



Universidad
Politécnica
de Cartagena



OPERACIÓN E INGENIERÍA DE RED

MÁSTER EN INGENIERÍA DE TELECOMUNICACIÓN
CURSO 2019-2020

Lab work #3. Optical WDM line engineering with Net2Plan NIW framework

(2 sessions)

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1 Objectives

The goals of this lab work are:

1. Cover concepts related to WDM line engineering, like optical amplifier placement, optical power and impairments calculations.
2. Learn how to use the NIW framework of Net2Plan for this purpose.

2 Duration

This lab work is designed for two sessions of two hours.

3 Evaluation

This lab work has been designed to guide the students in their learning of the subject. The annotations the students make in this document are for their use when studying the course, and do not have to be delivered to the teacher for evaluation.

4 Documentation

The resources needed for this lab work are:

- Lecture notes of the course.
- Net2Plan tool and their documentation (see <http://www.net2plan.com/>).
- Instructions in this wording.

5 Previous work before coming to the lab

- Read lecture notes related to IP over WDM networks.

6 Creating the WDM topology

In this section we create the WDM plant that will be later used for our line engineering studies. The network is composed of four Optical Add/Drop Multiplexers (OADMs) interconnected in a ring topology, as the one shown in Fig. 1.

6.1 Adding OADMs and fibers

Follow the next steps for creating the WDM network:

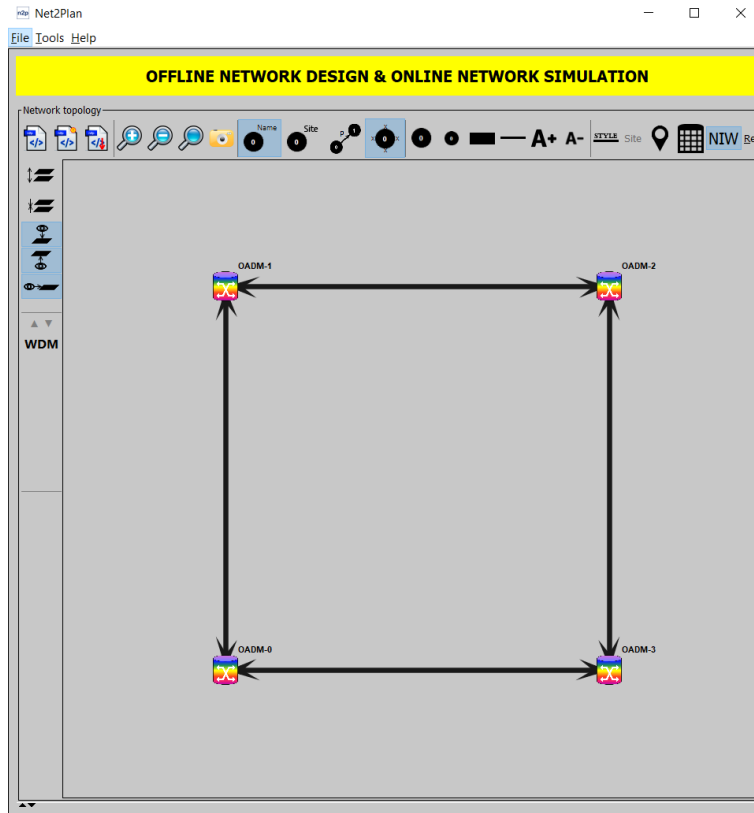


Figure 1: Ring WDM architecture.

- Activate the NIW framework in Net2Plan, clicking the NIW button in the topology panel (left side of the graphical user interface). Then, press the **Reset** button to create an empty NIW-valid design. Finally, in the **What-if analysis** tag, click the checkbox that activates the what-if analysis mode.
- Remove the IP layer from the design. For this, in the **Network** tab of the **View/edit network state** tab, remove the IP layer, so the design will be restricted to the WDM layer.
- Add four nodes (OADMs) to the design in any positions (e.g. as those in Fig. 1), right-clicking in the topology panel.
- Add four bidirectional¹ WDM links between the created OADMs creating a ring topology. For creating a bidirectional WDM link between two nodes, press the SHIFT key, click in a node and drag to the other node. Alternatively, you can use the **Add fiber** right-click menu option in the **View/edit network state** tab, **Fibers** subtab.
- Set the length of all the WDM links to 240 km, using the appropriate right-click menu option in the **Fibers** subtab, or just editing the appropriate column in the table. Which is the default value for the attenuation coefficient of the fibers? and the chromatic dispersion coefficient? And the link design value for PMD contributed by the fiber?

¹In Net2Plan NIW framework, a bidirectional WDM link is just composed of two unidirectional WDM links (fibers) in opposite directions.

- From the previous values, which is the total attenuation (dB) added by the fiber in a single WDM link?

- Activate the **Optical amplifiers' params** view in the **Fibers** table, using the appropriate option in the **View** right-click menu. Is there by default a booster amplifier? Is there a pre-amplifier at the end of the fiber by default?

6.2 Setting the OADM parameters

Follow the next steps:

- Go to the **OADM**s table in **WDM** tab. Observe the parameter in **OADM type** column: which is the type of OADM set for the OADM's?

- Read in the Appendix of this lab work the characteristics of the built-in generic type of OADM.
- In the ring network, all the OADM's have a degree two, meaning that they are connected to two other nodes. Fig. 2 illustrates the type of OADM that should be configured. For this, use the appropriate right-click options in the **OADM**s table, and mark the following characteristics for all OADM's:
 - Set the number of add/drop directionless modules to zero.
 - Set the OADM's to have a directionful add/drop module in all its fibers..
 - Set the architecture type to be broadcast-and-select, i.e. the optical signal is *broadcasted* by a splitter at the input module of each degree. Add/drop modules are built using passive mux/demux elements, with losses of 6 dB, and added PMD of 0.5 ps. Output modules are based on WSSs, that receive all the optical channels from all the input fibers and *select* the ones to switch to the output fiber. WSS loss will be 6 dB and will add a PMD of 0.5 ps.
 - Configure the splitter losses at the input module of each degree to be of 3 dB.
- In the **OADM**s table, activate the **Generic OADM model params** view, and observe the values in the columns added to the table, to check that the amounts introduced are correctly settled.
- The OADM's are assumed to *not* implement power equalization in the output modules. Configure this characteristic using the appropriate right-click menu option in the **Fibers** table.
- Save the design with the name **ringWdm.n2p**.

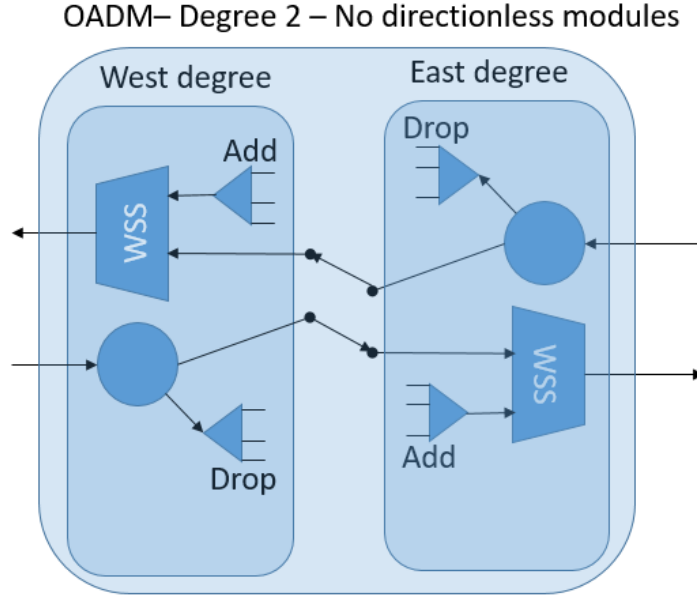


Figure 2: Degree 2 OADM to configure.

7 Line engineering

In this section we study the line engineering of the WDM network depicted. We assume a line system technology that provides a spectrum of 4.8 THz per fiber, consisting in a fixed grid of 96 channels, with 50 GHz of separation between adjacent channels. This is a classical ITU configuration in the C-band, for instance with a range from 196.1 THz (1528.77 nm) to 191.35 THz (1566.72 nm), at steps of 50 GHz.

In our study, we will define a so-called worst-case situation, and concentrate in creating a WDM design that is valid for it. The worst-case scenario to be considered is characterized by:

- The design includes lightpaths between all the node pairs, so we can estimate the end-to-end performances for all the lightpaths.
- All the fibers in the network will have the 96 channels occupied by traversing lightpaths. Fully occupying the fibers permits checking if the optical amplifiers saturate at that power.
- The design is feasible according to power, OSNR etc. for all the lightpaths, in particular for the *longest lightpath*. In our case, this means a lightpath traversing three hops.

We can easily create the target worst-case scenario under study by creating 16 *bidirectional* lightpaths with a *1+1 configuration*, between each node pair. Then:

- The primary lightpaths will occupy the WDM links between the end nodes in the shortest path, in both directions.
- The backup lightpaths will occupy the other WDM links in both directions.

By creating 16 bidirectional lightpath requests between each node pair, we have a total of 96 bidirectional lightpath requests in the network (192 unidirectional lightpaths requests).

Follow the next steps for creating the target worst-case scenario:

- First, observe the optical slot size in GHz defined in the network, in the **Network** subtab under the **View/edit network state** tab. Which is the default optical slot size defined?

The bandwidth of any lightpath in the network must be an integer multiple of such slot size. In flexi-grid use cases, different lightpaths can use different modulations and have a different bandwidth. In our case, all the lightpaths will have the same bandwidth of 50 GHz. Therefore, it is easier to define the slot size as 50 GHz, meaning that all the lightpaths will occupy one slot. Set the slot size to 50 GHz.

- Now we should define the grid of acceptable channels in the fibers. For this, in the **Fibers** table, use the right-click option **Set valid optical slot ranges to selected fibers** to select the appropriate range for our use case. Note that the first optical slot should have a central frequency of 191.35 THz and that last a frequency of 196.1 THz. In NIW (and according to the ITU), the central frequency f of optical slot n in the 50 GHz grid is given by:

$$f \text{ (THz)} = 193.1 + n \times 0.05$$

Therefore, the slot corresponding to central frequency 196.1 is 60, and the slot associated to 191.35 is -35. The number of slots is then exactly 96: the number of integer numbers between -35 and 60, both included.

- Observe the **Fibers** table columns. Which is now the number of valid optical slots in each fiber? how many are occupied? how many are available? Which is the central frequency of the first and last valid optical slot? Which is the size of the valid spectrum in the fiber (in THz)?

- In the **OADMs** table, select all the nodes, and use the right-click menu option **Add full-mesh of bidirectional lightpath requests among selected nodes**, to create 16 bidirectional requests among all node pairs, with a line rate of 100 Gbps, requesting 1+1 protection.
- In the **Lightpath requests** table, use the option **Add lightpath to selected requests**, to create lightpaths for all the created requests, occupying 1 optical slot (50 GHz) each, and not using directionless add/drop modules (since the OADMs do not have them). This option implements a sequential first-fit algorithm to assign a path and spectrum to the lightpaths:
 - First, the lightpaths are ordered according to its id, and processed by one one.
 - The shortest path route is selected for the lightpath. In 1+1 case, two routes are selected that are maximally disjoint: the algorithm tries to find two node-disjoint paths, and if not a pair where the number of overlapping fibers is minimum. In our case, being a ring topology, there are always two disjoint paths between every node pair.
 - Once the path or 1+1 paths are selected, in each one we assign the *first* (with lower frequency) idle range of contiguous optical slots where the lightpath fits, i.e. a range not clashing with other lightpaths. If no idle valid range exists, the request is blocked.

Is there any blocked lightpath request?

7.1 Spectrum occupation

As described above, the algorithm used by the `Add lightpaths to selected requests` option, allocates spectrum to the lightpaths using a sequential first-fit heuristic. Answer the following questions:

- Observe the spectrum occupation information of the lightpaths in the `Lightpaths` table. Are the primary and backup lightpath of the same lightpath request using the same spectrum? (see the occupied slots column for this)

- Identify two lightpath requests that are opposite bidirectional pairs (and thus would be assigned to the same bidirectional IP link in IP over WDM networks), and now see the lightpaths realizing them. Are they assigned the same spectrum? do they clash with the lightpaths of the opposite direction?

- Check in the `Lightpaths` table that no lightpath has clashing of spectrum, and in the `Fibers` table that all fibers have zero optical slots with clashing. Which is the number of optical slots occupied and idle in all the fibers?

- In the `Reports` tab, open the report `ReportNiw_wdm_routingSpectrumAndModulationAssignments`. This report summarizes spectrum occupation information of the lightpaths. Use the report to answer the same questions above.
- Check in the `Lightpaths` table that all the lightpaths start and end in the directed (i.e. non-directionless) Add/Drop modules. If no fiber has optical slots with spectrum clashing, would it be possible to have clashing in the directed add/drop modules? why?

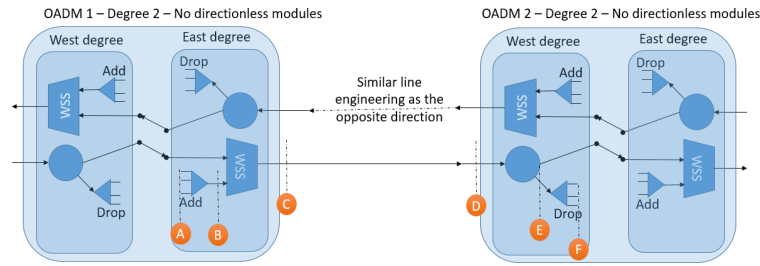


Figure 3: Diagram of a WDM link with no amplification.

7.2 Lightpath optical signal performances

In this section we will observe the signal quality performances for the lightpaths in the current design. For this, activate the **Optical signal** profile in the **View** right-click menu of the **Lightpaths** table.

- Fig. 3 shows a diagram with the steps that follows a primary lightpath traversing a single WDM link in the current network design.

Fill in the following table, indicating the lightpath power at the different points **A**² to **F**³ in Fig. 3, observing the information in the **Lightpaths** table, and the information on the attenuations added by the different elements inside the nodes, already configured.

Primary lightpath signal power (dBm)	
Point A	
Point B	
Point C	
Point D	
Point E	
Point F	

- Which is the received power at the transponder in the lightpaths traversing three fibers? Where is the difference coming from?

- Which is the sensitivity of the transponders (i.e. the minimum acceptable input signal power)? Is the design valid according to this?

- Note that this version of NIW, informs that received the OSNR of the transponders is infinite. This is because the design has no optical amplifiers, and the optical impairments model in this version of NIW does not consider other sources of noise like the caused by nonlinear effects in the fibers.

²This is the transponder injection power.

³This is the transponder reception power.

- Which is the chromatic dispersion accumulated at the end of the lightpaths of one hop and of three hops? Where these numbers come from (i.e. what optical elements are contributing to this)? Are the CD values within the transponder tolerance margins?

- Which is the polarization mode dispersion (PMD) accumulated at the end of the one hop and three hop lightpaths? Where these numbers come from (i.e. what optical elements are contributing to this and how)? Are the PMD values within the transponder tolerance margins?

7.3 Adding amplifiers to the design

From the previous data, it seems clear that we need to add optical amplification to increase the lightpaths' reception power towards their tolerance margin.

With that aim, we will apply a common amplification practice consisting in:

- Add optical line amplifiers and a pre-amplifier in each fiber. The gain of each amplifier is selected to compensate the attenuation in the fiber span right before them.
- Add booster amplifiers in every fiber, with a gain equal to the attenuation suffered by the express lightpaths (from the point after the pre-amplifier to the point before the booster) when traversing them.

Typical gains achievable with optical line and pre-amplifiers are in the order of 15 to 25 dB, while it is common to have booster amplifiers with a gain of 6 to 10 dB.

Follow the next steps to place the optical amplifiers:

- In the **Fibers** table, use the right-click option **Add OLAs uniformly spaced to selected fibers** to place optical line amplifiers with a maximum separation of 80 km. How many optical line amplifiers are created in each fiber? Which are the amplifier positions (in km from the fiber origin)?

- In the **Fibers** table, use the appropriate right-click option to set the gain of the line amplifiers as that which compensates the previous span losses. Which is the required gain?

- Which is the (default) noise figure of the added amplifiers? According to this value, are they likely to be EDFA or Raman? Do the amplifiers include any chromatic dispersion compensation? which is the added PMD?

- In the **Fibers** table, use the required right-click options to place pre-amplifiers in all the fibers, and to set its gain to the one that compensates the previous span losses. Which is such required gain?

- In the **Fibers** table, use the required right-click options to place booster amplifiers in all the fibers, and to set its gain to the one that compensates the attenuation suffered by the express lightpaths of the OADM. Which is such required gain?

- In the **Fibers** table check if the amplifiers output power are within acceptable margins. Which are the output power acceptable margins (in dBm)? Is the output power of all the booster, line and pre-amplifiers, in all the fibers the same? Is it inside the acceptable margins?

- Which would be the output power of the amplifiers if we had just one, instead of 96 lightpaths in each fiber? (calculate it dividing the power by 96 (in dBs subtract $\approx 19.82dB$)). would it be within the operational margins?

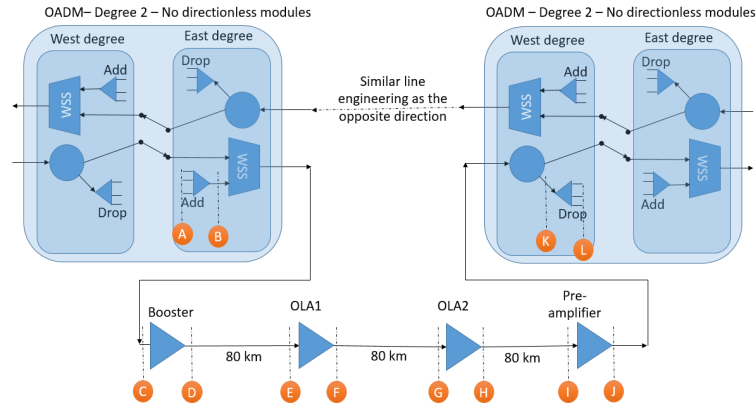


Figure 4: Diagram of a WDM link with amplification.

- In the **Lightpaths** table: which is the minimum acceptable OSNR for the transponders? Is the OSNR of all the lightpaths within the operational limits?

- Why is the OSNR different for different lightpaths traversing the same path? Is this difference significant in practice?

- In the **View reports** tab, open the line engineering report (**ReportNiw_wdm_lineEngineering**). Go to the detailed information per lightpath, that shows information at the inputs and outputs. Which is the input power of each lightpath in each of the line amplifiers? which is the input power of each lightpath at the input of the pre-amplifier, and in the booster amplifiers? Is it the same for all lightpaths?

- Fig. 4 shows a diagram with the steps that follows a primary lightpath traversing a single WDM link in the current network design.

Fill in the following table, indicating the lightpath power at the different points A to L in Fig. 4. For this, observe the information in the **ReportNiw_wdm_lineEngineering**, that can be accessed from the **View reports** tab. In the report, move to the section of detailed per-lightpath information, and find there a lightpath traversing one hop.

Primary lightpath signal power (dBm)	
Point A ⁴	
Point B	
Point C	
Point D	
Point E	
Point F	
Point G	
Point H	
Point I	
Point J	
Point K	
Point L ⁵	

- Save the design with the name `ringWdm_badOsnr.n2p`.

7.4 Producing an OSNR valid design

In this section we show two options for increasing the OSNR of the receiver lightpaths:

- Increasing the injection power of the lightpaths. Note that this would increase the total power in the fibers, which can produce added noise caused by nonlinear effects in the fibers (not contemplated in this lab work).
- Reducing the distance between amplifiers, so the input power in each is increased, producing lower OSNR contributions.

Follow the next steps:

- Increment the injection power of all the transponders to 3 dBm, keeping all the gains of the amplifiers unchanged. How much did the OSNR improved in all the lightpaths? Are now all the lightpaths' OSNR above the quality limit? Which is the received power of the lightpaths? Is it within the applicable limits? Which is the new total output power in the amplifiers? Is it within limits?

- Reduce again the injection power to 0 dBm, producing again a design where the OSNR of the 3-hop lightpaths is off-limits. Assume that the injection power of the lightpaths cannot be increased, and instead, increase the number of optical line amplifiers as follows:
 - Remove all the optical line amplifiers.
 - Add again optical line amplifiers for all the fibers, but now with a separation of 60 km between them, leading to 3 instead of 2 line amplifiers per fiber.
 - Set again the gain of (i) the line amplifiers, and (ii) the pre-amplifiers, to be the required to compensate the previous span losses.

Which is the new OSNR in the lightpaths? Are now all the lightpaths' OSNR above the quality limit? Which is the received power of the lightpaths? Is it within the applicable limits? Which is the new total output power in the amplifiers? Is it within limits? Which is the new gain of the line and pre-amplifiers? Is it within limits?

7.5 Power equalization

It is of interest in WDM networks, to simplify operational complexities, and to avoid potential problems with the optical amplifiers, that all the lightpaths traversing the same fiber have the same (or approximately the same) power density.

Modern broadcast-and-select or route-and-select OADMs can include the capability to equalize the power density in the fiber in the output module WSS. However, this means an extra cost.

The scheme described in Section 7.3 guarantees that, if the fibers and amplifiers attenuate / amplify all the wavelengths equally⁶, the power in the fibers of all the traversing lightpaths is the same, i.e. the lightpaths power are equalized, without the need of WSS-based equalizer.

Follow the next steps:

- See the column named **Max. to min. lp power density ratio**, in the **Fibers** table. This column includes the ratio (in dB) between the power at the fiber input of the lightpath with higher power and the lightpath with lower power. A 0 dB value means perfect equalization among the channels. Which value is shown for all the lightpaths?

- At this moment, booster amplifiers' gain is selected to compensate the losses of an express lightpath. Change the gain of a booster amplifier to 10 dB. What is the effect in the equalization ratio? which fibers are affected?

- In the **Fibers** table, use the option **Set fiber origin OADM pre-booster power equalization** to activate the power equalization in all the fibers. Which is the power density to apply (in mW per GHz), if we want to set a per-lightpath power of -12 dBm? After applying it, is the power now equalized in all the fibers, even if change the gain of booster or other amplifiers?

⁶This is an ideal situation, since fiber attenuation is slightly dependent with the wavelength, and the amplifiers do not have a perfectly flat amplification among the different wavelengths. These effects can accumulate along the lightpaths' routes, creating significant differences.



8 Work at home after the lab work

The student is encouraged to complete all the tasks that he/she could not finish during the lab session. Additionally, the student should repeat these exercises with other non-regular topologies.

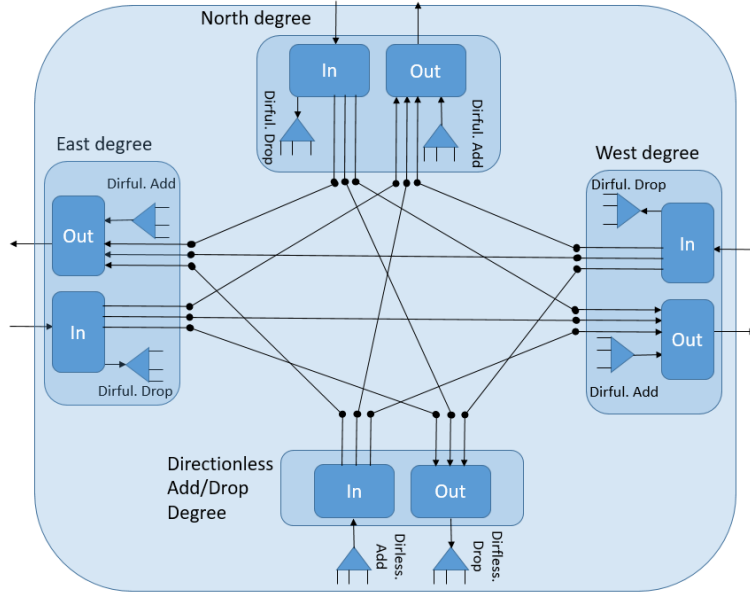


Figure 5: Generic OADM architecture. Example OADM of three degrees, directionful add/drop modules per degree, and one shared directionless add/drop module.

Appendix: The generic OADM type in NIW

The OADM generic type is a built-in OADM in NIW framework, which is intended to be flexible enough to accommodate multiple optical switching architectures. We describe it in this appendix.

Fig. 5 illustrates the structure of an OADM of a generic type, with three degrees (i.e. connected to other 3 OADMs). Degrees are named as East, North and West: it is typical to call OADM degrees like that in a configuration of up to 4 degrees.

Each fiber can have or not a booster amplifier at the start of the fiber, and a pre-amplifier at the end. Their characteristics can be configured in the **Fibers** tab. They are not included in Fig. 5.

More details follow in the next sections.

The per-degree input/output modules

The optical signal entering via an input fiber of a degree (after the pre-amplifier, if any) is processed by an input module which can be:

- A Wavelength-Selective-Switch (WSS)⁷, that optical switches each optical channel to the desired output module.
- A passive splitter that spreads all the incoming optical channels through all its outputs.

Each input module is connected to all the output modules of each out degree, and optionally to:

⁷A Wavelength Selective Switch is a device able to switch each optical wavelength in its input fiber independently to a desired output fiber. For instance, in a WSS of one input and multiple outputs, can switch each different wavelength in the input fiber to a different output fiber.

- The *directionful* drop bank, where they can be placed the transponders of the lightpaths (i) ending in the node, and (ii) that enter the node through this particular input fiber.
- Zero one or more directionless add/drop modules. These modules are similar in their structure to any other degree. If we place a transponder in these directionless modules, they could be used to drop any lightpath coming from any input fiber.

Each output module of a degree (Out in Fig. 5), receives the input optical channels from:

- Each of the input modules of the regular degrees. If the input modules are WSS-based, then only the lightpaths that have to bypass the OADM reach the output modules. If the input modules are splitter based, then all the optical channels reach this output module.
- Each of the input modules of the directionless add/drop modules, if any. From here, the output module receives the optical channels added in this OADM (just the ones to be forwarded through the output module degree, if the input module is WSS-based, or all if it is splitter-based).
- If the OADM has a directionful transponder bank for this degree, the output module has an input receiving the optical channels to be added in the node, that will be forwarded through the degree.

Output modules can be implemented via:

- WSSs, that switch to the output fiber only the desired optical channels present in their inputs.
- Passive couplers, that forward to the output fiber all the optical signals appearing in their inputs.

The OADM model permits representing output degree modules that implement a power equalization, a possibility enabled by WSS-based output modules. In this case, it is assumed that the WSS incorporates variable optical attenuators that produce a flat optical power along all the wavelengths, at the output.

To represent this, in NIW it is possible to define for each fiber:

- If the output module of the OADM at the origin of the fiber, is implementing power equalization or not.
- If the power is equalized, we can state the power density to configure at the output of the output module, measured in miliwatts per GHz. Note that the power equalization would happen at the output module, right before the booster amplifier (if any).

Directionless vs. directionful add/drop modules

From the previous explanation, we see that there are two forms of adding and dropping lightpaths in a node. Typically, each OADM is configured to have one of the two forms, but not both.

- *Directionful add/drop* (or also directed add/drop). In this case, each degree input module is connected to a demultiplexer where we connect the receiver side of the transponders of the lightpaths that end in the node AND enter the OADM via the related input fiber. Alternatively, the transmission side of the transponder is attached to a multiplexer connected to the output module of the first hop of the lightpath.

- **Directionless add/drop.** In this case, the OADM has one or more so-called add/drop directionless modules. The transponders placed there can be used for lightpaths add/dropped, they enter the OADM (drop side) and leave the OADM (add side) through any input/output fiber.

Directionless add/drop modules have pros and cons:

- *Advantage.* Directionless modules permit to dynamically change the route of the added/dropped lightpaths. For instance, if a degree of the OADM fails (e.g. because of a fiber cut), the lightpaths added or dropped in the node through that fiber could be rerouted, and enter/leave the OADM via other degrees. In directionful modules this is not possible without manually detaching the transponder from a degree and attaching them to other degree.
- *Disadvantage.* Directionless modules are as expensive as a degree module. Additionally, directionless modules are subject to *internal blocking*, since it is not possible to add or drop two lightpaths with overlapping optical channels in the same module. For instance, in Fig. 5, it would not be possible to add two lightpaths in the node that use the same wavelength, one heading to the East and one to the West, since their spectrum would be mixed in the multiplexer. To make this double add possible, we would need two directionless add/drop modules, placing each lightpath in a different one.

Another degree of freedom in the add/drop operation is the so-called *colorless* add/drop. In the described configuration so far, directionless or directionful add/drop modules are based on passive multiplexer and demultiplexer modules where the transponders are attached to. In the (de)multiplexers, the port where the transponder is attached to determines its transmission/reception wavelength. That means that if we wanted to change the wavelength of an added or dropped lightpath, a technician would need to physically change the port where it is attached. This prevents any possible fast reconfiguration of a lightpath wavelength, and adds operational cost. The alternative consists in replacing the passive mux/demux by active WSSs, that permit a remote reconfiguration without a technician visit. Instead of an WSS, a passive splitter/combiner could be used. The problem with this latter option is that their attenuations are large when the number of ports grows (e.g. a passive splitter/combiner with 50 ports for placing transponder has an attenuation of at least $10 \log 50 \approx 17$ dB, and would likely require one amplifier just to compensate these losses).

Architecture types

Three OADM architectures can be represented in the generic OADM scheme of NIW:

- *Broadcast-and-select* (B&S). In this case, the In (*broadcast*) modules are basic splitters, and the signal is consequently broadcasted to all the output degrees and directionless modules. In contrast, the output modules (*select*) are implemented via WSSs, that only permit the propagation to the degree of the desired received signals.
- *Route-and-select* (R&S). In this case, both the input and output modules are implemented via WSSs. This removes the power losses associated to the passive splitter in B&S architecture, that can be significant if the number of degrees is high.
- *Filterless switching.* Recently, a new alternative has appeared called *filterless switching*. In this case, WSSs are avoided and both the input and output modules are implemented using passive splitters and combiners. Note that in this case, it happens that the OADM forwards to all the output fibers even those lightpaths that should not be forwarded (e.g. the ones to be dropped in the OADM, or the lightpaths that should be forwarded to just *one* among the output fibers).

This optical signal is called *waste*, and occupies an spectrum in the fibers that cannot then be used by legitimate lightpaths. The performance loss of the resulting filterless network should be balanced against the cost reduction in the OADM thanks to its simpler hardware.