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All optical multicasting in wavelength routing mesh networks with power considerations: design and operation

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All optical multicasting in wavelength routing mesh networks with power considerations: design and operation

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DEDICATION

I affectionately dedicate this thesis to my parents, Mohammad and Sara, to my wife, Ala'a, and to my daughters, Sarah and Noor, for their continuous love, encouragement, and support.

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ABSTRACT

Wavelength routing Wavelength Division Multiplexing (WDM) are optical networks that support all-optical services. They have become the most appealing candidate for wide area backbone networks. Their huge available bandwidth provides the solution for the exponential growth in traffic demands that is due to the increase in the number of users and the surge of more bandwidth intensive network applications and services. A sizable fraction of these applications and services are of multi-point nature. Therefore, supporting multicast service in this network environment is very critical and unique. The all-optical support of various services has advantages, which includes achieving the signal transparency to its content. Nevertheless, the all-optical operational support comes with an associated cost and new issues that make this problem very challenging.

In this thesis, we investigate the power-related issues for supporting multicast service in the optical domain, referred to as *All-Optical Multicasting* (AOM). Our study treats these issues from two networking contexts, namely, *Network Provisioning* and *Connection Provisioning*. We propose a number of optimal and heuristic solutions with a unique objective function for each context. In this regard, the objective function for the network provisioning problem is to reduce the network cost, while the solutions for the connection provisioning problem aim to reduce the connection blocking ratio. The optimal formulations are inherently non-linear. However, we introduce novel methods for linearizing them and formulate the problems as Mixed Integer Linear Programs. Also, the design of the heuristic solutions takes into account various optimization factors which results in efficient heuristics that can produce fast solutions that are relatively close to their optimal counterparts, as shown in the numerical results we present.

CHAPTER 1. Introduction

Wavelength Division Multiplexing (WDM) is a technology that concurrently multiplexes many optical wavelengths over a single optical fiber. Since its introduction as a new fiber-optic communication technology in the 1970s, WDM has been a great drive for research in different areas. These areas include, but are not limited to, advancements in optical devices and switches, development of new protocols, and the introduction of new applications.

The development in hardware was realized by enhancing the optical layer condition via improving the status of the various optical devices and components of the WDM ecosystem [4, 5, 6, 7]. These efforts resulted in increasing the effective useful capacity of the fiber optic, which could be achieved by:

1. Increasing the number of available wavelengths from 2 wavelengths in the first WDM system built in the laboratory in 1978 to hundreds of channels in current commercial systems. This number is in terms of thousands of channels per fiber in the research laboratories.

2. Operating each of these channels at a high transmission speed. The current available systems operate at 10 and 40 Gb/s; however, speeds of 80 to 120 Gb/s are achievable in research laboratories using more sophisticated techniques, such as Optical Time-Division Multiple-Access (OTDMA).

On the protocol side, accelerated research efforts have been made in the literature to define, formulate and solve many challenging problems in order to support the various traffic types and services in WDM based networks. These problems are specific to this networking environment as they result from the unique characteristics and requirements of the WDM technology. Among these classical problems is the Routing and Wavelength Assignment (RWA) problem. This is an important problem that has been studied extensively in the literature under different traffic types [8, 9]. Solving this problem is fundamental to supporting a number of design and operational issues in mesh WDM networks, including the virtual topologies problem, the traffic grooming problem and the optical amplifiers placement problems.

These problems were investigated under different types of networks, namely, opaque, translucent and transparent. This classification is based on the impact of the transmission system on the signal's transparency level. In the opaque scheme, the signal is regenerated electronically at every node while the translucent scheme allows the signal to travel in the network as much as it can before it gets regenerated [10]. The transparent communication, also referred to as all-optical communication, relies on keeping the signal in the optical domain all the time and does not allow conversion between the optical and electronic domains except at end points. While still impractical, the deployment of the all-optical communication scheme is the ultimate goal of researchers and network operators; hence, tremendous efforts have been made toward achieving this goal.

Finally, on the application side, we witness a surge in the number and volume of investments that are made by various vendors and providers to present new bandwidth-extensive applications to their customers. This interest has intensified recently, especially after delivering optical fibers to homes and businesses as a last mile network solution becomes commercially available with competitive prices. One class of applications, which can capitalize on these advances in networks, is the class of multicast or multi-point service. Multicasting refers to the simultaneous delivery of information from a single point (called, the source) to a group of subscribers (called, the destinations). The set of multicast-based applications includes, but is not limited to: TV and video distribution, online gaming, database replication and search queries, storage area networks updates and backups, multi-party video-conferences, computer-supported collaborative work, etc.

This thesis studies the multicasting service mode in all-optical networks under realistic conditions, and in particular the presence of optical power impairments. We conduct this study in the context of two main networking problems, namely, the network design and network operation. In this chapter, we start our thesis by presenting an overview of the main components of the problems at hand. The rest of this chapter covers the following topics:

- A brief background about the optical networks.
- The various lifetime stages of the optical networks.
- All Optical Multicasting (AOM) support in wavelength routing networks.
- The challenges of supporting AOM.
- The methodology we employ in developing our solutions and the contribution of this thesis.
- Some introductory information about the system and the assumptions we employ in this thesis.
- The thesis organization.

1.1 Optical Networks Evolution

Optical networks have gone through two generations of development. These generations are depicted in Figure 1.1 with respect to the non-optical networks. While this classification is of no timing significance as many networks that are widely used today belong to these different categories, it is mainly based on the degree of usage of the optical components and related protocols.

Prior to using fiber optics as their transmission medium, communication networks that are based on copper (e.g., twisted pairs and coaxial cables) and air were widely deployed. In order to efficiently operate them, great investments were made in these networking technologies, either in the form of network elements or protocols. As a result, most of these conventional networks are still in use. However, these networks are not scalable to meet the rapid increase in bandwidth demands since their transmission rates are upper bounded by their maximum theoretical capacity according to Shannon-Hartley Theorem.

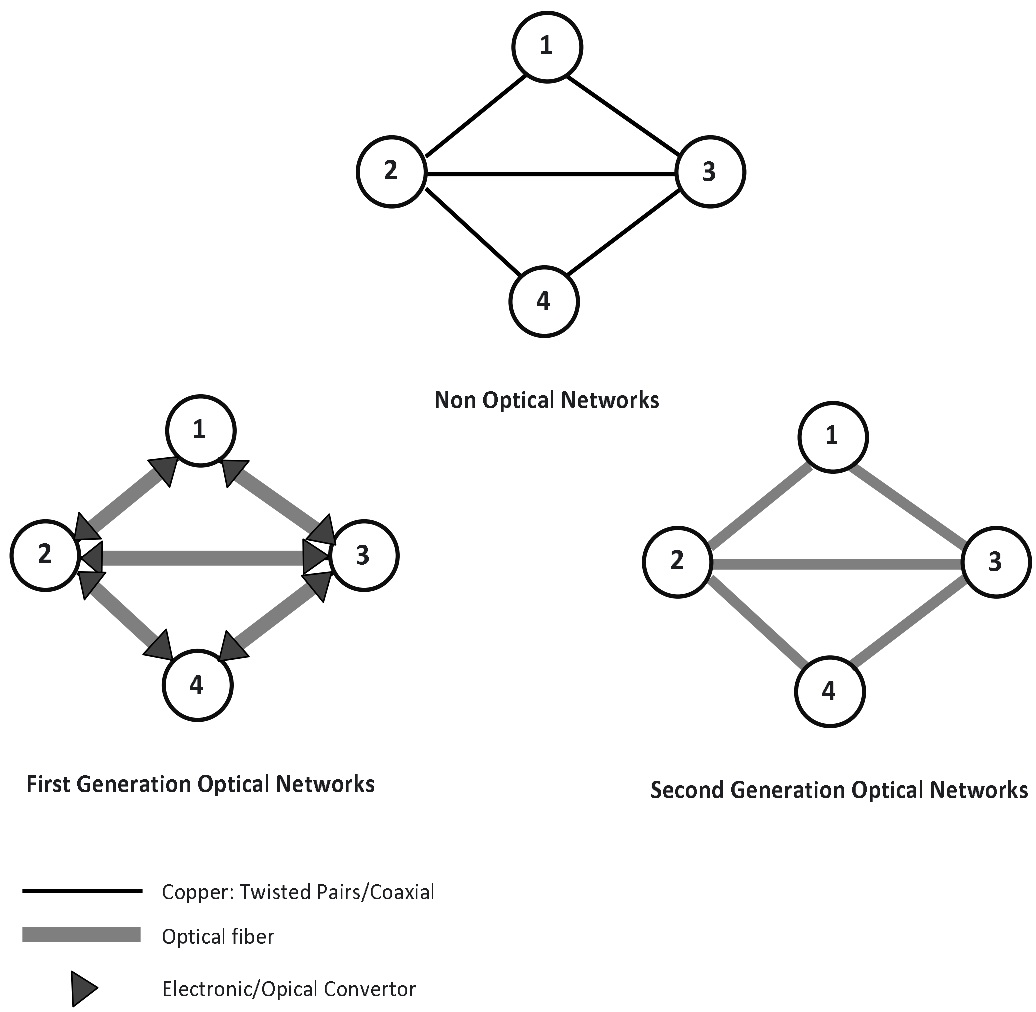


Figure 1.1 Optical Networks Generations

Motivated by the need to break this physical limitation, optical fibers were introduced as a new transmission medium to replace copper. This mere replacement of the transmission medium while using the same network protocols introduced the *First Generation* of optical networks. In these networks, data signals are converted back and forth between the optical and the electronic domains at every node. While data transmission and reception at the nodes are done in the optical form, data processing is performed electronically. Processing of data includes all types of networking functions and protocols which includes routing, switching and management. This operation scheme allows using the same set of solutions and protocols that were used with the conventional non-optical networks, yet at faster speed and with better performance. Hence, these networks are characterized as being the high-speed version of the traditional networks. Examples of the first generation optical networks include the Synchronous Optical Networks (SONET) and Synchronous Digital Hierarchy (SDH) networks, Enterprise Serial Connection (ESCON), High-Performance Parallel Interface (HIPPI), Fiber Distributed Data Interface (FDDI) and gigabit Ethernet.

Despite the enhancement in the network speed and performance, the effective capacity achieved by the first generation optical networks is in terms of few Gigabits per second only which is still much below the available capacity provided by the fiber (which is in terms of tens of Terahertz). This transmission bottleneck is limited by the maximum electronic processing speed at each node which allows converting the signals between the electrical and optical domains at a maximum speed of few Gigabits per second.

On the other hand, the *Second Generation* of optical networks consist of several optical solutions. However, these solutions are based on one common operational technology, called the Wavelength Division Multiplexing (WDM) technology. WDM is proposed to overcome the electronic bottleneck of the first generation networks by partitioning the optical spectrum into independent non-overlapping channels. In order to support simultaneous transmissions, each channel is centered at a specific frequency and assigned a certain bandwidth which allows them to operate individually at the peak electronic speed using state-of-the-art technology.

Based on their architecture, WDM networks can be classified as *Broadcast and Select Networks* and *Wavelength Routing Networks*. The operation of the first type is based on two elements, namely, the broadcasting capability of the transmission medium and the tuning capabilities of the nodes (if such capabilities exist). Due to the first element, no routing is needed in the broadcast and select networks. Nevertheless, sharing the same transmission medium requires the use of special medium access control (MAC) schemes in order to arbitrate the usage of this medium. On the other hand, the second element has direct impact on the design of these MAC techniques since it determines when and which channel each node can transmit and receive its packets.

Two topologies are used in the broadcast and select networks, namely, the star and the linear bus topologies. The star topology is based on the use of a special device, called the Passive Start Coupler (PSC), whose job is to deliver the transmitted signal launched by each node to all other nodes. This is achieved by internally combining the incoming signals from the various nodes and splitting their power into multiple output copies that are delivered individually to every node. However, only those nodes that listen to the correct channel and are destinations of the specific session are able to process the received data. On the other hand, the bus topology is based on using a single bus by all the nodes such that transmitting/receiving the data from/to the bus is done through separate power couplers. Due to the power limitation imposed from using the power couplers, and because simultaneous usage of the same channel by multiple transmissions is not allowed, WDM networks based on the broadcast-and-select architecture are suitable for the use by the local and metropolitan area networks only and several protocols were developed for packet switching on such networks using single and multihop delivery strategies [11, 12].

Unlike the broadcast-and-select WDM architecture, the wavelength routing architecture is more sophisticated as the network nodes have more networking functionalities (e.g., routing, switching, wavelength conversion and multicasting capability). Under this architecture, the network consists of a collection of Optical Cross Connects (OXCs) that are connected by fiber links in an arbitrary mesh topology. Therefore, this architecture is widely deployed in wide area networks. The OXCs are capable of routing different wavelengths at an input port to different output ports which allows different nodes to use the same wavelength on different fibers in the network using the spatial diversity property.

Depending on the traffic type and the employed protocol, the communication in wavelength routing networks is carried over clear all-optical delivery structures that are constructed between the communicating nodes. The signal is transmitted in these structures in the optical domain and is not converted back to the electronic domain until it reaches its destination node(s). These delivery structures take the form of a light-path [13], light-tree [2] or light-forest [14], which are the generalized form of the regular path, tree and forest used in conventional

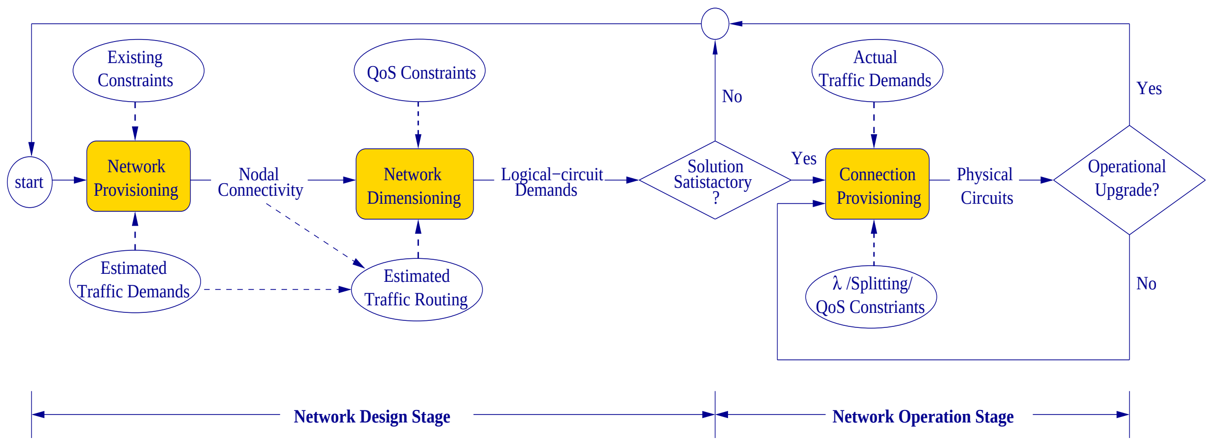


Figure 1.2 Optical Network Planning Stages under Multicast Communication

non-optical networks. Each session is delivered using a single delivery structure that is solely used by that session alone and not shared by any other session. In order to avoid wavelength collision and, hence, data loss in any of these structures that span many optical links, it is not permitted to use the same wavelength along a single fiber link by more than one session. Also, unless wavelength conversion is employed, each session must use the same wavelength over its entire path. This constraint is widely referred as the *wavelength continuity constraint*.

Finally, in addition to its support for end-to-end all-optical transparent service, these delivery structures are characterized by their high cost and the long time taken for setting them up. Therefore, they are used for circuit-switched service only, and packet switched service must be carried over such circuits.

1.2 Network Lifetime and Stages

The lifetime of any communication network, including optical networks, consists of two stages, namely, the network design or planning stage and its operation stage. During the planning stage, the network planners attempt to architect and design the network to be deployed by determining the various network components and resources along with their capacities and capabilities [15]. In doing this, the goal of the network designers is to accommodate a given set of traffic demands, while satisfying certain levels of quality of service (QoS), and incurring minimal cost. Network planning is a very complex, and imprecise process. On the one hand, the optimal allocation and determination of network resources is usually an NP-hard problem. On the other hand, determining the exact volume, characteristics and requirements for future traffic demands is an impossible task as these traffic properties are subject to change. Therefore, coming up with a design that takes care of such imprecise determination of conditions is a very challenging problem.

The network operation stage deals with a different set of challenges and problems. During this stage, the network is already provisioned and up and running. Network operators need to efficiently allocate the existing resources to the actual traffic demands present in the network. As these demands can be totally different from the ones used during the network design stage, the objective of the network operators during the network operation stage is to utilize the available network resources efficiently in order to minimize the loss in the QoS and/or the loss in the carried traffic. While the first objective is translated to minimizing the degradation in the provided service quality, the latter objective is viewed as minimizing the number of dropped sessions.

Based on the type of problems tackled, the network lifetime can be divided into three conceptual phases, namely, Network Provisioning, Network Dimensioning, and Connection Provisioning phases. These phases are executed iteratively. The relation, and interaction between the three phases is shown in Figure 1.2 and are explained in the following subsections. As shown in Figure 1.2, the Network Provisioning and Network Dimensioning phases are performed during the network design and are closely related, while the Connection Provisioning phase is performed during the network operation.

1.2.1 Network Provisioning Phase

Network Provisioning is the first task faced by the network designer. The purpose of this phase is to determine the network topology, which includes determining:

- The locations and the quantities of the various network resources, such as the: optical fibers, OXCs, optical amplifiers, wavelength converters, and light splitters.

- The virtual topology to be used to provision the estimated traffic demands given the network resources. This entails computing the light-paths, light-trees and light-forests for these traffic demands

The traffic demands used in this phase form a challenging problem for the network planner. The traffic information consists of both the current and the projected traffic demands and it describes the traffic volumes, characteristics, duration, and QoS. Usually, such traffic demands are overestimated in order to extend the lifetime of the network.

The problems tackled in this phase are also subject to a number of *existing* constraints. These constraints include, for example, the peer-nodes connectivity constraints, the geographical distribution of the nodes, and the existence of other networks that can be used to deliver part of the traffic, or at least participate in switching it.

These problems are usually formulated as optimization problems, (e.g., a constrained resource allocation problem), whose solutions are obtained using conventional optimization techniques. The objective function of these problems takes the form of minimizing a cost function of the optical components used in the network.

The output of the Network Provisioning phase takes the form of a connectivity matrix that specifies the connection pattern between the various network components along with their optimal (or near optimal) physical locations in the network. This output in conjunction with the estimated traffic demands and their QoS requirements form the input to the next phase of the network design stage, namely, the Network Dimensioning phase.

1.2.2 Network Dimensioning Phase

The second phase of the network design stage is the Network Dimensioning phase. Its goal is to determine the optimal dimension (i.e., size) of the various network resources such that the QoS requirements are met. The input parameters to this phase include the projected traffic demands, a specific routing strategy, and the network resources determined during the Network Provisioning phase. The output results of this phase include determining:

- The link capacity in terms of the number of fibers per link,

- The fiber capacity in terms of the number of wavelength channels per fiber, and
- The channel capacity in terms of the transmission rate.

Up to this point, the network design in terms of its topology and resources capacities is complete. Validating such a design is needed to examine its effectiveness before the physical deployment of the network. A Design Effectiveness Metric (DEM) [15] is used for this purpose, and it can be defined in a number of ways. The most widely used definition for the DEM is the ratio of the number of accommodated (accepted) calls to the total cost of the designed network. This metric is also referred to as calls per dollar. If the DEM of a certain solution for the network design stage fails to satisfy a specific threshold measure, the network design is revised in an iterative manner until the most appropriate network design candidate is found.

1.2.3 Connection Provisioning Phase

The network realization is the process of putting the network into operation and it comprehends the actual construction of the network from the design-blueprints and setting up the protocol stacks. Once the network is launched, the network operators become in charge and the network lifetime enters its operation stage.

As the projected traffic used to design the network is no more than an assessment of the actual traffic, the traffic demands during network operation may, or may not, meet these assessments. The difference in these traffic values may result in not accommodating all the sessions in the network. This requires operating the network with its current provisioned resources in a manner that maximizes the effective network utilization while guaranteeing the different connections QoS requirements. This directly translates into greater revenue to the network operator. Network utilization can be maximized by maximizing the ratio of the actual accepted calls with respect to the total number of arriving calls which is referred to as the calls acceptance probability.

This problem is known as the Connection Provisioning problem. In optical networks, the Connection Provisioning problem is responsible for all of the following tasks:

1. Route determination,
2. Wavelength assignment and resource allocation along the computed routes,
3. Power allocation.
4. Call establishment,
5. Error recovery due to nodes and/or links failures,
6. Traffic rerouting and wavelength reassignment in order to accommodate more traffic sessions (especially in the case of dynamic routing and wavelength assignment), and
7. Call termination and the deallocation of their associated network resources[1].

As such, the Connection Provisioning problem lasts for the duration of the network operation as it is exercised before call establishment, during the lifetime of calls, and after the termination of calls.

1.3 All Optical Multicasting (AOM)

Traditionally, multicast communication refers to transmitting the information (data, audio or video) from one source node to multiple receipts which helps reducing the amount of required bandwidth. In the literature, it is also referred to as multipoint and 1-to-many communication. Being a fundamental communication type in many networks, supporting multicast-based traffic and services had been investigated in almost every networking environment and wavelength-routing optical networks is not an exception. Nevertheless, what makes multicast support in this environment more interesting is its capability to support a special form of multicasting, called the All Optical Multicasting (AOM).

While supporting the same operational goal (i.e., 1-to-many data delivery), the main difference between the AOM and the conventional multicasting is in their operation layer. In a nutshell, AOM operates in the lowest optical networking layer, namely, the optical layer,

[1] Please note that the wavelength assignment and power allocation requirements are optical network specific while the other tasks are common among the different types of networks.

while the conventional multicasting protocols reside at higher layers[2]. Consequently, AOM eliminates any conversion of the transport signal between the electronic and optical domains at the intermediate nodes and data duplication is achieved using passive power splitters as was introduced in [2]. This operation scheme has the following advantages:

1. Removing the dependencies on the signal type, modulation, coding, bit rates and protocol. This provides signal transparency which has the advantage of enabling the optical layer to support different networking layers at the same time (e.g., IP or ATM data). Also, it contributes to reducing the nodes complexity and cost.

2. Since signal transparency is already achieved in unicast traffic by using light-paths, supporting multicast traffic all-optically presents another huge step toward achieving the all-optical service delivery as a unified delivery mechanism for the various traffic types in the wavelength routing networks. Such unified transmission scheme provides consistency in the network services which can reflect positively towards simplifying its design and operation,

3. Using power splitters to duplicate multicast data in the optical domain is much simpler than packet duplication used by the conventional multicasting. On one hand, these devices are passive, namely, no power is needed to operate them; therefore, its operation is more cost effective. On the other hand, this operation does not require the use of any buffer for data duplication as it is the case with higher layer multicasting. With high speed networks, this buffer can be so huge and consume a significant percentage of the node power and processing capacity.

4. Simplifying the logical network stack structure by increasing the number and complexity of the functions to be handled optically in the optical layer. Also, it enhances the quality of the produced solution and improves response time to any changes in the optical layer.

[2]For example, IP multicasting is implemented at the IP layer while Ethernet multicast addressing and ATM point-to-multipoint Virtual Circuits (VCs) are at the data link layer.

5. Reducing the OXCs cost by eliminating the need for using the signal converters to transform the signal between the optical and electronic domains.

6. As a result of eliminating the signal conversion and packet duplication using buffers, the delay encountered by AOM at each OXC is much less than that of the conventional multicasting. This has a positive impact on meeting the QoS requirements, especially the delay and the delay jitter, of the received signals at all the destinations.

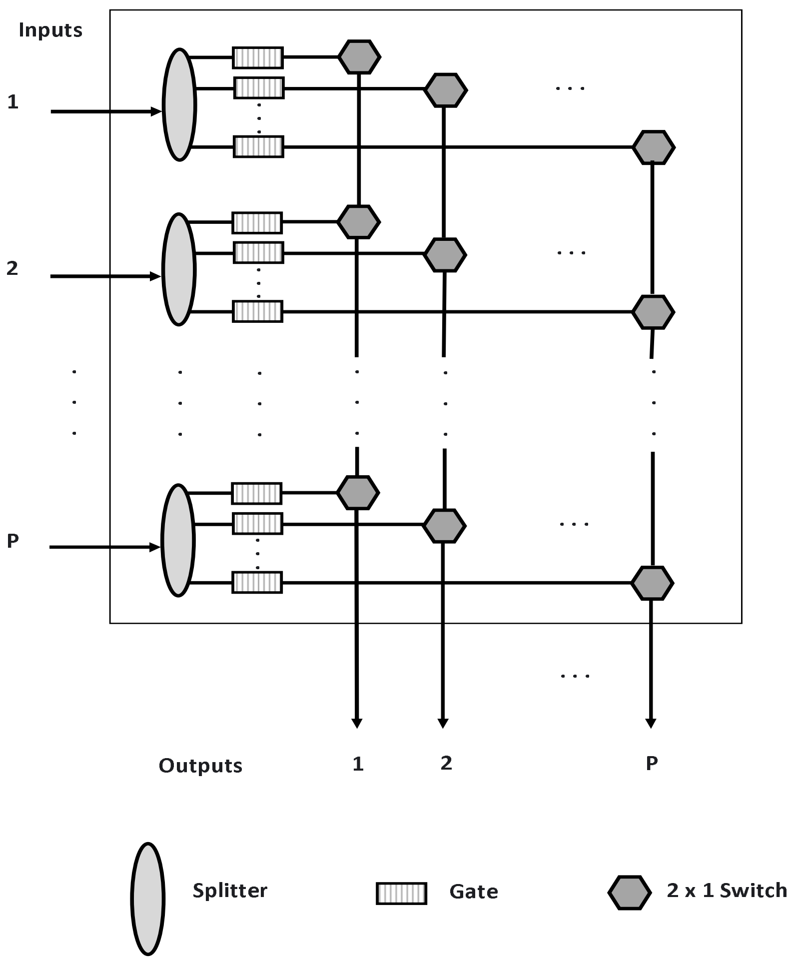


Figure 1.3 Splitter-and-Delivery (SaD) OXC.

In order to support the AOM service in wavelength-routing networks, it is necessary to integrate the splitting capability into the OXC architecture. OXCs that are equipped with the splitting functionality are called the Multicast-Capable (MC) switches while those with no splitting capability are referred to as the Multicast-Incapable (MI) switches [16].

Several MC nodal architectures have been proposed in the literature. For example, the Splitter-and-Delivery (SaD) switch was introduced in [17] and it is depicted in Figure 1.3. The design of the SaD switch consists of two stages. In the first stage, each input signal is initially split into a number of sub-signals that equals the nodal degree. In the second stage, the split signals are then switched to the appropriate output port using a combination of 1×2 switches. This design of the SaD switches has the advantage of providing a non-blocking service, namely, no call is dropped due to lack of the splitting or switching resources. However, it is a very complicated design which does not distinguish between the different traffic types. Therefore, the unicast traffic undergoes unnecessary power loss.

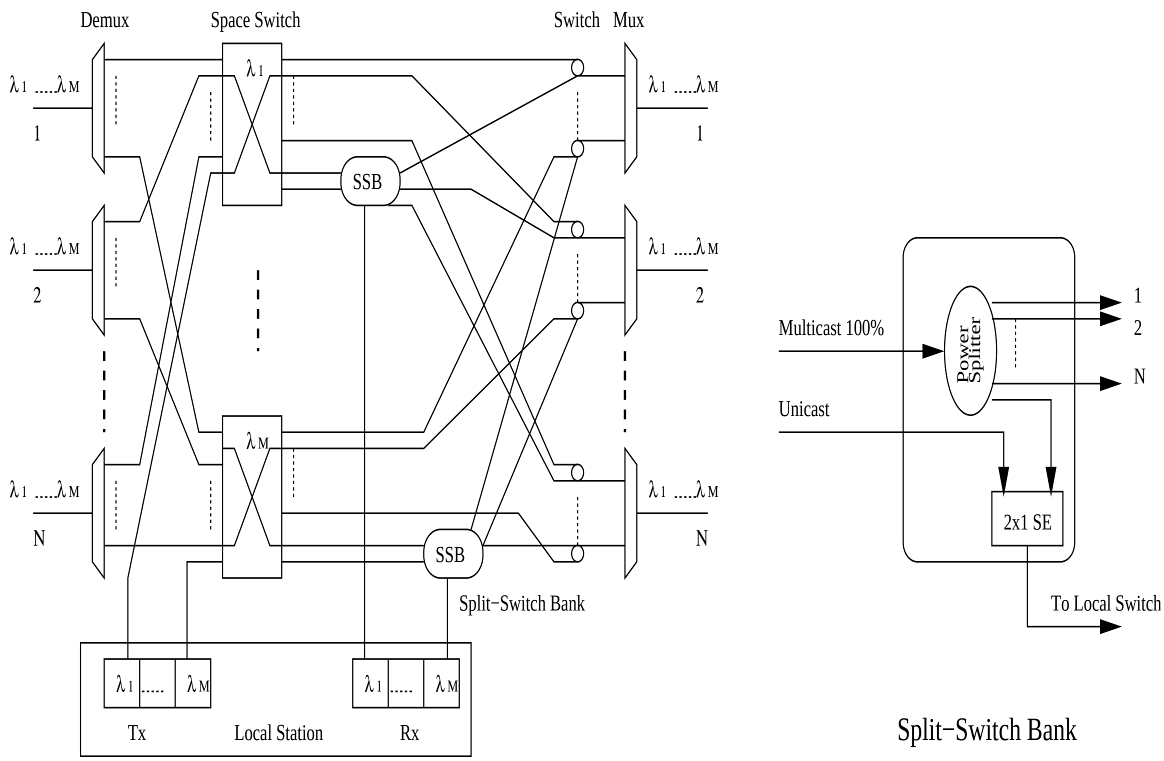


Figure 1.4 Multicast-only Splitter-and-Delivery (MOSaD) OXC.

To address the limitations of the SaD switch, the Multicast-Only Splitter-and-Delivery (MOSaD) switch was proposed in [18]. First, it reduces the complexity of the switch by sharing the splitters by a group of multicast sessions which reduces the number of used splitters. Second, signal splitting is performed only for the multicast traffic. Figure 1.4 shows the basic structure of the MOSaD OXC. As shown in the figure, the wavelengths are first optically demultiplexed on all the input fibers and the signals of the same frequency are directed to the corresponding space switch. Each space switch in turn switches the input signal to either a corresponding output link if it is of unicast type or to a special component called Split-Switch Bank (SSB) if it is of multicast type. Only one SSB is attached to each space switch and its purpose is to split the incoming multicast signal and then switch it to the corresponding output link. This contributes to reducing the structure complexity; yet, at most one multicast session over each channel can be provisioned at the same time while others will be blocked.

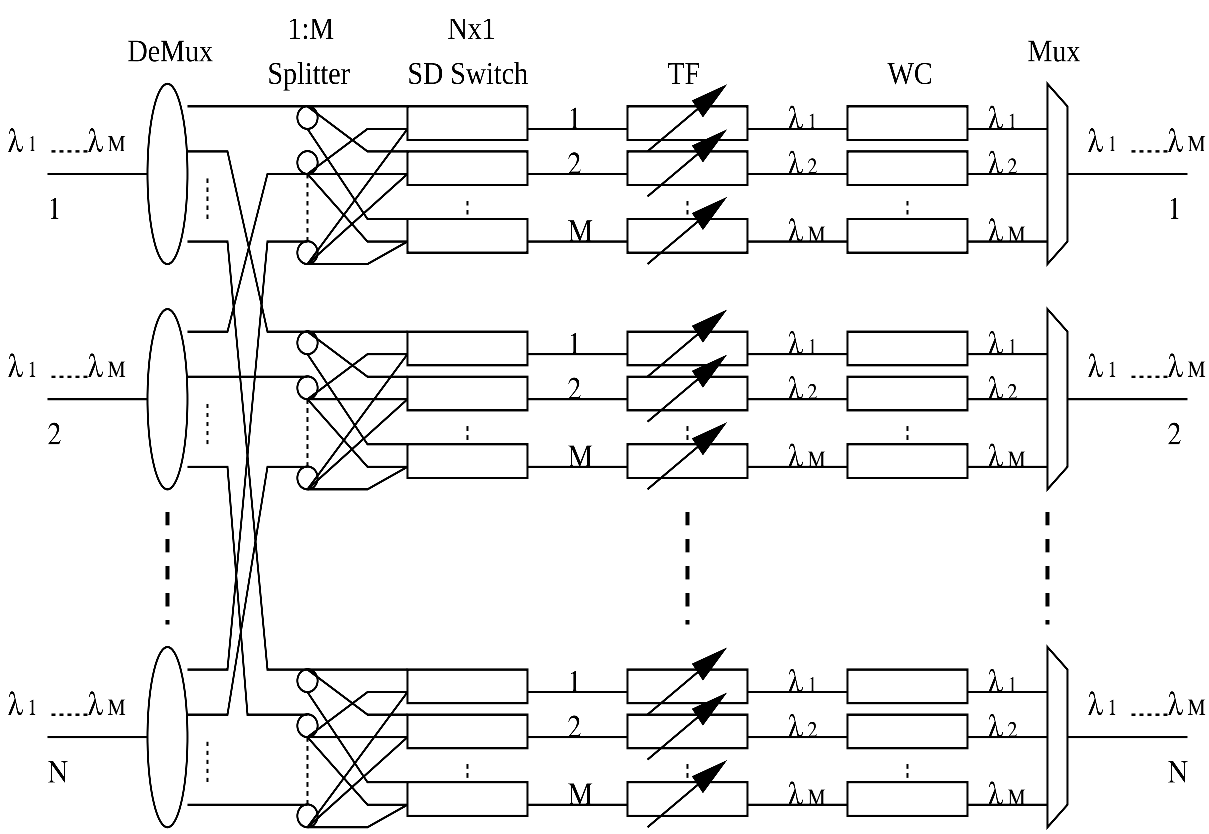


Figure 1.5 An example of Multicast Capable Switch with Wavelength Conversion reported in [1].

In order to enhance network performance, wavelength conversion capability was also introduced in the MC OXCs [1, 2, 3]. The architecture proposed in [1] is depicted in Figure

1.5. First, the signals are split. The split signals then pass through a space-division (SD) switch which can then be converted into different wavelengths by using wavelength converters. Finally, the signals are then multiplexed on an output port fiber.

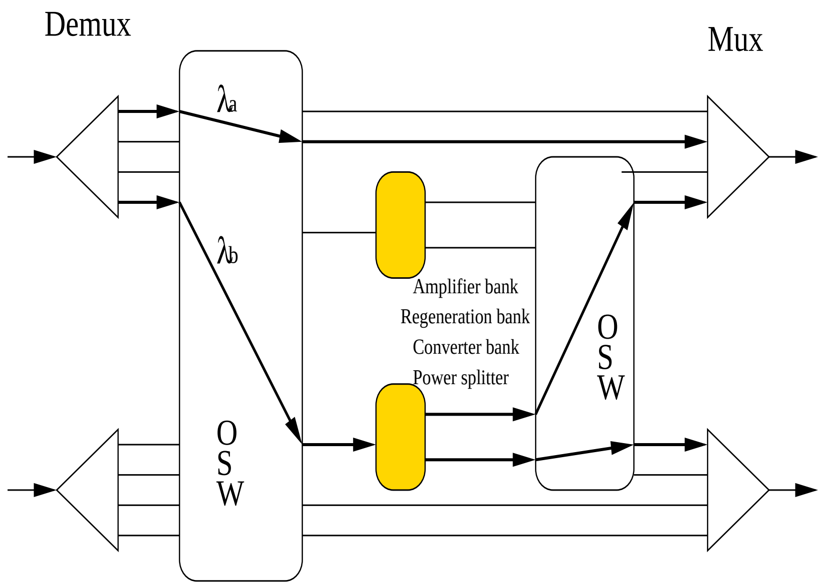


Figure 1.6 An example of Multicast Capable Switch with Wavelength Conversion reported in [2].

In [2], the proposed MC structure employs two stages of optical switches. After demultiplexing, input signals pass through the first optical switch, and only multicast signals are switched to a splitter. After that, the split signals pass through an amplifier bank. Then the signal passes through the second switch which routes it to the appropriate output port, as shown in Figure 1.6.

Finally, a splitter converter sharing switching structure was introduced in [3] and it is depicted in Figure 1.7. As its name indicates, this structure is based on sharing the splitters and converters by all the input signals. Therefore, some of the sessions might be blocked based on the availability of the splitting and conversion resources. As shown in Figure 1.7, this structure uses three optical switches. After demultiplexing the signals on each fiber, each wavelength is switched by the first optical switch (OSW). The purpose of the first OSW is to route the signals that are non-multicast and do not need wavelength conversion directly to the corresponding output links. Multicast signals or those that need wavelength conversion are routed to a

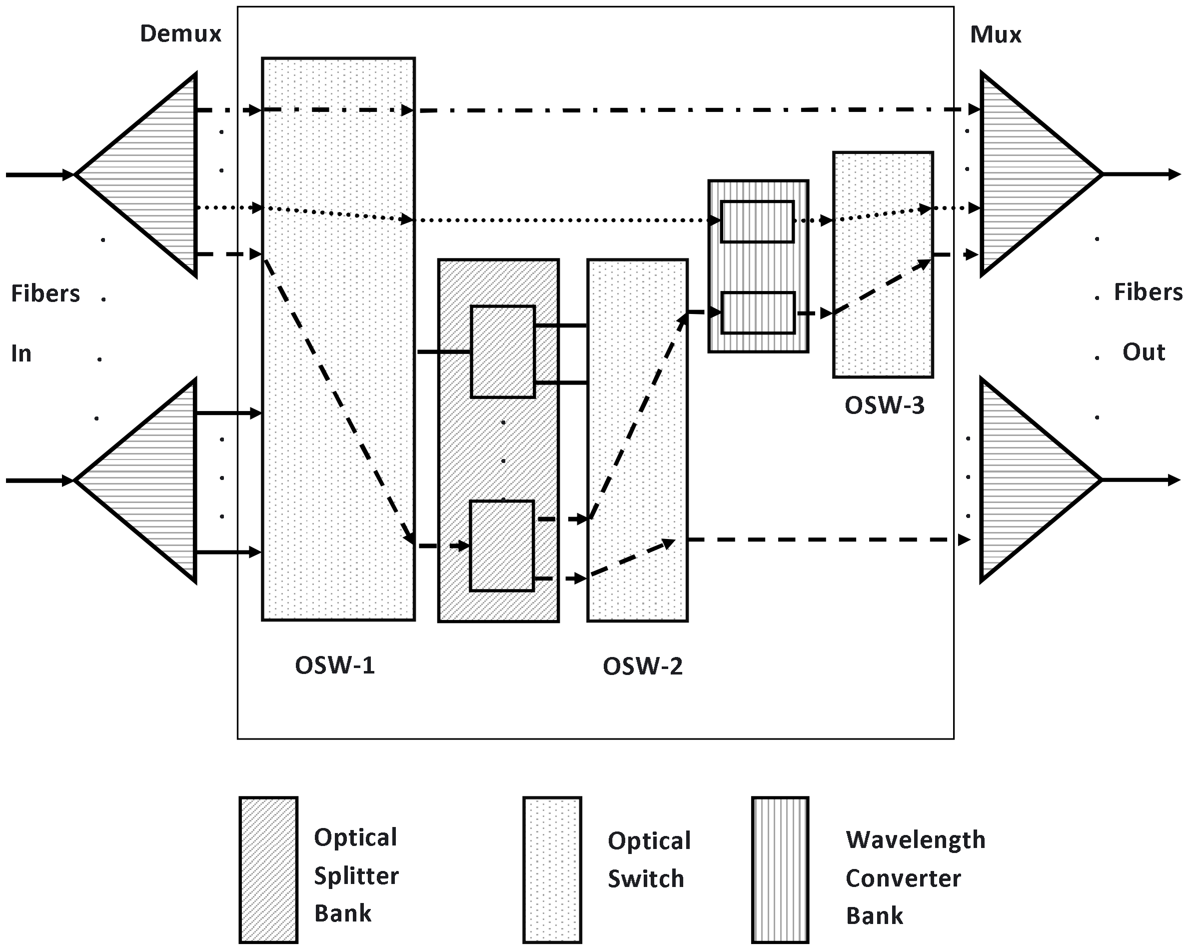


Figure 1.7 Splitter converter sharing switch reported in [3].

port connecting with an optical splitter bank, or a wavelength converter bank, respectively. After splitting the signal, they pass through the second OSW which routes the signals to the wavelength converter bank if they need to be converted or to their respective output links, otherwise. The wavelength converter bank is followed by the third optical switch, which routes the signals to the output links. The results reported in [3] indicated that equipping 50% and 12.5% of the nodes with the splitting and wavelength conversion capabilities, respectively, is sufficient to make the system performance in terms of the calls blocking probability close to optimal.

At the end of this section, it is worth mentioning that supporting AOM in wavelength routing networks can be achieved even without the use of optical splitters. In order to do so, a new architecture, called the Tap-and-Continue (TaC) OXC was proposed in [19]. The basic structure of the TaC OXC is similar to that of the MOSaD OXC [18]. However, the SSB modules used in the MOSaD OXC are replaced by a new module called the TaC modules (TCM) in the TaC OXC. In the TCM, instead of using splitters to split the signals, power taps are used. When a multicast signal passes through a TCM, only a small fraction of this signal is tapped and forwarded to the local station, while the remaining power is switched to an output port. Special routing schemes are needed in TaC-based networks as the routing problem is more difficult and involved.

1.4 Challenges of Supporting AOM Service in Wavelength Routing Networks

Supporting multicast communication in single channel networks (e.g., IP networks) presents a number of challenges, and has thus been the subject of extensive research [20, 21, 22, 23, 24]. These challenges become even more critical in multi-channel wavelength-routing networks which also introduce their own set of unique problems that prevent having an easy application of the traditional multicast solutions on wavelength routing networks.

The uniqueness of these problems stems from the distinctive characteristics of the wavelength-routing networks. Among these characteristics is the operation mode of these networks. As shown earlier in Subsection 1.2.3, the connection provisioning phase of the network operation includes two operations which are unique to optical networks, namely wavelength assignment and power allocation tasks. Therefore, any traditional multicast protocol that operates on a non-optical network cannot perform well in its wavelength-routing counterpart due to lack of consideration of these additional operations. Another unique source of challenges comes from the optical hardware components of the networks. The impact of each optical component on the signal quality and the degree of deployment of these elements in the network are two fundamental factors in determining the success of any optical multicasting scheme.

However, other challenges and limitations also exist. To resolve all of these limitations and to achieve an efficient use of the various network resources, the AOM protocols should be carefully designed. In the following subsections, we will address these different challenges individually, and we will discuss how they impact the implementation of AOM in wavelength-routing networks.

1.4.1 Challenges Due to High-Transmission Rates

With the use of WDM technology, the transmission rate of the individual channels is on the order of 10 Gb/s to 40 Gb/s. Therefore, the delay-bandwidth product[3] in WDM networks is very large, and it increases with the increase in the network diameter. As a result, network operation that depends on the feedback from the network is adversely impacted and might not be a good choice. For example, on-demand routing strategies which probe the network resources when a connection is to be established will result in bandwidth wastage and increased connection latency.

In addition, optimal provisioning, which requires increased computation, and node coordination, can also result in far from optimal resource utilization. Therefore, it is essential to design lightweight protocols that are efficient, but simple enough so that it can be executed fast enough and don't form a bottleneck to the network. However, the simplicity and the efficiency of the protocols seem to be two conflicting goals.

1.4.2 Challenges Due to the Characteristics of the Wavelength-Routing Networks

Wavelength-routing networks are unique environment and they have a number of special characteristics that affect its support for AOM service. These characteristics include the use of multiple channels, the circuit-switched connection mode and the employment of the various optical components. We will briefly describe each of these characteristics and the limitations they impose in the following subsections:

[3]The delay-bandwidth product is the ratio of the propagation delay to the packet transmission time. This metric provides an indication of the number of data packets in the transmission pipe.

1.4.2.1 Multi-Channels Environment Limitations

Although WDM networks consist of multiple independent channels over any link, the usage of these channels is not totally independent of each other, either on the same link or on different links. Such channels dependency precludes the use of several conventional multicasting techniques (e.g., IP multicasting) in the wavelength-routing networks as such techniques treat these channels independently.

For example, different channels must be used by different sessions over the same link in order to prevent data corruption. Also, in the case of no, or limited, wavelength conversion in the network, maintaining the wavelength continuity constraint is required for the success of any multicast session. Wavelength continuity constraint must be satisfied both in depth due to signal propagation, and in breadth, due to multicasting and signal branching.

Finally, the availability of transceivers (i.e., transmitters and receivers) at the end points of the trees (i.e., source and destination nodes, respectively) is necessary to ensure correct operation of the network. These transceivers can be either fixed or tunable. To guarantee the correct delivery of the data, the source's transmitter and the destinations' receivers should be available and tuned to the same transmission channel.

1.4.2.2 Circuit-Switched Communications Limitations

Circuit-switching is the main communication mode employed in wavelength routing networks. Circuit-switching has the following characteristics [15]:

- Resource reservation is performed along each determined route,
- Setup time for each session route is long,
- Any connection request can be blocked due to lack of resources, and
- The connections are static and have long-duration.

These characteristics can be addressed in AOM at different contexts. First, the performance metrics for multicasting must be chosen carefully. For example, since blocking can occur due to lack of resources, the call acceptance probability can be defined differently. In this context, data delivery to a subset of the multicast group is allowed instead of delivering it to all the members of the group as was proposed in [25, 26]. Other performance metrics also include: reducing the connection setup time [27], reducing the propagation delay per receiver [1] and reducing the total multicast tree cost [1, 28, 29, 30].

Second, this operation mode affects the choice of applications to be supported in the network. The circuit-switching nature best suits those applications that are of high utilization, require low delay and are not affected by the high setup time of the connections. Such applications include for example the uncompressed audio and video and the various multimedia applications. However, the real-time applications, especially those that require stringent constrains in terms of setup time, cannot directly fit into such network and they require special treatment.

Third, these features do not only affect network operation, but also the network provisioning and dimensioning, as they impact the cost of the network, and its ability to handle the projected traffic.

1.4.2.3 Optical Hardware Limitations

The limitations of the state-of-the-art of optical components, and the high cost associated with their usage preclude full deployment of such components at all nodes of the network. This results in deploying different OXC structures in the network. For example, some nodes may be MC nodes while others are MI. Also, only subset of the nodes (can be MC nodes themselves) may be equipped with wavelength conversion capability. Moreover, the splitting and conversion capabilities, if they exist, may be incomplete. In this context, the fanout of the splitters can be less than the nodal degree while wavelength conversion can be done between specific regions of the optical spectrum only. This asymmetric deployment has a significant effect on the multicast routing and tree maintenance. In the following, we will describe the impact of the various optical components on AOM.

- Optical Splitting Impact

Light splitting is equivalent to packet replication in the electronic domain, yet, it is theoretically simpler. In addition, a simple version of the splitting capability, which is assumed to be available at all the nodes, is the Drop-and-Continue (DaC) [1, 28] (or sometimes called the Tap-and-Continue (TaC) [19, 30]) capability. This refers to tapping a small amount of the power which is used for signal detection by the receiver connected to the node.

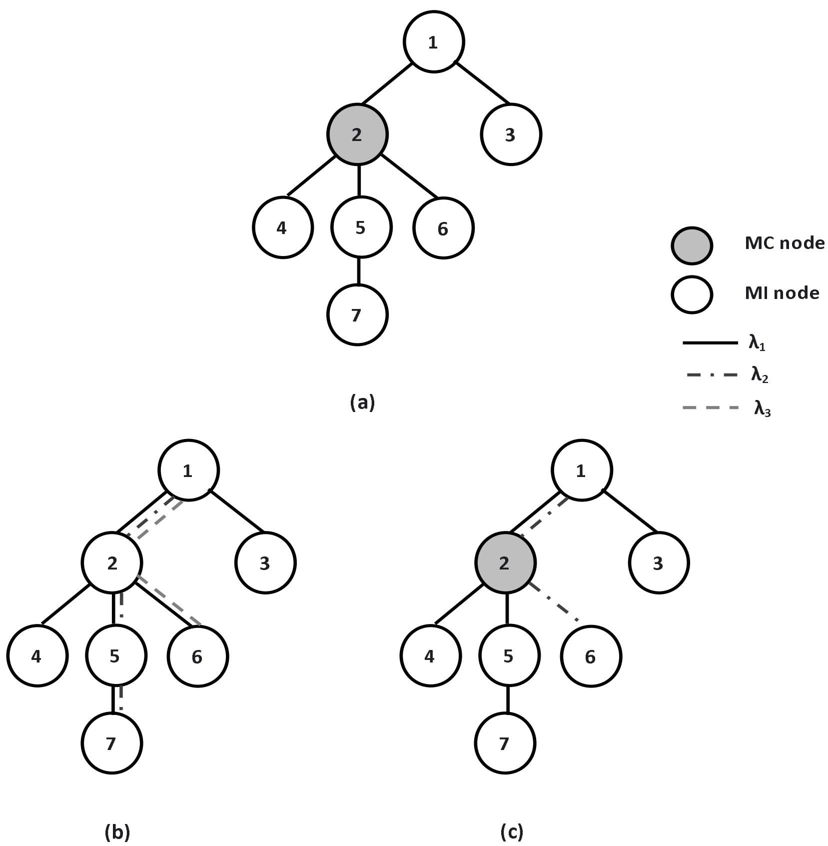


Figure 1.8 An example that illustrates the construction of the multicast delivery structure (light-tree or light-forest) for the multicast session m=(1,{3,4,6,7}) when: (a) node 2 is an MC node with complete splitting capability, (b) node 2 is an MI node, and (c) node 2 is an MC node with limited splitting capability and splitting fanout equals 2 only.

The wavelength splitting capability is a key enabling technology for multicast communication in wavelength-routing networks. In order to illustrate the significance of light-splitters for routing multicast sessions, we use the example depicted in Figure 1.8 for routing a sample session, denoted by m=(1,{3,4,6,7})[4]. While all nodes are assumed to have the DaC capability, node 2 is an MC node. Figure 1.8-(a) depicts the multicast light-tree and it shows that a single multicast light-tree is sufficient to support the multicast connection, m, using one wavelength. In this light-tree, node 3 receives the signal transmitted by the source node 1, while nodes 4, 5 and 6 receive the signal after being split by node 2. Node 7 will then receive the same signal received by node 5, but after tapping a small amount of power for signal detection using the DaC capability.

Figure 1.8-(b) illustrates the case when no MC nodes are available in the network. In this case, constructing a single multicast distribution tree for session m is not feasible because only a single offspring can be attached immediately to node 2 on any particular wavelength. Instead, the source node 1 transmits the same information on three different wavelengths, namely, (λ_1, λ_2 and λ_3), to node 2, which in turn relays these transmissions to the different branches in order to reach destinations 4, 5 and 6. Multicast routing in this case takes the forms of light-forest which consists of three distinct light-trees and uses three wavelengths.

As shown by this example, the use of splitters for AOM reduces the amount of bandwidth wastage and the unnecessary usage of network resources. However, using splitters at the optical switches comes with a price in terms of the power-budget and devices/nodes implementation. In addition to the added complexity to the OXC structure as explained earlier in Section 1.3, using splitters reduces the signal strength and in order to maintain the signals at detectable levels, optical amplifiers may have to be used. Using optical amplifiers has its own limitations. First, optical amplifiers are still expensive devices. Second, they impact the signal quality as they degrade the signal to noise ratio due to amplification to spontaneous emission [7]. Third, integrating optical amplifiers within optical switches adds significantly to the OXC switch design complexity [18].

On the other hand, the deployment degree of MC nodes in the network influences directly the design of multicast routing algorithms. Empirically, it was shown that about 50% only of

[4]In this thesis, we use the notation (s,{d_1,...,d_k}) to describe any multicast session, such that s determines the session's source node while each d in the set determines a destination node.

the nodes in the networks need to be MC nodes in order to achieve good performance level [31, 32]. Networks in which both MC and MI nodes coexist are known in the literature as networks with *sparse-splitting* [31] and they are known to implement Partial Packet Replication (PPR) [33]. Many schemes were introduced to deal with sparse-splitting situation as in [1, 29, 30, 28]. In addition, two extreme strategies for MC node deployment were investigated in the literature in which all the nodes are either MI nodes, e.g., [19], or MC nodes, e.g., [25, 2, 26]. These strategies are called, *no*-splitting (or No Packet Replication-NPR), and *full*-splitting (or Full Packet Replication-FPR), respectively.

Moreover, multicast support in wavelength-routing networks is also influenced by the splitting fanout, which is the maximum number of multicast tree branches supported per node. The fanout of an MC node is denoted by *f*, where $1 \leq f \leq d$-1 and d is the nodal degree. When f equals d-1, the switch is said to have a *complete* splitting capability; otherwise, the splitting capability of the node is *limited* since only a selected subset of the node's neighbors can receive the split signal. The splitting fanout is an important parameter in the design of multicast trees and it also impacts the choice of the number of amplifiers, their placement, and signal-to-noise ratio.

In order to illustrate the importance of the splitting degree on the resultant multicast delivery structure, consider the same example and system setup depicted in Figure 1.8-(a) but with the assumption that the f factor for node 2 is 2. This example is shown in Figure 1.8-(c). With this configuration, the branching node 2 can forward the signal to only two of its offsprings, say nodes 4 and 5. In order to deliver the data to the remaining node, namely node 6, a new light-tree connection from the source node 1 must be established via node 2 using a new wavelength (λ_2). As a result, the multicast delivery structure is a light-forest that consists of 2 light-trees that are carried on two different wavelengths.

Finally, the splitting ratio also influences the multicast tree construction. Signal splitting ratio can be either *fixed* or *adjustable*. With fixed splitting, the light-splitter ideally divides the input signal equally into f output signals (assuming no other loss is encountered), where f is the fanout factor. This splitter type is a passive one, which is simple and inexpensive. However, it can be power inefficient, especially when the multicast tree is unbalanced. In this case, some signal power is wasted and the multicast tree size is affected. On the other hand, splitters with adjustable splitting ratios can significantly reduce the power wastage which may lead to increasing the multicast group size[5]. It is also worth mentioning that the use of splitters with adjustable splitting ratios becomes imperative in the context of dynamic multicasting where the multicast tree structure dynamically changes. However, splitters with adjustable-ratio are active devices that are more expensive than their fixed-ratio counterparts, may be unstable and may not be noise-immune.

- Wavelength Conversion Effect

Wavelength-converters are active optical devices which shift the optical signal from one optical frequency to another. The employment of wavelength converters provides flexibility in the network operation and enhances its performance. Using wavelength converters eliminates the wavelength continuity constraint which results in simplifying the multicast routing computation.

All-optical wavelength converters [34, 35], however, are still very expensive and immature. Also, equipping the switch with wavelength converters complicates the switch design and increases its cost, which hinders the *full* deployment of wavelength converters in the network. Instead, the no- and sparse- wavelength conversion options are more practical options. The full (no) wavelength conversion capability is the most (least) flexible and provides the best (worst) blocking probabilities for the calls; however it is the most (least) expensive. The sparse-wavelength conversion option, on the other hand, refers to the situation in which only a subset of the nodes are equipped with converters. It can achieve a balance between the cost and the network performance, and thus, it seems to be the most practical option.

On the other hand, wavelength conversion capability can be limited. Limited conversion means that conversion from a certain wavelength is limited to only a sub-band of the optical spectrum. Sparse-, no- and limited-conversion configurations requires some degree of wave-

[5]Please refer to [9] for a detailed analysis of this issue

length continuity, which restricts the multicast tree construction.

Moreover, integrating wavelength converters with splitters can take two forms, namely, *Pre-Conversion* or *Post-Conversion*. As shown in Figure 1.9, these schemes correspond to placing the converters before or after the light splitter, respectively[6]. Since a single converter is needed, the cost associated with the Pre-Conversion scheme is much less than that of the Post-Conversion scheme. Both schemes provide the same degree of flexibility if converters always convert from λ_i to λ_j. Otherwise, the Post-Conversion scheme in general exhibits more flexibility and results in higher system performance.

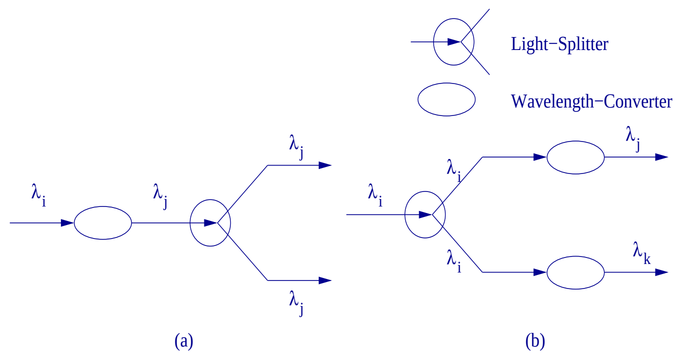


Figure 1.9 Splitter-converter relative locality in the switch (a) Pre-Conversion Scheme, and (b) Post-Conversion Scheme.

- Optical Amplification Impact

The final hardware-related challenge is the amplifier placement problem. In multicast communication, power loss can be due to fiber attenuation and splitter loss, if any. One of two techniques for signal amplification may be used, namely, *on-site* and *on-link* amplifications. With the on-site amplification, the amplification is performed inside the switching node itself. There are two methods to integrate the amplifier and the splitter within the node. In the first one, called the *Pre-Amplification* technique, the amplifier is placed before the splitter, while in the other case, called the *Post-Amplification* technique, it is placed after the splitter, as shown in Figure 1.10. Both configurations exhibit the same performance in terms of power values at

[6]Because each wavelength requires a separate converter, Figure 1.9 depicts the requirements for a single input-output channel pair (i.e., λ_i and λ_j, or λ_k), regardless of the range of the wavelengths at their input and output.

the output links when the optical amplifiers operate in the non-saturated region. However, if they are working in the saturation region, the post-amplification scheme will result in better power strengths than the pre-amplification scheme.

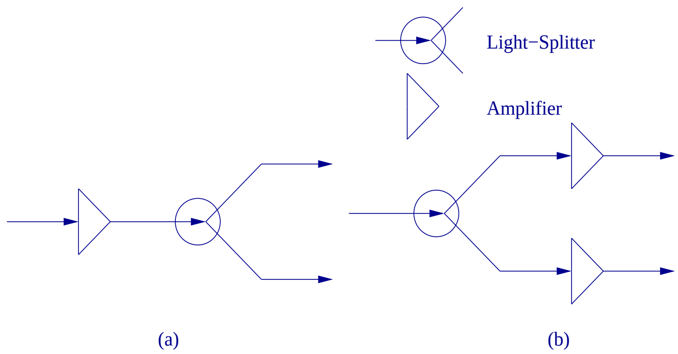


Figure 1.10 Splitter-Amplifier relative locality in the switch (a) Pre-Amplification Scheme, and (b) Post-Amplification Scheme.

Also, the first scheme is less expensive. However, it is to be noted that the SNR at the output signal under both schemes will be the same. This is because splitters are passive devices which theoretically do not introduce noise, and because the spontaneous emission amplification in all-optical amplifiers is proportional to the signal power.

On the other hand, the on-link amplification is performed by amplifying the signal while it is traversing the physical links. For multicasting, placing amplifiers on fiber links can increase the number of potential receivers. An optimal placement configuration can reduce the total number of amplifiers in the network. There are several studies, e.g. [36, 37], which deal with the problem of amplifiers placement for unicast service. The ability of such schemes to accommodate multicast traffic is not a simple task as will be shown later in Chapters 3-5.

In addition, an ideal optical amplifier applies a flat gain over all the input signals. Therefore, the power strengths of all the input signals increases with the same gain. Consequently, a weak input signal will still be weak at the output, and the maximum gain of an amplifier becomes limited. Although the same situation is encountered with unicast traffic, the difference in the power levels of the different input signals is more significant; thus its impact is more severe, in the context of AOM. This is mainly due to the additional power loss from signal splitting.

This implies that a multicast signal may not obtain enough power if it is accompanied by other stronger signals.

Moreover, to find an optimal amplifier placement for a multicast tree, at least two parameters, namely, signal power and source-destination distance, should be given. However, dynamic multicasting and the use of adjustable splitting coefficient aggravate the problem since the former results in changing the communication diameter, while the latter changes the signal power. This problem can be solved by using the splitter with Post-Amplifier configuration shown in Figure 1.10-(b) or by introducing equalization at each amplifier stage [7].

Finally, using optical amplifiers impacts the SNR. All-optical amplifiers, e.g., Erbium-Doped Fiber Amplifiers (EDFA), amplify noise due to spontaneous emission [7], which impacts the signal quality levels and imposes an upper bound on the number of optical amplifiers the signal can traverse before getting regenerated. Therefore, this contribution of the optical amplifiers in the noise level has a direct influence on the network design and operation.

1.4.3 Challenges Due to Routing and Wavelength Assignment

In this subsection, we focus on two basic functions in wavelength-routing networks, namely, Routing (R) and Wavelength Assignment (WA), from the multicasting viewpoint. R and WA problems have been extensively studied under unicast communication [7]. Solving the combined R and WA problems (conventionally referred to as RWA problem) produces the optimal solutions. However, due to the difficulty of the RWA problem, the R and WA subproblems are treated separately. The multicast extension of the conventional RWA problem is referred to as MCRWA [25] or MC-RWA [26].

MCRWA problem is mainly concerned with establishing the multicast route in the network, and determining the appropriate wavelength to be assigned to it. It has the objective of minimizing the required network resources, especially the number of wavelengths, or maximizing the number of accepted calls. The combined problem has been proven to be NP-Complete [25, 38] since it involves finding an optimal multicast tree which is the well-known NP-Complete Steiner Minimum Tree (SMT) problem [39]. Hence, it is solved using heuristics. The combined MCRWA can also be characterized as a *wavelength-aware* approach because computing the multicast delivery structure is directly influenced by the status of the wavelengths in the network and the cost associated with their use.

Similar to the traditional RWA in unicast networks, the MCRWA can be solved as two separate problems, namely, the multicast tree is first determined, followed by appropriately selecting wavelength(s) on this route. Therefore, the uncoupled version of MCRWA is a *wavelength-unaware* approach. The routing part of the problem is still NP-Complete since it involves the construction of the SMT, but the wavelength assignment part can be solved in polynomial time for some special cases, e.g. [38, 40]. Decoupling the routing and wavelength assignment problems simplifies the problem slightly, and also provides flexibility in enhancing routing protocol designs and integrating extra operations and features, such as QoS guarantees, fault-tolerance, and security.

Furthermore, different operational modes for the R and WA operations were proposed in the literature. Each mode has its own performance degrees and associated costs. The performance-cost trade-off of these operation modes must be considered in the protocol design process. In this context, and at the routing side of the problem, the routing schemes have been traditionally characterized as either: (1) *fixed*: in which a fixed route per call is established, (2) *alternate*: a set of paths are assigned for each call which are searched sequentially in a specific order in order to pick the route, and (3) *adaptive*, in which the route is found dynamically based on the network status. The flexibility of these schemes increases from the fixed to the adaptive, but at the cost of increased overhead and complexity.

Similarly, many schemes have been proposed in the literature for WA. However, four of these schemes were inherited from unicast communication, namely: (1)*random*, in which wavelength selection is performed randomly from the set of available wavelengths, (2) *first-fit*, which chooses the first available wavelength, (3) *least-used*, and (4) *most-used*, in which the wavelength to be chosen is based on the degree of its usage. In general, the complexity of the wavelength assignment problem is a design factor that must be considered.

Finally, the routing and wavelength assignment in optical network can be performed in two computational modes: *on-line* and *off-line*. The *on-line* mode allows requests to be processed as they arrive to the system, i.e., it does not assume prior knowledge of the traffic in the network, and the admission decision of the connection is based on the instantaneous network state. If the connection request is admitted, its route and the assigned wavelengths are usually not changed during the lifetime of the connection. Otherwise, and because of the no waiting feature of circuit-switched service, the connection is blocked. The *off-line* mode, on the other hand, assumes prior knowledge of all the connection requests which makes it possible to obtain an optimal allocation for the routes and the wavelengths. The first computation mode is more practical, but optimal operation is more difficult, while the opposite is true for the second computation mode.

1.4.4 Challenges Due to the All-Optical-Multicasting (AOM) Characteristics

All-Optical Multicasting (AOM) inherits all the problems of conventional multicasting. For example, the ideal operation of the multicast session entails hiding the information about the various receivers from the source node, and vice versa. This information includes the nodes' addresses, locations and their total number. A dedicated address is assigned to the multicast session, which is globally known. This requirement is still not yet fully achieved in most routing and wavelength assignment techniques of AOM, which are based on a key assumption of global (or partial) knowledge about the network topology, and the nodes membership. However, [27] appears as an exception in which the source node needs not to know about the destination nodes and their locations.

In addition, different attributes of the multicast session may necessitate the use of routing strategies, which may look suboptimal, but are necessary because of the all-optical nature of the session. For example, consider the case when the multicast session has a short duration, and its member group size is small and are geographically far away from each other. Under such scenario, the designers might find it more efficient to use separate unicast connections, one for each destination, instead of attempting to construct a single optimal tree that joins all the nodes. Such a solution may be even critical if free wavelengths exist, but wavelength continuity among all the branches cannot be maintained.

Furthermore, the connection acceptance metric may take different levels. Nodes in the destinations set are assigned weights, and a call is accepted if a certain total weight is achievable. For example, the multicast session may be rejected (blocked) if the traffic cannot be delivered to at least one member. This is referred to as the *full* acceptance criterion. This all or nothing strategy provides simple and cost-effective mechanisms for connection management, but with relatively reduced network utilization. On the other hand, a partial acceptance criterion can be used in which a call is successful if a minimum number of destinations are reachable. The other unreachable members will be blocked. This scheme enhances network utilization; however, the cost associated with tree maintenance, network management and control-information flows is very high. The suitability of connection acceptance metric is application dependent.

On the other hand, the implementation of dynamic multicasting can be quite challenging in the all-optical environment. For example, the wavelength assignment may have to be done in a way that maximizes the probability of accepting new members, given the set of potential multicast members. This may sometimes lead to an underutilization of network resources. Moreover, in order to provide an efficient implementation of dynamic multicasting, splitters with adjustable splitting ratios may have to be deployed, which are more costly, and harder to control.

1.5 Methodology and Contributions of the Thesis

The goal of our study here is to investigate the impact of power impairments of the optical layer on the network design and operation processes. We realized the significance of this topic as part of our survey study in [9] where we found out that this research subject was overlooked by most research efforts in the literature. Nevertheless, the power consideration is vital for the success of any network design and operation, therefore, this topic must be studied in these contexts.

It is important to emphasize that the problems at hand are very hard and challenging. In this context, it was reported that the network provisioning problem is NP-Complete [32] and the connection provisioning problem is NP-Hard [41]. In tackling the issues at hand, our strategy is based on solving these problems in an efficient fashion, but without compromising the solution quality. In order to achieve these two aspects, namely, efficiency and quality, our solutions methodology consists of two approaches. In the first approach, we start by formulating the problems using Mixed-Integer Linear Programs (MILP) in order to obtain the optimal solutions of the problems. As these problems are inherently non-linear, obtaining the MILPs was not straight-forward and a number of novel linearization techniques were introduced. In the second approach, we designed a set of efficient heuristics that provide fast and near optimal solutions. These heuristics divide the problems into their natural subproblems while considering the inter-dependencies between them, and then they are solved separately. In order to determine the quality of the solutions from these heuristics, they are compared to the optimal solutions of the MILPs. The results show a good match between the two types of solutions.

Our contributions to the AOM field fall in two domains. We address the network design problem by introducing an optimal, power-constrained design for the network. Despite the nonlinear nature of several constraints, our approach presents a novel linear formulation of the problem. Moreover, we consider a practical setting in which signal at the OAs entry points can assume different levels. Such a case was considered for unicast traffic in the simpler broadcast-and-select architecture and it was solved in a nonlinear fashion using Mixed Integer non-Linear Programming (MInLP) [36]. Our scheme provides a linear formulation for this problem in the form of MILP and in the more general wavelength-routing mesh environment, in which routing and wavelength assignment are involved. Our MILP finds the minimum total gain needed in the network along with the power values at the beginning and end of each link. These outputs are then used off-line to find the exact number and locations of the OAs per link. Also, our treatment determines the optimal number and locations of the splitters.

As minimizing the total link gain does not always translate to minimizing the total number of optical amplifiers, we then propose a second MILP formulation whose objective is to minimize the total number of optical amplifiers. This formulation assumed a symmetric power strength levels at the entry points of the links.

On the other hand, we also formulate the network operation problem as MILP problem while considering the unequally powered-signals scenario. In order to achieve this, a set of mapping schemes are proposed in order to linearize highly-nonlinear relations. This is a new and novel formulation of the problem. The formulation in [42] is MInLP and deals with unicast traffic only.

Due to the high complexity of the MILP formulations proposed for the network design and operation, we introduce a number of efficient greedy heuristics in order to provide faster solutions for larger networks and higher traffic volumes. The novel feature of these heuristics is the manner in which multicast trees are constructed. The routing phase of the problem is not completely disjoint from the other two phases, namely, wavelength and power assignments. This is achieved using a unique cost function for links and sessions. Also, the design of these algorithms allows one to control the complexity degree of the computation, and hence the solution quality and it tries to capture several factors in its processing. In addition, although we don't consider the nonlinear power constraints in our treatment, the design of our heuristics is flexible enough to allow the addition of these new constraints.

1.6 Preliminaries

Before presenting the details of our work, we first introduce the basic assumptions of our research. This includes the power constraints, Optical Amplifier model and the system model.

1.6.1 Power Constraints and Optical Amplifier Model

Two power-related constraints must hold at any point in the network. First, the power level of the signal on any individual wavelength must not degrade below a certain lower bound measured in dBm, called P_{Sen}^{dBm}, whose value is determined by the sensitivity level of the receivers and OAs. Equal receiver and OA sensitivity levels are assumed in our research. However, this can be trivially modified to include different sensitivity levels. Second, due to fiber non-linearity effects, the aggregate power of all the wavelengths on the fiber should not exceed an upper bound measured in dBm, called P_{MAX}^{dBm}. This limits the maximum output

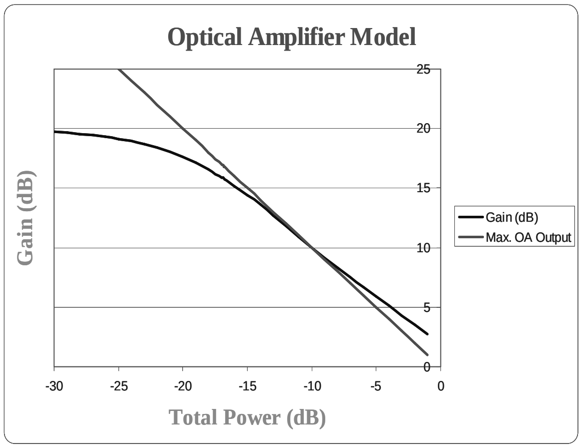


Figure 1.11 OA model in Equation (1.1)

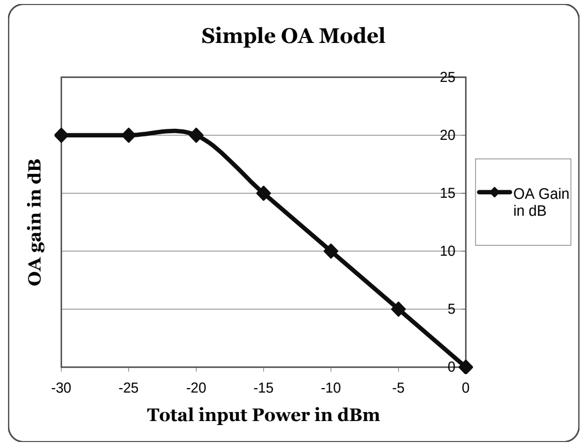


Figure 1.12 OA model in Equation (1.2)

power of the OAs and the transmitters.

On the other hand, the gain of an OA is a non-linear function of the input signal power, and it can be approximated using the following functional equation:

$$\frac{P_{in}}{P_{sat}} = \frac{1}{G-1} \ln \frac{G_0}{G} \tag{1.1}$$

where P_{in} and P_{sat} represent the aggregate power of the input signal, and the internal saturation power, respectively (both in mW). Also, G and G_0 are the actual gain, and the small-signal gain, respectively (both in absolute scale). The gain is shown in Figure 1.11. Another simple model for the OA gain is shown in Figure 1.12 and it is determined by:

$$G(10 \times log_{10}(P_{in})) = MIN\{G_0, (P_{MAX}^{dBm} - (10 \times log_{10} P_{in})\} \tag{1.2}$$

The amplifier gain applies to all input wavelengths (assuming a flat gain over all channels) and it drops when the total input power exceeds certain threshold and the OA becomes saturated.

1.6.2 System Model

The main components of the system model used in our solutions is described in this subsection. Any additional system assumptions that are specific to any problem will be presented in the corresponding chapter.

The network is modeled as a connected undirected graph, where the vertices are OXCs. Each undirected edge corresponds to two fibers which are used to carry signals in opposite directions (the formulation can still be easily extended to the multiple fiber case). Each fiber supports the same set of wavelengths. Also, each node is assumed to have the Drop-and-Continue (DaC) capability. However, only a subset of the nodes are MC nodes. The splitting ratio is adjustable based on the tree fanout, and it is equal to the reciprocal of the fanout. Also, no wavelength conversion is assumed. In addition, each node is equipped with an array of a sufficient number of fixed-tuned transceivers (transmitters/receivers). The all or nothing (i.e., full) acceptance policy is used, where a multicast connection is blocked if at least one destination cannot be reached.

The delivery structure of the multicast data takes the form of a light-forest consisting of one or more light-trees. In order to reduce the power loss due to splitting, each such light-tree is carried out using a separate laser regardless of whether or not an MC switch is available at the source node. Although wavelength continuity must be preserved on a light-tree, light-trees in the same light-forest may use different wavelengths. Moreover, light-trees must be assigned different wavelengths if they share at least one fiber link. Also, a destination can receive multiple copies of the same data over different light-trees. This can happen if data delivery to downstream members requires the use of more than one channel, e.g., when no splitters are used.

We consider three sources of power loss, namely, fiber attenuation with a propagation loss ratio of $\beta\ dB/Km$, splitting loss at tree branch nodes (which is dependent on the splitting ratio), and tapping loss of $\gamma\ dB$ at each node. Other sources of power attenuation, e.g., multiplexing, demultiplexing, switching, cross-talk, etc., are ignored for the sake of simplicity. However, they can be easily incorporated in the formulations at the cost of added complexity. Also, all the power levels are in dBm, while power gain/loss are in dB. Finally, the P_{Sen}^{dBm} value is assumed to be large enough in order for the receivers to withstand noise due to OAs amplified spontaneous emission, and to guarantee adequate Bit Error Rate (BER).

Symbol	β	P_{Sen}^{dBm}	P_{MAX}^{dBm}	P_{sat}	G_0
Value	0.2 dB/km	-30 dBm	0 dBm	1.1298 mW	20 dB
Symbol	P_1	P_2	δ	v	w
Value	$-5 \times M$	$-2 \times M$	0.01	$20 \times M$	$-M$

Table 1.1 Typical values for the system parameters that are used in the experiments

1.6.3 Experimental Setup

For the purpose of conducting our experiments, we assume static traffic where multicast sessions are generated randomly such that each multicast group size has a uniform distribution between 1 and N, where N is number of nodes in the network. Node membership in each multicast session is determined uniformly from all nodes after excluding the source node. In addition, each multicast session a is represented by an ordered-pair (Src_a,D_a), where Src_a represents the source node and D_a is the set of destinations. Also, we use two networks in our experiments, namely, the 6-node mesh network and the 14-nodes NSFNET shown in Figures 1.13 and 1.14, respectively. Table 1.1 summarizes the values used for the system parameters in our experiments. Finally, the optimal solutions from MILP are obtained using CPLEX [43], and the heuristics are implemented using the C++ Programming Language.

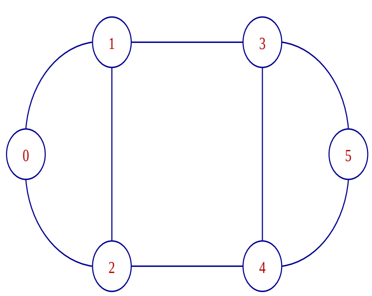


Figure 1.13 Six Nodes Mesh Network.

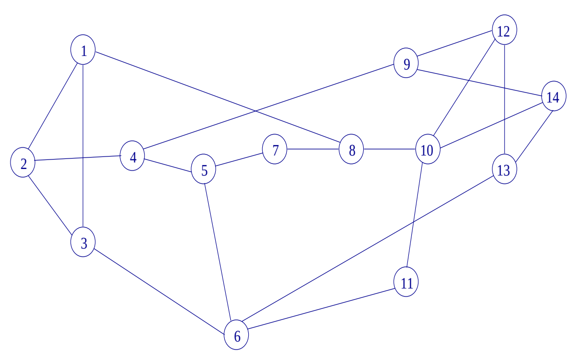


Figure 1.14 NSFNET.

1.7 Thesis Outline

The remainder of this thesis is organized as follow. In the next chapter, we present an overview of the related work in the literature in the area of AOM. The main goal of this overview is not only to survey the most related works, but also to provide the motivation for the power aware network and connection provisioning of AOM. In Chapters 3, 4 and 5 of the thesis, we study the network design aspect of the problem. In this context, we introduce the various elements of the problem in Chapter 3 followed by the proposed solutions under the asymmetric and symmetric power constraints in Chapters 4 and 5, respectively. Similarly, the connection provisioning aspect of the problem is then presented in Chapter 6. Finally, we conclude this dissertation in Chapter 7 and outline some future directions in AOM.

CHAPTER 2. Literature Review

Different aspects of AOM have been addressed in the literature under different system configurations and assumptions. We provide a review for these research efforts in this chapter. For a detailed treatment of these various research efforts, the reader is referred to [9]. Our review of the literature will first present those schemes that target network design in Section 2.1, followed by contributions to network operation in Section 2.2. The goal of this chapter is not just to set up the background to the AOM field, but to also motivate our research.

2.1 Network Design Schemes

Several network design related issues of AOM were investigated in the literature. These issues are either network provisioning-related or network dimensioning-related problems. In the context of network provisioning, two main problems were studied, namely, MC nodes allocation and optical amplifiers placement problems. Allocating the MC nodes entails determining their number and locations. This problem was proven to be NP-Complete in [32], even with the existence of the routing and wavelength assignment (RWA) of the multicast sessions. In addition, the simulation results reported in [31] showed that:

1. Full light splitting capability can reduce the bandwidth consumed by an average of $8\% - 18\%$ only
2. By equipping 50% of the network nodes with splitting capability, the network can obtain around $80\% - 90\%$ of the benefit of full light splitting capability.
3. No more than 70% of the network nodes need to be equipped with light splitting capability to obtain almost the same benefit as full light splitting capability.

The optimal placement of splitters was investigated in [14], in which an MILP formulation is proposed for the RWA of the light-trees which is then extended to design logical topologies for multicast streams. In [44], an iterative heuristic is proposed to optimize the placement of a given number of splitters with an objective of minimizing the blocking probability of the given multicast sessions whose routing trees are pre-computed. This algorithm proceeds for k iterations to place a total of k splitting nodes in the whole network. In each iteration, all the nodes without multicast capability are chosen one at a time to explore the possibility of being equipped with a splitter. The traffic blocking probability is computed and the node with minimum blocking probability is chosen as a new splitting node in the network. After k iterations, the allocation assignment is returned as the best configuration of the sparse splitting nodes placement.

The optical amplifier placement problem under multicast traffic is another open and challenging network provisioning problem. An optical amplifier gain model was developed in [36] that considered fiber attenuation, amplifier saturation, sensitivity of detectors, as well as the maximum power of transmitting light sources in fiber. The authors proposed a scheme that minimizes the number of amplifiers for the LAN/MAN passive-star-based optical networks without the restriction that wavelengths in the same fiber must be at the same power level. This is a reasonable assumption due to the *near-far* phenomenon in which signals on different wavelengths can originate from different locations in the network, and when they arrive at an amplifier, their power levels can be different due to the propagation attenuation in fibers. The difference in power levels of the input wavelengths can significantly limit the amount of amplification available to lower powered wavelength because the higher powered wavelengths could saturate the amplifier.

The authors formulated this problem as a Mixed Integer non-Linear Program (MInLP) with the objective of minimizing the number of optical amplifiers in the network. The output of the MInLP is used to allocate the determined number of optical amplifiers off-line. Two placement policies were introduced in [36], namely, As Soon As Possible (ASAP) and As Late As Possible (ALAP) methods. For each link, the ASAP places the optical amplifiers (except the last one) on the link as soon as the total input power is low enough to allow the *maximum* gain, while the last amplifier is placed such that the input power is low enough to allow it to generate the *remaining* required gain. The ALAP method operates in a similar fashion, except that it places the amplifiers such that the total input power is at its minimum detectable level (i.e., the power of one or more of the individual input channels is at P_{sen}) which results in placing the amplifiers closer to the destination side of the link.

However, the equally powered version of the problem defined in [36] was also studied in [45] where the signals over each link are assumed to be equal. This symmetric assumption helped formulate the same problem using Mixed Integer Linear Program (MILP).

On the other hand, two new methods were proposed in [46], namely, Genetic Algorithm implementation for amplifiers placement (GA2), and Smallest Gain First (SGF) algorithm. The GA2 algorithm started with a set of placement topologies of amplifiers sorted with transmitting power on the link. The two placement topologies with lowest powers are then selected as the parents, and genetic functions are used to combine parents with a structured, but randomized information exchange to form a child, and the child is then inserted in the whole set. The SGF attempts to find a better amplifier placement by assigning the minimum transmission power to every light-path, then it would add all the light-paths of the chosen permutation link by link according to their length (longest one first). According to the simulations results presented in [46], GA2 performs better than SGF with lower transmission powers for all light-paths.

The influence of amplifier noise power on the transmission signal is considered in [47]. However, it only considered the effect of the noise in saturating the amplifier, without using the SNR concept. Such problem can be possibly solved by increasing the receiver sensitivity, which is not the case if SNR is very low.

With multicast service, the amplifier placement problem must consider the power loss due to light splitting or the use of DaC devices. Signal power decreases dramatically when it passes through these devices. For example, the power loss is $3dB$ after passing through a splitter. This requires adding new set of constraints to the optical amplifier placement formulation to take care of these new requirements. Therefore, the demand for optical amplifiers (OAs) can be more critical with multicast traffic than with its unicast counterpart. Since OAs are expensive devices, every effort must be made to minimize their number in the network. Moreover, because of the requirement of SNR, the total number of amplifiers on a link should also be considered in the amplifier placement problem.

Finally, several efforts were reported in the literature in the network dimensioning field in order to minimize the number of consumed network resources. Due to the space constraints here, and since the design problems we address in this thesis are network provisioning problems, the reader is referred to [9] for a brief description of some of these efforts.

2.2 Network Operation Schemes

Supporting AOM during the network operation stage is achieved by designing a set of protocols and solutions for delivering the multicast traffic while maximizing the utilization of the available network resources and/or minimizing the number of dropped calls. Like the case of unicast traffic, the support of AOM in wavelength-routing networks is treated as a Routing and Wavelength Assignment (RWA) problem. Solving the RWA problem is NP-Hard; thus, it is commonly treated as two problems, namely, routing (denoted as AOM-R) and wavelength assignment (denoted as AOM-WA). The techniques that address the AOM-R problem are presented in the following subsection while those that are related to the AOM-WA problem are demonstrated in Subsection 2.2.2.

Nevertheless, some efforts that tackled the RWA as a joint problem were also reported in the literature. For example, the work in [48] investigated the RWA problem of the AOM under the loss-balance constraint with sparse splitting and wavelength-conversion deployment. In this context, loss-balanced light-forests are composed of a set of light-trees that are bounded in size (number of destinations per multicast tree), in size variation (difference in the number of destinations among different multicast trees), and in dimension (maximum source-to-destination distance on each multicast tree). These bounds are used to ensure that the different destinations in a multicast session can receive the optical signal with relatively equivalent signal quality. This problem is formulated as an Integer Linear Program (ILP).

2.2.1 All-Optical-Multicasting Routing (AOM-R) Problem

Figure 2.1 depicts the classification framework we will follow in representing the multicast routing algorithms in wavelength-routing networks. Based on the degree of coordination between the WDM and IP layers, these AOM solutions have been developed in two environments, namely, Pure WDM-Layer and IP Multicasting Over WDM schemes. In the first approach, all the necessary functionalities are solely handled by the WDM layer, which eliminates any role for the IP layer. However, in the second approach, both layers coexist and cooperate. The main focus of this thesis is on the first type of AOM and they are treated here. IP Multicasting Over WDM is outside the scope of this thesis and due to space constraints, the reader is encouraged to refer to [9] for a brief discussion of these schemes.

As indicated in Figure 2.1, the AOM-R techniques are divided into three different categories based on the degree of deployment of the MC nodes in the network. Such deployment has direct impact on the protocol design and, therefore, on the type of the delivery structure. In this context, these algorithms are targeted for the networks with full, sparse and no splitting capabilities. Under full splitting configuration, the conventional multicast routing protocols can be used to construct a single light-tree as any node in the network can be a branching node. Although these networks provide the highest flexibility, the cost of the full deployment of MC nodes is too high, especially for large networks. On the other extreme, namely, for networks that are not equipped with any splitting capability, building a distribution tree for routing the multicast session is not possible due to the lack of branching capabilities. Therefore, other routing structures need to be used like establishing a separate unicast session to each destination node [49], or relying on the DaC functionality of the nodes to construct a trail [18]. Finally, the cost and flexibility of the networks with sparse splitting are in between these two extreme configurations. In this case, constructing a single multicast tree may not always be feasible to include all the destination nodes, and light-forests are more commonplace.

In the following subsections, we will present the various AOM-R techniques based on the network splitting capability. In our treatment, we propose a novel simple notation to describe the system model used by each of these techniques. Using this notation scheme provides a

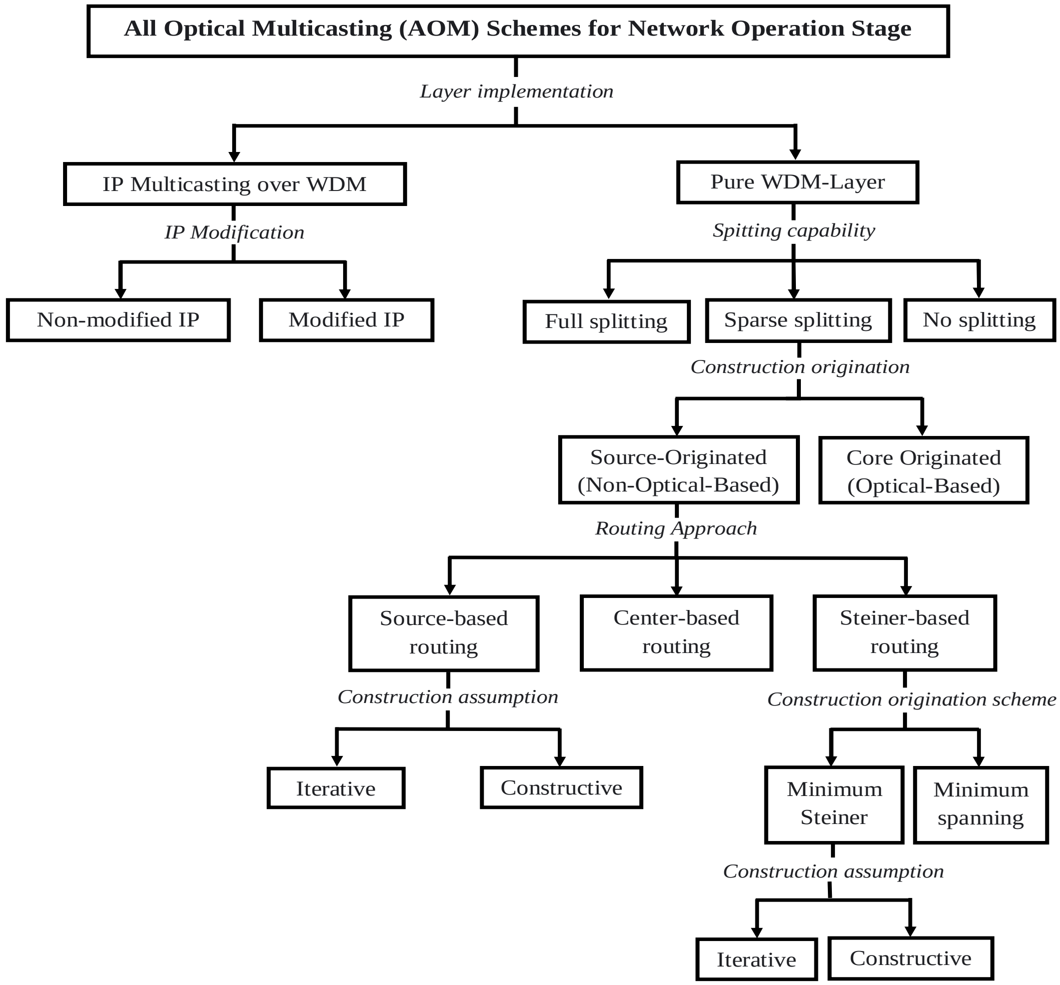


Figure 2.1 Classification Map for Multicast Routing Algorithms in Wavelength-Routing Networks.

unified and expandable way to capture the major optical capabilities of the network model. In this context, the following notation is adopted: [N,W,B] - S^i F^j R^k - C^x D^y - M^z, where:

1. N, W and B: denote to the number of nodes, number of channels (wavelengths) per fiber, and number of fibers per link in the network, respectively. However, including N, W and B in the notation is optional.

2. S: represents the network's splitting capability, where the superscript i equals either f, s, or n to represent *full*, *sparse*, and *no* splitting network configurations, respectively.

3. F: represents the fan-out of the splitting nodes, where the superscript j is either c for splitters with *complete* fan-out, or l for splitters with *limited* fan-out. It may also use the symbol m for a *mixed* situation in which complete and limited splitters coexist.

4. R: which indicates whether the splitting ratio of the splitting node is either *fixed* (with the superscript k equals x) or *adjustable* (with k equals a).

5. C: represents the conversion capability in the network, such that the superscript x is either *f*, s, or n to indicate that the network has *full*, *sparse* or *no* wavelength conversion capability, respectively.

6. D: indicates the conversion degree, where that the superscript y can be either c, l or m to represent complete, limited or mixed situations, respectively.

7. M: represents the *on-site* amplification, and has the following cases: full, sparse or no, and they are represented by letting superscript z equal *f*, s or n, respectively.

Although the above notation can be extended to include other capabilities if needed, it is also intended to keep it as compact as possible by omitting the F^j and R^k parts if the network has no splitting capability, and D^y if no conversion is employed.

2.2.1.1 AOM-R in Networks with No Splitting Capabilities

The system model of the routing algorithm proposed in [18] is [N,W,B] - S^n - C^n - M^n. The algorithm assumes that all the nodes are equipped with the Tap-and-Continue (TaC) capability. The routing problem is solved by constructing an optimal *trail* which originates from the multicast source node and spans all the destination nodes in the multicast group such that these nodes are traversed no more than two times.

The problem is formulated with the objective of minimizing the number of traversed directed edges and it is referred to as the problem of Multiple-Destination Minimum-Cost Trail or MDMCT. The MDMCT was proven to be an NP-Complete problem that always has a solution if the network is strongly connected. The authors proposed a heuristic of polynomial time complexity in order to find a feasible trail and it works in two steps.

The first step assumes that all nodes are MC nodes and constructs a Steiner tree for the multicast session using the Minimum Cost Path Heuristic (MCPH) proposed in [50]. Based on the computed Steiner tree, the multiple-destination trail is then computed accordingly by re-routing around the nodes in the Steiner tree which have an out-degree that is greater than one. The algorithm for finding the trail starts from the Steiner Tree root, i.e., multicast source, and recursively repeats at each node in the tree, referred to as the *Current* node, if this node is not a leaf node. In the downstream direction, the algorithm attempts to include all the downstream links between the *Current* node and all its children destinations. *Backtracking* is required when a leaf node is reached and there are still some destination nodes which have not been visited. In this case, backtracking is performed to the nearest branching node which has some outgoing branches that have not been visited yet. Because of backtracking, and in order to traverse as few edges as possible, the sub-trees rooted at each node are traversed according to their depths, and in ascending order.

The advantage of this method is that it eliminates the high cost of having splitting nodes. However, it traverses more link, and requires a longer set up time and the delay encountered by the connection becomes higher.

2.2.1.2 AOM-R in Networks with Full Splitting Capabilities

Reference [25] studies the RWA problem of the AOM when all the nodes in the network have complete, and fixed ratio splitting capability. However, various wavelength conversion capabilities were investigated, i.e., no/full and complete/limited. Constructing the multicast tree is done using the Minimum Cost Path Heuristic (MCPH) [50] under two traffic models, namely, static and dynamic models. Under the static traffic model, a set of routing trees, t_i, are pre-calculated for each multicast session, i. Selecting a single tree from set t_i for routing the multicast session can be done in a *fixed* or *alternate* fashion. With the fixed fashion, only one tree is used to route the multicast session. However, the alternate scheme computes multiple tree per session, and the search for an available tree in t_i is performed in a certain order.

Two criteria for multicast call acceptance were defined in [25]. With the first policy, called the *Full Destination Blocking Policy* (FDBP), a multicast session is established only when all the destinations are reachable using a distribution tree from set t_i. The performance of this policy is measured by the session blocking probability metric. The second policy is the *Partial Destination Blocking Policy* (PDBP) and is based on launching the multicast connection even if some of its destinations are not reachable by the multicast tree. Adopting any of these policies is application dependent. The FDBP policy is appropriate for those applications that have collaborative nature and require the simultaneous availability of the member nodes (e.g., teleconferencing, distributed databases and distributed computing). On the other hand, the PDBP can be used with those applications that do not require all the destinations to be connected to the multicast tree (e.g., Video-on-Demand and newsgroups).

The simulation results reported in [25] show that the dynamic scheme outperforms both static schemes (fixed and alternate) with FDBP for single fiber and the performance of using multiple unicast connections is the worst. Also, using PDBP enhances the system performance significantly and it is the best under the static fixed scheme. Moreover, the results showed that using wavelength-conversion improves the system performance, especially in the dynamic case and most of this improvement is obtainable with a small conversion degree.

In addition, the concept of light-trees was first introduced in [2] as a generalization form of the light-paths. As such, the light-tree operates as a point-to-multipoint all-optical channel that provides a logical single-hop optical communication between the source node and the destination node(s). However, the light-tree may traverse multiple links in the network. As it is the case with light-paths, light-trees are subject to the wavelength-continuity constraint in the absence of wavelength-conversion capability. However, the treatment in [2] assumes full wavelength conversion; thus, the system model is denoted as [N,W,B] - S^f F^c R^x - C^f D^c - M^f.

The light-tree idea discussed in [2] makes use of a single tree to deliver one or more traffic demand to a set of destinations. Each traffic demand is assumed to be a fraction of the total channel capacity. These traffic instances originate from the source node and can be of any type (e.g., unicast, multicast, or broadcast). Also, each destination node can be a member of one or more of these sessions, but not necessarily all. Although the primary focus in [2] was to provide a better solution to support the unicast traffic streams whose traffic demands are much less than the wavelength capacity, the light-tree idea can be extended naturally for the multicast traffic case with full wavelength capacity requirements.

The problem of light-tree virtual topology design was formulated as a Mixed Integer Linear Program (MILP) and was solved for the unicast and broadcast traffic types only. The results showed that light-trees are better than light-paths since they require fewer transceivers for both traffic types and less number of hops for the unicast communication.

Finally, the work done in [26] is another example of multicast routing in wavelength-routing networks with full splitting capability. With the S^f F^c R^x- C^n - M^f system model, the RWA problem of AOM was studied in [26] with the objective of maximizing the total number of served users using the PDBP described earlier by accommodating partial trees. The multicast tree for each session is pre-computed by any conventional algorithm. Then, a Non-linear Integer Program (NIP) was formulated for the general AOM-RWA case where the multicast sessions in the network have different sources. Due to the difficulty of solving the NIP, two heuristics were proposed to support multicast with PDBP in single-source systems, which is a special case in which all the multicast sessions belong to a single source.

The first heuristic employs a two-step linear program (LP) based algorithm that consists of two Integer Linear Programs (ILPs). The first ILP is responsible for accommodating the completely served multicast sessions and then assigning the appropriate wavelength to each tree. The link capacities are updated and the network topology is modified in order to exclude any link with no available wavelength. The second ILP is then iteratively executed in order to include as many users as possible from the remaining unserved multicast sessions.

The second heuristic is called the MAX-FIRST (MAX-1^{st}) algorithm. It is an iterative simple approach which accommodates the multicast sessions according to the number of their users that can be served using an available wavelength. At each iteration, the multicast session with the maximum number of *serveable* users is assigned an available wavelength, then the link capacities and the network topology are updated accordingly. Based on the new system status, the new multicast session with the maximum serveable users is identified, and the procedure continues until no more users can be served.

Both heuristics are extended to allow re-routing. Rerouting is achieved by constructing new trees on the available wavelengths for the remaining unprovisioned sessions. This step allows accommodating more users that could not be reached according to the computed fixed trees and the wavelength availability.

The user blocking probability is used in [26] as a performance metric in the simulation experiments. These results show that both LP-Based and MAX-1^{st} heuristics have comparatively similar performance with an advantage of simplicity for the MAX-1^{st} algorithm. The results also show that allowing re-routing decreases the user blocking probability significantly, and 10%-20% performance improvement is achieved when PDBP is employed over the FDBP.

2.2.1.3 AOM-R in Networks with Sparse Splitting Capabilities

Multicast routing algorithms that have been proposed under the sparse splitting configuration can be classified into two basic groups based on their originating scheme, namely, from where the light-tree/light-forest construction originates. The first group is referred to as the *Source-Originated* scheme because building the multicast distribution medium is initiated by the source node itself regardless of its optical capabilities[1]. Therefore, this group can also be called the *Non-Optical-Capabilities-Based*, or simply *Non-Optical-Based*, multicasting techniques. On the other hand, constructing the multicast delivery medium can also originate from an assisting node or a set of assisting nodes that have special optical capabilities and form a special optical structure. This structure is referred to as the *core structure* and is employed as an original structure in the final distribution structure of the multicast session. Hence, this approach is called the *Core-Originated*, or *Optical-Based*, approach.

While Optical-Based schemes are unique for AOM, the Non-Optical-Based strategies exist in non-optical networks too. Traditionally, the *Source-Originated* routing algorithms is further divided into three main categories according to their routing approach, namely, Source-Based Routing, Steiner-Based Routing and Center-Based Routing [51]. Essentially, the Source-Based

[1] These optical capabilities are expressed in terms of splitting, wavelength conversion and/or amplification.

Routing approach constructs the multicast distribution medium by connecting the multicast source node to each receiver individually using the appropriate least cost path. Therefore, this approach aims to minimize the per source-receiver path cost.

Instead of minimizing the cost of each source-receiver pair path, the objective function of the Steiner-Based Routing schemes is to minimize the overall cost of the multicast distribution medium. This cost is defined as the total cost of all its links and these schemes are known to be NP-Complete. Considering the membership requirement of the nodes, the algorithms under this category can be furthermore subdivided into Minimum Spanning and Minimum Steiner techniques. With the first approach, all the nodes in the routing structure are member nodes only, while the second approach eliminates this restriction [20].

On the other hand, the objective of Center-Based Routing schemes is to provide a single shared delivery medium that supports many-to-many communication. The heart of this approach is the choice of a certain center node to serve as the root for the multicast medium that spans all the member nodes. All communication must take place through the selected center node and from which it is directed to the destinations.

To the best of our knowledge, none of the currently proposed AOM-R techniques is a Minimum-Spanning Steiner-Based or a Center-Based scheme. However, the map shown in Figure 2.1 includes these categories for the sake of completeness. The various techniques that are designed for sparse splitting deployment are presented in the following subsections.

A. Source Originated Techniques: Source-Based Routing

Two schemes were employed for constructing the multicast delivery medium in a form of a light-forest in the source-based routing schemes. The first scheme adopts the *iterative* (i.e., *improvement*) approach in which the routing medium is initially constructed as a single tree with the assumption that all the nodes in the network are equipped with splitters. The medium is then iteratively modified if any of the branching nodes happens to be an MI node. The forest modification entails keeping one of the MI's node children only, and attempt to reconnect all the remaining ones through some other node. Alternatively, the second approach is *constructive* in nature since it forms the routing medium from scratch and by checking the splitting capability of nodes during the construction stage. The Re-Route-to-Source (RR2S) and the Re-Route-to-Any (RR2A) algorithms [1] are *iterative* source-based routing algorithms while Member-First ($M1^{st}$) algorithm [1] is an example for the *constructive* approach.

Both the Re-Route-to-Source (RR2S) and the Re-Route-to-Any (RR2A) algorithms [1] assume the following system model: [N,W,B] - S^S F^C R^x - C^S - D^C - M^S. Both algorithms start by computing a minimum spanning tree that starts from the source node and spans all the nodes. A single multicast tree is obtained by pruning those links that do not lead to member nodes in the minimum spanning tree. Then the splitting capability of each node in the multicast tree is checked in breadth-first or depth-first orders to check if the output degree of any MI is greater than 1. Both algorithms operation terminate when all these nodes are checked. However, the algorithms operation differ in the way the initial tree is reconstructed. As such, each algorithm defines its own criterion in choosing the set of candidate nodes through which the disconnected nodes rejoin the multicast structure.

Basically, the RR2S defines the set of candidate nodes that are used to rejoin any disconnected node to be all the nodes that are located along the reverse tree path from the disconnected node to the source node and are equipped with both splitting and complete conversion capabilities. However, if no such nodes are available, then the disconnected node rejoins the multicast delivery structure directly at the source node. The availability of a wavelength converter at the MC node is essential for the success of the algorithm operation. This wavelength converter is used to ensure that all the disconnected children from the MI node are carried over different channels on the same links that constitute the reverse path to the source node. Although this re-joining strategy guarantees the use of shortest paths for the cutoff members, it results in concentrating the traffic on certain links which results in exhausting the wavelengths along them rapidly.

In an attempt to achieve load balancing in wavelength usage, the Re-Route-to-Any (RR2A) algorithm eliminates the requirement proposed in RR2S of using the same backward shortest path on T by all the disconnected children of a branching MI node. Instead, the RR2A permits each of the disconnected nodes to choose its own path to reconnect itself to the multicast delivery structure through the nearest node that is: (1) already part of the multicast delivery structure, and (2) it is an MC, a source node or a leaf node.

Unlike the RR2S and RR2A algorithms, the Member-First ($M1^{st}$) algorithm [1] takes the splitting capability of the nodes into account while constructing the light-forests. The $M1^{st}$ algorithm is designed to work with the [N,W,B] - S^s F^c R^x - C^n - M^s system model. It constructs one light-tree of the light-forest at a time such that each light-tree is assembled on a link by link basis through a special *Priority Queue* structure, called the *Fringe Link List*. This list consists of a set of links, referred to as *fringe links*, which are to be included in the light-tree. The Fringe Link List is updated whenever a node is to be included in the light-tree and the link of the least shortest path distance to the source node has the highest priority.

The tree expansion starts by adding the source node to the light-forest and then the Fringe Link List is updated by including all its outgoing links. For each subsequent tree expansion, the fringe link with the highest priority in the list, denoted by (v, u), is selected. In this context, node v of the link is a tree node, while node u is a new node to be added to the tree. The algorithm distinguishes between the two cases where node u is a member node or not. In the latter case, node u is attached to the current light-tree using the highest priority link and the list is updated with its links. However, if node u is a member node in the multicast session, the optical-multicasting capabilities of the tree node v is then examined.

A direct connection is established from node u to node v if the latter is an MC node. Otherwise, the backward shortest path on the current tree that connects node v to the source node is traced one node at a time in order to find the first MC node. If such a node is found, node u is then connected to it; otherwise, a new separate connection to the source node is established. At the same time, each MI node along this path undergoes additional two operations, referred to as the *cut* and *remove* operations to process their links. In this case, the algorithm *cuts* all the links in the current tree that originate from the MI nodes, except the one that leads to node u. The *cut* process is also performed over all the fringe links that originate from the MI nodes. Then, each of the cut links are examined to check whether it is part of the current tree. If so, the *remove* operation is applied to all the links in the sub-tree that expand the cut link as well as the corresponding fringe links. While the *removed* links are allowed to participate in any future expansion for the current light-tree, the *cut* links are not.

More light-trees are necessary if the Fringe Links list becomes empty while some of the members are not yet included in the light-forest. In such a case, all the links (either *removed*, *cut* or are already part of the existing light-trees) are restored and can be used for the new light-tree construction. Finally, the final light-forest becomes ready after pruning all the links that do not lead to member nodes.

B. Source Originated Techniques: Steiner-Based Routing

Similar to the Source-Based Routing schemes of the previous subsection, the Minimum Steiner-Based schemes can be described as being either *constructive*, e.g., Member-Only [1], and Virtual-Source Capacity-Priority algorithm [28], or *iterative*, e.g., Centralized Splitting algorithm [29], and Tabu-Search Based AOM [30].

The first Steiner-based source-originated routing scheme to be presented is the Member-Only (M-Only) algorithm [1]. Like M1^{st} algorithm, the M-Only algorithm is proposed for the [N,W,B] - S^{s} F^{c} R^{x} - C^{n} - M^{s}, system model. Unlike the M1^{st} algorithm, the M-Only algorithm uses the member nodes only to expand each light-tree, such that a single member is added at each iteration. Hence, no pruning is required.

The algorithm starts by including the source node to the current light-tree. It proceeds in iterations such that at each algorithmic iteration, the light-tree grows by including one destination node. Tree expansion is done through a set of expandable nodes that are updated at the end of each iteration and by using the path with the least cost from among all the candidate paths. The set of expandable nodes includes the source nodes, all the MC nodes in the current tree and all the leaf nodes. The algorithm attempts to include as many member nodes as possible, and it terminates only when all member nodes are included. If this is not the case and it happened that no more qualified paths exist for expanding the current light-tree, a new light-tree is needed and the same procedure is repeated.

The simulation results reported in [1] reveal that the M-Only algorithm requires the least number of branches per forest (bandwidth) with respect to RR2S, RR2A and M1st. Both M1st and M-Only result in the smallest number of channels per link, while the RR2S requires the largest number of channels per link, as well as the highest bandwidth requirement. On the other hand, RR2S achieves the shortest delay while M-Only exhibits the longest delay.

In addition, the Virtual-Source Capacity-Priority (VS-PC) algorithm proposed in [28] is another Steiner-based source-originated technique. Its system model is characterized as [N,W,B] - S^{s} F^{c} R^{x} - C^{s} D^{c} - M^{s}. In this work, the authors introduced the concept of a *Virtual Source* (VS), which is an MC node that is equipped with wavelength conversion capability. VS-CP algorithm is an enhancement to the M-Only algorithm [1] described earlier. The enhancement is based on two key observations that lead to more savings in the network resources, especially, the number of wavelength channels per forest (i.e., the number of the links in the forest) and the required wavelengths (i.e., maximum number of wavelengths) per link.

The first observation is about the selection of the tree node from which the light-tree is to be expanded when several qualified shortest paths of the same length exist. Because such selection is performed without considering the optical capabilities of the various nodes to which the connection is to be made, it may happen that an MI node is chosen while MC or VS alternatives are available. This exhausts the expansion capability of the MI node and may force the remaining unprovisioned members to search for longer qualified paths; hence, more links are used. This may also necessitate the construction of a new light-tree(s) if no qualified shortest path is available; thus, more wavelengths per link are required. Therefore, the authors in [28] propose assigning different priorities to the nodes based on their optical capabilities. The highest-priority is assigned to the VS nodes, followed by the MC nodes, the MI nodes with wavelength conversion capability (referred to as wavelength converter, or WC, nodes), and finally the MI nodes with no wavelength conversion capability with the lowest priority.

This priority scheme reflects the flexibility of each node in expanding the light-tree. The higher the priority of the node, the more is its flexibility. Therefore, the priorities assigned to the VS and MC nodes are higher than the MI-nodes. However, the significance of VS over the regular MC node stems from its ability to support more than one connection (the split signals) over the same link using different wavelengths; hence, it is assigned higher priority. Moreover, the WC-MI nodes provide more flexibility than the non-WC MI nodes in terms of their ability to carry the connection over any wavelength although they both have the same expansion capability. The priorities of the nodes are then used in the routing algorithm such that the node with the highest priority is selected in order to expand the light-tree. This postpones the use of the various MI nodes, and may give more chance to utilize their expansion capability more efficiently. This scheme is called the *Capability-Based-Priority Heuristic.*

The other observation is related to the mechanism of constructing the new light-trees. In this context, the M-Only algorithm starts the construction of the new tree from scratch and tries to connect the new node(s) to the source node itself. Instead, connecting these new node(s) to a VS node that is closer than the source node can result in using less network resources. This approach is called the *spawn-from-VS Heuristic*, and it gets its name from the fact that the VS behaves like a source from which a sub light-tree is spawned.

Like the M-Only algorithm, the VS-CP algorithm attempts to include as many destinations as possible in each light-tree and it deals with the member nodes only; thus, it is a prune-free procedure. The VS-CP algorithm proceeds like the M-Only algorithm; however, unlike the M-Only algorithm, the Capacity-Based Heuristic is invoked to break the tie between those paths of the same smallest length that connect between the member nodes and the expandable nodes such that the link that leads to the highest priority node is chosen. Once this node is determined, the algorithm investigates the possibility of connecting the destination node to this expandable node if and only if the length of this path is less than or equal to its distance from the source node. If this is the case, the algorithm expands the current light-tree by connecting the member node to the selected expandable node. Otherwise, if the path between the new member node and the source node is shorter than that between the member node and the expandable node, or even when there is no qualified expandable node exist, then the Spawn-From-VS Heuristic is invoked. In this case, the member node is connected to the closest VS tree node provided the distance from the member node to the selected VS node is less than its distance to the source node itself.

When any of the destinations cannot be included in the current light-tree, the algorithm repeats for a new tree construction and it terminates when no more destinations are to be added to the light-forest. Comparing the performance of the VS-CP algorithm with that of the M-Only algorithm, the simulation results in [28] show a considerable saving in the network resources, in terms of number of wavelengths per link and the number of links per light forest, especially with large group sizes.

On the other hand, the Centralized Splitting Algorithm (CSA) proposed in [29] is a Steiner-based source-originated routing scheme that it designed to work in [N,W,B] - S^{s} F^{c} R^{x} - C^{s} D^{c} - M^{s} system model. CSA takes care of the power-budget requirements when constructing the multicast delivery structure. It aims to construct a minimum Steiner tree that achieves an efficient utilization of the network resources and a reasonable delay while achieving small power loss in order to maintain the delivered optical signal above the sensitivity threshold.

An adaptive strategy is presented in [29] where an initial light-forest is constructed using the M-Only algorithm [1] and without considering the power-level requirements. If this light-forest, denoted by F_{M_Only}, does not satisfy the receiver sensitivity requirements, it is adjusted by following certain set of rules that aim to minimize the maximum power loss. The rules for reconstructing F_{M_Only} are based on the following two main observations.

The first observation is related to the effect of signal splitting dimension (i.e., performing splitting *in-depth*, or *in-breadth*) on the signal power loss. While it is true that power loss is multiplicative when the splitting nodes are concatenated in a particular (sub) light-tree, such an effect diminishes when the splitting capability of a single node is increased, and fewer splitters are concatenated. For example, assume nodes x and y are two splitting nodes with splitting fan-outs A and B, respectively, and that node x is the parent for node y in the light-tree, either directly, or through some other non-splitting node(s). Neglecting the signal attenuation due to light propagation in the fiber, the power at the output of node y is $\frac{1}{A.B}$ of the total power inserted at node x. On the other hand, and without loss of generality, if the fan-out for node x is increased from A to A+1, then the growth in the power loss due to splitting, i.e. ($\frac{1}{A+1}$ - $\frac{1}{A}$) of the input power, becomes small as A increases. These two observations suggest that increasing the number of branches spawned by an MC-node in the light-tree is more preferable from the point of view of power loss than concatenating various MC nodes to each other. Therefore, the authors were motivated to propose the concept of the *Centralized Splitting Node*, in which a splitting node is chosen (based on a certain criterion) to replace a set of concatenated splitting nodes.

The second observation is related to the splitter location with respect to the root of the light-tree. Although signal distribution can be more balanced if light-splitting occurs near the root, this strategy has a side-effect of exposing more member nodes to this power reduction, which can make them unable to detect the signal. Hence, placing the splitters as far away as possible from the source node can achieve better power reception.

Modifying F_{M_Only} is performed on each of its light-trees that has concatenated splitting nodes. The modification begins by determining a centralized splitting node, denoted as node h. Node h is chosen such that it is any MC-node in the network that has the smallest average distance to the *member nodes* in the current light-tree. In order to find h, a path structure, denoted as the *Main Path* (P), is determined as the shortest path between the source node and the nearest splitting node. Also, a special set of nodes, G', is computed such that it consists of all the nodes in the light-tree after excluding those non-member nodes that lie on P. The average distance between all the nodes in the network and each node in G' are computed and node h is chosen as the MC node with the smallest computed average distance.

After determining node h, the next step modifies the light-tree such that: (1) light-splitting at the nearest splitting node to the source node is removed and is *pushed* away from the root to node h, and (2) node h represents a new branching node in the modified tree where all the remaining *members* are reconnected to. The first requirement is achieved by extending the main path P to include node h using the shortest path from the nearest splitting node. The second requirement is fulfilled through establishing shortest paths connections from node h to each *member* such that no nodes on the extended P are included in these new connections. If this restriction is not satisfied, the member node is added to a special list, called the DropList.

After handling each light-tree in F_{M_Only}, CSA attempts to reconnect those member nodes in the DropList (if any), such that each member node is reconnected to any established light-tree using the shortest path to the nearest MC-node, MI-leaf node, or the source node.

The simulation experiments in [29] compared the CSA with the M-Only algorithm [1] using the NSFNET. The results show that the CSA can achieve bandwidth utilization similar to that achieved by the M-Only, while it can reduce the power loss by 17% when the multicast traffic generation rate is high and group size is large.

Incorporating the power issues during the AOM-R was also considered by the authors in [52] who introduced the concept of *balanced tree*. Using balanced trees in AOM-R is motivated by the need to achieve two objectives. First, guaranteeing a certain level of quality for the signal received by the destination nodes. Second, fulfilling fairness between these destinations. These objectives are achieved by defining a set of constraints on the end-to-end paths to account for the power losses at the optical layer. Both fiber attenuation and splitting loss are considered in this treatment. The set of Source-Originated routing algorithms in [52] run in an iterative manner. In this context, an initial tree first computed without any power considered. This initial tree is then modified by identifying the node that suffers from the maximum total power loss and move it closer to the source node in the logical light-tree.

Moreover, another Steiner-based source-originated routing algorithm was proposed in [30] and its objective is to minimize the number of used links. It is based on the Tabu-Search scheme and its system model is described as S^s F^c R^x - C^n - M^s. The TS-AOM heuristic [30] considers the light-tree computed at each iteration as a solution. Two solutions are computed using the MCPH and a modified version of the M-Only algorithm, and the better one is chosen as the initial solution. During each iteration, the neighborhood of the current solution is defined with the assistance of two operations, i.e., *Insertion*, and *Deletion*, that are performed over all the nodes, except the source and the destinations.

The *Insertion* operation is carried out if the node under consideration is not part of the current solution, and is done as follows. A path is established between the new node and the only node in the current solution. This path is called the *disjoint path*. Connecting to an MC or a leaf node in the current solution is given a higher priority, otherwise, the connection is made to an MI node. Once the disjoint path is established, the connections from the new node to the remaining nodes in the current solution is done (if possible) one at a time and starting with the nearest. With each added node, its path in the current solution is pruned in order to maintain the tree structure.

On the other hand, the *Delete* operation is performed on each node that is part of the current solution. When a node is to be deleted, the pruning operation is performed to delete its path that leads to the source node and all its outgoing links in the current solution. The cut children are then reconnected to the source node.

An ILP was developed in [30] for the sake of comparison with the TS-AOM heuristic. Simulation results show that the TS-AOM heuristic is able to determine a solution that is within 10% of the optimal solution almost all the time, and within 5% in about half the time.

C. Core-Originated Techniques

The set of routing algorithms that belong to this category is based on employing a special *core structure* in constructing the multicast delivery tree. The core structure, denoted by CS, connects a subset of nodes, called core nodes, who have special optical capabilities in terms of light-splitting and wavelength conversion. The multicast session is then established with the assistance of the CS. Although the connection is still rooted at the source node, the process of establishing the multicast delivery structure does not originate from it, and instead it originates from the CS. Currently, two different approaches belong to this category of algorithms, namely, [27] and [33]. However, the CS-based routing algorithms can be characterized by their implementation of the CS concept. Such distinction can take several forms which include, but not limited to: (1) the nature of the intra-CS connections (namely, the type of connections established between the various core nodes which can take the form of a tree, or a collection of interconnected unicast connections, etc), (2) the membership requirements of the core nodes, and (3) the setup time needed for establishing the CS.

The combined optical capabilities of light-splitting and wavelength conversion in VS nodes are exploited again in the Virtual Source Based (VS-Based) algorithm proposed in [27]. The system model proposed in [27] is attributed as [N,W,B] - S^s F^c R^x - C^s D^c - M^s. A single CS that is shared among all the *active* multicast sessions is pre-established before starting any multicast session. The CS connects all the VS nodes whether they are source or member nodes in any active multicast session or not. Such CS may include some non-VS nodes that lie on the established connections between each pair of VS nodes. These connections in the CS are carried out over unicast connections using a dedicated wavelength for each VS-to-VS light-path; thus, two distinct wavelengths are required to establish the bidirectional connection between each pair of VS nodes. The basic operation of the VS-Based algorithm is then to extend these light-paths to form a single light-tree for each connection.

The VS-Based algorithm runs in two stages. The first stage is of long term significance and it consists of allocating the VS nodes, connecting them, and then *clustering* the network according to VS nodes locality. Each cluster forms a sub-tree with the VS as the root, and the nearest non-VS nodes as its children. The VS nodes are selected such that its nodal degree is high, so that it can be connected to a large number of nodes, and the average distance from the VS node to its cluster-nodes is nearly the same for all clusters[2].

The second stage is the tree generation stage and it exploits the pre-established CS, and the virtual node-clustering organization resulting from the first stage for setting up the multicast tree. This stage is repeated for each new multicast session. For a successful establishment for the multicast session, two conditions must be satisfied. The first one is related to the VS-availability while the second one is concerned about wavelength-availability.

Each multicast session must be established through a *free*VS node, i.e., through a VS node that is not associated with any other multicast session. The VS nodes are checked in sequence according to the source node distance from them, and the first free VS, called the Primary VS (PVS), is chosen. Since wavelength conversion is available in the CS only, the same wavelength should be available over all the links from the source node to the selected VS; otherwise, the connection cannot be established and the next nearest VS is examined. The connection is

[2]Although the CS is physically established, the clustering is performed virtually and will be employed when the connection for multicast session is actually taking place.

blocked if no VS node is free and/or no single wavelength is available over the links of the shortest path to a free VS. This mechanism relieves the source node from determining the routes to destinations which achieves good scalability for the proposed algorithm.

On the receiver(s) side, each member node establishes a connection to its cluster VS, called the Secondary VS (SVS), using a unicast connection over a single wavelength. The destination is blocked only if no single wavelength is available over all the links between the destination node to its SVS. This scheme allows the VS-Based algorithm to support dynamic multicasting since it provides an easy means for the receivers to join/leave the multicast session at anytime during the session lifetime.

In addition, establishing the connections from the member nodes to their SVS is done in parallel which reduces the required setup time for the multicast session. This reduction in the setup time is a direct result of the pre-establishment of the CS. However, reserving two wavelengths per VS-VS connection pair to maintain the CS forms a bottleneck on the system performance in terms of the number of multicast sessions that can be supported by the system, which is equal to the number of VS nodes in the network. Therefore, the cost of increasing the number of multicast sessions in the system is very high and is determined by the cost of increasing the number of VS nodes in the network. Alternatively, more wavelengths can be reserved for maintaining the CS (which increases the possibility of the inefficient usage of the network resources), or an efficient time division multiplexing scheme over the wavelength channel may be employed. However, it is worth noting that this bottleneck affects only the number of *outgoing* multicast sessions that a single VS can support, i.e., as a PVS, but not the number of *incoming* multicast sessions, i.e., as a SVS.

Similar to the VS-Based algorithm, the Partial Packet Replication All-Optical Multicast Heuristic (PPR-AOMH) proposed in [33] uses the CS concept to construct the multicast distribution trees. However, the PPR-AOMH differs from the VS-Based algorithm in many ways. First, the CS implementation in the PPR-AOMH takes the form of a tree that connects the MC nodes instead of the interconnected unicast paths. Second, the core nodes are basically MC nodes that are members in the multicast session, but they may also include some *assist-*

ing non-member MC nodes besides some MI nodes. Third, a single CS is constructed per multicast session at the time of connection establishment. In addition, the AOMH takes into consideration the fan-out constraint while constructing the multicast trees.

The PPR-AOMH is designed to support multicast traffic in S^s F^c R^x - C^f D^c - M^s, or S^s F^c R^x - C^s D^c - M^s, where wavelength conversion can be deployed fully or sparsely, respectively. However, the MC nodes are the only nodes which have the DaC capability while the MI nodes can support the Drop-Only (DO) or Continue-Only (CO) capabilities using Add-Drop Multiplexer (ADM)[3]. Due to this hardware limitation, each of the destination nodes that are MI must be connected to an MC destination through a dedicated unicast connection. Hence, the MI nodes will be leaf nodes in the constructed tree.

The construction of the multicast tree is triggered by a new connection request, and employs three phases. The first phase is the *Preparation Stage*. In this stage, the algorithm divides the *member nodes*, D, into two disjoint sets, i.e., Multicast Capable Group (MCG) and Multicast Incapable Group (MIG), based on their splitting capability. Since each connection to an MI node is established using a dedicated channel, the number of these connections will be limited by: (1) the potential splitting capability over the path to the destination nodes, which is referred to as the fan-out constraint $f = W\sum \delta_i > D$ where δ_i determines the nodal degree of the i's MC destination and W is the number of channels per link, and (2) the number of available wavelengths on the links, i.e. link capacity constraint. If the MCG is empty or the fan-out constraint is not satisfied, then the MCG is expanded to include some assistant MC nodes, called Proxy MC (PMC) nodes, until such constraint is satisfied.

Then, the second stage starts to construct the CS. The CS, or the MCG-tree, is constructed to include all the nodes in the MCG, and assumes that all the nodes in the network have the splitting capability. Any source-based, shared-tree or Steiner-based tree construction algorithm can be used to construct the MCG-Tree. Then, the branching nodes in the MCG-Tree are examined one by one to check if they are MC nodes, and are hence capable of supporting splitting in the tree. If a fork node happens to be an MI node, the algorithm pushes light

[3] Although the ADMs are one possible hardware implementation at the MI nodes, other implementations that achieve the DaC capability in an all-optical fashion are possible too.

splitting to the nearest ancestor MC node along the shortest path from this node to the source node. In the worst case, if no MC nodes are encountered, then data duplication takes place at the source node using multiple wavelengths. Finally, the third stage connects each remaining MI node to the nearest MC node in the CS using a dedicated unicast connection, even though if more than one MI destination lie on the same shortest path to the nearest MC core node because of the limitation in the optical-capabilities explained earlier. This results in different MIG sub-trees than the ones produced by the VS-Based algorithms. Moreover, the direction of each connection is determined by whether the MI node is the source node or not. If the MI node is the source node itself, then the connection will be directed towards the core MC node; otherwise, the direction is reversed. The resulting sub-trees are called MIG-Trees.

Two deployment strategies for the MC nodes were proposed in [33]. The first one deploys the MC nodes randomly in the network, hence the name RAND. The second one, called PRIOR, makes use of the nodal degree and deploys the nodes semi-randomly such that a node with a higher degree is chosen to be an MC node with higher priority. Simulation results show that the number and the deployment strategy of the MC nodes have direct impact on the system performance. The PPR-AOMH exhibits good performance when 20% of the nodes in the network are MC nodes and they are deployed using the PRIOR scheme. However, the PPR-AOMH may result in high delay.

2.2.2 All-Optical-Multicasting Wavelength Assignment (AOM-WA) Techniques

The AOM-WA has been investigated in the literature in two main directions. In the first direction, researchers determine the wavelength requirements for supporting multicast in the network. For example, in [53] some properties from expander graphs were exploited to derive an asymptotic upper bound on the number of wavelengths needed to support AOM. According to [53], such bound is impractical; however, it still can be used as a bound on the rate of growth of the number of wavelengths. In [54], the authors derived bounds on the minimum number of required wavelengths in some regular network topologies, which include linear arrays, rings, hypercubes and meshes. Also, in [55] the author considers power limitation constraints and assumes that a multicast message can be dropped or split only at a limited number of nodes along a light-path or a light-tree. Based on this, the upper and lower bounds on wavelength requirements for establishing a multicast connection in different topologies, such as mesh torus, mesh, hypercube, and general topologies, are proposed and proved. Similar to [55], the work in [56] computes the wavelength requirements of multicast communication when a limited number of light-dropping or tapping is allowed in a multi-hop fashion. The author proved that determining the minimum wavelength requirements in an arbitrary network is NP-Complete; however, a solution for such a problem can be found in polynomial time in some regular topologies, such as rings, tori and hypercubes.

In the other direction, several techniques were developed to assign wavelengths to multicast sessions such that the number of wavelengths is minimized. These techniques were either formulated as an optimization problem (e.g, [18]) or solved using heuristics. The wavelength assignment optimization problem in [57] was studied in the context of several Quality of Service (QoS) requests. Initial multicast trees along with their wavelength assignments are computed. Then, minimizing the number of required wavelengths in the network can be solved by rerouting the multicast trees that either contain the links of the maximum load, or are initially assigned the least used wavelengths. Simulation results in [57] showed that the second approach performs better than the first one. On the other hand, the AOM-WA is solved in [28] using a simple heuristic in which the light-forest is divided into segments, each of which is a sequence of links such that a wavelength converter resides at one end of each segment, or both. Then all the links that constitute the segment are assigned one wavelength.

References [38, 58] proposed two different heuristics for the wavelength assignment problem. The work in [38] aims to minimize the number of wavelength conversion occurrences in the multicast tree. The nodes on the computed light-tree are processed using bottom-up approach, namely, computing the wavelength conversion cost starts from the leaf nodes first. Each leaf node selects a wavelength with minimum wavelength conversion cost compared to the incoming wavelength from its parent node. The algorithm continues with the next node up the tree such that each node adds its child nodes' conversion cost, and includes its own wavelength conversion, if any. The authors of [38] proved that such selected wavelength set is optimal.

The authors in [59] extended the work in [38] by allowing multiple available wavelengths in a link to carry the multicast signal from the source node instead of one wavelength. In this scenario, each wavelength is launched from the source node as a separate light-tree and it can share some links with other light-trees. This scheme proved to significantly reduce the wavelength conversion cost since instead of converting the signal at a node, a separate signal from the source is used. This approach is employed with the assumption that the wavelength conversion cost is much higher than the wavelength and splitting costs.

On the other hand, the objective function of the work in [58] is to minimize the number of used wavelengths. The scheme is based on using an auxiliary bipartite graph whose vertex-sets correspond to the set of wavelengths, and the set of nodes in the original network. An edge between a wavelength and a node exists if and only if this wavelength can cover that node. The wavelength assignment problem is then transformed to choosing the minimum wavelength set that covers all nodes in the auxiliary bipartite graph. At each iteration, the wavelength that covers the maximum number of nodes is selected. The auxiliary graph is then updated by removing the covered nodes and the used wavelength. The algorithm is repeated until all the nodes are removed.

2.3 Chapter Summary

In this chapter, we provided a literature review of the field of AOM in wavelength routing networks. In this review, we addressed some design and operation aspects of the AOM. We also introduced a detailed classification framework for the various AOM-R techniques and a new notation for describing the system models of these techniques. The significance of this framework and notation stems from the fact that they provide a clean and compact, yet comprehensive, way to study the various aspects of AOM-R. These concepts can be easily extended to include new concepts or components in the future. Table 2.1 summarizes the basic features of these schemes. One of the key issues that can be concluded from this table is the absence of support of the various power impairments issues of the optical layer in most of these

Tech.	Ref.	System Model	Structure	Membership	Policy	Pow.
MDMCT	[18]	S^n-C^n-M^n	Trail	Static	FDBP	No
RWA/WANs	[25]	$S^fF^cR^x$-$C^{f/n}D^{c/l}$-M^f	Tree	Static/ Dynamic	FDBP/ PDBP	No
Light-Tree	[2]	$S^f\ F^cR^x$-$C^f\ D^c$-M^f	Tree	Static	FDBP	No
RWA/SS	[26]	$S^fF^cR^x$-C^n-M^f	Tree/ Forest	Static/ Dynamic	PDBP	No
RR2S	[1]	$S^sF^cR^x$-C^s-D^c-M^s	Forest	Static	FDBP	No
RR2A	[1]	$S^sF^cR^x$-C^s-D^c-M^s	Forest	Static	FDBP	No
M1st	[1]	$S^sF^cR^x$-C^n-M^s	Forest	Static	FDBP	No
M-Only	[1]	$S^sF^cR^x$-C^n-M^s	Forest	Static	FDBP	No
VS-CP	[28]	$S^sF^cR^x$-C^sD^c-M^s	Forest	Static	FDBP	No
CSA	[29]	$S^sF^cR^x$-C^sD^c-M^s	Forest	Static	FDBP	Yes
TS-AOM	[30]	$S^sF^cR^x$-C^n-M^s	Tree	Static	FDBP	No
VS-Based	[27]	$S^sF^cR^x$-C^sD^c-M^s	Tree	Dynamic	FDBP	No
PPR-AOMH	[33]	$S^sF^cR^x$-$C^{f/s}D^c$-M^s	Tree	Static	FDBP	No
logical-Network	[14]	$S^sF^cR^x$-C^sD^c-M^s	Forest	Static	FDBP	No

Table 2.1 Comparison between multicasting techniques in wavelength- -routing networks in terms of: system model, multicast delivery structure (Structure), membership policy (Membership), destinations blocking policy (Policy) and power-budget awareness (pow.) .

routing schemes. This motivates us to explore this subject in this thesis, and to investigate the impact of power issues on AOM. Our treatment includes both the design aspects of networks for AOM support, as well as the operation of such networks.

CHAPTER 3. Power-Aware Design of All-Optical Multicasting in Wavelength Routed Networks

3.1 Introduction

The quality of the optical signal traveling through the network links and nodes is directly affected by the various impairments of the optical layer. This impact is accumulative and it is described by the degradation in the Signal to Noise (SNR) ratio. This degradation in the signal quality can render it undetectable at the receivers. Such degradation can take two forms, namely, a decrease in the signal strength and/or an increase in the noise associated with the signal. Both factors can happen simultaneously and the various optical components in the network contribute differently toward these factors.

The focus of our study in this thesis is to investigate the impact of the first factor only, namely, the power loss, on the signal quality. Therefore, we ignore any noise-related issues. In addition, since power loss impairment results in a number of design-related and operation-related issues, we investigate these issues separately. The design-related issues are formulated as network provisioning problems and are handled in Chapters 4 and 5, while the operation-related matters are formulated as connection provisioning problems in Chapter 6.

In the following two chapters, we study the impact of the power loss under the context of AOM on one of the most prominent problems in all-optical networking, namely, the Optical Amplifiers Placement (OAP) problem. Optical Amplifiers (OAs) are optical devices that are used to restore the strength of the passing optical signals without the need to convert them to the electronic domain. Using OAs in the network is very essential in order to keep the optical signals at detectable levels. However, the operation of OAs has high associated cost. This cost is not expressed in terms of its capital and maintenance cost only, but also by its impact on the signal quality due to the noise it introduces to the signal. Therefore, finding the optimal number and location of the OAs in the network becomes a challenging problem under regular unicast traffic. Nevertheless, the introduction of AOM operation makes the OAP problem even more profound and challenging. This is mainly because of the additional power loss the signals encounter at the branching nodes due to signal splitting. In addition, the OAP problem was addressed at different network topologies, including the point-to-point [60] and ring networks [61]. However, the problem becomes more complicated in wavelength-routing mesh network as it involves three integrated subproblems, namely, Routing (**R**), Wavelength Assignment (**WA**) and Power Assignment (**PA**) subproblems.

In our treatment, we consider two system configurations. In the first configuration, called the asymmetric configuration, the power strengths of the optical signals are not assumed to be equal at the entry points of the links and OAs. However, these input signals are assumed to be equal in the second configuration, referred to as the symmetric configuration. In order to distinguish between these two cases, we refer to the OAP problem under the asymmetric and symmetric system configurations as the OAP-Asymmetric and OAP-Symmetric, respectively.

For each system configuration, we introduce an optimal power-aware design of the wavelength-routed optical networks. The network design problem is formulated using Mixed-Integer Linear Programming (MILP) technique. While the objective of the MILP-based solution of the OAP-Asymmetric problem is to minimize the total required gain in the network, the MILP solution of the OAP-Symmetric problem aims to minimize the actual number of OAs. Also, both MILPs find the optimal number and placement of the splitters. We used the CPLEX linear optimization package in order to solve the MILPs formulation. Then, the number and location of the optical amplifiers per link is computed off-line.

On the other hand, an efficient heuristic solution is then proposed for the symmetric case. The solution is based on dividing the problem into subproblems and solving them separately while taking the interdependency between these subproblems into consideration. By comparing the results obtained from the heuristic solution to the optimal counterparts, we find out that our heuristic scheme succeed to provide fast solutions that are near-optimal.

The contribution of the work done in the following two chapters is summarized as follows:

- The MILP formulations are designed to solve the combined problems of determining the best RWA, power assignments, number/locations of splitters. From these values, we can determine the number and locations of OAs. To the best of our knowledge, this is the first attempt to solve such a combined problem in wavelength-routing networks for AOM. Other schemes solve one part of the problem only with no consideration to the impact of power issues or the other subproblems on their solutions. In this context, we find that the optimal placement of the splitters was investigated in [14], in which an MILP formulation is proposed for the RWA of the light-trees which is then extended to design logical topologies for multicast streams. In [44], an iterative heuristic is proposed to optimize the placement of a given number of splitters with the objective of minimizing the blocking probability of the given multicast sessions whose routing trees are precomputed. However, none of these design schemes considered the power issue.

- The combined problem we are investigating is nonlinear in nature. However, we are able to formulate the problem as a linear problem in the form of MILP by using a set of linearization mapping techniques. These techniques are used to convert the nonlinear constraints of the formulation into their equivalent linear counterparts. The significance of this effort can be clear when compared with the existing similar efforts in the literature. In this context, the OAP-Asymmetric problem was addressed in [36] for the unicast traffic in the simpler broadcast-and-select architecture (where no routing is involved) and it was solved using MInLP. Our scheme provides the linear solution for this problem and in the more general wavelength-routing mesh environment where RWA subproblem is involved. On the other hand, OAP-Symmetric case was considered in [45] which solved the equal powered-signals instance of the problem proposed in [36] using MILP. Hence, our solution for the OAP-Symmetric problem is designed to solve the more complicated problem.

- The MILP formulations determine the optimal number and locations of the splitters. This is in contrast to all previous studies which considered the number of splitters as a predetermined input parameter.

- We present a set of heuristic solutions for the OAP-Symmetric problem that are able to provide fast, but, near optimal solutions for large problem instances. These algorithms implement a set of optimization schemes that help in achieving their goal and they are based on the use of novel set of cost routing functions for the network links and trees.

3.2 Additional System Model Parameters

In addition to the system model parameters defined in Subsection 1.6.2, the following system parameters are assumed by our formulations in Chapters 4 and 5. First, the splitters have *complete* splitting capability (i.e., the splitting fanout of the node equals, at least, its out-degree) with *fixed* splitting ratio (i.e., each copy of the signal acquires the same fraction of the total signal power). Second, the network does not support wavelength conversion; hence, wavelength continuity constraint should be maintained. Third, OAs can be placed either *on-site* or *on-link*. The on-site placement is sparse and it can be at the node's input (called Pre-Amplification), or node's output (called Post-Amplification). Accordingly, and based on the notation introduced in 2.2.1, our system model is characterized as $S^sF^cR^x$-C^n-M^s.

In addition, in order to maintain the aggregate power levels over the links below P_{Max}, the power over the individual wavelengths is assumed to be upper-bounded by $P_{Max} - 10 * log_{10}|\Lambda|$, where $|\Lambda|$ is the number of wavelengths. We make this assumption for the sake of simplifying the formulation of both MILPs in Chapters 4 and 5. The greedy heuristic for the OAP-Symmetric approach does not impose such assumption. Finally, the solution for the OAP-Asymmetric problem uses the nonlinear OA gain model described by equation (1.1), while the solution for the OAP-Asymmetric problem uses the simple piece-wise OA gain model determined by equation (1.2)

3.3 MILP parameters and variables

In this section, we introduce the notations used by the MILP formulations that are defined in Chapters 4 and 5. The notations consist of two parts, namely, the network parameter and the formulation variables.

3.3.1 Network Parameters

The following parameters are used in the formulations:

N	The set of nodes in the network.
E	The set of fiber links in the network.
Λ	The set of wavelengths supported per fiber.
i, j, k	Node identity, where $i, j, k \in N$
λ	Wavelength identity, where $\lambda \in \Lambda$
$e(i, j)$	Fiber link directed from node i to node j.
SP	Maximum number of splitters.
β	Propagation loss ratio.
γ	Tapping power loss value at each node.
$L_{i,j}$	Length of $e(i, j)$ in Km.
K	Number of multicast sessions.
a	Multicast session identity, $0 \leq a \leq K - 1$.
src_a	Multicast session source node.
D_a	Multicast session a destination set.
Φ_i	Connections set in which node i is a member.
Γ_i^a	Binary-indicator: 1 if $i \in D_a$, and 0 otherwise.
P_{Sen}	Minimum detectable power level on a channel.
P_{Max}	Maximum aggregate power on a link.
P_1, P_2	Negative constants that are used to represent the case of $(-\infty)$ dBm, such that $P_1 < P_2$.
δ	Very small number used for the linearization of the logarithmic splitting loss.

v, w Integer constants, such that $v > w$.

$LG_{i,j}^{Max}$ Auxiliary constant that determines maximum total gain on $e(i, j)$.

O_i Degree of node i.

O_i^{Max} Maximum node degree in the network.

M Very large number

In our implementation, the value of M is chosen such that:

$$M \geq \max\{|E|, |\Lambda|, \frac{LG_{i,j}^{Max}}{K * |\Lambda|}, 10 * \log(O_i^{Max} - 1)\} \tag{3.1}$$

3.3.2 MILP Variables

The following variables are used in the MILP formulations:

$LG_{i,j}$ Total amplification gain needed over $e(i, j)$.

$n_{i,j}$ Number of OAs on $e(i, j)$.

$T_{i,j}^{a,\lambda}$ Tree link binary-indicator: 1 if $e(i, j)$ is used by session a over λ; and 0 otherwise.

$\Im_i^{a,\lambda}$ Binary-indicator: 1 if λ is used by session a on any output (outgoing) tree link from node i; and 0 otherwise.

Υ_i^a Binary-indicator: 1 if session a uses at least one output (outgoing) tree link from node i.

$R_{i,j}^{a,h}$ Binary-indicator: 1 if h hops are needed to reach node j from node i for session a; and 0 otherwise.

$H_i^{a,\lambda}$ Number of hops between src_a and node i over λ.

$SL_i^{a,\lambda}$ Splitting loss on channel λ at node i for session a.

f Tree fanout, i.e., number of outgoing tree links.

A_f^i Binary-indicator that is used for the linearization process of power splitting. It is equal 1 if the value f is less than or equal the actual computed tree fanout; 0 otherwise.

Ω Power inspection site on a link, such that $\Omega \in$ {beg,end}.

$P_{i,j}^{\Omega,a,\lambda}$ Power level (in dBm) measured at the beginning (when $\Omega = beg$) or end (when $\Omega = end$) of $e(i,j)$ for wavelength λ that is used by session a.

α_i Binary-indicator of node i's splitting capability: 1 if it is an MC node; and 0 otherwise.

CHAPTER 4. Optical Amplifiers Placement Problem: Asymmetric Power Case

In this chapter, we solve the asymmetric case of the OAP problem. Our solution is based on the system model and notation defined earlier in Chapter 3. The OAP-Asymmetric problem is formulated as a MILP with the objective of minimizing the total needed gain in the network. The total network gain is defined as the summation of the gain required over all the links. Each link gain is an abstraction of the accumulative gain achieved by a number of physical OAs[1] whose number and location are computed off-line based on the power values at the beginning of the links. For example, consider the case when the total gain over a link equals 53 dB and assuming that the power strengths of the input signals allow the OAs to work in the non-saturated region; hence produces the maximum gain. In this case, three OAs will be needed to achieve this total gain value such that two OAs will provide the maximum gain value, i.e., 20 dB, and the third one operates in the saturated region and provides the remaining 13 dB gain. If all the OAs operate in the saturated region, the number of OAs might increase and this depends mainly on the variation (i.e., the degree of symmetry) of the input signals strengths.

The MILP solution provides the optimal solution for the OAP-Asymmetric problem by solving all the constituent subproblems jointly. The OAP-Asymmetric problem we are trying to solve here is formally defined as follows:

OAP-Asymmetric Problem Definition: *"Given the network topology, the maximum number of wavelengths and splitters, the traffic matrix, and assuming asymmetric power scenario, the OAP-Asymmetric Problem attempts to find a feasible allocation of the OAs and splitters (namely, their number and locations) such that all the traffic demands are satisfied and de-*

[1] In order to accommodate for any on-site amplification, the link gain includes any post-amplification at the beginning of the link and any pre-amplification at end of the link, if available.

tectable by the receivers and while minimizing the total needed network gain".

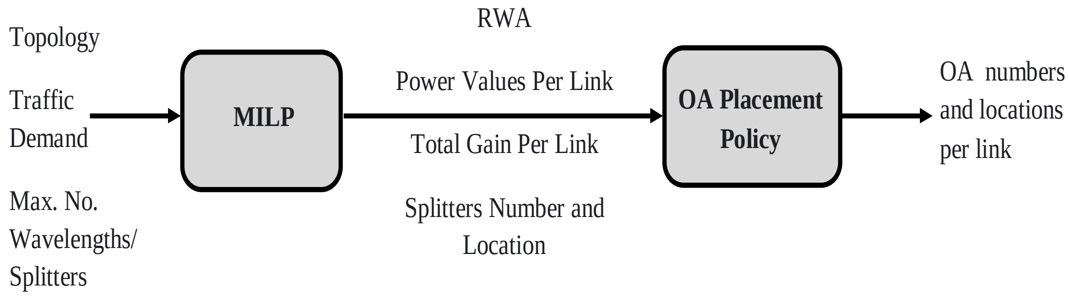


Figure 4.1 Solution Steps for the OAP-Asymmetric Problem.

We formulate the OAP-Asymmetric optimization problem as a MILP. Figure 4.1 depicts the solution methodology we use in solving the OAP-Asymmetric problem. As shown in the figure, the solution consists of two stages or modules. The MILP formulation represents the first module whose input parameters includes (based on the problem definition above): the network topology, traffic demand and the maximum number of wavelengths and splitters. The outputs of the MILP are: the RWA solutions of all the traffic demands, splitters allocation solution (i.e., number and location), the power values at the beginning and end of each link, and the total gain per link. These solutions constitute the input parameters for the second solution module, namely, the OA Placement Policy Module which uses these input values to determine the OA allocation solution (i.e., number and location) per link.

The remainder of this chapter is organized as follows. The details of the MILP formulation are presented in the next section followed by the OA Placement Policy Module in Section 4.2. Finally, some numerical results are shown in Section 4.3 and then the chapter is concluded in Section 4.4

4.1 MILP Formulation

The MILP formulation consists of an objective function to be optimized and it is subject to a set of constraints that determine the boundaries of the solutions. The objective function is determined by the total amplification gain required on the network links, and is expressed as follows:

$$Minimize \sum_{e(i,j)\in E} LG_{i,j} \tag{4.1}$$

On the other hand, the OAP-Asymmetric problem spans several subproblems. Each subproblem has its own limitations that are represented in the form of constraints. Based on their origin, the set of constraints are categorized as follows:

4.1.1 Routing and Wavelength Assignment Constraints:

$$\Im_i^{a,\lambda} \geq \sum_{j,e(i,j)\in E} \frac{T_{i,j}^{a,\lambda}}{M} \quad \forall i \in N; 0 \leq a < K; \forall\lambda \in \Lambda \tag{4.2}$$

$$\Im_i^{a,\lambda} \leq \sum_{j,e(i,j)\in E} T_{i,j}^{a,\lambda} \quad \forall i \in N; 0 \leq a < K; \forall\lambda \in \Lambda \tag{4.3}$$

$$\Upsilon_i^a \geq \sum_{\lambda\in\Lambda} \frac{\Im_i^{a,\lambda}}{M} \quad \forall i \in N; 0 \leq a < K; \forall\lambda \in \Lambda \tag{4.4}$$

$$\Upsilon_i^a \leq \sum_{\lambda\in\Lambda} \Im_i^{a,\lambda} \quad \forall i \in N; 0 \leq a < K; \forall\lambda \in \Lambda \tag{4.5}$$

Constraints (4.2) and (4.3) set $\Im_i^{a,\lambda}$ to the disjunction between all $T_{i,j}^{a,\lambda}$ variables, for all the neighbor nodes j of node i. These constraints are used to indicate wether the wavelength λ is used by session a over at least one outgoing tree link from node i. Similarly, constraints (4.4) and (4.5) set $\Upsilon_i^{a,\lambda}$ to the disjunction between all the $\Im_i^{a,\lambda}$ variables for all λ. These constraints are used to determine if node i is a non-leaf node in the light-forest of session a. This is true if at least one of its outgoing links is a link in the light-forest of session a over any wavelength.

$$\sum_{\lambda\in\Lambda} \Im_i^{a,\lambda} = \sum_{\lambda\in\Lambda} \sum_{k,e(k,i)\in E} T_{k,i}^{a,\lambda} - \{\Gamma_i^a * (1 - \Upsilon_i^a)\} \qquad \forall i \in N/\{src_a\}; 0 \leq a < K \tag{4.6}$$

These constraints guarantee that the number of the incoming channels equals the number of the *distinct* outgoing channels of node i, except when node i is a leaf destination node. This constraint is responsible for constructing the light-forest by making sure that each node in the light-forest has at least one input (incoming) link if it is a destination or has at least one output (outgoing) link. This applies to both MC and MI nodes.

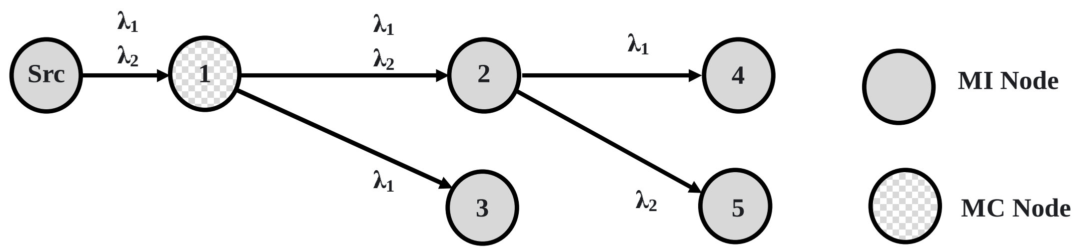


Figure 4.2 An illustrative example for the light-forest of the multicast session $(Src, \{2, 3, 4, 5\})$.

In order to illustrate how this set of constraints works, please consider the sample light-forest constructed in Figure 4.2 for the multicast session $(Src, \{2, 3, 4, 5\})$. In this figure, node 1 is the only MC node in the light-forest which consists of two light-trees carried over channels λ_1 and λ_2. The first light-tree carried over channel λ_1 spans the destination nodes 2, 3 and 4 by splitting the signal at node 1. The second light-tree carried over channel λ_2 is needed to reach destination node 5. In this example, one can see that the constraints set in (4.6) applies correctly over all the nodes. For example, nodes 3, 4, and 5 are member leaf nodes in the light-forest, therefore, each one of them has one incoming channel and no outgoing channels. Consequently, node 2 will have two outgoing links, each carries a different wavelength. Therefore, at least one input link is required at node 2 which needs to carry two distinct channels as shown in the figure. Similarly, at node 1, in which the number of different input channels carried over its input link equals the number of different channels carried over its outgoing links. Please note that because node 1 is an MC node, the total number of outgoing channels is three, however, this constraint cares about one instance of each channel type over all the node's outgoing link, which is 2 in this case.

$$\sum_{k,e(k,i)\in E} T_{k,i}^{a,\lambda} \leq 1 \qquad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda \tag{4.7}$$

Constraints (4.7) is used to help preventing loops in the light-tree of session a constructed over wavelength λ. This is done by not allowing the light-tree to traverse any node more than one time. However, this constraint is not sufficient by itself to prevent all sources of creating loops in the light-tree. It works along with the other loop avoidance constraints defined below in

Subsection 4.1.2.

$$\sum_{0 \le a < K, e(k,i) \in E} T_{i,j}^{a,\lambda} \le 1 \qquad \forall i, j \in N; i \ne j; \forall \lambda \in \Lambda \tag{4.8}$$

The above constraints guarantee that link $e(i,j)$ is used by at most one light-tree over wavelength λ for each connection. This guarantees the data integrity and correctness over each link by avoiding using the same channel over the same link by multiple sessions.

$$\sum_{j, e(i,j) \in E} T_{i,j}^{a,\lambda} \le M * \alpha_i + 1 \qquad \forall i \in N/\{src_a\}; 0 \le a < K; \forall \lambda \in \Lambda \tag{4.9}$$

Constraints (4.9) prevent branching at MI nodes by ensuring that node i has at most one outgoing tree link if it is an MI node. In this context, the left-hand side of the constraints determine the number of outgoing link of node i. If node i is an MI node, i.e., $\alpha_i = 0$, the right-hand side of the constraints will equal 1; thus, the number of outgoing link is either zero or 1. In addition, the constraints take care of the MC node case by using the large constant M to ensure that the right-hand side of the constraint is large enough to accommodate any number of outgoing link at node i.

$$\sum_{j, e(j,i) \in E} T_{j,i}^{a,\lambda} \ge \sum_{k, e(i,k) \in E} \frac{T_{i,k}^{a,\lambda}}{M} \qquad \forall i \in N/\{src_a\}; 0 \le a < K; \forall \lambda \in \Lambda \tag{4.10}$$

Due to lack of wavelength conversion capability in the network, constraints (4.10) are implemented to guarantee wavelength continuity for each session a. This is fulfilled by ensuring that node i has an incoming link on wavelength λ if it has at least one outgoing link employing the same wavelength. The usage of the constant M in the right-hand side of the constraint is essential to represent the multiple outgoing links at the branching MC nodes that carry the same wavelength. In the same time, the constraint handle the MI node correctly. For example, consider the same example depicted in Figure 4.2. At node 1, the number of its outgoing links over channel λ_1 is 2; therefore, the right-hand side of the constraint becomes greater than 1. This requires that the right-hand side, which represent the total number of input links over the same channel λ_1, should equal at least one. With assistance of constraints (4.7) and constraints (4.12)-(4.16), the right-hand side is always 1. The same applies to all the other non-leaf nodes in the light-forest.

$$\sum_i \alpha_i \leq SP \qquad \forall i \in N \tag{4.11}$$

Constraint (4.11) ensures that the number of used splitters does not exceed the maximum number of splitter, SP.

4.1.2 Loop-Avoidance Constraints:

The following set of constraints are used to guarantee that each light-tree of the light-forest is loop free. These constraints are based on determining wether each destination node is *reachable* from the source node through a number of hops that does not exceed N-1, where N is the number of nodes in the network.

$$R_{i,j}^{a,1} \geq \sum_\lambda \frac{T_{i,j}^{a,\lambda}}{M} \qquad \forall e(i,j) \in E; 0 \leq a < K \tag{4.12}$$

$$R_{i,j}^{a,1} \leq \sum_\lambda T_{i,j}^{a,\lambda} \qquad \forall e(i,j) \in E; 0 \leq a < K \tag{4.13}$$

$$R_{i,j}^{a,1} = 0 \quad \forall i,j \in N; \forall e(i,j) \notin E; 0 \leq a < K \tag{4.14}$$

Constraints (4.12) and (4.13) determine that, for session a, node j is reachable from node i by one hop if link $e(i,j)$ exists and is used by the light-tree at any wavelength. This is done by setting the variable $R_{i,j}^{a,1}$ to the disjunction between all the $T_{i,j}^{a,\lambda}$ variables for all the channels. On the other hand, constraints (4.14) ensure that $R_{i,j}^{a,1}$ is zero if the link $e(i,j)$ does not exist in the network.

$$R_{i,j}^{a,h} = \bigvee_k R_{i,k}^{a,h-1} \wedge R_{k,j}^{a,1} \qquad 0 \leq a < K; \forall i,j \in N; i \neq j; k \neq i; k \neq j; 1 < h < N \tag{4.15}$$

Constraint (4.15) represents the general rule for determining the reachability of node j from node i using h hops, where h is more than 1. This is a recursive equation which states that node j is reachable over exactly h hops from the source node if there exist at least one path that satisfies the following two conditions simultaneously:

1. Node j is reachable from an intermediate node, k, by one hop.

2. The intermediate node, k, is reachable from the source node by exactly $h-1$ hops.

For example, consider the case for node 4 in the sample example depicted in Figure 4.2. At this case, node 4 is reachable from the Src node through node 2 over 3 hops; thus, $R^{a,3}_{4,Src}=1$, $R^{a,1}_{4,2}=1$ and $R^{a,2}_{2,Src}=1$. The variable $R^{a,2}_{2,Src}$ equals 1 since node 2 is reachable by the source node via node 1 using 2 hops because both $R^{a,1}_{2,1}$ and $R^{a,1}_{1,Src}$ equal 1 based on constraints (4.12) and (4.13).

Please note that the expression $c = a \wedge b$, which is the conjunction operation, is represented by the following set of constraints: $c \leq \frac{a+b}{2}$ and $c \geq a+b-1$. Similarly, $c = a \vee b$, which is the disjunction operation, can be represented by: $c \geq \frac{a+b}{2}$ and $c \leq a+b$. In both cases, $c \in \{0,1\}$.

$$\Gamma^{a}_{dst} \leq \sum_{h=1}^{N-1} R^{a,h}_{src_a,dst} \qquad 0 \leq a < K; \forall dst \in \Phi_a \tag{4.16}$$

Constraints (4.16) ensure that any destination node is reached from its source node by no more than $N-1$ distinct hops. Since the left-hand side of the constraint is always 1, then, the right-hand side must equal at least one, which means that each destination of the multicast session much be reachable from the source node over at least one path who does not exceed N-1 hops.

It is worth mentioning here that other schemes for loop avoidance are possible too. For example, the loop avoidance scheme that was proposed in [14] relies on the use of the session propagation delay bound in ensuring loop free construction of the light-forests. We also implement another simpler set of constraints for loop avoidance for the second MILP formulation. These constraints will be presented in the next chapter.

4.1.3 Power Constraints:

The following constraints address the power constraints and the OA gain model issues. In order to ensure that the total power constraint is met, we assume that the power value of each wavelength cannot exceed $\frac{P_{Max}}{|\Lambda|}$, where $|\Lambda|$ is the number of wavelengths. Although this can result in using more OAs per link than needed (as more power can be used to reach longer distance over links with more free channels), this helps in simplifying the MILP formulation significantly.

$$P^{\Omega,a,\lambda}_{i,j} \geq P_{Sen} * T^{a,\lambda}_{i,j} + P_1 * (1 - T^{a,\lambda}_{i,j}) \qquad \forall e(i,j) \in E; \Omega \in \{beg, end\}; 0 \leq a < K; \forall \lambda \in \Lambda \tag{4.17}$$

$$P_{i,j}^{\Omega,a,\lambda} \leq (P_{Max} - 10 * log_{10}|\Lambda|) * T_{i,j}^{a,\lambda} + P_2 * (1 - T_{i,j}^{a,\lambda})$$
$$\forall e(i,j) \in E; \Omega \in \{beg, end\}; 0 \leq a < K; \forall \lambda \in \Lambda \quad (4.18)$$

Constraints (4.17) and (4.18) ensure that each power level at the beginning and the end of $e(i,j)$ is within the valid ranges based on whether the light-forest uses $e(i,j)$ over wavelength λ or not. In the former case, $T_{i,j}^{a,\lambda}$ will equal 1; hence, constraints (4.17) ensure that the power value is greater than P_{Sen} and constraints (4.18) ensure that the power value is less than $\frac{P_{Max}}{|\Lambda|}$. In the case when link $e(i,j)$ is not used by the light-forest, this value should be equal to, *theoretically*, $-\infty$ dBm (i.e., 0 mW). This case is represented by the constraints by ensuring that the power value is a very small negative number that lies between two large negative constants, namely, P_1 and P_2. The values of P_1 and P_2 are chosen to be $(-5) * M$ and $(-2) * M$, respectively. The calculation of the value of $P_{i,j}^{beg,a,\lambda}$ is done *before* on-site Post-Amplification, while $P_{i,j}^{end,a,\lambda}$ is measured *after* on-site Pre-Amplification, if any.

$$(1 - T_{i,j}^{a,\lambda}) * M + P_{i,j}^{end,a,\lambda} = (1 - T_{i,j}^{a,\lambda}) * (-M) + P_{i,j}^{beg,a,\lambda} + LG_{i,j} - \beta * L_{i,j}$$
$$\forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \quad (4.19)$$

Equation (4.19) is used on link $e(i,j)$ to express the power on wavelength λ at the end point of the link in terms of the power at the beginning of the link and the gain and loss due to amplification and attenuation, respectively. It should be noted that when the link is not part of the light-forest, i.e., the corresponding $T_{i,j}^{a,\lambda}$ equals 0, the power value at the end of the link is guaranteed to be between P_1 and $P2$.

$$(1 - T_{i,j}^{a,\lambda}) * v + P_{i,j}^{end,a,\lambda} - SL_j^{a,\lambda} - \gamma \geq (1 - T_{j,k}^{a,\lambda}) * w + P_{j,k}^{beg,a,\lambda}$$
$$\forall e(i,j), e(j,k) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \quad (4.20)$$

$$(1 - T_{i,j}^{a,\lambda}) * w + P_{i,j}^{end,a,\lambda} - SL_j^{a,\lambda} - \gamma \leq (1 - T_{j,k}^{a,\lambda}) * v + P_{j,k}^{beg,a,\lambda}$$
$$\forall e(i,j), e(j,k) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \quad (4.21)$$

Constraints (4.20) and (4.21) are used to relate the values of the power levels between the end of an edge, say $e(i,j)$ and the beginning of the following hop, say $e(j,k)$, if any. In order to maintain consistency with equations (4.17)-(4.19), and to be able to handle all the four cases of the usage of the links $e(i,j)$ and $e(j,k)$, the values of v and w are chosen such that $v \geq |P_1| + M$, and $w < 0$. The rationale of choosing these values is demonstrated with the help of an example. Consider the case when both $T_{i,j}^{a,\lambda}$ and $T_{j,k}^{a,\lambda}$ equal 0. Recall that equations (4.17) and (4.18) ensure that $P_{i,j}^{beg,a,\lambda}$ and $P_{j,k}^{beg,a,\lambda}$ are between P_1 and P_2. The value of v is chosen to be $(6*M)$ in order to guarantee that left hand side of inequality (4.20) is still greater than the right hand side even when both power values equal P_1. The same holds for the left hand side of inequality (4.20). Choosing the value of w to be negative helps in ensuring this too. Proving that this criterion for choosing v and w hold for all the other cases of links usage is straightforward.

$$\frac{SL_i^{a,\lambda}}{M} \leq \alpha_i \quad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda \tag{4.22}$$

Constraints (4.22) ensure that the splitting loss value at an MI node is 0 dB for any connection carried at any channel. In the case when node i is an MI node, the right-hand side of the constraint is zero, which forces the left-hand side to be zero too; hence the splitting loss (SL) at this node is zero over all channels. However, when α_i is 1, the splitting loss can be more than zero. In this case, the value of the splitting loss at the MC node is determined in dB by this relation:

$$SL_i^{a,\lambda} = 10 * \log_{10} f \quad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda \tag{4.23}$$

Since the splitting degree, f, is a variable that is computed as part of the MILP solution, incorporating this loss directly in the formulation will make it non-linear. Here, we introduce an elegant way to find $SL_i^{a,\lambda}$ at MC nodes using a set of linear equations that are equivalent to the non-linear one define by equation (4.23).

$$\frac{\sum_{j,j \neq src_a, e(i,j) \in E} T_{i,j}^{a,\lambda} - f + \delta}{M} \leq A_f^i \quad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda; 2 \leq f < O_i \tag{4.24}$$

$$A_f^i * \{10 * \log_{10} f\} \leq SL_i^{a,\lambda} \quad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda; 2 \leq f < O_i \tag{4.25}$$

$$SL_i^{a,\lambda} \geq 0 \quad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda \tag{4.26}$$

In this context, we use the binary variable A_f^i to determine the actual tree fanout at the specified node, i, that is computed by the formulation. Constraints (4.24) ensure that the value of A_f^i is 1 for all the values of f that are less than or equal the actual computed tree fanout at node i. Otherwise the value of A_f^i is either 0 or 1. This can be illustrated by the following example. Assume that the actual fanout value at node i computed by the formulation is 3. This value is represented in constraint (4.24) by the term $\sum_{j,j \neq src_a, e(i,j) \in E} T_{i,j}^{a,\lambda}$. When f= 2 and 3, we find out that the left-hand side of constraints (4.24) is always a positive real number that is less than 1. Therefore, in order to satisfy this constraint, the value of A_f^i should equal 1. Similarly, if we check for any value of f that is greater than 3 (the actual fanout of the node), we find out that the left-hand side of the constraint is always negative; hence, the constraint is satisfied whether A_f^i is 0 or 1.

Then, we use the value obtained for A_f^i from constraints (4.24) in conjunction with the constraints in (4.25) in order to determine the exact splitting loss at node i over channel λ. Two important things must be considered here with regards to the constraints defined in (4.25), namely:

1. They are linear constraints since the log function is applied to a constance value, i.e., f.
2. The log function is an increasing function, namely, as the value of f increases, the splitting loss increases.

Because the value of A_f^i is 1 as long as f equals the actual tree fanout, the splitting node at node i should equal at least the amount of splitting loss corresponding to the actual f. For example, when the actual fanout is 3, constraints (4.25) are satisfied for both $f = 2$ and 3 since A_2^i and A_2^i equal 1. But, since the splitting loss for the case of f=3 is greater than the case when f=2, the actual SL value cannot be less than that of f=3. This draw a lower bound on this value. Yet, no upper bound can be established using these constraints alone since they can be still satisfied for the case when f is greater than the actual fanout (3, in our example). In this case, the value of the splitting loss can grow indefinitely with no bound wether the value of A_2^i is 0 or 1.

Luckily, this upper limit is implicity defined with the assistance of the objective function. Since the objective function minimizes the total amplification gain, it indirectly attempts to minimize all sources of power loss in the network including minimizing the fanout of the nodes. Consequently, any unnecessary splitting loss value is eliminated from the computation which forms the upper bound limit for the $SL_i^{a,\lambda}$ that is set to 0 for any f that is greater than the actual fanout. Therefore, in order to satisfy the constraints in (4.25), the value of A_f^i in this case will be set to 0 and the splitting loss is the actual splitting loss value of the node. Finally, constraints (4.26) ensure that the splitting loss is always a non-negative value.

At the end of this section, we find out that this formulation has the following basic variables: $T_{i,j}^{a,\lambda}$, $P_{src_a,j}^{beg,a,\lambda}$, and $LG_{i,j}$. The remaining variables are either topology-related variables, or can be determined from the basic variables. Also, the number of variables and constraints used in the formulation are found to be $O(k * |N|^4)$ and $O(k * |N|^3)$, respectively.

4.2 OA Placement Procedure

The second module of our solution is the OA Placement Policy Module. Many OA placement policies are proposed in the literature. Our MILP formulation is generic and does not assume any particular placement policy. Therefore, any OA placement policy can be used in our implementation. We adopt the As Soon As Possible (ASAP) scheme [36] to find the number and locations of the OAs per link. The policy is applied at each link and it uses the power levels computed by the MILP formulation at the beginning and end of the link as well as the total gain per link. The following steps are performed at each link and it repeats over all the links in the network:

1. Initialize the remaining total amplification gain of the link (RLG) with the total amplification gain (LG) obtained from the formulation.
2. Traverse the link in the downstream direction and place an OA on the link if any of the following conditions is satisfied:
    (a) The total power over the link drops to a level that allows the OA to provide the maximum gain, provided all power constraints are satisfied.
    (b) The least-powered signal dropped to the minimum detectable level, namely, P_{Sen}.

(c) The distance of the segment traversed in the link is less than the remaining untraversed segment of the link.

3. RLG is then updated by subtracting the gain obtained by placing the OA from its current value.

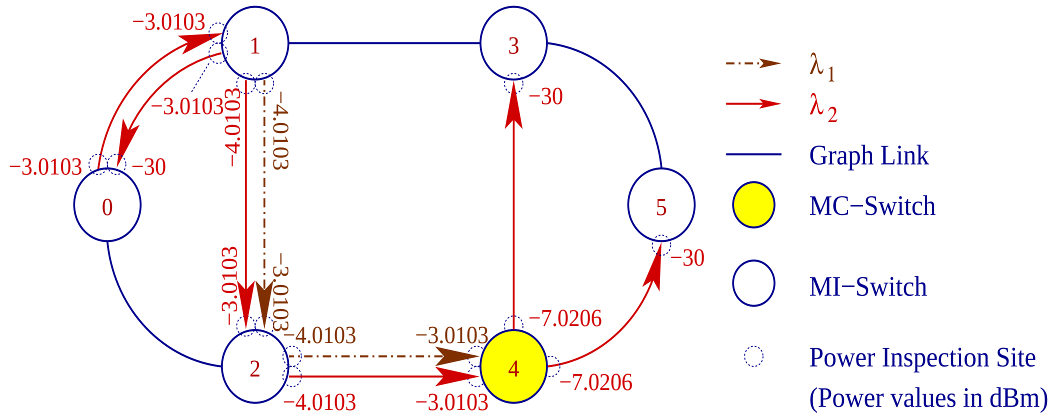
4. Steps 2 and 3 are repeated until RLG is zero or condition 2.b is not satisfied. In the latter case, this means that the last OA should is placed before the end of the link and its location is determined by the value of RLG. This is achieved by determining the total input power that satisfy RLG and then compute the distance to which this total power is obtained.

4.3 Numerical Results

In this section, some numerical results for the optimal solutions obtained using CPLEX [43] are presented for the sample 6-nodes mesh network that is shown in Figure 1.13. We use the experimental assumptions presented earlier in Subsection 1.6.3. Six connections are used in the experiments and are denoted by: $x_0 = (0, \{1, 2, 3, 4, 5\})$, $x_1 = (1, \{0, 2, 4\})$, $x_2 = (5, \{0, 1, 3, 4\})$, $x_3 = (1, \{5\})$, and $x_4 = (1, \{3, 5\})$, and $x_5 = (2, \{0, 1, 3, 4, 5\})$. The results presented in this section serve two purposes. First, they validate the correctness of the proposed solution, and this done in the following subsection. Second, they present some numerical values of the network resources computed by the MILP formulation. These results are provided in Subsection 4.3.2.

4.3.1 Solution Validation

In order to validate the correctness of our solutions, Figure 4.3 depicts an example of the optimal solutions obtained for the multicast sessions x_0 and x_1 when $|\Lambda| = 2$. The solutions from the MILP formulation is shown in Figure 4.3-(a). The solutions include both the RWA along with the power values measured at the beginning and the end of the tree links. Also, the optimal number of splitters is found to be 1 and it is located at node 4. In addition, the



(a)

Fiber (0,1): Length = 1347Km; LG $_{0,1}$ = 269.4 dB, Number of OAs= 14
Distances measured from node 0 (in Km): 84.949; 183.517; 282.086; 380.654; 479.223; 577.792; 676.360; 774.929; 873.497; 972.066; 1070.634; 1169.203; 1267.7719; 1331.948
Fiber (1,0): Length = 1347Km; LG $_{1,0}$ = 242.4103 dB, Number of OAs= 13
Distances measured from node 1 (in Km): 84.949; 183.517; 282.086; 380.654; 479.223; 577.792; 676.360; 774.929; 873.497; 972.066; 1070.634; 1169.203; 1197.000
Fiber (1,2): Length= 766Km; LG $_{1,2}$ = 154.2 dB, Number of OAs= 8
Distances measured from node 1 (in Km): 95.000; 192.199; 289.397; 386.596; 483.795; 580.994; 678.192; 766.000 (Pre Amplification)
Fiber (2,4): Length= 845Km; LG$_{2,4}$= 170.0 dB, Number of OAs= 9
Distances measured from node 2 (in Km): 95.000; 192.199; 289.397; 386.596; 483.795; 580.994; 678.192; 775.391; 845.000 (Pre Amplification).
Fiber (4,3): Length= 383 Km; LG $_{4,3}$= 53.6206 dB, Number of OAs= 3
Distances measured from node 4 (in Km): 64.897; 163.466; 233.000
Fiber (4,5): Length = 808Km; LG $_{4,5}$ = 138.62 dB, Number of OAs= 8
Distances measured from node 4 (in Km): 64.897; 163.466; 262.034; 360.603; 459.171; 557.740; 656.309; 658.000

(b)

Figure 4.3 Sample output for connections x_0 and x_1 only when $|\Lambda| = 2$. (a) RWA and power values, (b) Detailed solution per fiber link.

formulation solution determines the total gain per tree link, which shown in 4.3-(b). Using this sample example, one can verify that all the system constraints discussed in subsection 4.1 are satisfied. For example, the computed light-forest are loop free and satisfy the wavelength continuity and other connectivity constraints. Also, the total power values are always below P_{Max} and the received signals by each receiver is no less than P_{Sen}. Also, power loss sources are taken care of correctly in the solution. For example, at node 4, the output power values are half of that of the input signal strength after subtracting the tapping loss.

These values are used by the OA Placement Policy module to determine the number and

Table 4.1 Summary of the results obtained for the different number of sessions, K, in the 6 node mesh sample network when $|\Lambda| = 2$.

K	1	2	3	4	5	6
No. of OAs	41	55	94	108	165	252
No. of Splitters	0	1	1	0	2	1
MC Nodes	-	4	4	-	$1, 4$	4

locations of the OAs over each tree link. These results are depicted in Figure 4.3-(b). Please note that our formulation is able to capture the special case of the on-site amplification. The last OAs on $e(1, 2)$ and $e(2, 4)$ are examples for the on-site Pre-Amplification case.

4.3.2 MILP Results

Table 4.1 summarizes the results of the CPLEX experiments. Each experiment with K multicast sessions was conducted using the ordered x_0, ..., x_{K-1} multicast sessions, such that $K \leq 6$. For example, for $K = 4$, multicast sessions x_0, x_1, x_2, and x_3 were used in the experiment.

The results reported in Table 4.1 show that the total numbers of OAs increases with the increase in the number of connections. This is because more sessions are competing for the available limited resources. One form of these limited resources is the free wavelengths. In this case, when more connections are provisioned, the need for finding alternate paths increases, which increases the number of OAs. Another limited network resource is the available power budget over the links. This power budget is shared among all the sessions over the link. As more sessions share the same link, their share of the common power budget decreases, which necessitates the use for more OAs in the network.

Table 4.1 also shows the number and locations of the MC nodes, if exists. One interesting result can be concluded from these results which is that the number of splitters does not necessary increase with the increase of the traffic load. This is true because the objective function of the formulation does not include minimizing the number of needed splitters. Instead, splitting should be used if this helps reducing the total amplification gain in the network. Another case when splitting is used is when there is a shortage in the wavelengths. In this case, splitting can help accommodating more sessions in the network. For example, one splitter is needed when $K = 3$, while no splitter is needed when $K = 4$. This is due to the fact that by adding the fourth connection to the network, a new situation is encountered in which different links are used than those in the case of $K = 3$ and it is more beneficial in terms of total gain not to use splitters.

4.4 Chapter Summary

In this chapter, we consider the OAP-Asymmetric problem under AOM in wavelength routing networks. Despite its nonlinearity, we successfully formulate the problem as a MILP with the objective of minimizing the total required gain in the network. The following conclusions can be drawn from this chapter:

1. Due to the complexity of the proposed MILP formulation, this solution is not scalable for problems with bigger network size and higher traffic load. Therefore, efficient power-aware heuristics are needed and this proposed MILP can act as a baseline against which the accuracy of such heuristics can be assessed.

2. The objective function represented in (4.1) helps simplifying the formulation significantly. Unfortunately, this objective function is not always a true representation of the actual physical cost of the network which is represented by the number of OAs. The difference in the power strengths of the different input signal at the entry point of the OAs is of great importance too. For example, a link gain of 100 dB can be achieved using 5, 10 or 20 OAs each of which operates with a gain of 20, 10, or 5 dB, respectively, based on their input powers.

   Therefore, ensuring the symmetric of the input signals can play a significant role in saving the number of OAs. Also, this formulation is considered as a basis for a more involved formulation that takes care of the relationship between the link gain and the number of

OAs.

These two conclusions can be considered as the motivation of the work presented in the next chapter which handles the OAP-Symmetric version of the problem. In this context, we make use of the symmetric property to ensure good allocation of the OAs. Also, we devise a new MILP formulation that takes care of the relation between the number of OAs and the link gain in order to provide more accurate presentation of the network cost. Finally, we develop a set of fast algorithms that provide near-optimal solutions for the large problem instances of the OAP-Symmetric problem.

CHAPTER 5. Optical Amplifiers Placement Problem: Symmetric Power Case

Motivated by the findings and remarks reported earlier in Section 4.4, we investigate the OAP problem in this chapter under the symmetric power assumption. In order to address these issues, our study here takes two directions. In the first direction, we formulate the OAP problem as MILP with the objective of minimizing the total number of OAs needed in the network. This new objective function provides the exact representation of the network cost as it relates this network cost to the actual (or physical) presence of the OAs in the network instead of relying on their collective effect. The latter case was used in Chapter 4 and it was represented by the total amplification gain. Using this new objective function requires modifying the MILP formulation introduced in Section 4.1 by including new set of constraints that ensure the correct computation of the total number of OAs while maintaining the linearity of the formulation.

In this chapter, we use the same two stages solution methodology depicted in Figure 4.1 to solve the OAP-Symmetric Problem. The formal definition of the OAP-Symmetric Problem is similar to that of the OAP-Asymmetric Problem presented earlier in Chapter 4 with respect to their input parameters. However, they differ in their objective function as well as their power symmetry assumption. The OAP-Symmetric Problem is formally defined as follows:

OAP-Symmetric Problem Definition: *"Given the network topology, the maximum number of wavelengths and splitters, the traffic matrix, and assuming symmetric power scenario, the OAP-Symmetric Problem is a network provisioning problem that aims to find a feasible allocation of the OAs and splitters (namely, their number and locations) such that all the traffic demands are satisfied and detectable by the receivers and while minimizing the total number of* *optical amplifiers in the network".*

The solution from the proposed MILP formulation provides the optimal solution for the OAP problem by solving all the constituent subproblems jointly. However, the MILP formulation cannot provide fast solution for large instances of the problem. Therefore, in the second direction of our study, we solve the problem using a greedy heuristic that provides faster, yet near optimal solutions for the OAP problem. The operation of the heuristic approach is based on solving the subproblems of the OAP problem separately, but without ignoring their impact on each there. This could be achieved using novel set of routing cost functions for the links, paths, and sessions that are represented in terms of the needed optical amplifiers. Using these cost functions make it possible for the algorithm to make routing decisions that reduce the required number of optical amplifiers; thus, minimize the network cost. In addition, the heuristic solution is designed to provide a balance between the computation complexity and the solution quality. This is achieved by defining two modes of operations, namely fixed and adaptive, each of which can use fixed or alternate routing.

Our treatment of the OAP-Symmetric problem in this chapter is organized as follows. Section 5.1 presents some additional system assumptions that we use in this chapter. This is followed by an example that aims to present the significance of power symmetry in reducing the number of OAs, and consequently the network cost, in Section 5.2. The details of the MILP formulation and the heuristic algorithms are introduced in Sections 5.3 and 5.4, respectively. Comprehensive set of results that report several system performance results are then introduced in Section 5.5, and finally, we conclude this chapter in Section 5.6.

5.1 Addition System Model Assumptions

In addition to the two power constraints defined earlier in Subsection 1.6.1, our treatment for the OAP-Symmetric problem requires the consideration of one additional power constraint in our model, namely, the power symmetry over each link. In this context, all the channels over any link must be of equal strength. Power Symmetry constraint is achieved by equipping each output port of every OXC in the network with an optical power equalizer [7].

Moreover, the set of results reported in this chapter are obtained by using the As Late As Possible (ALAP) OA placement policy [45, 36]. However, choosing any other policy does not affect the main objective of this work, namely, determining the cost of the network in terms of the number of OAs. It will only change the locations of these OAs.

5.2 Impact of Power Symmetry on Number of Optical Amplifiers: An Example

The significance of the power symmetry constraint stems from the fact that it does not only simplify the OAP solution, but it also ensures fair utilization of the deployed OAs. Ideally, this can reduce the number of OAs by avoiding situations where the difference in strengths between the input power signals is large enough to cause the OAs to be saturated by high-powered input signal(s). This situation results in small OA gain and consequently small span between the optical amplifiers.

In order to illustrate the significance of power symmetry constrain in reducing the number of needed OAs over a link, let us consider the following example depicted in Figure 5.1 for link $e(1,2)$ of length 150 km when the input power values over channels λ_1 and λ_2 equal -25 dBm and -5 dBm, respectively. In this example, we use the ALAP OA placement policy. Figure 5.1-(a) shows the solution for the OAP-Asymmetric scenario where the number of needed OAs equals 4 OAs. In this case, the first OA is placed 25 km away from node 1 since the strength of the power signal over λ_1 reached P_{Sen}, i.e., -30 dBm. At this location, the strength of the other signal over λ_2 is -10 dBm. Therefore, the difference between the two power strengths is -20 dBm (0.01 mW), and the total input power to the first OA is -9.957 dBm (0.101 mW). Based on the simple OA model described by equation (1.2), the OA operates in the saturation region. Therefore, its gain value equals 9.957 dB and the strengths of its output signals over λ_1 and λ_2 increased to -20.043 dBm and -0.043 dBm, respectively. Similarly, the remaining OAs are placed on the link such that the distance of the span between each consecutive OAs equals 49.783 km. Finally, the length of the remaining link span between the last OA and node 2 equals 25.43 km.

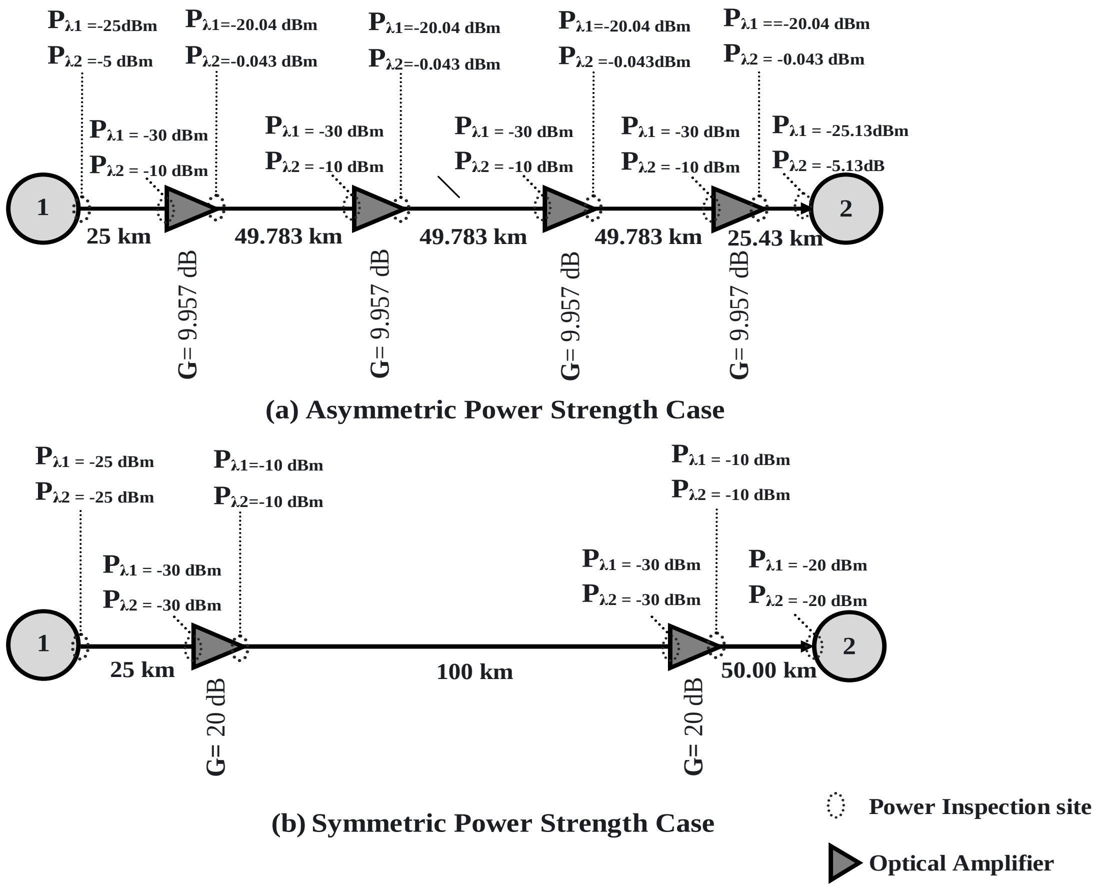


Figure 5.1 An example that shows the impact of using symmetric power values on saving the number of OAs over link $e(1,2)$, whose length is 150 km, when ALAP OA placement policy is used. (a) 4 OAs are needed for the OAP-Asymmetric scenario, (b) 2 OAs are needed for the OAP-Symmetric scenario.

While 4 OAs are needed under the OAP-Asymmetric scenario, 2 OAs are sufficient to satisfy all the power constraints when the OAP-Symmetric scheme is used. The details of this solution is shown in Figure 5.1-(b). In this figure, the power strengths of the input signals are equalized at node 1 to the minimum input powered value, namely, to -25 dBm, which is the value of the power over λ_2. While the first OA is placed at the same distance as the first OA in the previous scenario, equalizing the input power strengths enables the first OA to operate in the non-saturated region; hence it can produce the maximum gain (i.e., 20 dB) which is applied equally to both input signals. Therefore, the powers of the output signals of the first OA are still symmetric and higher than the output power signals produced from the OAP-Asymmetric case. Using this hight powered strength, the signals can then reach further away in the link (100 km in this case) without the need to amplify them.

5.3 MILP Formulation

In this section, we introduce the details of the proposed MILP formulation for solving the OAP-Symmetric problem. The objective function of this formulation is to minimize the network cost that is defined as the total number of OAs needed in the network to satisfy all the required constraints. This objective function is expressed as follows:

$$Minimize \sum_{e(i,j)\in E} n_{i,j} \tag{5.1}$$

where $n_{i,j}$ is the number of OAs over each link.

The following subsections present the set of constraints we use in this formulation. However, the MILP formulation we propose here to the solve the OAP-Symmetric problem shares some of the constraints that were employed by the MILP formulation of the OAP-Asymmetric problem in Chapter 4. For the sake of simplicity and due to the space constraints, the reader is referred to these common constraints, whenever applicable.

5.3.1 Routing and Wavelength Assignment Constraints:

We use the same set of the Routing and Wavelength Assignments constraints defined earlier in subsection 4.1.1 by constraints (4.2)-(4.11).

5.3.2 Loop Avoidance Constraints:

In this subsection, we define a new set of constraints that are used to ensure that the constructed light-trees for each session do not include any loop. These sets of constraints rely on computing the number of hops from the source node to each destination node and they ensure that these number of hops do not exceed $N-1$.

$$H^{a,\lambda}_{src_a} = 0 \qquad 0 \le a < K; \forall\lambda \in \Lambda \tag{5.2}$$

$$1 - T_{i,j}^{a,\lambda} - \frac{H_i^{a,\lambda} + 1 - H_j^{a,\lambda}}{M} \geq 0 \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{5.3}$$

$$\Gamma_i^a + \frac{H_i^{a,\lambda} - (|N| - 1)}{M} \leq 1 \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{5.4}$$

By definition, the number of hops from the source node of any session to itself over any λ is zero. Therefore, constraints (5.2) are used to ensure that this is true for each session under investigation. In addition, constraints (5.3) ensure that if the link $e(i,j)$ is used by session a over a particular channel (i.e., $T_{i,j}^{a,\lambda} = 1$), then node j is *exactly* one more hop away from the session's source node than node i over the light-tree carried by that channel. In this case, the term $(1 - T_{i,j}^{a,\lambda})$ of the left-hand side of constraints (5.3) is zero, and for these constraints to hold correctly, the fraction $(\frac{H_i^{a,\lambda}+1-H_j^{a,\lambda}}{M})$ must be a non-positive quantity (i.e., either zero or negative). This implies that $H_i^{a,\lambda} + 1 \leq H_j^{a,\lambda}$ is correct too. Since the formulation tries to minimize the total number of OAs, it indirectly tries to minimize the total number of hops. This results in forcing an upper bound on the number of hops, and the previous inequality indicates that the difference in number of hops between any consecutive nodes connected by a tree link is exactly 1. Please note than when $(T_{i,j}^{a,\lambda} = 0)$, constraints (5.3) is always true due to the use of the large constant, M, which makes the fraction in the third term a very small number that is less than 1.

Finally, constraints (5.4) ensure that a tree structure is generated with no loop by ensuring that the number of hops from the source node to each destination node is no more than $|N| - 1$ hops. In this context, if a node i is a destination node of session a, i.e., $\Gamma_i^a = 1$, the fraction in the second term of constraints (5.4) must be a non-positive value in order for these constraints to become true; which implies that $H_i^{a,\lambda} \leq (|N| - 1)$. On the other hand, when $\Gamma_i^a = 0$, the left hand side of these constraints is always less than 1 because the use of the large constant, M, in the second term makes it very small fraction that is much smaller than 1.

5.3.3 Power Constraints:

We use the same set of power constraints that were defined in Subsection 4.1.3 by constraints (4.17) - (4.26). Nevertheless, in order to take care of the new objective function and the power symmetric constraint, we define the following additional constraints:

$$P_{i,j}^{beg,a,\lambda_1} - P_{i,j}^{beg,b,\lambda_2} = 3 \times M \times (T_{i,j}^{a,\lambda_1} - T_{i,j}^{b,\lambda_2})$$
$$\forall e(i,j); 0 \leq a, b < K; \forall \lambda_1, \lambda_2, \in \Lambda, \lambda_1 \neq \lambda_2 \quad (5.5)$$

Constraints (5.5) are used to enforce the power symmetric constraint by ensuring that all the active signals at the beginning of each link have the same power strength. As the propagation loss and power gain are both linear, enforcing these constraints at the beginning of the link is sufficient to ensure that all the power signals over the whole link are symmetric. Please note that when light-forest links (of the same connection or different connections) use link $e(i,j)$, the right hand side of constraints (5.5) becomes zero and both power values at the beginning of the link should be equal. The same occurs in the case when both light-forest links do not use the same link. However, when only one of them exist over the link, the difference in their power values is guaranteed to be in the range between $|P1|$ and $|P2|$, which is in compliance with constraints (4.17) and (4.18).

$$LG_{i,j} \leq g_{max} \times n_{i,j} \qquad \forall e(i,j) \quad (5.6)$$

$$LG_{i,j} > g_{max} \times (n_{i,j} - 1) \qquad \forall e(i,j) \quad (5.7)$$

These constraints determine the relation between the total gain and the needed number of OAs per link such that the minimum number of OAs are used. Similar constraints were used in [45] where g_{max} determined the maximum gain available at any amplifier which occurs when all the input signals are at P_{Sen}. However, as the number of occupied channels per link is determined by the MILP solution, we use an approximate approach to compute g_{max} in which we assume that all the channels over all the network links are occupied. This assumption enables us to pre-compute g_{max} using the OA model define in (1.1) such that the total input power (P_{in}) is calculated as $10 \times log10(\Lambda \times 10^{\frac{P_{Sen}}{10}})$. This approximation provides an exact value for g_{max} when Λ is small, which is the case with our numerical results.

5.4 The Heuristic Algorithm

The OAP problem consists of three main subproblems. These subproblems are: Routing (**R**), Wavelength Assignment (**WA**), and Power Assignment/Amplifiers Placement (**PAAP**) subproblems. The solution of one subproblem impacts the solutions of the other subproblems. Hence, the MILP formulation presented above solves the problem optimally by solving these subproblems jointly. Despite its optimality, the MILP formulation is not scalable as it cannot solve big-sized problem instances in a time efficient manner due to its high complexity. Such complexity is represented in terms of the numbers of constraints and variables which are on the order of $O(|N|^4 \times |C| \times |\Lambda|)$ and $O(|N|^2 \times |C| \times |\Lambda|)$, respectively.

Therefore, there is a need for a heuristic approach that produces fast solutions with high quality degree. Such heuristic must be able to capture the main characteristics of the problem under investigation. In this section, we present a heuristic solution, referred to as Optical-amplifiers Placement (**OP**) algorithm.

5.4.1 Greedy Algorithm Motivation and Main Characteristics

The main goal of the OP algorithm is to achieve the balance between the produced solution quality and the computation time. In order to achieve this goal, the operation of the OP algorithm relies on the Divide-and-Conquer concept by dividing the problem into its natural subproblems that are solved separately. However, the impact between these modules are taken into account by employing a special set of cost functions for the links, network and sessions. The significance of these cost functions stems from the fact that they are defined in terms of optical amplifiers numbers. As these cost functions are used for the light-forest construction and session routing, this allows us to capture the influence between **R** and **PAAP** subproblems and results in efficient solutions.

Moreover, the design of the OP algorithm realizes the influence of the *Power Sharing* concept. We introduced the Power Sharing concept in [62] as a means to capture the impact of the various power issues on the network during the various stages of its lifetime. This concept represents the result of sharing the available power by wavelengths at the entry point of the links and OAs. Such influence is translated as connection blocking (called Power Sharing Blocking) [62] during network operation phase. As a design problem, the power sharing concept still holds, but it has different influence as all the connections must be accommodated (i.e., no connection drops are allowed). In this context, the power sharing concept results in changing the **Network Power Status** (**NPS**), which defines the network condition in terms of its power values at the beginning of each link[1], as well as the number, locations and gain values of the OAs. The change in the NPS is a result of any of following behaviors:

1. As optical signal traverses from one link to another, its power strength may decay below P_{Sen} anywhere in the light-forest, even with the use of the source node's maximum available power. This can result in adding more in-line, pre-amplification and/or post-amplification OAs, which increases the network cost. We refer to this behavior as *Power Shortage Behavior.*

2. Routing a new connection that shares links with some already provisioned connections in the network can change the NPS by either:

   (a) Dropping the gain of at least one OA to a level that causes a service disruption for at least one session. Such service disruption occurs if the gain drop yields to changing the strengths of its passing signals. As these signals traverse in the network, a sequence of changes in the signals strength and other OAs gains can occur, which might result in violating any of the power constraints. We refer to this behavior as *Gain Dropping Behavior.*

   (b) Changing the power values assigned to an already provisioned light-forest(s) in order to maintain the power symmetry and maximum total power constraints defined by constraints (4.18) and (5.5), respectively. Therefore, we call this behavior, the *Power Adjustment behavior.*

The NPS is highly dynamic and sensitive to any change introduced to the NPS from these

[1]Knowing the power values at the beginning of each link is merely sufficient to determine the power values everywhere in the network.

behaviors. This is because any adjustment made to the network condition at one point in the network may propagate to other network locations and can affect multiple connections. This can create a complicated power management issue, especially if a large number of connections are involved. Nevertheless, the OP algorithm is designed to tackle this dynamic nature by allowing changes to occur to the NPS while ensuring that their impacts are handled in an efficient manner.

Finally, the OP algorithm is designed to optimize the solutions at two levels. At the lowest level, namely, the light-forest construction level, it allows the destinations to be attached to the sub-forest using multiple alternate paths, instead of a single path. Using alternate routing in this manner allows the OP algorithm to explore a bigger solution space and the light-forest can expand to new destinations using the path of the minimum (present) path. In addition, the OP algorithm allows constructing more than one light-forest per session. The one with the least cost is then chosen to be placed in the network. At the light-forest placement level, the algorithm defines two operation modes, namely, *Fixed* and *Adaptive* Modes. In the Fixed mode, light-forests are constructed based on the initial NPS and then they are placed in the network according to their costs. With the Adaptive mode, however, placing each light-forest in the network is followed by reconstructing the remaining light-forests that are not yet provisioned based on the most recent NPS. Rerouting the remaining sessions allows the OP algorithm to account for the impact of light-forests on each other which improves the solution accuracy, yet, at the cost of extra computation.

5.4.2 Cost Functions Definitions

The following set of cost definitions are employed by the OP algorithm:

- The current cost of link $e(i,j)$ is defined as the current number of OAs needed over the link, namely $c_{e(i,j)} = |n_{i,j}|$. This includes any Post-Amplification at node i, and any Pre-Amplification at node j.
- The current network cost is computed as the total number of OAs over all the links in the network. In other words, $C = \sum_{e(i,j)} c_{e(i,j)}$

- The cost of the path that connects a destination to the subtree-forest is defined as the change in the network cost that results if such a path is used for expanding the subtree-forest to that destination.

- The session cost is also calculated as the change in the network cost if its light-forest is placed in the network.

Using these cost functions has the following advantages:

1. It is possible to base the routing decisions of the light-forests on the system power budget. This establishes a connection between the R and PAAP subproblems and can result in better solutions.

2. These cost functions are dynamic as their definition is based on the the most recent NPS. This is important to ensure the correctness and goodness of the produced solutions.

3. Using the definitions of the path and session costs is effective in relating the routing and placement decisions to its future consequences. This post-influence scheme help in capturing the influence between the connections.

4. Finally, the link cost function is a positive increasing function. Therefore, link costs increases as more of its channels become occupied with routed sessions. This is useful in balancing the load in the entire network

5.4.3 OP Algorithm Details

We present the details of the OP algorithm in this subsection. The OP algorithm is designed as an iterative algorithm such that the final solution is the result of a set of optimized sub-solutions. Figure 5.2 depicts the basic operation of the algorithm which consists of three main stages. These stages are: the Light-Forests Construction (LFC) Stage, the Light-Forests Placement (LFP) Stage and the Light-Forest Reconstruction (LFR) Stage. The core operation of the LFC and LFR stages is the Light-Forest Construction Module which is depicted in

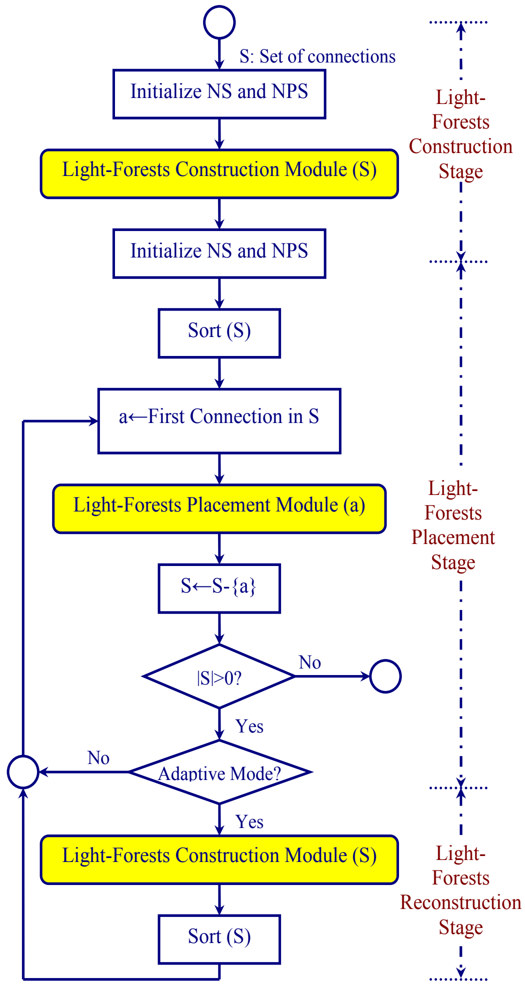


Figure 5.2 Basic Operation of the OP Algorithm.

Figure 5.3 while the core operation of the LFP stage is the Light-Forest Placement Module which is depicted in Figure 5.4.

The LFC stage starts by initializing all the data structures, which include: the Network status (NS), the Network Power Status (NPS) and the set S. While NPS is defined earlier in subsection 5.4.1, NS defines the channels and links status in the network and the set S determines the set of sessions which are not yet provisioned (placed). Initially, the set S includes all the multicast sessions.

Then, the Light-Forest Construction Module is invoked in order to construct the light forest for each multicast session in S. NS and NPS are then re-initialized and the set S is sorted according to its sessions' costs. The second stage, namely, the LFP stage, is then invoked for the first session, a, in the sorted S and its light-forest obtained from the LFC stage is placed in the network. Accordingly, the algorithm updates NS, NPS, and S and it proceeds with the remaining multicast sessions in S in two fashions based on its operational modes, i.e., Fixed or Adaptive. In the Fixed mode, the algorithm places all the initial light-forests constructed in the LFC Stage without changing them. On the other hand, the Adaptive mode involves the use of the LFR stage in which new light-forests are constructed for all the sessions in S based on the current NS and NPS. Therefore, the Light-Forest Construction Module is invoked again in this stage with the latest NS, NPS and S. After sorting S, the LFP stage is invoked with the first session in set S. The algorithm stops when all sessions are placed. For the sake of completeness, the details of all the Light-Forest Construction and Placement Modules are explained below.

5.4.4 Light-Forest Construction Module

As indicated by its name, the purpose of the Light-Forest Construction Module is to produce a light-forest for each multicast session according to the recent NS and NPS. Each light forest is constructed as if it is the only light-forest in the system. The purpose of this construction scheme is to determine the cost of each session (in terms of the change in the network cost) using the recent NS and NPS.

In addition, due to the randomness involved in its operation, the Light-Forests Construction module generate more than one light-forest for each session such that the best (least cost) light-forest is then chosen[2]. The input to the Light-Forest Construction module is the set S. As shown in Figure 5.3, each construction trial for the multicast session starts by restoring the latest NS and NPS in order to ensure the correctness of the light-forest instance construction.

The light-forest construction is performed iteratively using an extended version of the Member-Only (M-Only) algorithm proposed in [1]. Initially, the light-forest structure, called sub-forest or T', includes the source node only, src_a. After each iteration, T' is expanded

[2] The number of construction trials per connection is an input parameter.

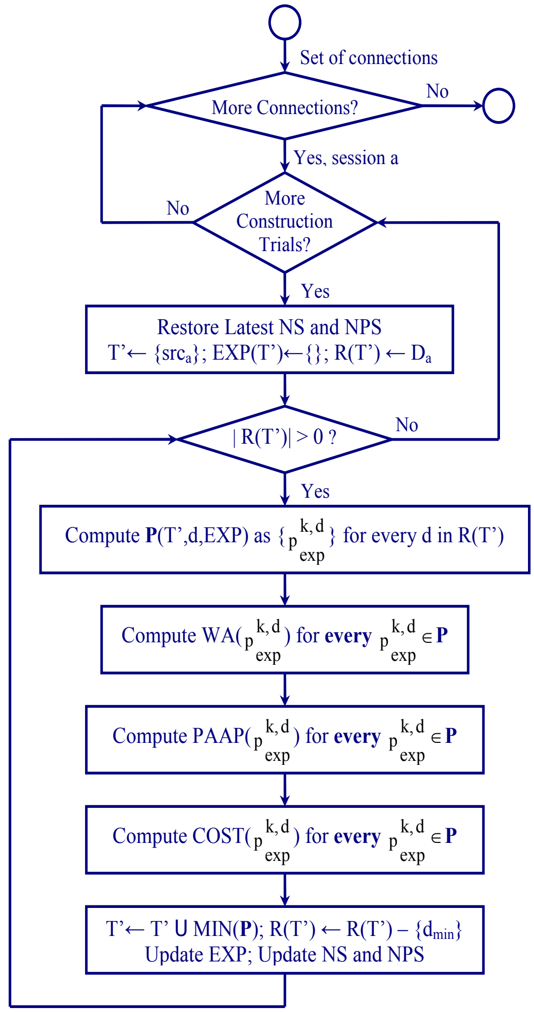


Figure 5.3 Tree Construction Module.

such that a new (i.e., unconnected) member is attached to T' via one light-forest node. The light-forest growth is permitted through only a specific set of nodes, called the expandable nodes set or EXP(T'). This set consists of the source node, all the light-forest nodes with Multicast Capability (MC nodes) or/and leaf nodes. Instead of a single path, the Light-Forest Construction Module computes k alternate paths to each remaining destination. Among all these computed paths, T' is then expanded using the path of the least cost. The module stops when all the remaining nodes, R(T'), are included in the light-forest.

All relative data structures are updated at each iteration during which the following operations are performed:

1- Path Computation (PC):

In this step, a set of k-shortest alternative paths from each unconnected destination, d, to each expandable node in T', EXP(T'), is computed. Please note that the shortest path does not always translate to the least costly path (in terms of the increase in the number of OAs). Using k alternate paths increases the chance for the member node to join the sub-forest structure, T', using the least-cost shortest path. Nevertheless, it should be clear that this step still requires checking and removing any overlapping or looping in the resultant sub-forest. This step is necessary since the selected path may share some nodes and links with T'.

2- Path Wavelength Assignment (PWA):

The PWA step is performed for each computed path from step 1. Depending on the expandable node, two scenarios are possible in this operation. On one hand, we employ the First-Fit scheme (in which the first available common wavelength over all links in the path is chosen) if the path under investigation connects the destination node to the source node itself (i.e., new forest branch is created). On the other hand, if the attaching node is not the source node, the new forest segment from the expandable node to the destination should continue using the same channel (if available) used over the forest segment connecting the source node to the expandable node. If such a wavelength is not available, the previous wavelength assignment is ignored and a new wavelength is computed using the First-Fit scheme over the new path from the source node to the connecting destination node via the expandable node.

3- Path Power Assignment/Amplifiers Placement (P-PAAP):

For each path instance passed the PWA step, the P-PAAP operation is responsible for determining the power values and the OAs placement over each of its links. The P-PAAP module relies on using a queue structure, called Q, which consists of unique entities of the link identities and aims to separate the links identities from their power values.

The P-PAAP operation starts by marking the session under investigation as affected and adding the first link of the path to Q. Then P-PAAP runs iteratively such that at each iteration, the link at Q's head is processed by performing the following operations:

- **Initial Power Determination Operation.**

  This operation is responsible for determining the power values at the beginning of the head link in Q such that no power constraint is violated and that the power symmetry constraint is maintained. Two factors determine these power values, namely, whether the head link is connected from the source and/or it has more than one channel. For instance, if the link is launched from the session's source node and it is the only channel on the link, the maximum power value can be assigned to the channel. Otherwise, if the head link is not launched from the session's source, this step adjusts these power values according to the power and symmetry constraints.

- **OA Placement Operation.**

  Using the power values at the beginning of the head link, the OAs are placed over the link based on the ALAP policy[3]. In order to accommodate for the change in NPS, this step may involve changing the OAs locations (hence, their total number) over the head link which were computed from the previous algorithm iteration.

  Allowing such modification to happen by the OP algorithm is essential to provide accuracy to our solution and allows the system to adapt to any changes. However, this will be done with the minimum maintenance overhead with the help of the Q structure and its rules of addition/deletion of links to/from it, as will be shown below.

- **Update Q Operation.**

  Q is then updated by adding more links, if any. The set of potential links to be added to Q are chosen from the set of outgoing links, $\Re$, launched from the sink node of the current link at Q's head. In order to prevent Q from being unnecessarily modified, Q is updated with those outgoing links that satisfy the following conditions:

[3]Please note that we assume the As Late As Possible (ALAP) OA placement policy; yet, any other policy can be used in our algorithm.

– They are part of the light-forest of the current session under investigation. This should guarantee the continuation of power investigation for the current sub-forest.

– They are part of the light-forest of all the other sessions over the link, provided that a new power value is observed at the end of the head link which is different from the one computed from the previous iteration. Such change in power values from iteration to iteration indicates a change in the system status that needs to be propagated. Hence, we use Q to trace such a change in the NPS.

Once processed fully, the link at the Q's head is removed and the P-PAAP operation continues with the next link in Q and it stops when Q becomes empty. Please note here that a link can be revisited more than once during the iteration lifetime[4]. This occurs because the same link can be at different depth of the various light-forests. During each link traversal, more power values over the link become available. P-PAAP deals with those power values that are currently available which enables it to work even with partial knowledge of the power values. However, allowing several traversals of the links ensures the complete availability of the power values at the link.

4- Compute Path Cost:

Finally, the cost of all the computed paths is evaluated as explained in Subsection 5.4.2, and T' is then expanded using the path of the least cost. The Light-Forest Construction module then stops when all the remaining nodes, denoted by R(T), are included in the light-forest.

5.4.5 Light-Forest Placement Module

This module is responsible for placing the light-forest constructed in the Light-Forest Construction module in the network and then change the NS and NPS accordingly, as shown in Figure 5.4. Therefore, there is no routing in this module and it focuses on solving the WA and PAAP subproblems at the forest level. These two operations are similar to the corresponding ones introduced in the Light-Forest Construction Module. However, the delivery structure

[4]Although multiple traversals of the link is permitted during the P-PAAP, Q contains at most one instance of the link at each algorithm step. Preventing multiple copies of the same link in Q eliminates any unnecessary calculations since power values are separate from the link identities.

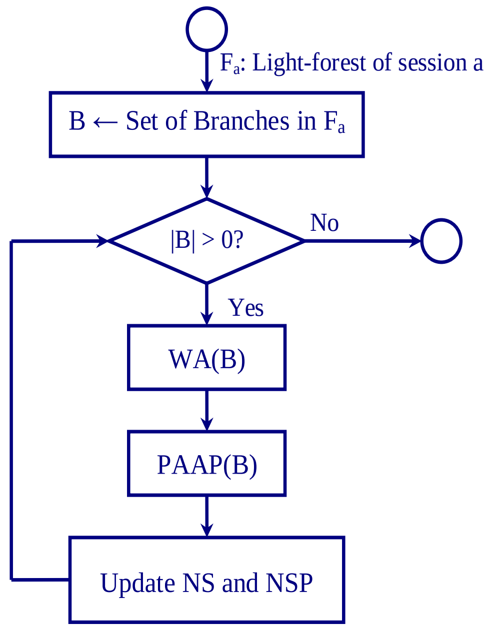


Figure 5.4 Tree Placement Module.

unit here is determined in terms of light-forest's branch instead of a path. For instance, the WA is performed for each branch of the light-forest such that it always finds the first available wavelength over all the branch's links (i.e., no continuation of usage of upstream channels involved). Similarly, the PAAP entity in the Light-Forest Placement Module operates like the PAAP entity in the Light-Forest Construction module (i.e., P-PAAP module). However, building Q starts from the first branch's link launched from the source node itself rather than from the first link of the path.

Please note that we can bypass this module in the Adaptive operation mode as we can use the final NS and NPS information from the LFR stage when the chosen light-forest is placed in the network. However, it is essential to apply this module for the fixed operational mode in order to determine the WA and PAAP results for each placed light-forest in the network.

5.5 Numerical Results

We present some numerical results in this subsection for the OAP-Asymmetric Problem. These results are obtained using CPLEX [43] for solving the MILP formulation and using the C++ Programming Language for implementing the OP algorithm. We first examine the quality of the solutions produced by the OP algorithm by comparing them with the optimal solutions of the MILP formulation using the 6-nodes mesh network shown in Figure 1.13. After establishing such quantitative comparison, we present various results that illustrate different aspects of the proposed OP algorithm using the 14-nodes NSFNET shown in Figure 1.14.

In addition to the experiments parameters and assumptions defined in Subsections 1.6.3 and 5.1, these results are obtained under the following assumptions:

1. Descending-order policy is used by the OP algorithm for sorting the set of connections constructed in the LFC stage.

2. The OP algorithm runs for at least 10 times per problem instance and the best solution that produces the minimum number of OAs is chosen.

5.5.1 Comparative Results Between the Optimal and Heuristic Numerical Results

Tables 5.1 and 5.2 compare the results obtained from CPLEX to their counterparts obtained from the OP heuristic for the 6-nodes mesh network. It is important to note that the MILP formulation aims to solve the OA Placement (OAP) problem with more restrictive constraints than the OP heuristic. In this context, the optimal solutions from CPLEX are obtained not only for the number of OAs, but also for the number of splitters and their locations. Also, CPLEX experiments are conducted with limited number of available channels in the network. These constraints are relaxed in the OP heuristic solutions as the number/location of the splitters is predetermined and no upper bound is imposed on the number of available channels.

Therefore, in order to make a meaningful comparison between these results, the following three actions are taken into account:

1. The OP heuristic experiments are carried out with the same number/location of splitters obtained from CPLEX for the same problem instance.

2. The quality of the solutions obtained from the OP heuristic with respect to the optimal solutions will be determined by two factors. First, the difference in the number of OAs (i.e., the objective function) obtained from both solutions. Second, how much extra network resources (if any) are needed by the OP algorithm.

3. Due to Constraints (4.18), we also make sure that the individual signal strength produced by OP algorithm does not exceed $\frac{P_{Max}}{\Lambda}$ dBm [5].

4. The operation of the OP algorithm initializes the number of OAs per link $e(i, j)$ with the least number of OAs needed over the link, denoted by $|OA|_{i,j}^{min}$. The value of $|OA|_{i,j}^{min}$ is computed as if P_{Max} is used over the link $e(i, j)$ to deliver the signal from node i to node j only. Effectively, each link, $e(i, j)$, will have at least $|OA|_{i,j}^{min}$, whether or not it is used by any session in the network. The current MILP formulation reports that the number of needed OAs is zero when link $e(i, j)$ is not used in the network. Therefore, we modify the OA Placement Policy Module to include the computation of $|OA|_{i,j}^{min}$ in the reported results.

Table 5.1 determines the number of OAs obtained from CPLEX ($|OA|_C$) compared to those obtained from the OP heuristic ($|OA|_i$). The index i determines the number of alternate paths used in constructing the light-forest in LFC stage. Each $|OA|_i$ solution takes the (x/y) format to determine the $|OA|$ when the Fixed and Adaptive schemes are employed, respectively. The same symbolic notation and (x/y) format is used in Table 5.2 to determine the network resources consumed by the produced solutions.

Basically, there are two network resources that are of interest to us and which are computed at the network-wide scale. These resources are:

1. The maximum number of distinct channels used over any link; this is referred to as ψ.

2. The number of links used in constructing all the light-forests (i.e., links with at least one used channel); this referred to as Ł.

[5] As this action is taken for comparison purposes only, we do not take this limitation into account for all the results presented in Subsection 5.5.2.

Table 5.1 Comparison of OAs numbers obtained by CPLEX ($|OA|_C$) and OP heuristic ($|OA|_i$; where $i = 1, 2, 3, 4$ represents the number of alternate paths) for the 6-mesh network. K and Λ represent number of sessions and available lambda, respectively.

K	Λ	$\|OA\|_C$	$\|OA\|_1$	$\|OA\|_2$	$\|OA\|_3$	$\|OA\|_4$
1	2	157	158/158	158/158	158/158	158/158
2	2	158	160/158	158/158	158/158	158/158
3	2	159	160/160	159/159	159/159	159/159
4	2	159	160/160	159/159	159/159	159/159
5	2	159	160/160	159/159	159/159	159/159
6	2	159	160/160	159/159	159/159	159/159
7	2	159	161/161	161/161	160/160	160/160
8	2	159	161/161	161/160	161/160	161/160
1	3	159	159/159	159/159	159/159	159/159
2	3	159	159/159	159/159	159/159	159/159
3	3	160	160/160	160/160	160/160	160/160
4	3	160	160/160	160/160	160/160	160/160
5	3	160	160/160	160/160	160/160	160/160
6	3	160	160/160	160/160	160/160	160/160
7	3	160	160/160	160/160	160/160	160/160
8	3	161	161/161	161/161	161/161	161/161
9	3	161	161/161	161/161	161/161	161/161
1	4	159	159/159	159/159	159/159	159/159
2	4	159	159/159	159/159	159/159	159/159
3	4	159	160/160	160/160	159/159	159/159
4	4	160	160/160	160/160	160/160	160/160
5	4	160	160/160	160/160	160/160	160/160
6	4	160	160/160	160/160	160/160	160/160
7	4	161	161/161	161/161	161/161	161/161

Table 5.2 Comparison of used network resources for the 6-mesh network. ψ_C (Ł$_C$) and ψ_i (Ł$_i$) represent the maximum number of wavelengths (number of links) used by CPLEX, and the OP heuristic, respectively. $i = 1, 2, 3, 4$ represents the number of alternate paths, while K and Λ represent number of sessions and available lambda, respectively.

K	Λ	ψ_C	ψ_1	ψ_2	ψ_3	ψ_4	Ł$_C$	Ł$_1$	Ł$_2$	Ł$_3$	Ł$_4$
1	2	2	2/2	1/1	1/1	1/1	4	6/5	5/5	5/5	5/5
2	2	2	2/2	1/1	1/1	2/2	6	7/7	7/7	7/7	7/6
3	2	2	2/2	2/2	2/2	2/2	11	12/12	12/12	12/11	12/11
4	2	2	2/2	2/2	2/2	2/2	11	12/12	12/12	12/12	12/12
5	2	2	2/2	2/2	2/2	2/2	12	12/12	12/12	12/12	12/12
6	2	2	2/2	2/2	2/2	2/2	12	13/12	12/12	12/12	12/12
7	2	2	3/3	3/2	3/2	3/2	14	13/12	13/12	12/12	12/12
8	2	2	4/4	4/3	4/3	4/3	14	13/13	13/13	13/13	13/13
1	3	1	1/1	1/1	1/1	1/1	5	5/5	5/5	5/5	5/5
2	3	2	2/2	2/2	2/2	2/2	8	8/8	8/8	8/8	7/7
3	3	3	2/2	2/2	2/2	2/2	11	12/12	12/12	12/12	12/12
4	3	3	2/2	2/2	2/2	2/2	11	12/12	12/12	12/12	10/10
5	3	3	2/2	2/2	2/2	2/2	11	12/12	12/12	12/12	10/10
6	3	3	2/2	2/2	2/2	2/2	12	12/12	12/12	12/12	10/10
7	3	3	3/3	3/3	3/3	3/3	12	11/11	11/10	11/10	10/10
8	3	3	4/4	4/4	4/4	4/4	13	12/11	12/11	11/11	11/11
9	3	3	5/5	5/5	5/5	5/5	14	13/13	13/13	13/13	13/13
1	4	1	1/1	1/1	1/1	1/1	5	5/5	5/5	5/5	5/5
2	4	3	2/2	2/2	2/2	1/1	12	11/11	11/11	11/11	11/11
3	4	2	2/2	2/2	2/2	2/2	12	11/11	11/11	11/11	11/11
4	4	3	3/2	2/2	2/2	2/2	13	11/11	10/10	11/11	10/10
5	4	2	2/2	2/2	2/2	2/2	13	12/10	11/10	10/10	12/10
6	4	2	2/2	2/2	2/2	2/2	13	12/10	11/10	11/10	10/10
7	4	3	3/3	3/3	3/3	3/3	13	11/10	11/10	10/10	10/10

From the results in Table 5.1, it is clear that the quality of the solutions produced by the OP heuristic is determined by its computation complexity. Two factors contribute to this complexity, namely, the number of alternate paths used for constructing each light-forest, and whether or not rerouting is performed to reconstruct the remaining unplaced light-forests. The OP heuristic permits the use of any combination of these factors such that the computation complexity ranges from **minimum computation** (namely, Fixed scheme with one alternate path for routing) to **maximum computation** (namely, Adaptive scheme with maximum number of alternate paths for routing).

The following conclusions can be drawn from the results in Tables 5.1:

- The OP heuristic remarkably succeeds to obtain the optimal solution in most cases, even with the use of the minimum computation effort (For example, check the results for all the cases when Λ=3 and 4). For the other cases, on the other hand, the mismatch between the optimal solutions and the OP heuristics solution is 1 or 2 OAs only. This is relatively too small difference, especially for Wide Area Networks which is the focus of this study.

- Better solutions with lower mismatch are produced in most cases by increasing the computation complexity of the OP heuristic. For instance, the optimal solution for the case when Λ=2 and K=7 is 159 while the OP heuristic solutions improved from 161 to 160 when more alternate paths and Adaptive schemes are used. However, there is a trivial trade-off between the computation time/resources and the solution quality.

- Using more alternate paths alone (i.e., Fixed mode with multiple paths routing) or allowing rerouting scheme alone (i.e., Adaptive mode with single path routing) proves to provide good solution, especially when the system traffic is lightly loaded. For example, for the case when $\Lambda = 2$ and $K = 5$, using the Fixed mode with multiple paths routing improves the solution from 160 to 159 OAs (which is the optimal solution) starting from using two alternate paths and without the need for applying the Adaptive mode. On the other hand, for the case of $\Lambda = 2$ and $K = 2$, using the Adaptive mode with single path routing produces 158 OAs which is the optimal solution.

- The results also illustrate the fact that using alternate routing and allowing light-forest reconstruction do not conflict with each other when both are employed by the OP heuristic. On the contrary, they improve the performance of each other which results in a greater saving of OAs, especially when the system traffic load is high. For example, when $\Lambda = 2$ and $K = 8$, the $|OA|_2$ equals 160 OAs when the Adaptive mode is employed, which is an improvement from the 161 OAs solution achieved when $i = 1$ (for both Fixed and Adaptive schemes) and when $i = 2$ (for the Fixed scheme). This means that using more alternate paths alone did not help improve the solution quality in this case until it was accompanied by using the Adaptive mode.

  However, please note that the nature of the 6-node network as being a small network with limited number of links and nodal degrees, makes it hard to distinguish between the individual impact of each of these improvement schemes on the quality of the final solution. Such a distinction will be addressed in Subsection 5.5.2 when the results from NSFNET are presented.

- Finally, it is worth noting that because of Constraints (4.18), the ($|OA|_C$) can increase for the same number of sessions, K, when more number of channels becomes available in the system as the maximum power of each channel will decrease. For instance, $|OA|_C = 159, 160,$ and 161 for $K = 7$, while $\Lambda = 2, 3,$ and 4, respectively.

In order to complete our comparative investigation, we focus on Table 5.2 to determine the amount of resources used by the OP heuristic compared to those consumed by CPLEX. With respect to ψ, we note that the OP heuristic succeeded to use the same maximum number of wavelengths over any link in most cases (e.g., for all the cases when $\Lambda = 2$ and $K = 3$ to 6) which gives more credibility to these solutions as they are produced with similar experimental conditions as CPLEX. Interestingly, the value of ψ_i can be even less than ψ_C which is absolutely fine as it is not the objective of the MILP formulation to reduce ψ. This can happen especially when the number of available channels, Λ, is high enough with respect to the traffic load as it is the case when $\Lambda = 3$ and $K = 2$ to $K = 6$.

On the other hand, especially when the traffic load is high with respect to the number of available wavelengths, we note that the OP heuristic tends to use more wavelength channels per link than CPLEX. This is true for example when $\Lambda = 2$ and $K = 8$ and when $\Lambda = 3$ and $K = 8$ and 9. However, these extra resources are still within acceptable ranges (i.e., 1 or 2 extra wavelengths only) especially in Wide Area Network environments where the cost of adding extra channels to the system is comparatively much less than adding extra OAs.

With respect to Ł, we note that there is no direct relation between the CPLEX solutions and the OP heuristic solutions as the problem is not formulated to take this parameter into consideration. Generally, the results indicate that Ł used in both methods are comparable.

Moreover, it is important to note that ψ_i and $Ł_i$ decrease when more computation power is added to the OP heuristic. This is very significant result and will be addressed further in Subsection 5.5.2.

5.5.2 OP Heuristic Results

In this subsection, we use the NSFNET shown in Figure 1.14 to report various numerical results for the OP heuristic. In these experiments, we use two splitters placed at nodes 5 and 8, and we assume that there is no upper limit on the number of available system channels. These results address the following issues:

5.5.2.1 Impact of OP Heuristic on the Number of OAs

Figures 5.5 and 5.6 depict the impact of the OP heuristic on the number of OAs for the Fixed and Adaptive operation modes, respectively, at different traffic loads. From these figures, we find that the number of needed OAs, $|OA|$, increases as the traffic load increases. However, for each traffic load, $|OA|$ improves (i.e., decreases) as more computation power is employed. In this context, and in agreement with the results in Subsection 5.5.1, we notice that both solution improvement schemes (namely, using alternate routing and allowing light-forest reconstruction) contribute to this solution improvement in a constructive manner by joining

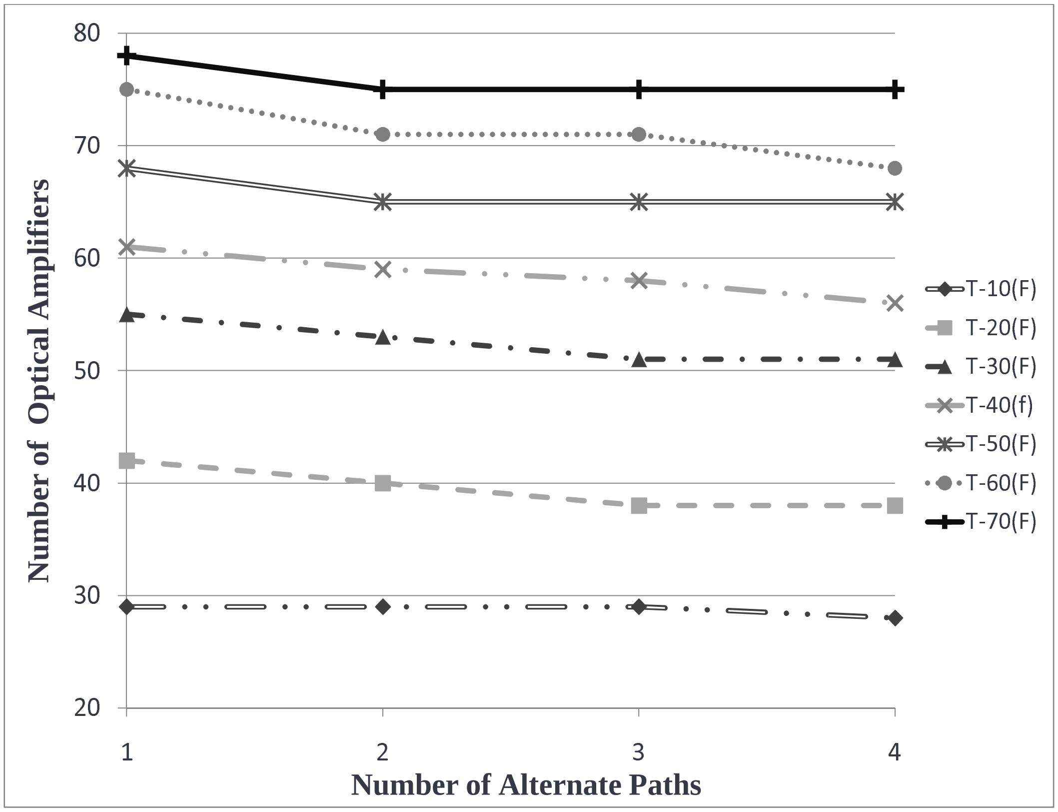


Figure 5.5 Impact of Using Alternate Routing on $|OA|$ for the Fixed Scheme at Different Traffic Loads. The notation $T - i(F)$ indicates that traffic load (T) is i sessions for the Fixed (F) scheme.

their forces together to find better solutions.

In order to illustrate this with some numerical results, we consider the case when traffic load is 40 sessions. The initial solution with minimum power computation is 61 OAs. By using more alternate paths only (i.e., using the Fixed mode), Figure 5.5 shows that the solution improved from 61 to 59, 58 and 56, when the number of alternate paths increased from 1 to 4, respectively. On the other hand, by using the Adaptive scheme only (i.e., no alternate paths), $|OA|$ drops from 61 to 56 too, as shown in Figure 5.6. Yet, more improvement could be achieved when alternate routing is employed with the Adaptive scheme and $|OA|$ drops as low as 50 OAs when 4 alternate paths are used.

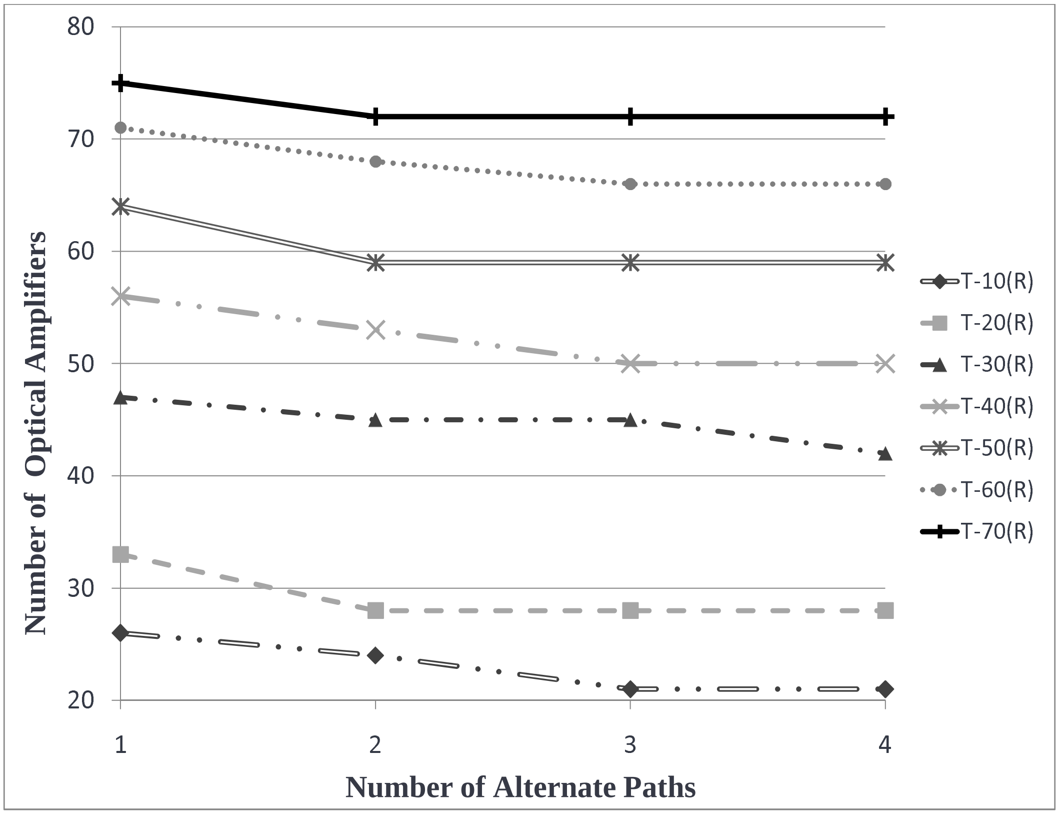


Figure 5.6 Impact of Using Alternate Routing on $|OA|$ for the Adaptive Scheme at Different Traffic Loads. The notation $T - i(R)$ indicates that traffic load (T) is i sessions for the Adaptive (or Rerouting, R) scheme.

5.5.2.2 Individual Contribution of Using Alternate Routing and Adaptive Rerouting Schemes on the Number of OAs

The results also show the relative contribution of the individual operation scheme to the solution quality. In order to demonstrate this individual contribution, we concentrate on the results obtained by applying each scheme alone in the OP heuristic. We define Δ as the difference in $|OA|$ obtained by subtracting the solution produced when alternate routing scheme with 4 paths is used alone from the solution produced when Adaptive rerouting scheme is used alone. Table 5.3 shows Δ at different traffic loads.

From Table 5.3, we can see that the values of Δ are non-negative. Therefore, the improvement achieved by using the Adaptive scheme alone is as good as or even better than

Table 5.3 The relative performance of using Adaptive method alone with respect to alternate routing at different traffic load.

Traffic load (sessions)	10	20	30	40	50	60	70
$\Delta(OAs)$	2	5	4	1	0	0	0

the solution produced by using the maximum number (i.e., 4) of alternate paths under the Fixed mode. For example, when $K = 30$, Δ equals 4 OAs as the solution obtained using the Fixed scheme with 4 alternate paths is 51 OAs while 47 OAs is obtained by using the Adaptive scheme alone.

Also, it is clear from Table 5.3 that Δ is highly affected by the network traffic load. When traffic load is small (i.e., 10 sessions), Δ is relatively small as Fixed scheme alone seems to provide a comparable solution. Adaptive scheme performs best when the traffic load is moderate (i.e., 20-30 sessions). Yet, Δ decreases with more traffic load until it becomes zero when the system traffic load is high. For example, both schemes produce the same number of OAs (i.e., 75 OAs) when traffic load is 70 multicast sessions.

Moreover, Δ is also affected by the network topology, hence, the above observations with respect to Δ do not always apply to the 6-mesh network results. For example, the Fixed scheme outperforms the alternate scheme when $\Lambda = 2$ and $K = 2$ to $K = 8$.

5.5.2.3 Impact of Using Alternate Routing and Adaptive Rerouting Schemes on the Network Resources

In this subsection, we present the amount of network resources used by each operation scheme. Figures 5.7 and 5.8 depict the values of ψ and Ł, respectively, consumed under the Fixed and Adaptive scheme at various traffic loads when the number of alternate paths is one. Similar results are obtained with more alternate paths, however, due to space limitations they are not presented here.

Generally, we find out that the Adaptive scheme has better utilization of the network resources than the Fixed scheme. Such utilization is affected directly by the traffic load. As

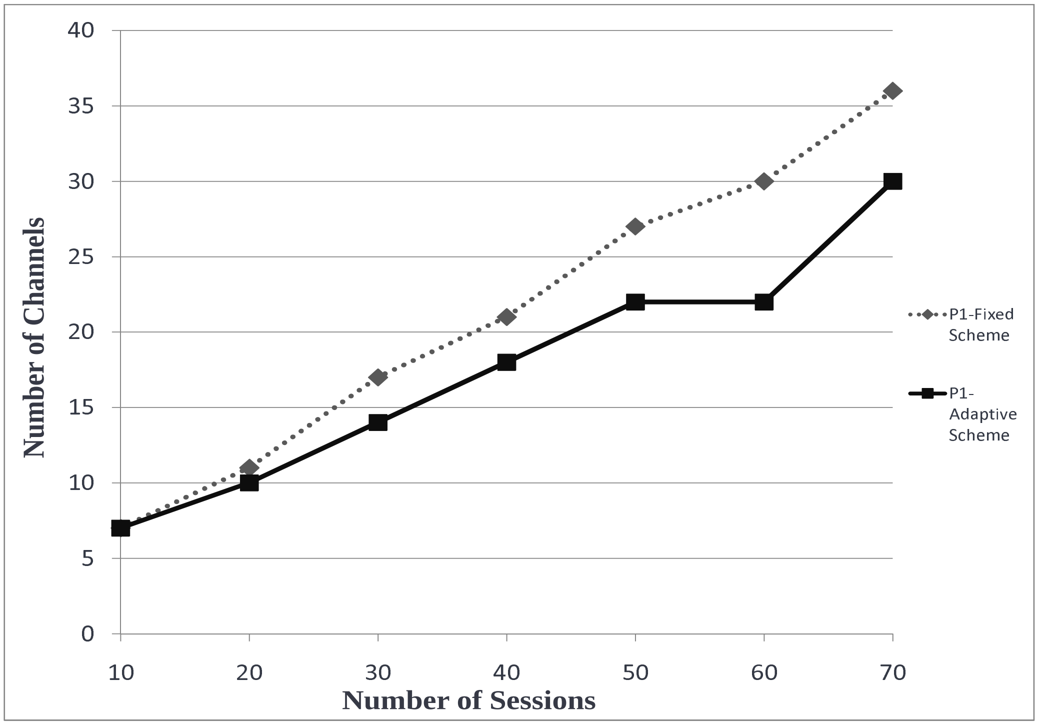


Figure 5.7 Maximum number of used channels (ψ) at different traffic loads for the Fixed and Adaptive schemes when number of alternate paths is 1.

shown by Figure 5.7, the Adaptive scheme succeeds to use fewer channels per link and the saving in ψ increases with the increase in traffic load until traffic load reaches 60 sessions. At this point, the gap in ψ between the two schemes is the maximum (i.e., 8 channels) and it then starts to decrease. This behavior can be understood with the aid of Figure 5.8 in which we see that the Adaptive scheme also consumes less Ł. However, the amount of saving in Ł between the two schemes decreases when traffic load increases. This means that the Adaptive scheme tends to use more links to accommodate more traffic which directly results in consuming less number of channels per link. This behavior continues until all the available network links (i.e., the 42 links) are used. As shown in Figure 5.8, this occurs starting when traffic load equals 60 sessions. beyond this point, the Adaptive scheme starts to utilize the available channels and the amount of saving in ψ starts to decrease.

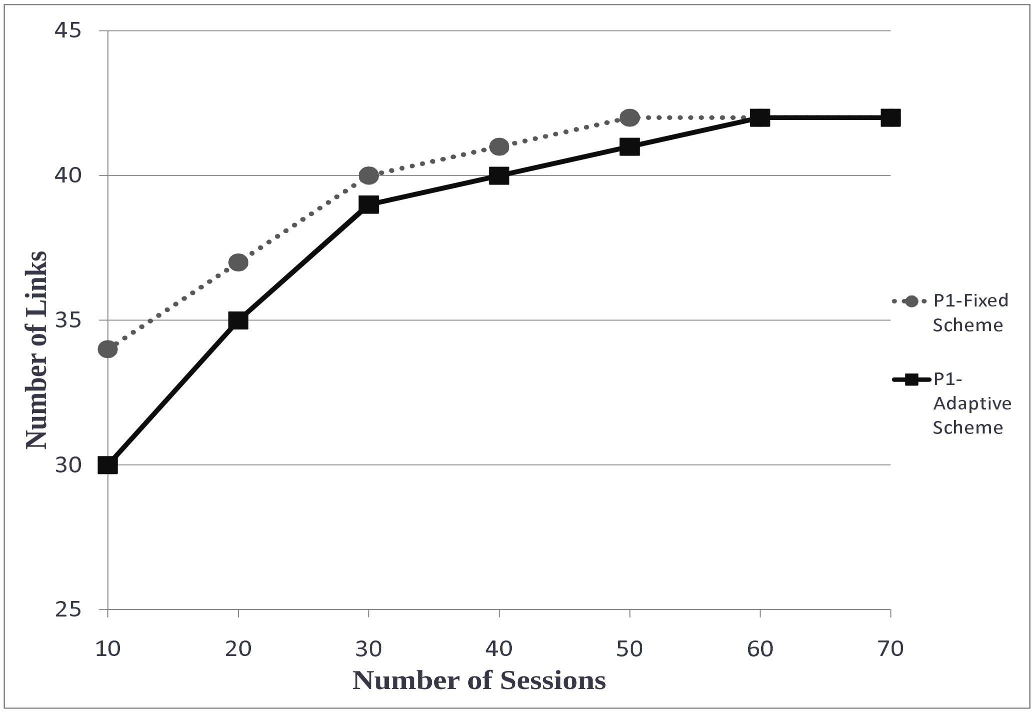


Figure 5.8 Number of used links (Ł) at different traffic loads for the Fixed and Adaptive schemes when number of alternate paths is 1.

5.5.2.4 Impact of the OP Heuristic on the Network Bandwidth Utilization

The Network Bandwidth Utilization (NBU) is computed as the total number of occupied (busy) channels used over all the network links. In Figure 5.9 we compare the NBU achieved by the Fixed and Adaptive schemes when the number of alternate paths is one at various traffic loads. However, similar results are obtained when more alternate paths are used. We note that the NBU achieved by the Adaptive scheme is always higher than the one achieved by the Fixed scheme. This result is best understood when considered in conjunction with Figures 5.7 and 5.8. In this context, we find out that while the Adaptive scheme is using less network resources in terms of ψ and Ł than the Fixed scheme, its NBU is higher. This means that the Adaptive scheme is utilizing these resources in a more efficient manner by reducing the waste due to channels fragmentation within each link.

In this context, by channels fragmentation, we refer to the case when the spectrum of available wavelengths over a link is not utilized in a consecutive fashion, which results in

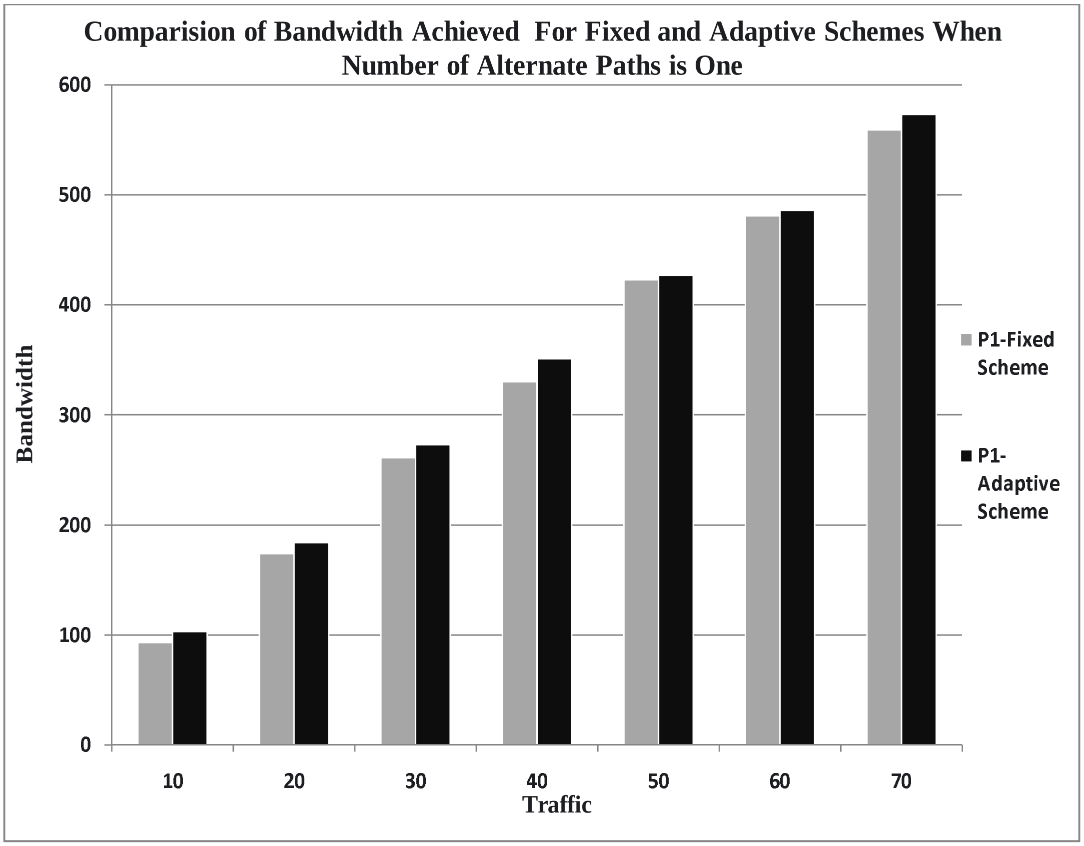


Figure 5.9 Network Bandwidth Utilization (NBU) achieved at various traffic loads by the Fixed Scheme and Adaptive Scheme when one Alternate path is used.

having gaps in the busy channels numbers. For example, consider the case when the number of available channels is 5, while only channels 1 and 4 are used. Channels fragmentation exists naturally over the link as it is a direct result of the wavelength continuity constraint and the WA scheme. However, reducing the amounts of channels fragmentation reflects positively on the bandwidth utilization of the network. This is mainly achieved in the Adaptive scheme by its ability to base its routing decisions on the most recent network status which enables it to utilize more contiguous channels per link.

After studying the impact of each operation scheme on the NBU, we finally investigate the impact of using different alternate paths on the NBU when Fixed and alternate schemes are used in Figures 5.10 and 5.11, respectively. From these figures, we find out that for each traffic

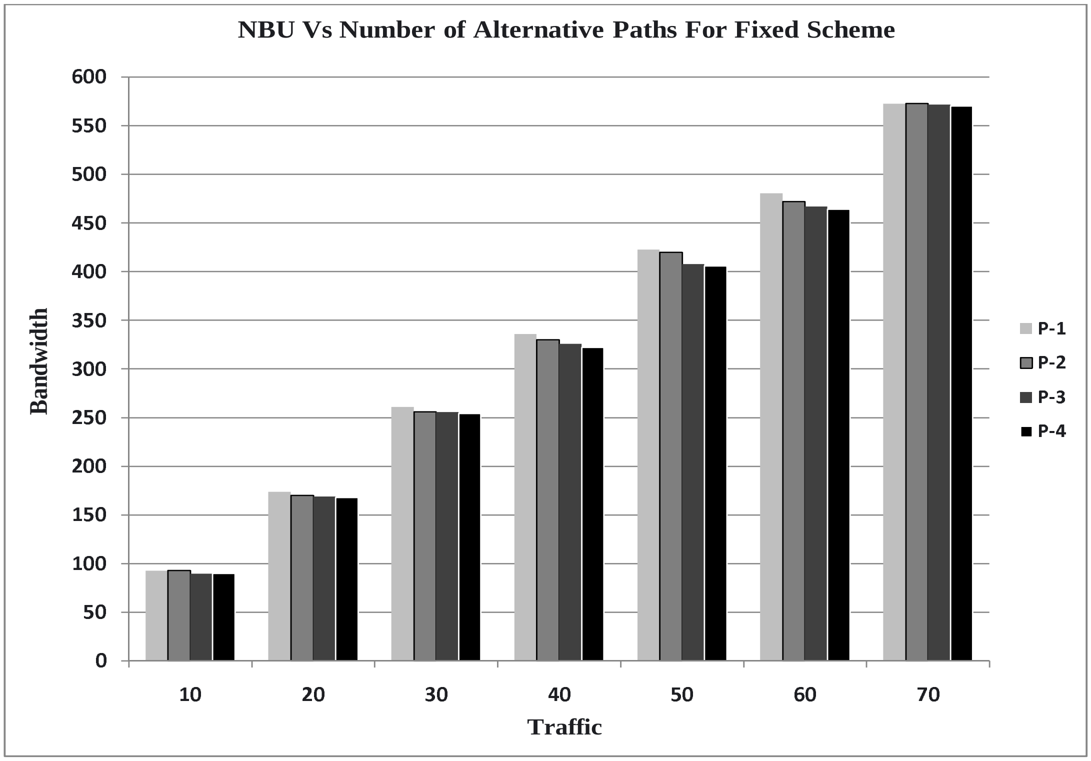


Figure 5.10 Comparison of the Network Bandwidth Utilization (NBU) achieved with different alternate paths When Fixed Scheme is used at various traffic loads.

load, the NBU decreases as the number of alternate paths increases. For example, for $K = 40$, the NBU decreases from 351 to 341 channels when number of alternate paths increases from 1 to 4, respectively. This behavior results as using more alternate path can yield to the use of less number of ψ and L resources in the network.

5.6 Chapter Summary

We studied the problem of OAP-Symmetric problem in this chapter. The motives behind our work and solution methodology are presented in Section 4.4. We proposed three schemes for solving the OAP-Symmetric. While the first scheme produces optimal solutions using MILP formulation. The other two schemes are proposed as two modes of operation for the same heuristic scheme (called the OP algorithm). We referred to these operation modes as:

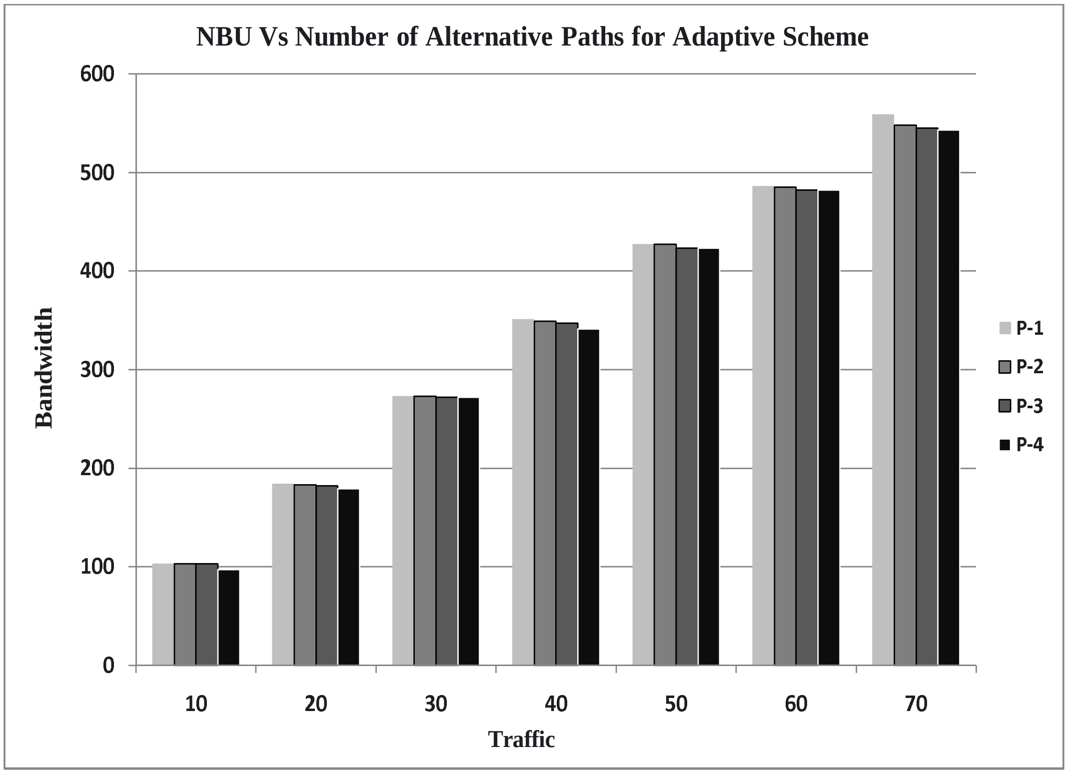


Figure 5.11 Comparison of the Network Bandwidth Utilization (NBU) achieved with different alternate paths When Adaptive Scheme is used at various traffic loads.

Fixed and Adaptive modes.

The goal of the OP algorithm is to produce fast solution without compromising the quality of the produced solutions. In order to achieve this balance between the solution quality and the consumed resource, the design the proposed algorithm is based on a set of appealing engineering and optimization characteristics. These characteristics are summarized as follows:

- The OAP-Asymmetric problem is divided into its subproblems that are solved separately.

- Although solved independently, the interdependency between these subproblems are taken into consideration to a great extend by using a set of routing cost functions that are defined in terms of OAs.

- We introduce several optimization levels at the different algorithm steps. We then use these well-defined optimization levels to determine the amount of computation needed to find the corresponding solution. This provides us a handy mechanism to study the impact of the OP algorithm at the various computation levels.

- The OP algorithm proves to be efficient in handling the management issues of the NS and NPS with minimal overhead. This is achieved by using special set of data structures, including the queue Q, that takes care of representing the network status in a very effective manner.

The results reported in this chapter is comprehensive and cover a wide range of system performance metrics. Generally speaking, these results show that the Adaptive scheme outperforms the Fixed scheme, in terms of both the number of OAs and the network resources, and it achieves better utilization of the network resources. However, this performance comes at the cost of extra computations. Such extra computation can be tolerated, especially that the problem at hand is a design problem, and taking more time to find a solution is mostly fine if it will result in saving more OAs, hence more money for the designers.

CHAPTER 6. Power Aware Multicasting (PAM) in Wavelength Routing Networks

6.1 Introduction

We focus in this chapter on the impact of power loss on the network operation under AOM traffic. We identify and formulate this problem as a connection provisioning problem, which is an optimization problem to find the best network operational strategy. In our study here, the performance of the network operation is measured by the ability of the proposed solution to minimize the number of dropped (blocked) sessions.

Like the OAP problem discussed in Chapters 3-4, the classical problem of Routing and Wavelength Assignment (RWA) [8] has a fundamental role in the network operation. However, due to its lack of consideration for any practical issues that are related to all-optical services, not all the solutions produced from the classical RWA are feasible in practice. Therefore, in our study here, the RWA is extended to include more realistic constraints which make it more complicated. One of these constraints is the power impairments, which include the: Optical Amplifiers (OAs) gain model, power loss and noise. In order to reduce the complexity of our study, we focus in this chapter on the impact of OA gain model and power loss only without considering the noise issues. This extension introduces a new dimension to the classical RWA problem, namely, the power dimension. We refer to this problem extension as Power-Aware RWA (PA-RWA) problem and we formally define it as follows:

PA-RWA Problem Definition: "*Given the network topology, the static multicast traffic demand matrix, the number and locations of the splitters and OAs, number of wavelengths, the Power-Aware Routing and Wavelength Assignment (PA-RWA) problem under AOM is defined* *as a connection provisioning problem that aims to find a feasible route (in the form of a light-forest) and a wavelength assignment for the maximum number of multicast sessions in order to minimize the connection blocking rate.*".

There are many of similarities between the OAP and the PA-RWA problems. First, the PA-RWA problem can be investigated in two system configurations based on the power symmetry assumption, namely, under equal and unequal power constraints. In our study here, we assume the asymmetric system configuration only where the symmetric system configuration needs separate investigation. Second, these problems share the same set of RWA and power constraints. Hence, some of these constraints are reused in our solutions here in this chapter.

However, unlike the OAP problem, the PA-RWA has its own aspects and challenges that distinguishes it from the OAP problem. This distinction is due to the fact that the PA-RWA problem is a network operation problem while the OAP is a design problem. Therefore, the PA-RWA problem has to deal with an existing network that is already provisioned and it is unlikely to be upgraded or modified. This situation forces the network operator to handle the RWA and power aspects differently than the network designer. These differences include, but not limited to, the following situations:

- The solution to the PA-RWA problem has to deal with a set of traffic that is (most likely) different than the one used to design the network. This mismatch in traffic demands can result in not satisfying all the constraints used in provisioning the network and might result in dropping some of these traffic demands.
- The objective function of the PA-RWA problem is different than that of the OAP problem as the goal of the network operator is to best utilize this network by dropping the least possible number of connections.
- Under OAP problem, the OA placement policy does not play a decisive factor in specifying the number of OAs over the link. This number is determined mainly by the total gain needed over the link and the input power values to the link. Therefore, the same number of OAs over a link can be placed differently using different OA placement poli-

cies. However, this policy becomes an important factor in determining the feasibility of the solutions for the PA-RWA problem as it determines the location of the OAs over the links, which in turn determines whether or not the power constraints are met. For example, using the ALAP placement policy might place the first OA further away from the beginning of the link compared to the ASAP policy. Therefore, if the input power to the link is weak, it has better chance to reach the first OA to get amplified if the ASAP policy is used, assuming all other power constraints are met.

- The OAP problem is solved without allowing any kind of connection blocking as the network is required to be provisioned for certain set of traffic demands. On the other hand, the PA-RWA problem has to deal with different types and sources of connection blocking. Some of these blocking sources are related to the shortage of network resources, while others are related to the power constraints. In our treatment, we tackle all the potential blocking sources and we investigate how these blocking sources impact the system performance.

In this chapter, we follow the same solution strategy we adopted in tackling the OAP problem. We first formulate the PA-RWA problem as a MILP with the objective of minimizing the total number of blocked sessions. While producing the optimal solutions, the MILP solutions are not fast and not scalable for large instances of the problem. Therefore, a greedy heuristic that provides fast and near optimal solutions for the PA-RWA problem is then introduced. The algorithm operation is based on creating a connection between the tree construction and power assignment. This connection is achieved using a special set of power-related cost functions for the links and sessions that are used for make the appropriate routing decisions.

The contribution of the work done in this chapter is summarized as follows[1]:

- The MILP formulation solves the combined subproblems of the PA-RWA problem in a jointly manner. These subproblems are the: Routing (R), Wavelength Assignment (WA)

[1]Although we are handling two different problems, some of these contributions presented here are similar to the ones presented in Chapter 3 for the OAP problem. This similarity in contributions is basically due to the fact that we are following the same methodology strategy in these works, namely, finding practical solutions that are fast without compromising the solution quality.

and Power Assignment (PA) subproblems. To the best of our knowledge, this is the first attempt to solve the power extension of the RWA problem using MILP scheme. Other MILP formulations reported in the literature are investigating the RWA problem under unicast traffic and without considering the power constraints. Please refer to [8] for more details on this subject. On the other hand, the PA-RWA problem was also formulated in the context of unicast traffic in [42] using the more complicated MInLP formulation.

- Like the OAP problem, the PA-RWA problem is nonlinear. The main source of the nonlinearity of the problem is the computations of the splitting power loss, OA gain, and the total power over the link. Nevertheless, we provide a linear formulation of the problem using a special set of mapping techniques to convert the nonlinear constraints into linear counterparts. In this context, we use the same mapping scheme we used earlier in Chapters 4 and 5 for computing the splitting power loss. However, in order to determine the gain of an OA and the total power over a link, we propose a novel set of mapping techniques that will be explained in the sequel.

- The set of heuristic solutions we present in solving the PA-RWA problem proves to provide fast solutions that are of good quality when compared to the optimal solutions. The operation of these heuristics is based on using a set of cost functions for the links and sessions that are able to capture the dependencies between the different subproblems. This allows the algorithm to work efficiently by solving these subproblems separately while taking the impact of each subproblem on the others.

- We incorporate the impact of the OA gain model in determining the gain of the individual OA in our MILP and heuristic solutions. Such consideration was either ignored [29] or abstracted with very constrained conditions [52] in most of the other efforts reported in the literature that handle the PA-RWA problem. In this context, an iterative heuristic was proposed in [29] in which an initial tree is constructed without taking any power constraint into consideration. This tree is then modified by replacing a set of adjacent splitters by a single splitting node, called the Centralized Splitting Node, in order to reduce the total amount of power loss. On the other hand, the heuristic algorithm that is proposed in [52] is based on constructing balanced light-trees in order to ensure a minimum signal quality and fairness among all destinations. An exception of this situation is the scheme proposed in [42] in which a two-phase hybrid solution employing a greedy heuristic and Genetic Algorithm for session establishment and power assignment was introduced.

- The results reported in this chapter provide a comprehensive coverage of the various system performance aspects under different experimental conditions. In addition, they provide good guidelines for the network operators, as well as designers, in determining the best choices for network upgrades.

The remainder of this chapter is organized as follows. The next section introduces the system model and assumptions which is followed by the MILP formulation details in Section 6.3. The details of the proposed heuristic are then presented in Section 6.4. The numerical results are reported in Section 6.5 and we finally conclude the chapter in Section 6.6.

6.2 Additional System Model Assumptions

In this chapter, we use the same system model described in Section 1.6. However, we use the piece-wise model for the OA gain which is determined by equation 1.2. Moreover, the network is pre-provisioned; therefore, the number and placement of the OAs is pre-determined and known. Also, using the notation introduced in Section 2.2.1, our system model is characterized as $S^sF^cR^x$-C^n. Also, our study does not consider partial destination delivery of the multicast session. Therefore, a session is accepted if and only if all members in its destination set are reached by the light-forest.

6.3 MILP Problem Formulation

In this section, we present the MILP formulation for the PA-RWA problem. We introduce the network parameters and the formulation variables, in subsections 6.3.1 and 6.3.2, respectively. The objective function and formulation constraints are then presented in subsection 6.3.3. Although some of these variables and constraints are shared with the previous formulation, we present them here for the sake of completeness and ease reference.

6.3.1 Network Parameters

The following network parameters are used in the MILP formulation:

N	The set of nodes in the network.
E	The set of fiber links in the network.
Λ	The set of wavelengths supported per fiber.
i, j, k	Node identity, where $i, j, k \in N$.
λ	Wavelength identity, where $\lambda \in \Lambda$.
$e(i, j)$	Fiber link directed from node i to node j.
$OA_{i,j}$	The set of optical amplifies on fiber $e(i, j)$.
$NOA_{i,j}$	Binary indicator: 1 if $\lvert OA_{i,j}\rvert > 0$; 0 otherwise.
o	OA identity on $e(i, j)$;$1 \leq o \leq \lvert OA_{i,j}\rvert$.
x, y	Optical component identity on $e(i, j)$;$0 \leq x \leq \lvert OA_{i,j}\rvert$ and $1 \leq y \leq \lvert OA_{i,j}\rvert + 1$. $x = 0$ and $y = \lvert OA_{i,j}\rvert + 1$ are source(i) and sink(j) nodes.
SP	The set of splitters.
SP_i	Binary indicator: 1 if node i is a splitter.
β	Propagation loss ratio.
γ	Tapping power loss value at each node.
$L_{i,j}$	Length (Km) of fiber $e(i, j)$.
$L_{i,j}^{x,y}$	Length (Km) between x and y of $e(i, j)$.
K	Number of multicast sessions.
a	Multicast session identity; $0 \leq a \leq K - 1$.

src_a	Multicast session source node.
D_a	Multicast session destination set.
Φ_i	Set of sessions in which node i is a destination.
Γ_i^a	Binary indicator: 1 if $i \in D_a$; 0 otherwise.
P_{Sen}^{dBm}	Minimum detectable power (dBm) level on a channel by a receiver or an OA.
P_{MAX}^{dBm}	Maximum power (dBm).
P_{Max}^{mW}	Maximum aggregate power (mW) on a link.
P_{Min}^{mW}	Minimum power (mW).
P_1, P_2	Two negative constants that are used to represent the case of $(-\infty)$ dBm, such that $P_1 < P_2$.
δ	Very small number used for mapping purposes.
v, w	Integer constants, such that $v > w$.
Out_i	Out degree of node i.
M	Very large number.

6.3.2 MILP Variables

The following variables are used in the MILP formulation:

R	Auxiliary terms used in the objective function.
W_1, W_2	Weights of objective function terms; $W_1 \gg W_2$.
$T_{i,j}^{a,\lambda}$	Binary indicator: 1 if $e(i,j)$ is used by session a over λ; 0 otherwise.
φ_a	Binary indicator: 1 if session a is carried out in the network; 0 otherwise.
ϑ_i^a	Binary indicator: 1 if node i is included in the light-tree of session a; 0 otherwise.
$\Im_{i,j}^a$	Binary indicator: 1 if $e(i,j)$ is used by session a over any wavelength; 0 otherwise.

$\Upsilon_{i,j}$ Binary indicator: 1 if $e(i,j)$ is used by any session over any wavelength; 0 otherwise.

$G^{o}_{i,j}$ Value of the amplification gain required from the o^{th} optical amplifier on fiber $e(i,j)$.

$H^{a,\lambda}_{i}$ Number of hops of the path between the source node of session a and node i over channel λ.

$SL^{a,\lambda}_{i}$ Splitting loss on channel λ at node i for a.

Ω Power inspection site; $\Omega \in \{beg, end\}$.

$P^{\Omega,a,\lambda}_{i,j,dBm}$ Power level (dBm) at beginning ($\Omega = beg$)/end ($\Omega = end$) of $e(i,j)$ for λ used by session a.

$P^{beg,a,\lambda,o}_{i,j,mW}$ Power level (mW) at beginning of o^{th} OA on $e(i,j)$ for wavelength λ used by session a.

$TP^{beg}_{i,j,mW}$ Total power (mW) at beginning of $e(i,j)$.

$TP^{beg,o}_{i,j,mW}$ Total power (mW) at entry of o^{th} OA on $e(i,j)$.

f Tree fanout; number of outgoing tree links.

A_f Binary indicator for power splitting linearization.

$AP^{o}_{i,j}$ Binary indicator for OA gain linearization.

y A linear equation instance.

Y Set of linear equations that are selected for unit conversion between mW and dBm/dB.

6.3.3 MILP Formulation

The objective function is to minimize the number of blocked sessions in the network, and is expressed as follows:

$$Minimize: \quad -W_1 \sum_{a} \varphi_a + W_2 R \tag{6.1}$$

where:

$$R = \sum_{e(i,j)\in E} \sum_{o\in OA_{i,j}} \sum_{a=0}^{K-1} \sum_{\lambda\in\Lambda} TP^{beg,a,\lambda,o}_{i,j,mW} + \sum_{e(i,j)\in E} \sum_{o\in OA_{i,j}} G^{o}_{i,j} \tag{6.2}$$

The rationale behind computing the auxiliary variable, R, in the objective function is to simplify the determination of the correct values of the total power per link and the OA gain variables, as will be shown below. The weight constant W_2 is chosen such that its value is much less than W_1. This is essential in order to ensure that the contribution of R to the value of objective function is much less than that of the number of admitted sessions.

Like the OAP problem, the objective function for the PA-RWA is subject to a set of constraints, which are discussed below:

6.3.4 Routing and Wavelength Assignment Constraints

The construction of the light-forest and its wavelength(s) assignment are determined by the following constraints:

$$\varphi_a \leq \sum_{i,i \in D_a} \frac{\vartheta_i^a}{|D_a|} \quad 0 \leq a < K \tag{6.3}$$

$$\varphi_a \geq \sum_{i,i \in D_a} \vartheta_i^a - (|D_a| - 1) \;\; 0 \leq a < K \tag{6.4}$$

The above constraints compute φ_a as the conjunction between all ϑ_i^a variables of session a's destination nodes. They guarantee that the session, a, is accepted if all its destinations are part of the session's light-forest.

$$\vartheta_i^a \geq \sum_{j,j \neq i, e(j,i) \in E} \sum_{\lambda \in \Lambda} \frac{T_{j,i}^{a,\lambda}}{M} \;\; \forall i \in N; 0 \leq a < K \tag{6.5}$$

$$\vartheta_i^a \leq \sum_{j,j \neq i, e(j,i) \in E} \sum_{\lambda \in \Lambda} T_{j,i}^{a,\lambda} \;\; \forall i \in N; 0 \leq a < K \tag{6.6}$$

Constraints (6.5) and (6.6) set ϑ_i^a to the disjunction between all $T_{j,i}^{a,\lambda}$ variables, for all incoming links from the neighbor nodes j of node i over all wavelengths. They indicate that node i is part of sessions a's light-forest if it is part of at least one of its light-trees variables.

$$\Im_{i,j}^a \geq \sum_{\lambda \in \Lambda} \frac{T_{i,j}^{a,\lambda}}{M} \;\; \forall i,j \in N; 0 \leq a < K \tag{6.7}$$

$$\Im_{i,j}^a \leq \sum_{\lambda \in \Lambda} T_{i,j}^{a,\lambda} \;\; \forall i,j \in N; 0 \leq a < K \tag{6.8}$$

Constraints (6.7) and (6.8) are used to determine if link $e(i,j)$ is used by session a by setting $\Im_{i,j}^{a,}$ to 1 if at least one of its tree link is used over $e(i,j)$ using any wavelength. This is achieved by computing $\Im_{i,j}^{a,}$ as the disjunction between all the tree links variables of session a that uses link $e(i,j)$ (i.e., $T_{i,j}^{a,\lambda}$) over all the wavelengths.

$$\Upsilon_{i,j} \geq \sum_{a=0}^{K-1} \frac{\Im_{i,j}^{a}}{M} \quad \forall e(i,j) \in E \tag{6.9}$$

$$\Upsilon_{i,j} \leq \sum_{a=0}^{K-1} \Im_{i,j}^{a} \quad \forall e(i,j) \in E \tag{6.10}$$

Similar to Constraints (6.7) and (6.8), constraints (6.9) and (6.10) set $\Upsilon_{i,j}$ to the disjunction between all $\Im_{i,j}^{a}$ variables, for all the sessions. They ensure that link $e(i,j)$ is used if it is used by at least one session.

$$\frac{\Gamma_i^a + \sum_{\lambda \in \Lambda} \sum_{k,k \neq i, e(i,k) \in E} T_{i,k}^{a,\lambda}}{M} \leq \sum_{k,k \neq i, e(k,i) \in E} T_{k,i}^{a,\lambda} + (1 - \varphi_a) \times M$$
$$\forall i \in N/\{src_a\}; 0 \leq a < K \tag{6.11}$$

The above constraints are used to create the light-forest per session by ensuring the connectivity of each of its destination. In a nutshell, this is achieved by guaranteeing that there should be at least one incoming link to node i if it is a destination or it has one outgoing link. This condition is fulfilled only when session a is accepted, i.e., $\varphi_a = 1$. For example, if node i is a destination and/or it has multiple outgoing links, then the left-hand side of the constraints becomes positive. Due to the use of the large constant, M, the left hand side is a positive fraction that is less than 1. In order for the constraints to be satisfied, the right hand side of the constraints, namely, the number of incoming links should be at least 1, if $\varphi_a = 1$.

Please note that these constraints have the same goal as the constraints defined by equation (4.6). However, the constraints defined in (4.6) cannot be used here as they do not consider the situation when the session is blocked.

$$\sum_{k,k \neq i, e(k,i) \in E} T_{k,i}^{a,\lambda} \leq 1 \qquad \forall i \in N/\{src_a\}; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.12}$$

Constraints (6.12) help preventing loops on the light-forest of session a on wavelength λ by preventing traversing any node more than once. These constraints are similar to the ones defined in (4.7).

$$\sum_{0 \leq a < K, e(k,i) \in E} T_{i,j}^{a,\lambda} \leq 1 \quad \forall i,j \in N; i \neq j; \forall \lambda \in \Lambda \tag{6.13}$$

These constraints guarantee that $e(i,j)$ is used by at most one light-tree over wavelength λ for each session. This guarantees the data integrity and correctness over each link by avoiding using the same channel over the same link by multiple sessions. These constraints are similar to the ones defined in (4.8).

$$\sum_{j,i\neq j,e(i,j)\in E} T^{a,\lambda}_{i,j} \leq 1 \qquad \forall i \in N/\{src_a\}; i \notin SP; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.14}$$

Constraints (6.14) prevent branching at MI nodes by ensuring that any MI node, say i, has at most one outgoing tree link over a particular wavelength.

$$\sum_{j,j\neq i,e(j,i)\in E} T^{a,\lambda}_{j,i} \geq \sum_{k,k\neq i,e(i,k)\in E} \frac{T^{a,\lambda}_{i,k}}{M} \qquad \forall i \in N/\{src_a\}; 0 \leq a < K \tag{6.15}$$

Constraints (6.15) are similar to the constraints defined in (4.10) and are used to guarantee the wavelength continuity for each session. This achieved by ensuring node i should have an incoming tree link over wavelength λ if node i has at least one outgoing link employing the same wavelength.

6.3.5 Loop-Avoidance Constraints

We use the same hop counting scheme we introduced earlier in Subsection 5.3.2 to prevent any loop in the constructed light-forests. Please refer to that subsection for the full details of the following constraints:

$$H^{a,\lambda}_{src_a} = 0 \qquad 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.16}$$

$$1 - \Im^{a}_{i,j} - \frac{H^{a,\lambda}_{i} + 1 - H^{a,\lambda}_{j}}{M} \geq 0 \qquad \forall e(i,j) \in E; 0 \leq a < K \tag{6.17}$$

$$\Gamma^{a}_{i} + \frac{H^{a,\lambda}_{i} - (|N| - 1)}{M} \leq 1 \quad \forall e(i,j) \in E; 0 \leq a < K \tag{6.18}$$

6.3.6 Power Constraints:

The following constraints we present here in this subsection address the power constraints and OA gain model:

$$P^{beg,a,\lambda,o}_{i,j,dBm} \geq P^{dBm}_{Sen} \times T^{a,\lambda}_{i,j} + P_1 \times (1 - T^{a,\lambda}_{i,j}) \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda; \forall o \in OA_{i,j} \tag{6.19}$$

$$P_{i,j,dBm}^{end,a,\lambda} \geq P_{Sen}^{dBm} \times T_{i,j}^{a,\lambda} + P_1 \times (1 - T_{i,j}^{a,\lambda}) \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.20}$$

These constraints ensure that the power level at specific power inspection sites is above P_{Sen}^{dBm} if the link is used by the light-forest. These inspection sites include: the beginning of each OA, as well as the end of each optical fiber. Maintaining this condition at these sites is sufficient to ensure that this lower bound is met everywhere in the network. This can help in reducing the formulation complexity by avoiding unnecessary calculations. Please note that these constraints also ensure that these power values are greater than P_1 if the link is not used by the light-forest. The significant of these conditions will be clear when they are used along with constraints (6.21) below.

$$P_{i,j,dBm}^{beg,a,\lambda} \leq P_2 \times (1 - T_{i,j}^{a,\lambda}) \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.21}$$

Constraints (6.21) ensure that the power level at the beginning of each link is less than P_2 if the fiber is not used as a tree link. In order to understand the important of these constraints, please note that the values of P_2 and P_1 are chosen to be much less than any power loss in the network such that $P_2 > P_1$. Therefore, these constraints are used along with constraints (6.19) and (6.20) to guarantee that the power values are very small (as it typically lies between P_1 and P_2) everywhere in the unused channels of each fiber.

$$TP_{i,j,mW}^{beg} \leq P_{MAX}^{mW} \times \Upsilon_{i,j} + P_{MIN}^{mW} * (1 - \Upsilon_{i,j}) \qquad \forall e(i,j) \in E; 0 \leq a < K; \forall e(i,j) \in E \tag{6.22}$$

The above constraints are used to ensure that the aggregate power level at the beginning of each fiber is below the P_{MAX}^{mW} threshold if the link is used by any session; and P_{MIN}^{mW} otherwise. Since P_{MIN}^{mW} is zero, we can remove the second term in the right-hand side of the inequality. Also, there is no need to extend this constraint to every OA since ensuring this upper bound at the beginning of the link guarantees that the total input power at the first OA cannot exceed P_{MAX}^{mW}. The OA gain model expressed by equation (1.2) guarantees that the output power from the OA does not exceed this upper bound too.

Please note that the aggregate power values at the beginning of the links are expressed in mW while the individual channel powers are expressed in dBm. In order to convert between these two units, the following relation needs to be implemented in the formulation:

$$P_{i,j,mW}^{beg,a,\lambda,o} = 10^{\frac{P_{i,j,dBm}^{beg,a,\lambda,o}}{10}} \quad \forall e(i,j) \in E; \forall \lambda \in \Lambda; 0 \leq a < K; \forall o \in OA_{i,j} \tag{6.23}$$

Unfortunately, this relation is non-linear. Therefore, we design a special set of linear constraints that are equivalent to (6.23). These constraints take the following format:

$$P_{i,j,mW}^{beg,a,\lambda,o} \geq A_y P_{i,j,dBm}^{beg,a,\lambda,o} + B_y \quad \forall e(i,j) \in E; \forall \lambda \in \Lambda; 0 \leq a < K; \forall y \in Y; \forall o \in OA_{i,j} \tag{6.24}$$

The idea is to define a set, called Y, of piece-wise linear segments such that each segment is represented by a linear equation, called y, whose value is greater than the non-linear curve of the relation defined in (6.23) over a specific period denoted by $Z_y = [\alpha_y, \beta_y]$. Z_y determines the mathematical domain over which y is defined. In order to guarantee the correct representation of these segments, the following conditions must be satisfied:

1. $Z = \bigcup_{y \in Y} Z_y = [P_{Sen}^{dBm}, P_{MAX}^{dBm}]$
2. $\alpha_y = \beta_{y-1} \;\; \forall y \in Y, \alpha_y \neq P_{Sen}^{dBm}$
3. $\beta_y = \alpha_{y+1} \;\; \forall y \in Y, \beta_y \neq P_{MAX}^{dBm}$

The first condition states that the union of the domains of the individual segments should equal the total domain over which relation (6.23) is defined (namely, $[P_{Sen}^{dBm}, P_{MAX}^{dBm}]$). The second condition states that the first value in function y's domain equals to the last value in the previous function's domain except for the first segment since its value should equal P_{Sen}^{dBm}. Similarly, the third condition ensure the last value in function y's domain equals to the first value in the next function's domain except for the last segment since its value should equal P_{MAX}^{dBm}. The last two conditions ensure that the total domain is represented in full by the individual segments.

As long as these conditions are satisfied, any set Y can be defined over any sub-domains. Trivially, the number of individual segment, i.e. $|Y|$, determines the accuracy of this approximation and can reflect on the formulation complexity. To help understanding the idea behind this approximation, please refer to Figure 6.1 which depicts an example of this setting such

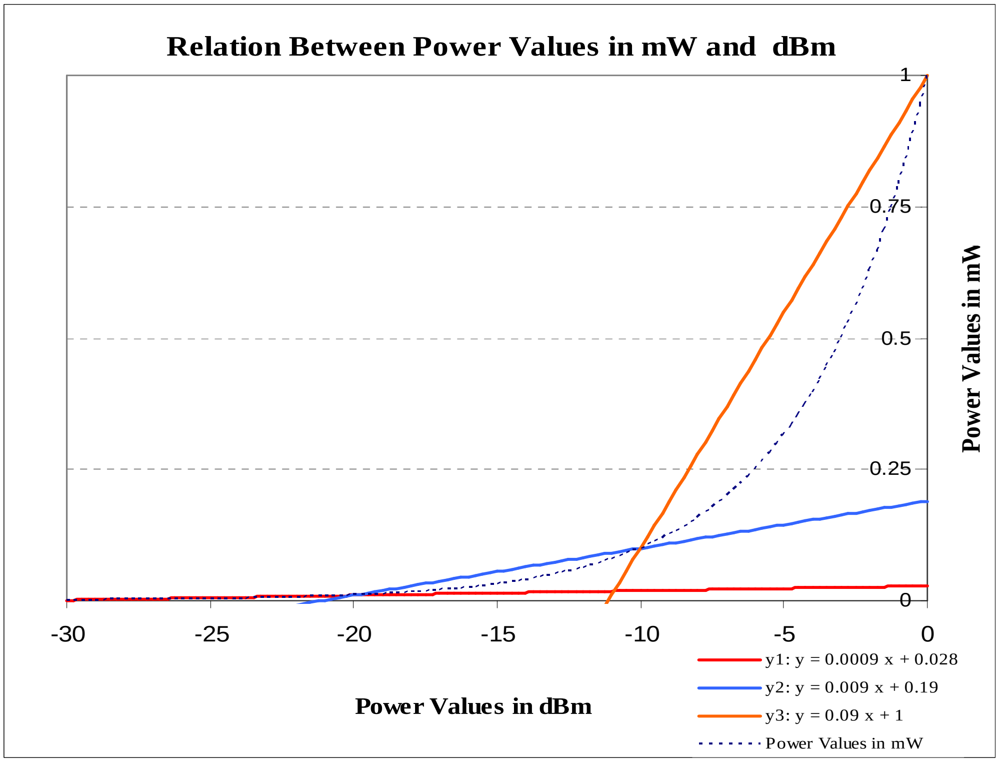


Figure 6.1 An illustration of the approximate linear conversion approach between power levels in dBm and mW.

that $|Y| = 3$ and $Z = \{[-30, -20], [-20, -10], [-10, 0]\}$. Assume that the power value that needs to be converted is -5 dBm. The corresponding values computed from y_1, y_2 and y_3 are 0.0235 mW, 0.145 mW and 0.55 mW, respectively. Constraints (6.24) ensure that the corresponding mW value is not less than the maximum value computed from the y's (i.e., the one that corresponds to y_3 in this case). With the assistance of the objective function defined in (6.1), the power value in dBm is successfully mapped to the exact value of the maximum power value. Please note that the convex nature of relation (6.23) ensures that exactly one function will have the maximum value within each domain. This function corresponds to the function that is used to represent this segment.

Also, it is worth mentioning that the power value in mW computed by the constraints defined by (6.24) may exceed the correct value. For example, while -5 dBm corresponds to 0.55 mW using y_3, the exact value is $0.316 mW$ using the relation (6.23). However, this is still acceptable and will result in correct operation since the purpose of this conversion is to only ensure that the total power on the fiber is not exceeded, as shown below.

$$TP^{beg}_{i,j,mW} = \sum_{\lambda \in \Lambda} \sum_{a=0}^{a=K-1} P^{beg,a,\lambda}_{i,j,mW} \qquad \forall e(i,j) \in E \tag{6.25}$$

$$TP^{beg,o}_{i,j,mW} = \sum_{\lambda \in \Lambda} \sum_{a=0}^{a=K-1} P^{beg,a,\lambda,o}_{i,j,mW}$$
$$\forall e(i,j) \in E; \forall o \in OA_{i,j} \tag{6.26}$$

Constraints (6.25) and (6.26) calculate the total power in mW at the beginning of every fiber and OA, respectively, as the sum of the power values in mW of the individual channels.

$$P^{beg,a,\lambda,1}_{i,j,dBm} = P^{beg,a,\lambda}_{i,j,dBm} - \beta \times L^{0,1}_{i,j} \qquad \forall e(i,j) \in E; \forall o \in OA_{i,j}; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.27}$$

$$P^{end,a,\lambda}_{i,j,dBm} = [(1 - NOA_{i,j}) \times (P^{beg,a,\lambda}_{i,j,dBm} - \beta \times L_{i,j})] +$$
$$[NOA_{i,j} \times (P^{beg,a,\lambda,|OA_{i,j}|}_{i,j,dBm} +$$
$$G^{o}_{i,j} - \beta \times L^{|OA_{i,j}|,|OA_{i,j}|+1}_{i,j})]$$
$$\forall e(i,j) \in E; \forall o \in OA_{i,j}; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.28}$$

$$P^{beg,a,\lambda,o+1}_{i,j,dBm} = P^{beg,a,\lambda,o}_{i,j,dBm} + G^{o}_{i,j} - \beta \times L^{o,o+1}_{i,j} \qquad \forall e(i,j) \in E; \forall o \in OA_{i,j}; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.29}$$

The set of constraints (6.27 - 6.29) determine the power relation between the various optical components over each link. The constraints in (6.27) find the relation between the power at the beginning of the first OA and the beginning of the fiber link where the power decays due to propagation loss only. Equations (6.28) are used on link $e(i,j)$ to express the power strength on wavelength λ at the end point of the link in terms of the power strength at the beginning of the link and the loss due to attenuation in the whole fiber length when $|OA_{i,j}| = 0$. However, if $|OA_{i,j}| > 0$, the power level at the link end is computed in terms of the power at the beginning of the last OA, its gain and the loss due to attenuation in the last fiber segment. Finally, the set of constraints (6.29) find the relation between the power at the beginning of an OA and the beginning of the previous one on the same fiber link in terms of its gain and the power attenuation in the fiber segment between the two consecutive OAs.

$$(1 - T^{a,\lambda}_{i,j}) \times v + P^{end,a,\lambda}_{i,j} - SL^{a,\lambda}_{j} - \gamma \geq (1 - T^{a,\lambda}_{j,k}) \times w + P^{beg,a,\lambda}_{j,k}$$
$$\forall e(i,j), e(j,k) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.30}$$

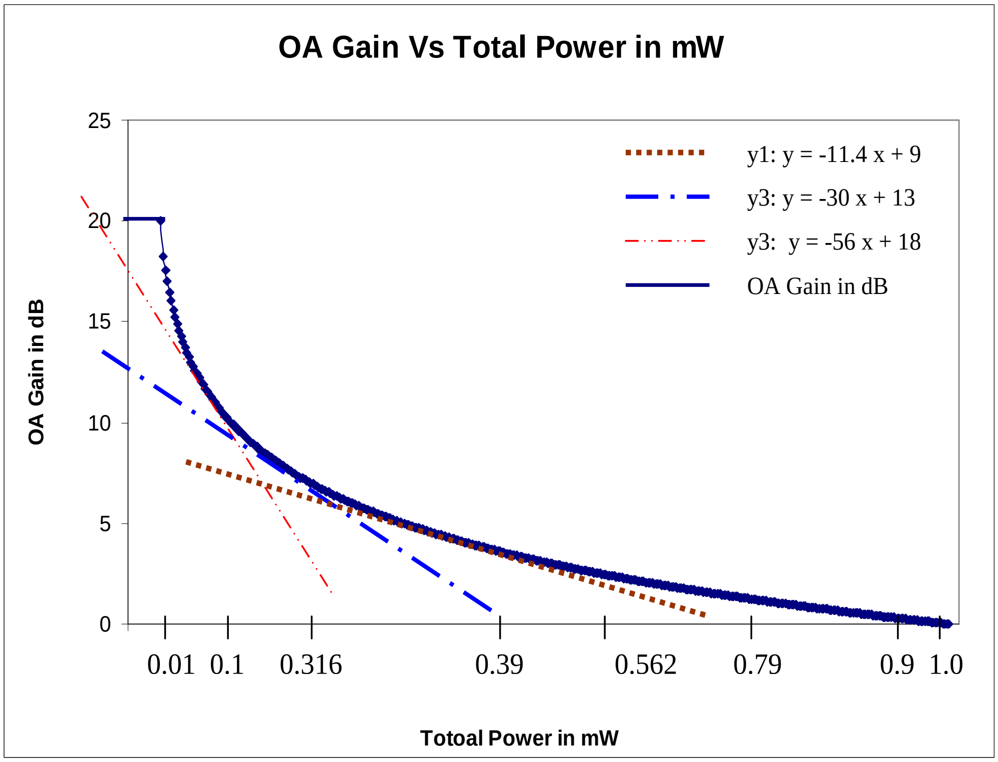


Figure 6.2 An illustration of the approximate linear conversion approach between total input power of OA in mW and the OA gain in dB.

$$(1 - T_{i,j}^{a,\lambda}) \times w + P_{i,j}^{end,a,\lambda} - SL_j^{a,\lambda} - \gamma \leq (1 - T_{j,k}^{a,\lambda}) \times v + P_{j,k}^{beg,a,\lambda}$$

$$\forall e(i,j), e(j,k) \in E; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.31}$$

Constraints (6.30) and (6.31) relate the power values at the end of a fiber link, say $e(i,j)$ and the beginning of the following link, say $e(j,k)$, if any. These constraints behave similar to the constraints defined earlier in (4.20) and (4.21).

In addition, we use another mapping scheme to compute the OA gain (in dB), from the total power (in mW) computed at the entry point of the OAs. The relation used in this mapping is shown in Figure 6.2. Unlike the previous mapping shown in Figure 6.1, the set of linear equations used in this approximation are chosen such that the resulting value is less than the actual gain value (the dashed lines in Figure 6.2). Since OAs can operate under saturation region, this creates two different operating zones for the OA which makes it harder to implement such mapping. To overcome this difficulty, we use the binary variable $AP_{i,j}^o$ to determine whether the o^{th} OA operates in the saturation region or not. $AP^{o}_{i,j}$ is ensured to be 1 if the total input power in mW is less than 0.01 mW (i.e., the cut off value of the total power which determines the saturation region of the OA), and zero otherwise, using the following set of constraints:

$$(0.01 - TP^{beg,o}_{i,j,mW}) + \delta \leq AP^{o}_{i,j} \qquad \forall e(i,j) \in E; \forall o \in OA_{i,j} \tag{6.32}$$

In this context, please note that when the total power is less than or equal the cut off value, the left hand is a positive fraction that is less than 1. Therefore, constraint (6.32) is satisfied only when the right hand side is 1. If the total power is greater than the cut off value, the left hand side is negative, and $AP^{o}_{i,j}$ can be either 0 or 1. Since the objective function tries to minimize the total power in the R component of the objective function, this indirectly helps in setting $AP^{o}_{i,j}$ to zero. $AP^{o}_{i,j}$ is then used in constraints (6.33) and (6.34) to convert between $TP^{beg,o}_{i,j,mW}$ and $G^{o}_{i,j}$.

$$(1 - AP^{o}_{i,j}) + \frac{G^{o}_{i,j} - 20}{M} \geq 0 \qquad \forall e(i,j) \in E; \forall o \in OA_{i,j} \tag{6.33}$$

$$AP^{o}_{i,j} + \frac{G^{o}_{i,j} - (A_y \times TP^{beg,o}_{i,j,mW} + B_y)}{M} \geq 0 \qquad \forall e(i,j) \in E; \forall o \in OA_{i,j} \tag{6.34}$$

Constraint (6.33) handles the maximum gain region, i.e., when $AP^{o}_{i,j} = 1$. In this case, $G^{o}_{i,j}$ should equal 20 in order for the constraint to be satisfied. On the other hand, constraint (6.34) handles the linear mapping for the saturation region in a fashion similar to the one proposed in (6.24). In this case, $AP^{o}_{i,j} = 0$ and $G^{o}_{i,j}$ is represented by the set of linear mapping equations $A_y \times TP^{beg,o}_{i,j,mW} + B_y$.

$$\frac{SL^{a,\lambda}_{i}}{M} \leq SP_i \qquad \forall i \in N; 0 \leq a < K; \forall \lambda \in \Lambda \tag{6.35}$$

Constraint (6.35) ensures that the splitting loss value at an MI node is 0 dB for any connection carried at any channel. However, splitting at MC nodes is determined in dB by this relation:

$$SL^{a,\lambda}_{i} = 10 * \log_{10} f \tag{6.36}$$

This relation is non-linear since the splitting degree, f, is a variable. Hence, we use the same set of constraints we defined earlier in constraints (4.24 - 4.26).

6.4 The Heuristic Algorithm

The MILP formulation presented in the previous section provides the optimal solution of the PA-RWA problem. However, the complexity of this formulation is of the order of $2 \times N^2 \times K \times |\Lambda| \times |OA|$ for both the number of variables and constraints. Due to this high complexity, obtaining the optimal solutions using MILP formulation is not practical or scalable for big problem instances that involve both larger network and traffic sizes. Hence, there is a need for a heuristic algorithm that can provide faster and efficient solutions.

In this section, we present a heuristic based approach for the PA-RWA problem under AOM service. We refer to this approach as Power-Aware Multicasting (PAM) Algorithm. Our scheme decomposes the PA-RWA into three subproblems, namely, Routing (**R**), Wavelength Assignment (**WA**) and Power Assignment (**PA**) subproblems. Although solved separately, the PAM heuristic considers the impact of these subproblems on each other by using a special set of cost functions for the links, network and sessions.

6.4.1 Motivation of the PAM Algorithm and Main Characteristics

Call blocking can be due to many sources, some of which can be related to power issues. The lack of availability of a continuous wavelengths on the light-trees is considered the main source of non-power related source of call blocking. We refer to this type of call blocking as *Wavelength-Shortage Blocking* and it occurs when the RWA algorithm cannot find a feasible light-forest that has a single common wavelength among its links. On the other hand, power-related sources of call blocking occur when the source nodes fail to launch their light-trees with the appropriate power levels without violating any of the power constraints described in Sub-section 1.6.1. This can happen even with the presence of network resources and wavelengths. The reason of this blocking type is mainly due to sharing of the available power by wavelengths at the links and OAs entry points. Hence, this blocking type is called *Power-Sharing Blocking* and it takes three formats:

1. *Power-Shortage Blocking*, which occurs if the power strength of the signal drops below P_{Sen} anywhere in the light-tree, even with the use of the source node's maximum available

power. This drop results in the loss of ability to detect the optical signals at the receivers and OAs.

2. *Service-Disruption Blocking*, which results when a new session is routed over links that are shared with some already provisioned sessions in the network. Assigning a power value to the new session can result in dropping the gain of at least one OA to a level which can result in a service disruption of one or more already established sessions even with the use of the minimum allowed power at the source node. Service disruption occurs when gain drop yields a sequence of changes in the optical signals strength and other OAs gains which results in violating the power constraints. In this case, the newly routed sessions are blocked.

3. *Non-linear Impact Blocking*, which is a direct result of violating the maximum total power constraint. This blocking can easily occur, even with the use of the minimum allowed at the source node. For example, the routed signal can enter the next hop link with a high power value that increases the total power over the link over P_{MAX}. Allowing this to happen causes the system to operate in the undesirable nonlinear region of the fiber[2].

In order to achieve good near-optimal solution for the PA-RWA problem, the design of the PAM algorithm is based on capturing the impact of the *Power-Sharing Blocking*. This is achieved in part by using a novel cost function for the network links that reflects this nature.

Also, the operation of the PAM algorithm has two characteristics. First, the algorithm deals with the sessions in a parallel (or grouping) fashion, rather than sequentially (or individually). In this context, all, or a subset of, the sessions are treated together at the same algorithmic iteration. This grouping mechanism provides a flexibility for the algorithm to take their impact on each other which can result in reducing blocking due to service disruption. Second, inspired by the fact that assigning the minimum power to each light-tree does not always give the best solution, the power module of the proposed algorithm adopts a semi-random scheme, that is closely controlled by a set of probabilities that are used to determine the best combination

[2]Although this blocking behavior can be prevented with the use of equalizers, like in [63][64], our system model does not assume the use of equalizers.

of power levels at the various source nodes. This semi-random power assignment scheme accompanied with the grouping consideration of the sessions, proves to provide better solution over the minimum power assignment and sequential treatment counterparts.

6.4.2 Link Cost Function

We need to define the following set of parameters first in order to define the link cost function. $P^{\lambda,MIN}_{i,j,mW}$ is defined as the minimum power (in mW) for channel λ that is needed to be observed at the beginning of link $e(i,j)$ in order for it to reach the first OA (if $|OA_{i,j}| > 0$) or the end of the link (if $|OA_{i,j}| = 0$) with a power that is equal to P_{Sen} exactly. We also extend this definition to each fiber segment that is defined between the o^{th} and $(o+1)^{th}$ OAs. $P^{\lambda,o,MIN}_{i,j,mW}$ specifies the minimum power (in mW) that is needed at the *output* of the o^{th} OA in order to reach the *input* of the $(o+1)^{th}$ OA, or the end of the link if the o^{th} OA is the last OA on the link, with P_{Sen}.

The maximum number of wavelengths that $e(i,j)$ can support, $|\Lambda^{MAX}_{i,j}|$, is then calculated using this relation:

$$|\Lambda^{MAX}_{i,j}| = MIN(|\Lambda|, \frac{P^{mW}_{Max}}{P^{\lambda,MIN}_{i,j,mW}}) \tag{6.37}$$

According to equation (6.37), $|\Lambda^{MAX}_{i,j}|$ is determined, not only by the wavelengths availability, but also by the signals ability to reach the first OA, if any, and still be detectable[3].

Also, we define $|\Lambda^{Add}_{i,j}|$ as the current number of wavelengths that link $e(i,j)$ can additionally support, given the current supported wavelengths and their power assignments at the beginning of the link. $|\Lambda^{Add}_{i,j}|$ is computed as the:

$$MIN(\lfloor \frac{P^{mW}_{MAX} - \sum_{\lambda \in |\Lambda^{Busy}_{i,j}|} P^{beg,a,\lambda}_{i,j,mW}}{P^{\lambda,MIN}_{i,j,mW}} \rfloor, |\Lambda^{Free}_{i,j}|) \tag{6.38}$$

where, $|\Lambda^{Busy}_{i,j}|$ and $|\Lambda^{Free}_{i,j}|$ represent number of used and unused channels over $e(i,j)$, respectively. From (6.37) and (6.38), it is clear that $|\Lambda| \leq |\Lambda^{MAX}_{i,j}| \leq |\Lambda^{Busy}_{i,j}| + |\Lambda^{Free}_{i,j}|$. The current cost of $e(i,j)$, $c_{e(i,j)}$, is then defined as the ratio of the maximum number of wavelengths

[3]This equation is based on the assumption that only one-hop sessions exist in the system (therefore, minimum allowed power values can be used) and it ignores the impact of the spans between subsequent OAs on the links. Hence, it is not a tight upper-bound, however, it is sufficient for the purpose of our algorithm design here.

supported over $e(i,j)$ and the current potential available wavelengths, namely,

$$c_{e(i,j)} = \frac{|\Lambda_{i,j}^{MAX}|}{|\Lambda_{i,j}^{Add}|} \tag{6.39}$$

Equation (6.39) has the following significant properties:

- It intelligently incorporates the useful concepts of power sharing and wavelength availability into the link cost, which is used in the **R** phase. This is important in relating the **PA** subproblems with the **R** subproblem and makes it possible to take the impact of these subproblems on each other.
- It is a dynamic function, i.e., link costs change with the accumulated power values. Hence, routing decisions are directly dependent on the changing network status.
- It is a positive increasing function, i.e., link costs increase with the increase in the link usage. This results in balancing the load in the entire network.

In addition, we define the network cost as the summation of the costs of the individual links. In order to take the impact of placing a light-forest on the remaining unplaced ones, the cost of each light-forest is calculated as the *increase* in the network cost. Selecting sessions for placement is performed using a certain order policy according to their cost. Any order policy can be used in our scheme. The simulation experiments in this chapter are conducted using the increasing ordering policy.

6.4.3 The PAM Algorithm Details

In this subsection, we present the details of the PAM heuristic whose basic operation is depicted in Figure 6.3. The output of the PAM algorithm is the number of admitted sessions, and their corresponding RWA and power values (or RWA-P).

As shown in Figure 6.3, the core operation of the PAM algorithm is the *RWA-PAM Stage*. The input to the RWA-PAM stage is the set of sessions to be constructed, the sharing degree and the construction mode. The sharing degree represents the number of sessions to be

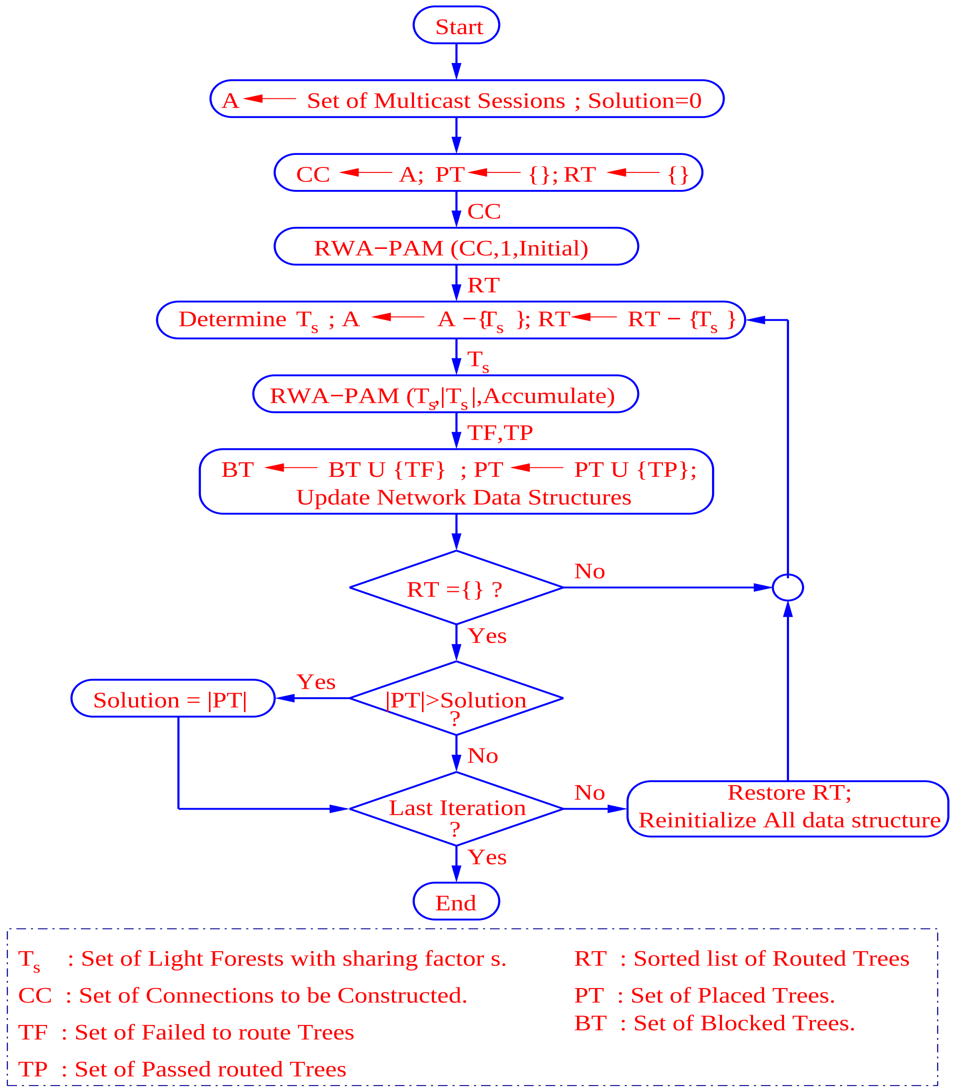


Figure 6.3 Flow chart of the PAM Algorithm Operation.

considered at each construction step of the RWA-PAM stage. If the sharing degree is 1, RWA-PAM constructs the RWA-P solution one light forest at a time, i.e., in an individual manner. Otherwise, the RWA-PAM module considers more than one light forest in its operation. On the other hand, two construction modes are defined, namely, *Initial* and *Accumulate*. In the first mode, each session's RWA-P is constructed using the initial setup of the network, i.e., as if no other sessions exist. In the Accumulate mode, solutions are conducted based on the current network status which is defined by the current power values at each point in the network and the wavelength availability. The output of the RWA-PAM stage consists of the sets of provisioned and blocked sessions.

Basically, the PAM algorithm consists of two main phases. In the first phase, called the Initial Phase, RWA-PAM stage operates at the Initial mode in order to identify the set of sessions that are blocked purely due to the physical setup of the network, and hence eliminate them from further investigation. This can happen, for example, if the OAs placement along all the possible paths from a source node to at least one destination node of the session makes the signal level drop below P_{Sen}. Such physical limitation cannot be circumvented and it occurs with or without the existence of other sessions in the network.

On the other hand, the second phase of the PAM algorithm is called the Iterative Phase. During each iteration of this phase, the RWA-PAM stage operates in the Accumulate mode and the number of sessions considered depends on the sharing degree. The solution found from each iteration is computed with respect to the current network status which is re-initialized before the next iteration starts. The best solution out of all the iterations is selected to be the final solution.

The RWA-PAM stage performs three basic operations, namely, (1) Routing, (2) Wavelength Assignment, and (3) Power Assignment. The PAM algorithm supports two flavors of routing operations, namely Fixed and Adaptive. With the Fixed mode, the routing operation is performed only in the Initial Stage based on the network status at that point of time. As its name suggests, no change is allowed for the light-forest at any other point of time. However, the Adaptive mode allows routing to occurs in the Accumulate Stage such that the light-forest of the set of sessions that are not yet provisioned are allowed to be recomputed based on the latest network status and with respect to the link, session and network cost functions.

The routing algorithm is performed using an extended version of the Member-Only (M-Only) heuristic proposed in [1]. In M-Only heuristic, the multicast tree is expanded iteratively to include at least one member node per iteration. Tree expansion is done via a specific node set, which includes the source node, MC nodes and MI leaf nodes. This set is updated at each iteration. Instead of using a single path, the extended version of the M-Only algorithm we propose employs k-shortest paths for constructing the tree. In this context, the member node

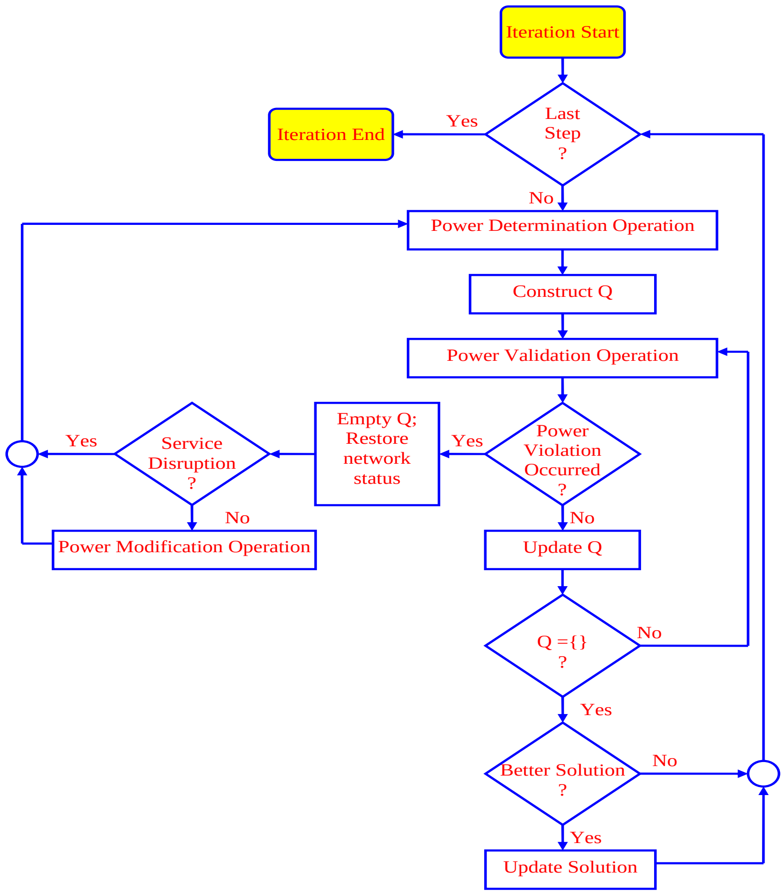


Figure 6.4 Flow chart of the operation of Power Assignment Module.

is connected to the tree through the path that causes the least increase in the network cost and which has sufficient power to reach the destination.

On the other hand, Wavelength Assignment is performed using the First-Fit scheme in which the first available wavelength over the tree links is chosen. The details of the Power Assignment module is more involved and it is described in the next subsection, and its operation is depicted in the flow chart of Figure 6.4

6.4.4 Power Assignment Algorithm

The design of the Power Assignment (PA) Module relies on three observations.

1. Service disruption can be minimized, if not avoided, by grouping the sessions and treating them together in each iteration in order to take their impact on each other.
2. The use of the minimum power at the source node is not always the best solution as it does not guarantee connection acceptance.
3. The impact of power change is not localized within the network due to overlapping between the sessions and the OAs operation that relies on the power sharing of the input signals. Therefore, allowing power and gain values to change at one network link may result in changing them at subsequent network links too. The situation becomes even worse if such chain of power/gain changes propagates back to the initial affected link. Note that not allowing these values to change is not an option since this results in poor algorithm results.

The design of PA module makes use of two important elements in order to tackle these observations with minimal overhead. First, it separates the link identities from their power values by using the queue structure, called Q, that we employed in Chapter 5. The queue consists of unique entities of the links identity. A link becomes part of the queue if it is part of the current light-forests under investigating and/or it is part of the affected links. Although multiple traversals of the link is permitted in the algorithm, Q contains at most one instance of the link at each algorithm step. The link at Q's head is examined and then is removed from Q. The second design element is the power assignment mechanism. In this context, we adopt a semi-random iterative scheme for determining the power values at the source nodes. This scheme is based on a set of probabilities that determine the update action as well as the amount of power change[4]. The details of these two elements are presented below.

[4]We describe this scheme as semi-random because the values of these probabilities are selectively chosen to reflect the source of power violations.

Basically, the Power Assignment scheme runs for a certain number of iterations and it consists of three main operations:

1. Power Determination Operation,
2. Power Validation Operation, and
3. Power Modification Operation.

Given the power values of the already provisioned sessions, these three steps work together during each iteration in order to determine the best power value to be launched at the source nodes of the sessions under investigation. The first step determines the power values set (called Power Vector) at the source nodes. The second operation determines if this Power Vector is valid over the link, i.e., it does not result in any power constraint violation, while the last operation is needed only to determine if a gain drop can be tolerated in the network. In this sense, a session service is considered disrupted only if it was already provisioned in an earlier algorithm step.

In the first iteration of the Power Assignment module, the Power Vector is initialized with the minimum power values at the source nodes. Q is then populated with all the outgoing links from the source nodes of the current sessions under investigation. The order of adding these links is immaterial. The module proceeds on a link by link basis, starting from the link at the queue head and it checks if power levels are valid on every points on this link. If so, the link is removed from Q while its outgoing links are added to Q, if (1) they are not there currently, and (2) they are part of the current sessions light-trees. At each algorithm step, Q contains one instance of the link, even it is shared by more than one light-tree.

The PA algorithm continues with the next link in Q and it stops when Q becomes empty. A link can be revisited more than once during the iteration lifetime. This occurs because the same link can be at different depth of the various light-trees. With each link traversal, more power values over the link become available. The algorithm deals with those power values that are currently available; thus, the algorithm works even with partial knowledge of the power values. However, allowing several traversals of the links ensures the complete availability of the power values at the link. Having said that, it is important to note that prevent having multiple copies of the same link in Q eliminates any unneeded calculations since power values are separate from the link identities.

If the Power Validation Operation indicates that a gain drop occurs, but no service disruption is encountered, then the Power Modification Operation is invoked. In this operation, the algorithm identifies the set of all sessions on the link where a gain reduction took place, and we refer to them as the affected sessions set. These sessions include the old placed sessions as well as the new ones. It then continues its normal operation. However, queue Q is now populated with links from the affected sessions set.

If power violation is encountered at any point in the network, Q is emptied, the network status is restored, and the Power Determination Operation is called in order to determine the new Power Vector. In this operation, the power violation type is identified, and the set of sessions that are involved in this power violation is determined to be the new sessions on the link where the violation occurs. From these sessions, the operation then determines, randomly, the sessions to be blocked from participating in the next iteration of the PA module. For each remaining session, the module determines whether these sessions can reuse their power value, or not. If the power value is to be changed, the algorithm then determines, randomly, whether to increase or decrease the current power based on the power violation type. This randomness is governed by certain probabilities that are carefully chosen to reflect the method used to resolve this power violation type. For instance, if power violation is due to power drop below P_{Sen}, then it is more probable that increasing the power value might solve the problem. Therefore, increasing power value is given high probability in this case. On the other hand, power violation due to service disruption is not necessarily always due to high-power input. For example, in a cascade of OAs, decreasing the source node power might increase the gain of one OA, which increases its output power. This results in more input power in the following OA, which might decrease its gain and service disruption persists. Therefore, we assign moderate values to the probabilities of increasing the power in the case of Service disruption. Finally, this probability is low in the case of total power exceeding P_{Max}.

Moreover, the amount of power change is determined randomly too. Changing the source power values is performed on the current sessions under investigation while those sessions which have already being provisioned are not changed. It is worth mentioning that we only change the power values associated with already provisioned sessions on the links, if a gain drop occurs, but not the source power itself. Due to the random nature of this solution, the PA module runs for a number of steps (or if the solution does not improve within some limits) and the maximum number of admitted sessions over all of these steps is chosen as the PA module solution.

6.5 Numerical Results

In order to validate our solutions and to understand their main characteristics, we present some numerical results in this section using the setup settings defined in Section 1.6.3. In addition, the following assumptions were used for the experiments:

1. We employ the increasing order policy of the corresponding light-forests costs in determining the set of sessions to be provisioned in the network.
2. We run the PAM algorithm at least 5 times per problem instance. The solution of the maximum number of accepted sessions is then chosen as the representative solution.

The results in this section are presented in two main parts. In the first part, we establish the quality of the solution produced by the PAM algorithm. This is done by comparing these results with the optimal counterparts collected from CPLEX while using the same network settings in the 6-node network. In this part, we also demonstrate the significance of two design elements of the PAM algorithm, namely, the concepts of sessions grouping (or sharing) and the semi-random power assignment scheme. In the second part, we quantify some basic characteristics of the PAM algorithm using the simulations results on the NSFNET. In this part, we also demonstrate the characteristics of the other two algorithm design elements, namely, using alternate routing and rerouting.

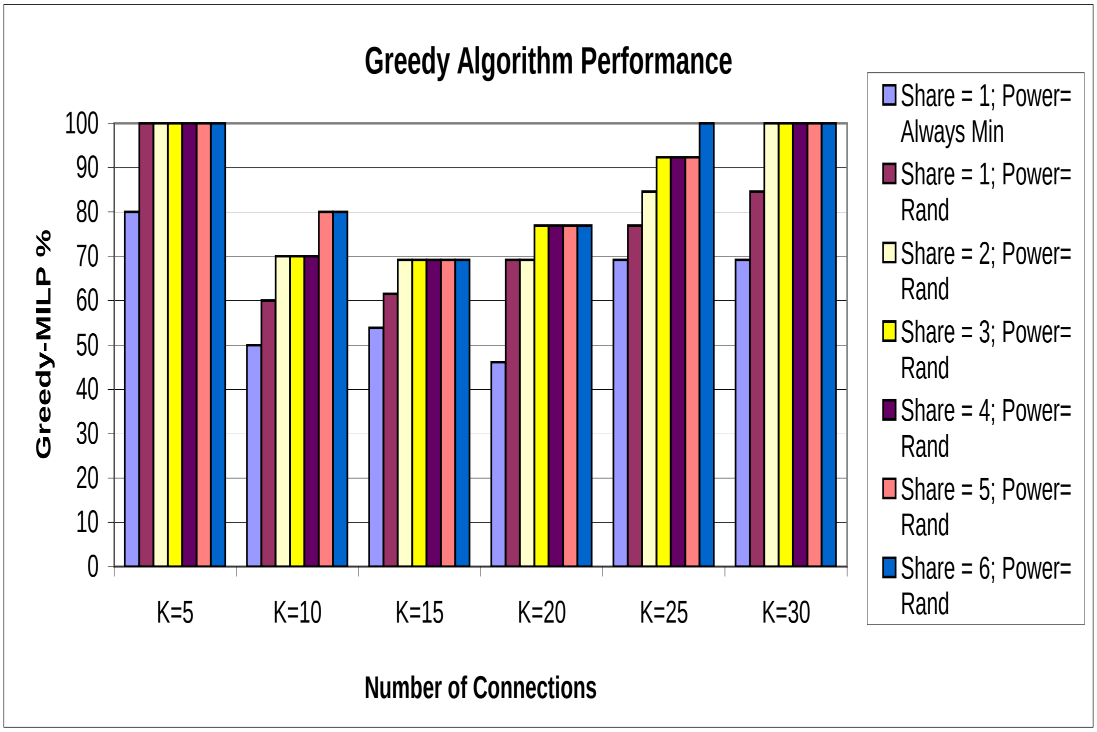


Figure 6.5 The greedy heuristic results with respect to the MILP for the 6 nodes mesh network, when $\Lambda = 4$ and for different values of K.

6.5.1 Solution quality of the PAM algorithm results

Figure 6.5 depicts the relative performance of the PAM algorithm compared to the optimal solutions from CPLEX when the number of channels in the system is 4. Similar behavior is observed with other number of channels too. This relative performance is measured as the ratio between the number of sessions accommodated by the PAM heuristic and by the MILP formulation for a given number of sessions, denoted as, K. We refer to this ratio here as the Greedy-MILP ratio. For the sake of comparison, these results are obtained using the Fixed scheme with one alternate path. However, we allow different degrees of grouping (or sharing) of sessions and we use different power assignment schemes.

In this context, we define the *Sharing (Grouping) Degree*, or simply *Share* as a rough measurement of the number of sessions that need to provisioned at each algorithm iteration. Therefore, if *Share* is 1, the sessions are provisioned in the network one session at a time, i.e., sequentially (or individually). however, if $S > 1$, the algorithm operates such that more than one session are considered at a time.

Choosing the value for *Share* has a direct impact on the solution accuracy and the algorithm performance and it can be a research topic by itself. However, it is important to note that this value is used to capture the interdependency between the sessions that share the same links in the network. Hence, it is essential to capture this sharing concept while constructing the groups of sessions. The details of grouping these sessions is implementation-dependent really. In our implementation, we simply relate the *Share* value with the number of sessions to share at least one link by a certain percentage, called the *Sharing Percentage (SP)*. In this sense, whenever possible, the size of each group must be equal at least the *Share* value [5]. More sessions will be added to the group if the number of sessions that share at least one link is less than $SP \times Share$.

On the other hand, for the sake of reference, we refer to the semi-random power assignment method proposed in Section 6.4 as the **Rand** method. In Figure 6.5, we compare the Rand method with another deterministic scheme, referred to as the **Min** method. The Min method operates by always choosing the minimum possible power value.

As shown in Figure 6.5, the performance ratio of the PAM algorithm with respect to the optimal solutions is represented by a set of bars at each traffic load, K. Each bar represents the experiment settings of the simulation at that traffic load. The results represented by the first left bar for each K (i.e., when $S = 1$ and Min Power Assignment scheme is used) serves as a benchmark to measure the usefulness of the *Share* and *Rand* aspects of the PAM algorithm.

The following important conclusions can be drawn from this figure:

1. The PAM algorithm performs very well with respect to the corresponding optimal solutions. Not only it provided near optimal solutions, it sometimes was even able to get the optimal solution. For example, the PAM algorithm produces the optimal solution (hence the Greedy-MILP ratio equals 100%) when $K = 30$ and *Share* $= 2$ to 6.

2. Applying the Rand power scheme results in a huge performance improvement compared

[5] An exception of this is when the number of remaining unprovisioned sessions is less than the value of the *Share*.

to the Min Method. This improvement is measured as the increase in the value of the Greedy-MILP ratio. The maximum performance improvement occurs when the value of *Share* equals 1 and it ranges from 8% for $K = 15$ and $K = 25$, and 23% for $K = 20$. However, the incremental improvement decreases as the sharing degree increases. This indicates that small sharing degrees are sufficient to reach an acceptable system performance that is close to the optimal solution. This has the advantage of reducing the system complexity since a fewer number of sessions per group can be considered at each algorithm iteration.

6.5.2 PAM Heuristic Results

After establishing the solution quality of the PAM algorithm in the previous subsection, this subsection is devoted to address the following characteristics of the PAM algorithm:

6.5.2.1 PAM Algorithm's Impact on the Objective Function

The impact of the PAM algorithm on the number of accepted sessions is depicted in Figure 6.6 at different traffic loads using the Fixed scheme and when the number of available channels is 10. Similar behavior is observed with the Adaptive scheme too. The results are collected at different computation power, determined both by the employed power assignment scheme and the number of alternate path. In this context, the least computational power configuration is the Min-P where the Min power assignment scheme is used with single alternate path. The maximum computational power configuration, on the other hand, is the one that involves Rand power assignment with 3 alternate path routing, referred to as RP-P3.

Naturally, the number of accepted sessions increases as the traffic load increases. However, It is obvious from this figure that for each traffic load, the objective function improves (i.e., increases) as more computation power is employed. For example, for $K = 40$, the number of accepted sessions increases gradually from 14 to 24 when the algorithm mode increases from Min-P to RP-P3.

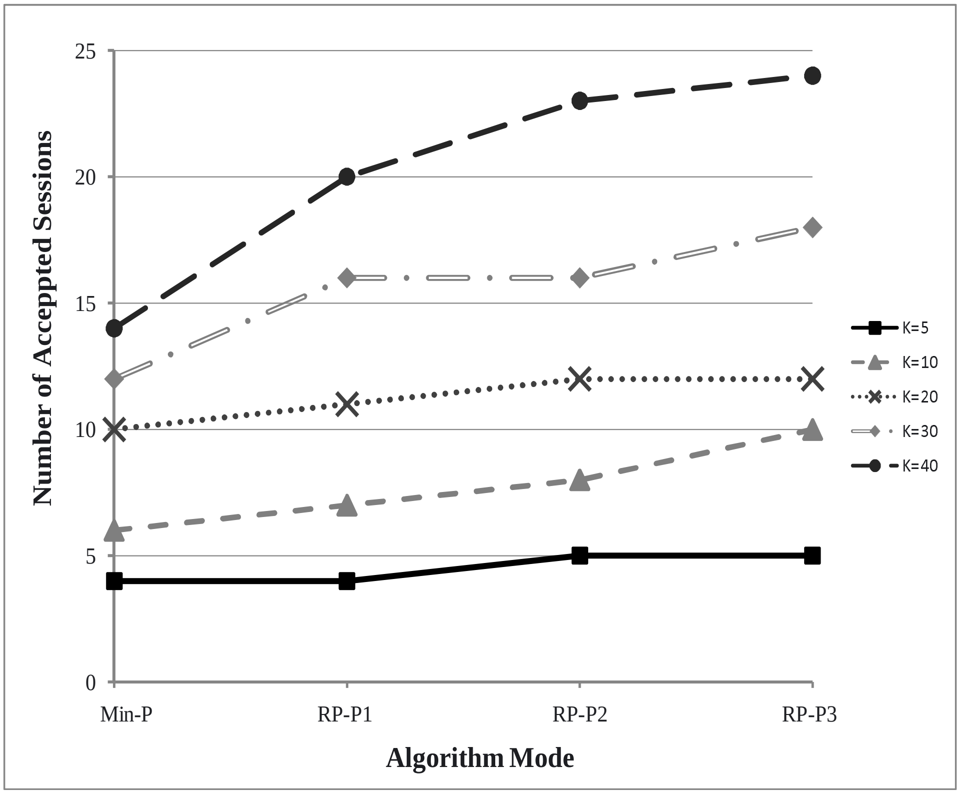


Figure 6.6 Impact of the PAM algorithm on the number of accepted sessions when the Fixed scheme is used and the number of available channels is 10. Min-P determines the case when Min Power scheme is used with one alternate path, while RP-P(i) indicates the case when the Rand Power Scheme is used with i^{th} alternate path.

6.5.2.2 Relative Performance of the Fixed and Adaptive Schemes

In the following, we compare the performance of the Fixed Scheme to that of the Rerouting (Adaptive)[6] scheme. In addition to their performance with respect to the objective function, we compare their performances in terms of the network resources. Two network resources are of interest to us, namely:

1. The maximum number of distinct channels used over any link; this is referred to as κ .

[6]We will use the term Rerouting to refer to the Adaptive scheme in this section as it emphasize the core purpose of this method.

Table 6.1 The relative performance of the rerouting scheme compared to the Fixed scheme in terms of the number of accepted sessions when $K = 10$ and 20. The symbols F and R refer to Fixed and Rerouting schemes, respectively.

K	Mode	$P1$	$P2$	$P3$
10	F	7	8	10
10	R	9	9	10
20	F	11	12	12
20	R	13	14	14
30	F	12	16	16
30	R	16	16	17

2. The number of links used in constructing all the light-forests (i.e., links with at least one used channel); this referred to as Ł.

The performance of each scheme in terms of the number of accepted sessions and network resources are shown in Tables 6.1 and 6.2, respectively. From Table 6.1, we find out that the rerouting scheme always accept higher number of sessions than that of the Fixed scheme at each alternate path. For instance, When $K = 20$ and P1, the solution improves from 11 sessions to 13 sessions by using rerouting scheme.

Nevertheless, one can notice a very important behavior from Table 6.1. Although using alternate path for routing and allow rerouting for the light-forests are conceptually two separate functions that can be used independently to improve the solution quality, we find out that they both work together in a constructive manner by joining their forces together to find better solutions. For example, for the case when $K = 20$, we find out that the solution improves from 11 sessions when one alternate path is used with Fixed scheme to 14 sessions when 3 alternate paths are employed with the Adaptive scheme.

The better performance of the Adaptive scheme does not come with no cost. As shown in Table 6.2, we see that the Adaptive scheme consumes more network resources in terms of κ and L. This can be explained by the fact that the Adaptive scheme responses dynamically

Table 6.2 The relative performance of the rerouting scheme compared to the Fixed scheme in terms of the consumed network resources when $K = 10$ and 20 and number of alternate path is 1. The symbols F and R refer to Fixed and Rerouting schemes, respectively.

K	Mode	Max number of channels	Number of consumed links
10	F	3	21
10	R	4	23
20	F	4	26
20	R	4	28
30	F	4	32
30	R	6	35

to the changes in the network status and attempts to explorer bigger solution space that may require the use of more network resources.

Interestingly, this behavior is different from the one we reported in Subsection 5.5.2.3 for the OAP-Symmetric problem where the Adaptive approach has better relative utilization of the network resources compared to the Fixed scheme. This can be understood in the context that unlike the design problem defined in Chapter 4, the operation problem we have here has a constrained wavelength availability, therefore, its solution search space is less which can result in such a behavior.

6.5.2.3 Impact of Power Constraints on the Available Network Channels

Finally, we use the PAM algorithm here to study the impact of the power constraints on the network resource utilization. In this context, we determine the system throughput in terms of the number of wasted channels due to the violation of power constraints. Figures 6.7 and 6.8 depict the relation between the maximum number of admitted sessions and the utilized wavelengths from one hand and the number of available wavelengths from the other hand in the 6 node mesh network and the NSFNET, respectively. These experiments are conducted

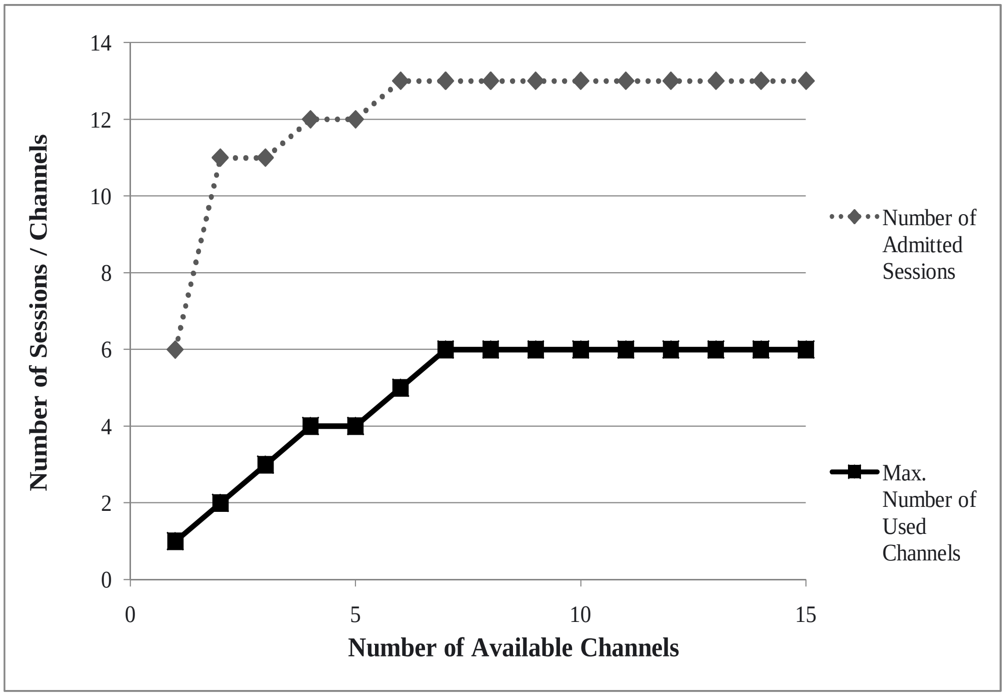


Figure 6.7 System behavior with the existence of power constraints in the 6 nodes network for 30 connections.

using the Fixed scheme with one alternate route with the total traffic load of 30 connections for the 6 mesh network and 20 connections for the NSFNET.

As shown in these figures, when the number of available channels is small, a large proportion of the sessions are dropped due to the wavelength shortage. The impact of the wavelength shortage continues until the number of available channels is less than 7 in the case of the 6 nodes network, and less than 5 in the NSFNET case. At this period, increasing the network resources in terms of the number of available channels *may* reduce the system blocking probability if the main source of call blocking is the Wavelength-Shortage Blocking. For example, this scenario is shown in Figure 6.7 where the number of admitted sessions increases from 6 to 13. However, this increase in the system performance stops when the Power-Sharing Blocking becomes the

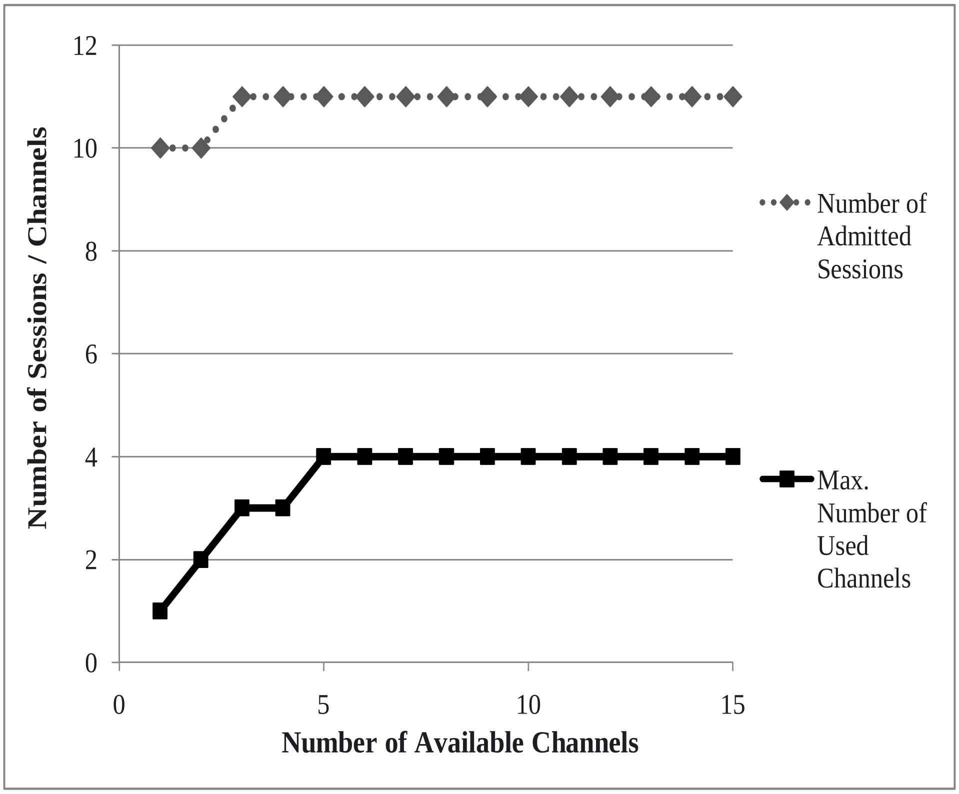


Figure 6.8 System behavior with the existence of power constraints in the NSFNET for 20 connections.

main source of call blocking and the OA placement [65] becomes the bottleneck for the PAM algorithm. At this point of time, increasing the number of channels does not improve the system blocking and these channels are wasted. Determining this cutoff value is essential for the network operators to determine the best usage of their network resources and the PAM algorithm provides a mechanism to provide such an important system metric.

6.6 Chapter Summary

In this chapter, we studied the problem of Power Aware Routing and Wavelength Assignment (PA-RWA) under All-Optical Multicasting (AOM) and we proposed two solution schemes. The first scheme produces optimal solutions using MILP formulation, while the other scheme proposed a heuristic scheme, called Power Aware Multicasting (PAM) algorithm. The design of the PAM heuristic consists of several optimization elements that make it able to produce near optimal solutions in an efficient manner.

On the other hand, the results show that the PAM algorithm performs well in comparison with the optimal solutions. It also provides a good understanding for the system performance. One of the main advantages of the proposed PAM Algorithm is its ability to determine the operation region for the network where adding more channels can benefit the overall system performance which is of great advantage for the network operators.

CHAPTER 7. Thesis Conclusions and Future Work

7.1 Summary

In this thesis, we study the impact of optical power loss on the design and operation of WDM networks under All Optical Multicasting (AOM). This impact was formulated as network provisioning and connection provisioning problems. The objective function for the network provisioning problem is to minimize the network cost in term of number of optical amplifiers. On the other hand, the objective function for the connection provisioning problem is to minimize the number of blocked sessions. The thesis introduces optimal solutions for both problems. While the optimal solutions are exact, they can only be used to solve small instances. Therefore, we also developed heuristic solutions, which are fast, and were found to yield near optimal results.

In Chapter 1, we provide introductory information about the main components of the problems we discuss in this thesis. This introduction covers background on optical networks, its lifetime, and the concept of AOM. We then cover the challenges and problems encountered when supporting AOM. These challenges are presented based on their sources. Also, we present the solution strategy we adopt in our study, along with the main contributions of this thesis. Finally, we determine the basic common information about the system and the assumptions we use in our study.

We then provide a review of the research efforts that addressed the network design and operation for AOM support in Chapter 2. This chapter serves two goals. First, it surveys the most related work in AOM in order to establish a clear and solid background in this field. In this context, we introduce a detailed classification framework for the various routing techniques and a new notation for describing their system models. Introducing this classification and notation provides a compact, yet comprehensive, way to present these schemes and help identifying their basic characteristics. Second, it motivates the power aware network and connection provisioning of AOM. From this chapter, we find out that the various power-related issues were ignored by most of these efforts.

Our treatment of the power-aware network design issues takes the form of solving the Optical Amplifiers Placement (OAP) problem which is tackled in Chapters 3, 4 and 5. Chapter 3 introduces the problem, and the motivation to study it under AOM. It then presents the two flavors of this problem, namely, OAP-Asymmetric and OAP-Symmetric, in which the power strengths are assumed to be unequal and equal per link, respectively. Our contributions in solving this problem as well as the system model and formulation notations are then provided.

We solve the OAP-Asymmetric problem in Chapter 4 using MILP. In this formulation, we introduce novel mapping techniques in order to find the equivalent linear constraints for some of the nonlinear power constraints. The objective of the formulation is to minimize the total amplification gain needed in the network. The formulation find the RWA solutions, the total link amplifications, the power values at beginning and end of each links, as well as the number and location of the splitters. These solutions from the MILP formulation are then used to find the number and location of the OAs using any optical amplifiers placement policy.

In Chapter 5, we solve the symmetric version of the OAP problem using MILP and heuristic approaches. The proposed MILP minimizes the number of OAs, instead of the total gain as it is the case in Chapter 4. The heuristic approach simplifies the solution of the combined problem by solving each of its subproblems separately. However, we use a special set of cost functions (that are represented in terms of the number of optical amplifiers) in order to compute the costs of the links and sessions. Using these cost functions for making routing decisions establishes a connection between the routing and power assignment subproblems, which contributes significantly to the solution quality. In addition, the algorithm operates at different computation levels, which are determined mainly by: (1) the number of alternate paths used in routing, and (2) the operation mode, namely, Fixed or Adaptive. The results show that the Adaptive scheme outperforms the Fixed scheme due to the extra computations involved, which might be acceptable in this problem where network design is done off-line.

Finally, the network operation aspect of the power-aware AOM is addressed in Chapter 6. The problem is investigated as an extension of the classical RWA problem. This extension, referred to as the power extension, takes care of the power loss impact on the RWA problem under asymmetric power configuration. The problem is first solved using MILP whose objective is to minimize the number of dropped sessions. The formulation incorporates several new linearization mapping techniques. Beside the optimal approach, we also provide a heuristic scheme using similar design guidelines that are used for the heuristic scheme in Chapter 5. As a result, the solutions obtained from the greedy algorithm proved to achieve good performance when compared to the optimal solutions. Also, the obtained results help understanding the impact of the proposed heuristic on the system performance at various system conditions. In particular, the proposed algorithm is able to determine when adding more channels to the network can help enhancing the system performance.

7.2 Future Work

This thesis covers many important and practical power issues while solving the OAP and RWA problems. Including more practical issues contributes more toward the solution correctness, however, it increases its complexity significantly. The major source of complexity for adding these additional constraints is due to their nonlinearity. Incorporating these additional constraints in the proposed solutions makes the OAP and RWA problems nonlinear; thus, more difficult to solve. Although some of these issues have been handled in the literature, several issues have still not been resolved, and they require further research. The following list identifies some of these topics and open issues in the field of power aware AOM:

1. Our investigation in this thesis limits the causes for power loss to three major sources only, namely, propagation loss, splitting loss and tapping loss. Practically, other sources for power loss exist, which include, but are not limited to, multiplexing/demultiplexing loss, switching loss, etc. Our proposed MILP and heuristic solutions are generic enough to

include these losses, provided that they are representable by linear constraints, especially in the MILP formulation.

2. The thesis concentrates only on the power loss impairments of the optical layer and it ignores the noise issues caused by many optical components in the system, especially the optical amplifiers. The main source of noise in optical amplifiers is the Amplified Spontaneous Emission (ASE) which is added to the optical signal when amplified. ASE accumulates in each optical amplifier, which imposes an upper limit on the number of optical amplifiers the signal can traverse before being regenerated. Using regenerators in the network compromises the signal transparency and increases the network cost due to the need to include more hardware. Some efforts which take these constraints and other power issues into account were reported in the literature, e.g., [66, 67, 68, 69].

   In this field, the following future research works are identified. First, we were able to extend our formulations to include the ASE noise issues, however, these formulations become nonlinear. These formulations need to be solved using nonlinear solvers. Alternatively, new sets of mapping schemes need to be developed to linearize these constraints. Moreover, the heuristic solutions needs to be extended to take the noise issues into consideration. In particular, new cost functions might be needed to represent the ASE impact.

3. The issue of power aware AOM in reconfigurable multicast topology did not receive much attention from the research community yet. Topology reconfigurability can be achieved under AOM by using power splitters of adjustable fanout outputs. Using such devices produces more efficient management for splitting power loss which can result in increasing the tree dimension and group size. Please refer to reference [9] for more details on this subject. However, using such devices is not cheap, neither in terms of their cost, nor in terms of the added complexity of the optimal formulation. It turns out that adding such constraint to the formulation makes it nonlinear, as was demonstrated in reference [63]. More investigation is needed to develop new mapping schemes for linearizing these

constraints and to include these constraints in the proposed heuristics.

4. In real life, placing the optical amplifiers at certain sites is not feasible or might entail additional costs. Incorporating the cost associated with the optical amplifier location can be of great impact on the solution credibility. More investigation is needed to study this dependency, especially on the network operation as the optical locations has direct impact on the computed gain.

5. Our work here assumes static traffic model where the demands are known beforehand and assumed to last for long period of time. Considering the case of dynamic traffic model can produce very challenging problems since the dynamic nature of the traffic forces a special treatment for the power aware AOM, either during the network design or operation. Nevertheless, some of the findings in this thesis can be of great help in exploring this field.

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