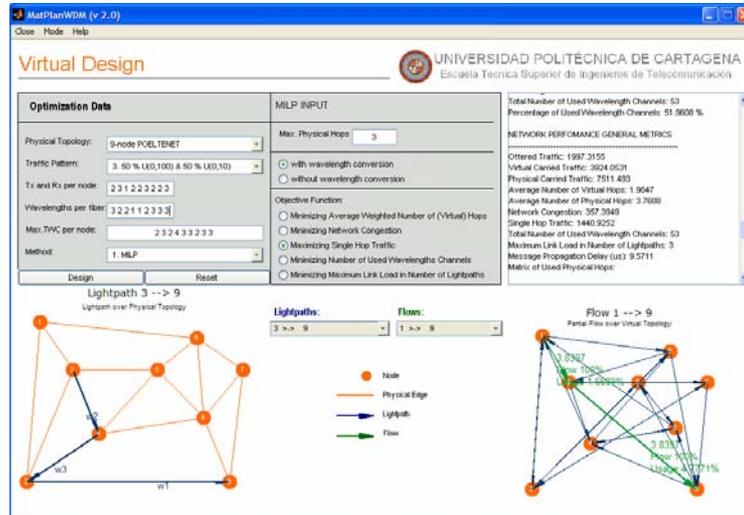
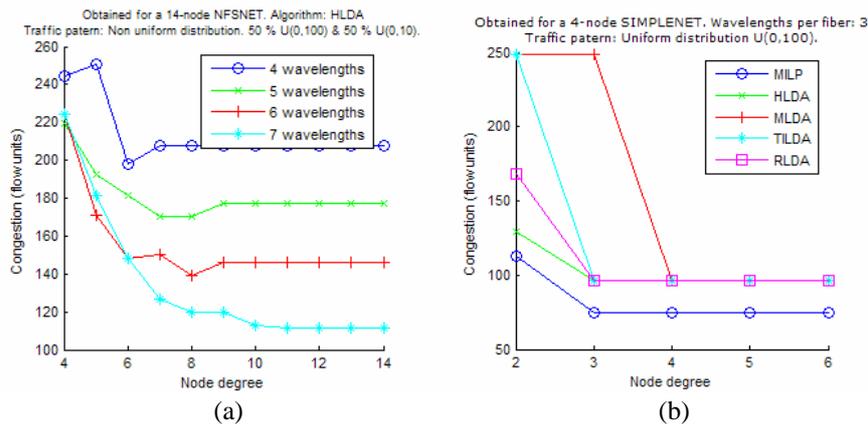Figure 3. Graphical User Interface. *Design mode* view.



|       (a)       |       (b)       |

Figure 4. *Results Graphs Area.* (a) *Evaluate* mode, (b) *Compare* mode.

The workspace of the GUI is divided into four areas; each of them refers to a specific and different task according to the function mode selected by the user:

1. The *Optimization Data Area*. This area is located at the upper-left corner of the workspace. It is used to enter the design input parameters in the mode 1) *Design Logical Lightpath,* and the comparison parameters in the modes 2) *Evaluate Heuristic Algorithm* and 3) *Compare Heuristic Algorithms*.

2. The *Results Reports Area.* This area is located at the upper-right corner of the workspace. It reports the measures and the metrics calculated by the optimization. The measures provided are different in each operational mode. In the mode 1) an exhaustive report about the implemented virtual

topology design is shown. For the modes 2) and 3), the reports contain only general information about the obtained comparison values.

3. The *Physical Topology Area*. This area is located at the lower-left corner of the workspace. It presents the physical topology of the design. In mode 1), it allows to select a particular lightpath, so that the traversing fiber links of the lightpath are highlighted in the physical topology.

4. The *Results Graphs Area*. This area is located at the lower-right corner of the workspace. Its purpose is to draw the results obtained in the different modes in an intuitive graphical way. In mode 1), this area displays the virtual topology obtained. It allows the selection of a particular high level traffic flow from the input parameters, so that the traversing lightpaths are highlighted in the virtual topology. In the mode 2), it shows a graph where the network congestion is represented in the ordinate axis, and the number of transceivers in the abscissa axis. A curve is plotted for several values of the number of wavelengths per fiber. Figure 4-(a) illustrates an example of the *Results Graphs Area* with the congestion curves for a given algorithm with different design input parameters. Finally, when the mode 3) is selected, a similar graph is displayed with one curve for each compared algorithm (Figure 4-(b)).

## 5 Conclusions and further work

This paper presents an educational WDM network planning tool, implemented as a MATLAB toolbox with a graphical interface. Virtual design and flow routing algorithms can be combined and tested with the tool. An optimal linear programming implementation of the complete virtual design and traffic grooming problem is also provided for comparison. The graphical interface to the toolbox has been implemented to aid in the educational process of results evaluation and comparison, lightpath plotting on top of the virtual topology, and traffic flow plotting on top of the virtual topology.

The tool has been specifically designed to be easily extended with new heuristic algorithms. As a current line of work, the input parameters and output parameters to the tool are being completed, to facilitate the assessment of heuristics which also take into consideration impairment constraints in the optical signal, and protection and restoration issues.

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