Automated Link Loss Compensation and Cost Effective Amplifier Placement in XHaul Optical Networks

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***Abstract*—Recent growth of interest in the deployment of 5G networks triggers the application of very different technologies in xhaul networks to support the increase in traffic growth and link distances. Critical network design constraints include for instance dense wavelength division multiplexing (D)WDM of channels operating at very different data rates, and the deployment of optical amplifiers and dispersion compensation modules (DCMs) to meet the limited link power and dispersion budget. Cost-optimized planning of such networks requires the optimization of the equipment to be added or minimizing its cost, which becomes a very challenging task when adding the diverse equipment constraints on top of this. In this paper we demonstrate an algorithmic approach that efficiently addresses the link loss and dispersion compensation and equipment allocation problem for xhaul networks. The presented method, which could be part of a comprehensive planning environment, allows optical network engineers to design cost effective amplifier and DCM configurations of superior performance with respect to optical signal to noise ratio (OSNR), received optical power (ROP) and accumulated chromatic dispersion (CD) at the receiver side. Our approach accounts for future channel loading, optical channel path parameters, signal rate, equipment parameters, and constraints arising from the insertion points of amplifiers and DCMs. We demonstrate the convenient operation of our method by designing an exemplary fronthaul network system.**

Keywords— Fronthaul, Xhaul, Optical Network, Design Automation, Performance Assessment, Cost Optimization, EDFA, OSNR, CD, DGD, Power Budget, DWDM.

I. INTRODUCTION

The continued interest in the deployment of 5G networks [1-4] and their significant growth expected in the near future [5-7] causes tremendous extensions and upgrades of existing fronthaul networks in particular, and xhaul networks in general [8]. As many mid and long distance optical paths exist in fronthaul networks (which become more and more highly meshed networks [3, 7]), the task of optical link loss compensation at minimal cost becomes a very crucial one. It requires accurate performance assessment and the consideration of many stringent constraints imposed by the optical equipment [8]. Along with the loss budget the CD budget needs to be met for low data rate services using direct detection schemes, which are still important for xhaul networks [7, 8]. This stays in contrast to modern long-haul networks [9], where coherent high data rate services are used and loss compensation represents the main task. Often, the design, performance assessment and optical link loss compensation is carried out manually [8] with the optimal amplifier placement being a repetitive and time consuming procedure.

A. *Problem Definition*

The task of optical network design is mostly considered as a set of subtasks ranging from designing optical link topology, traffic demand engineering, optical channel routing and wavelength assignment, to optical multiplex section and transmission section engineering [10-12]. In fact, the task of designing a single transmission line should address many constraints, among them:

- Network topology parameters, e.g. routes between transmitter and receiver
- Bit rates and modulation types of optical channels
- Fiber characteristics such as loss and chromatic dispersion
- Equipment capability, e.g. operating wavelengths, transmitter signal bandwidth and receiver sensitivity, which typically depend also on parameters of the transmission line or optical path
- Cost-effective amplifier & DCM placement taking into account equipment constraints and limitations on amplifier locations.

B. *Link Loss Compensation Issues*

For long and mid distance optical links in xhaul networks [8] amplification of a signal is required to meet the power operating range of a receiver, and to guarantee the required quality of a signal. Once amplifiers are added it is also vital to keep the OSNR above required threshold at the receiver. Another characteristic of an optical signal that should be tracked is accumulated chromatic dispersion; for some types of modulation formats optical dispersion compensation might even be required. Standalone DCMs (including FBG-based modules with low attenuation) introduce extra loss into an optical path and complicate the optimization of amplifier placement in

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WDM mesh networks. Power level equalization of added and passing through channels is crucial for effective placement of optical amplifiers due to their quite narrow input power range. In addition to issues listed above, which should be taken into account on a link-by-link basis, there is the problem of simulation deadlocking that can be fought through the use of iterative calculations [10] when ring or mesh WDM networks are being designed [3,5,7].

When an optimal configuration is desired, iterations or trial designs are attempted until the designer makes a judgment that one of these designs is optimal [8]. The necessity of an iterative refinement becomes glaringly evident with mesh networks consisting of many nodes [3, 7]. The automation of this process does require the emulation of the human driven process coupled with the possibility of exploring all options and strict metrics. This paper will approach the automation of link loss compensation and amplifier placement.

C. The Proposed Approach

A typical link loss and dispersion compensation workflow contains the following steps:

1) Analyze available equipment with respect to link loss and dispersion compensation capability and supported wavelengths. For instance, an amplifier can supply either variable or fixed gain, and provide specified gain within a specific wavelength range.

2) Analyze the network topology and optical paths and define the required amplifier configuration for each node, e.g. select an amplifier with a required gain and input power range accompanied by input and output attenuators in order to accommodate existing link loading and future traffic growth.

3) Add amplifiers, DCMs & attenuators taking into account parameters such as

- Characteristics of the network being designed, e.g. fiber plan, route lengths, mux/demux losses, etc.
- Engineering constraints, e.g. future channel loading, OSNR, power and dispersion margins
- Receiver sensitivity, e.g. OSNR floor, power and dispersion ranges, dispersion penalty for OSNR and power
- Launch power limits to mitigate nonlinear impairments
- List of available DCMs, amplifiers and attenuating pads and their parameters

This paper focusses on the automated link loss and dispersion compensation in WDM optical networks, which could be part of a complete network design environment [10,11]. Our approach yields a cost-effective solution that takes into account constraints imposed by network topology, design rules, and available equipment. The following part of the paper is divided into three sections. In Section II the approach to link loss and dispersion compensation of a typical DWDM network is described. This approach is based on two key components. The first one is a data model describing the network topology, available equipment including amplifiers, DCMs and attenuators and engineering constraints parameters. The second one is an algorithm generating a set of solutions that meet engineering constraints and have a minimized number of added amplifiers and DCMs, i.e. feasible solutions of lowest cost. In Section III the proposed approach is demonstrated using an example of a rather simple fronthaul network [8] and Section IV summarizes the paper.

II. DATA MODEL AND ALGORITHM WORKFLOW

Data model requirements are derived from typical problems of the link loss compensation and amplifier placement task. This includes two main areas: the support of all necessary features of a WDM optical network, and the capability of maintaining custom design rules and equipment libraries, which could vary significantly for different WDM network engineering teams [10].

A. WDM Network Representation

The WDM network needs to be represented by both, its physical and logical topology [10]. We will use the WDM System and Channel Assignment Table (ChAT) to model them. The WDM system is modeled by a set of bidirectional links. Each direction of a link is modeled as a photonic trail, which contains at least an optical fiber. Optical transceivers can be connected to a fiber either through the use of OADMs/MDXs or WSS ROADMs as it is shown in Fig. 1. Each fiber of specified type and length is characterized by different wavelength-dependent attenuation and dispersion coefficients and can carry

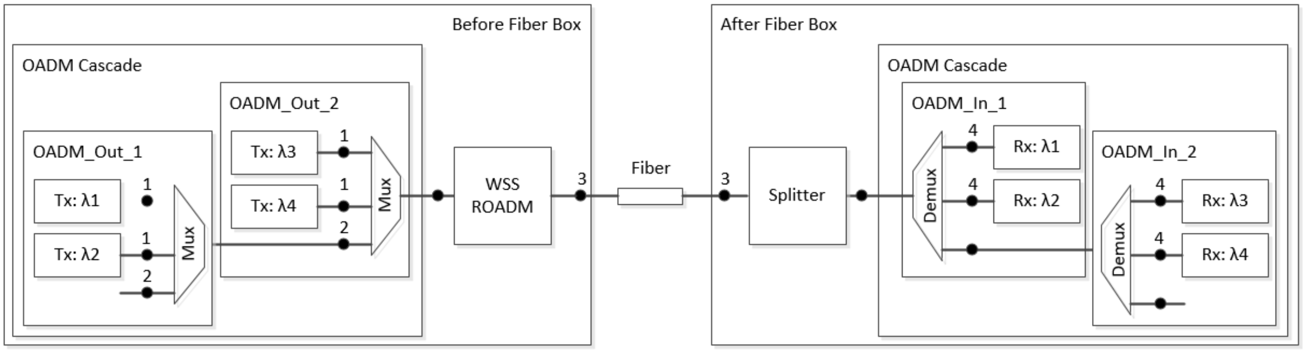


Fig. 1. Initial WDM system with wavelength specific Add/Drop equipment. Attenuating pads and or amplifiers can be added at insertion points 1-4, e.g. attenuators can be added to equalize add and express (glass-through) channels (1,2), to attenuate channels with high power before receiver (4); amplifiers, DCMs and attenuators can be added to compensate link impairments (3) and to balance channels (2).

different wavelengths in several optical channels. The optical channels are the realization of logical connections (traffic demands), which are described in the ChAT. Various types of logical connections can be defined when traffic demands are established, including primary and alternate routes, multi-lane configurations and OEO regeneration points. The optical channels define the connections between the trails. In another words: a WDM signal at the input of one photonic trail depends on one or several WDM signals at the output of another photonic trails, i.e. an optical network is represented as a directed graph. For the link loss and dispersion compensation algorithm it is important to configure equipment and check the configuration feasibility in a topologically-sorted manner [13]. Due to the complexity of an optical network there can be loops in the calculation graph, which should be removed [14] before the graph can be sorted. Afterwards, the system is calculated iteratively with the results from one run being fed as inputs to the subsequent iteration. This iterative process is carried out until convergence is reached. WSS ROADMs with built-in dynamic equalization functionality, for instance, induce strong coupling between channels making the problem even more complex. With care, even the most complex circulating topologies can converge to a stable result.

B. Equipment Library

The initial configuration of the WDM system may contain not only Add/Drop equipment [12] but also some amplifiers, DCMs and attenuators preplaced manually. To assess the performance of the initial WDM system and to decide whether extra amplifiers, DCMs and/or attenuators are required or not, the concept of transfer functions and parameterized signals [10] along with margins calculations [11] is used. The algorithm distinguishes six types of optical equipment: (R)OADMs, fibers, transceivers, amplifiers, attenuators and DCMs. Transmitter power, modulation type and bitrate along with receiver sensitivity [10] are crucial for a correct power budget calculation of optical channels. Keeping the received optical power within the operating range of a receiver may require adding amplifiers due to significant losses in an optical path [8]. Once amplifiers are added the signal to noise ratio should also be tracked at the receiver side. In case dispersion penalties are important for signals applying specific modulation formats, the dependency of receiver sensitivity on the accumulated CD is also an important receiver parameter. Furthermore, the wavelength dependence of key equipment metrics is important when modeling WDM optical networks. For example, attenuation and dispersion coefficients of fibers and DCMs, gain and noise figure (NF) of amplifiers, channel specific variable optical attenuation (VOA) in (R)OADMs are usually wavelength dependent. Aspects such as the dependence of NF on gain, or the dependence of Raman optical amplifier gain on fiber type and length should also be considered for an accurate performance assessment. With respect to engineering rules, amplifiers can be segregated by their application type or allowed insertion point. For example, booster amplifiers can be allowed before the fiber only and preamplifiers after the fiber only.

C. Engineering Constraints

Often, optimal amplifier placement means lowest cost of added equipment. So, algorithms that allocate amplifiers as well as DCMs using the smallest number of amplifiers are desirable. This is accomplished very efficiently through the use of link templates, which enumerate all of the acceptable arrangements of the loss and dispersion compensating items in a single link, coupled with carefully chosen heuristic rules or engineering constraints. Fig. 2 shows an exemplary link template based on

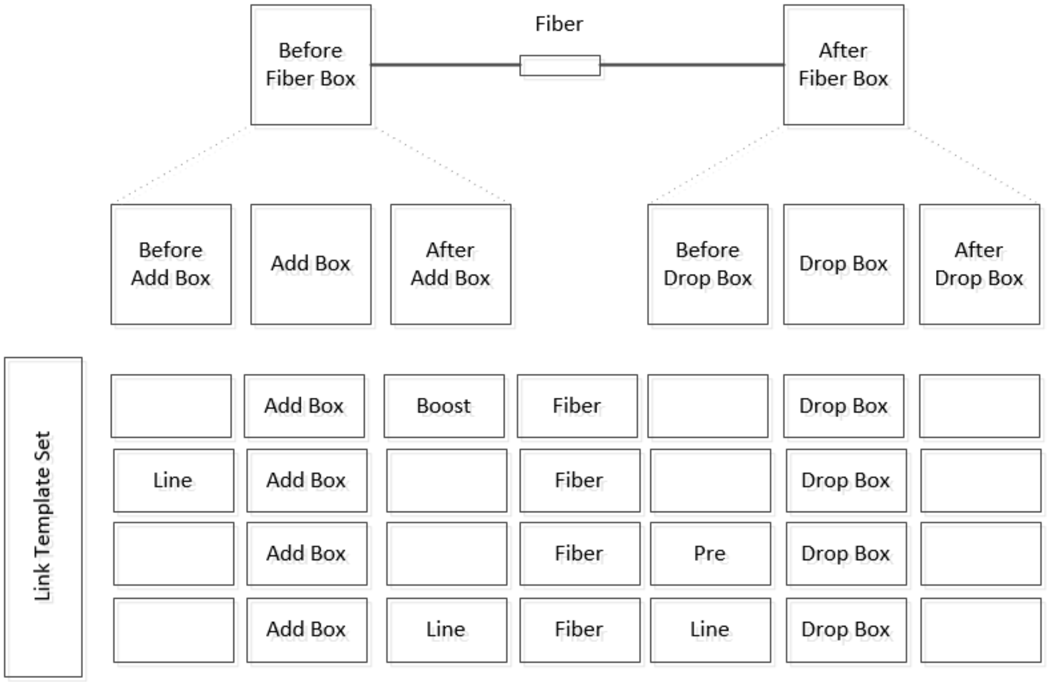


Fig. 2. Disaggregated representation of “Before Fiber” and “After Fiber” boxes of a photonic trail; “Add” and “Drop” boxes typically contain (R)OADMs, transceivers and channel specific VOA; Link templates define engineering constraints for amplifier placement.

the application type of an amplifier. Application type priorities specified along with link templates allow the algorithm to generate different solutions for the link loss compensation problem. In addition to link templates that define a unified strategy for placing amplifiers in the whole network there is a way to ban the placement of amplifiers at particular points of a network. This can be important when PON-based fronthaul networks are being upgraded [8].

The second group of constraints specify requirements to the optical signal [11], including the following:

- Upper and lower power and CD margins at a receiver
- OSNR margin at a receiver
- Upper limit for optical channel power launched into a fiber

The last group of constraints is represented by a list of equipment available for the algorithm, i.e. amplifiers, DCMs and attenuators that can be used to generate feasible solutions.

D. *Algorithm Workflow*

The algorithm steps are schematically illustrated in Fig. 3. In the first step, the physical and logical topology of the WDM network, available equipment and engineering constraints are analyzed. In the second step the disconnected graphs are detected. Further they are configured independently because the configuration routine is much faster on a smaller network. In the third step the algorithm checks whether there are cycles in subgraphs and removes them if existing [14]. Afterwards a topological sorting routine is applied. The following two steps are performed for each trail in each subnetwork. Depending on the remaining power budget of each optical channel passing through the current trail the link templates and available amplifiers are sorted in the fourth step. Then amplifiers and attenuating pads are added according to the template list, and the configuration feasibility is checked locally. In the sixth step optical signal metrics are calculated for each subnetwork. If necessary, iterations are performed until convergence is reached, and equipment and engineering constraints are checked. Each solution includes configuration of amplifiers and attenuators for each trail in the WDM system. Solutions may differ from each other in a variety of aspects: cost and insertion point of added equipment, number of unique amplifiers, power and OSNR margins at receivers. In the last step, the algorithm reports the solutions.

E. *Automated approach to Link Loss and Dispersion Compensation*

A synthesis script implemented through the use of an application programming interface of the network design environment [10] improves the usability of the algorithm realized as a separate executable file and, thus, accelerates the generation of solutions. As mentioned before dispersion compensation can be required along with loss compensation. Therefore, there are two aspects that should be accounted for:

- Extra loss of standalone DCMs
- Dependence of receiver sensitivity on residual CD

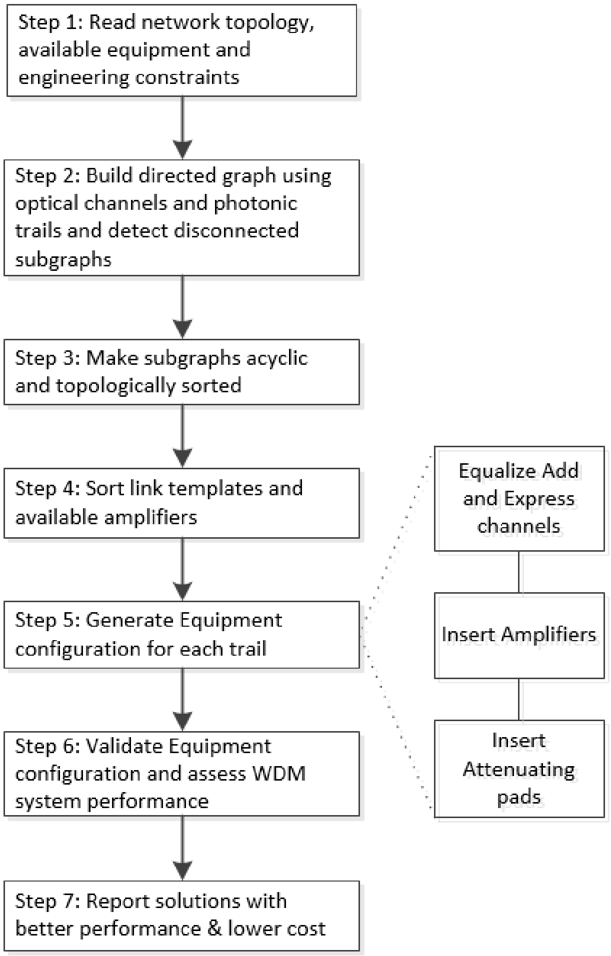


Fig. 3. Link loss compensation workflow.

The lower the number of standalone DCMs is the lower will be the extra loss they introduce into optical paths. So, likely the solution might have a lower number of added amplifiers and the better performance due to lower OSNR degradation. The use of pluggable DCMs, which loss is compensated automatically by amplifiers with mid-stage access point, may reduce the number of standalone DCMs and as a result reduce the extra loss. This speculation raises another complication: amplifiers should be allocated before DCMs, however the configuration might use standalone DCMs due to the lack of mid-stage access points at proper facilities. Hence the synthesis script realizes the following approach to the link loss and dispersion compensation task:

- Check whether amplifiers and DCMs are required.
- Check if amplifiers with mid-stage access are available for the link loss compensation algorithm.
- Run an executable file to compensate link loss and to provide insertion points for pluggable DCMs.
- For each link loss compensation solution build a map with DCM insertion points.

- Run the dispersion compensation algorithm for each unique map.
- Check if receiver sensitivities have changed due to a residual dispersion penalty or extra loss introduced by standalone DCMs has broken the optical power budget.
- If required, run the link loss compensation algorithm again to compensate penalties or extra loss for each dispersion compensation solution.
- Select the solutions with lowest number of added amplifiers.

The dispersion compensation task is an integer linear problem, which is solved using a corresponding numerical package [15]. If there is a solution with a fewer standalone DCMs, it will be configured to meet the performance requirements and constraints everywhere in the network.

Once link loss and dispersion compensation solutions are generated the synthesis script runs the solution visualizer, which lists the configurations generated by the algorithm along with key metrics such as number of added amplifiers and DCMs, cost of added amplifiers, minimal power and OSNR margins at a receiver, etc. Eventually one or several solutions can be selected within the solution visualizer and put into the network design environment for further performance analysis and reports generation [10].

III. DESIGN EXAMPLES AND DISCUSSION

An example of a fronthaul network consisting of one baseband unit (BBU) node, one remote radio head (RRH) node and twelve intermediate nodes hosting 10G DWDM signals is considered in [8]. We will design a slightly extended optical network, which includes four more RRHs optically connected to the BBU node, as shown in Fig. 4. The design is built and its performance is analyzed through the use of our network design environment [10]. As in the reference design [8] the distance between any two adjacent nodes is set randomly between 5 and 8 km. Depending on the available equipment different wavelengths can be allocated to connectivity services [12]. Add/drop equipment operating on the conventional 100 GHz fixed frequency grid is used here. Five adjacent wavelengths around 1552.52 nm are assigned.

The assessment of the initial WDM system performance indicates negative power margins at receivers, which means that at least one optical channel power at a receiver is below the sensitivity limit (light path from BBU to RHH: ROP is ~24.5 dBm and receiver sensitivity is -23 dBm). In another words the optical path loss should be compensated by adding amplifiers. The accumulated CD is within the operating ranges of the receivers, so no DCMs are required. However, some design rules impose more strict constraints for residual CD. Hence we will consider four scenarios of amplifier and DCM placement including stringent constraints to residual CD. In all cases minimal OSNR and optical power margins of 3 dB were set as engineering constraints.

A. *Minimal Number of Added Amplifiers*

The design of the optical network can be refined manually. However, it takes 10 minutes or more to build a solution with acceptable margins. This solution will become invalid when higher requirements to ROP for instance are specified. Our automated algorithm on the other hand generates several solutions within a few seconds – all with the same minimum number of added amplifiers, and margins of 9 dB and 6 dB for ROP and OSNR, respectively. There are three amplifiers added to this particular optical network when no restrictions on amplifier location are specified and no DCMs are required. The list of solutions generated by the algorithm is displayed by the solution visualizer with key metrics such as cost of added equipment, minimal ROP and OSNR margins. Once a particular solution is selected the corresponding equipment configuration is directly created within the network design environment. The performance charts for one of the solutions generated by the algorithm are shown in Fig. 5.

B. *Restrictions on Amplifier Locations*

Certain optical networks allow at some facilities only passive components. Hence there could be constraints on amplifier insertion points. For example, the algorithm generates with similar speed a set of solutions for the network where amplifiers are not allowed in nodes 2-8 (which form an inner ring subsystem). In comparison to the solutions described above these configurations contain 5 amplifiers and have lower margins at receiver: 5 dB for ROP and 4 dB for OSNR.

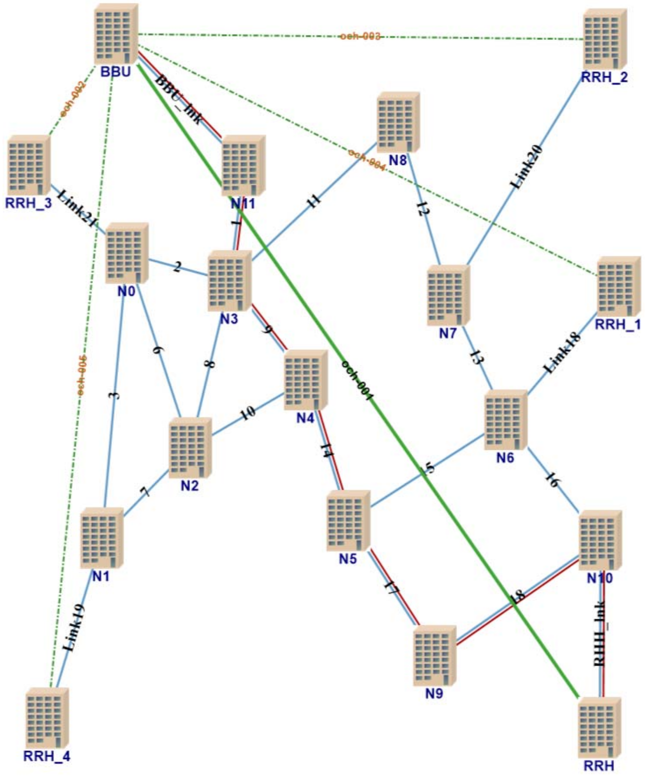
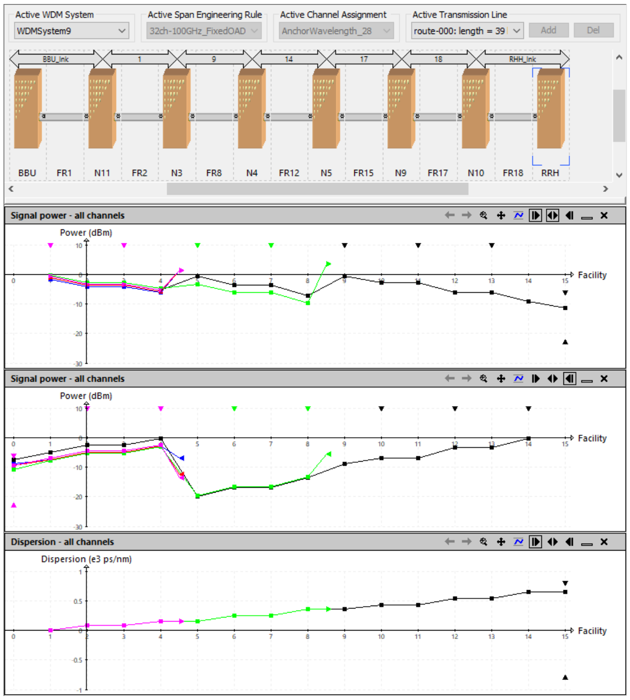


Fig. 4. Example of an optical network with 1 BBU node, 4 RRH nodes and 12 intermediate nodes for link loss and dispersion compensation.



Active WDM System: WDMSystem9

Active Span Engineering Rule: 32ch-100GHz_FixedOAD

Active Channel Assignment: AnchorWavelength_28

Active Transmission Line: route-000: length = 39

Fig. 5. Signal power and dispersion maps plotted for the longest transmission line between BBU node (west side) and RRH node (east side). The power map is shown in forward and reverse direction (east-west direction). Amplifiers are added to nodes N3, N5 (west-east direction) and node N3 (east –west direction).

C. Stringent Dispersion Constraints

In the previous two scenarios the value of the accumulated CD at the receiver point was of ~650 ps/nm and resulted in a dispersion margin of ~150 ps/nm as shown in the lower chart in Fig. 5. Sometimes engineers designing an optical network impose more tight dispersion constraints trying to keep the residual CD as low as possible. The dispersion compensation algorithm allocates four standalone DCMs to keep the residual dispersion for all optical channels as close to zero as possible while taking into account the receiver dispersion range and the list of DCMs available for the design.

For the scenario with no constraints on amplifier location the algorithm generates configurations with lower power and OSNR margins, 5 dB and 3.5 dB respectively, due to other amplifier locations and extra losses caused by the DCMs. However, the solutions still contain only three amplifiers as in the first scenario.

The configurations in the last set of solutions generated by the algorithm for the scenario with stringent constraints imposed on amplifier placement and residual CD have seven amplifiers per solution. Typically, the more complicated the topology is, or the more stringent the performance constraints are, the more expensive configurations will be required. For example an upgrade of connectivity services from 10G [8] to 25G or higher [2] with other modulation formats imposes more stringent constraints for OSNR, ROP and accumulated CD.

IV. SUMMARY

We have demonstrated the algorithmic approach that offers an efficient way of link loss compensation and amplifier placement. It permits for building a cost-optimized design of optical networks taking into account available amplifiers and DCMs, optical channel characteristics, network topology, and engineering constraints. Methods for comparing and selecting solutions and configuring the design are employed. Our approach is flexible enough to accommodate optical network topologies of different types and provide equipment configuration for either a newly designed WDM network or networks being upgraded to accommodate traffic demand growth. The result is a cost-optimized configuration with optimal amplifier placement.

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