# Multicast Routing and Allocation of Wavelengths in a WDM Network with Splitters and Converters

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**Abstract**

This paper deals with the problem of multicast routing and the allocation of wavelengths in a WDM network with optical splitters and converters. We present an exact formulation in integer linear programming (ILP) to find a set of optical structures connecting a source to a set of destination nodes. We use a new optical structure called hierarchical. In hierarchical structure, an optical signal can pass more than once through the same optical node and an intermediate node can belong to the set of destinations; this is a generalization of "light trails"). The problem of multicast routing with sparse wavelength conversion and sparse splitting using the hierarchical structure has not yet been studied. So, our main contribution consists of introducing new optical constraints of wavelength converters with the hierarchical structure. The objective is to focus on the benefits and performances of using wavelength converters in a WDM network. Simulation results show that the hierarchical structure gets better results in terms of overall link cost and number of wavelengths in the case of WDM network sparse wavelength converters than the WDM network without converters.

*Keywords:* Multicast routing, Wavelength division multiplexing (WDM), Wavelength converters, Optical networks, Hierarchical structure, Tree structure

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## 1. Introduction

A WDM optical network is a set of nodes linked together by optical links. In an all-optical network, an optical path is a succession of links and nodes between a source node and a destination node in which only one wavelength is used end-to-end [1, 2]. For a given multicast session (i.e., a source node and a set of destination nodes), a request for that session in an optical network requires establishing an optical structure that interconnects the source and the destinations. This optical structure could be one optical tree, a set of optical trees, or an optical hierarchy (see Section 2). An optical tree is an all-optical tree-like structure between a source node and a set of destination nodes [3, 4]. Optical networks can be divided into three types: opaque optical network, transparent optical network and translucent network [5]. In the first type, the data transmission is done in the optical domain while the switching is still performed in the electrical domain. In the second type, the optical signal is not converted into electrical signal in each node; both the transmission and the switching are performed in the optical domain, hence the name transparent optical network [6]. The third type of network called translucent network in which some communications will cross the node as if it were transparent and some others will travel the same node as if it were opaque. In this paper, the communications are considered to be established in core (or metropolitan) networks using active optical switches (passive optical network which is used to provide fiber to the end consumer is not considered) and both the transmission and the switching are performed in the optical domain.

Multicasting is an important research topic. It allows good utilization of bandwidth in a WDM optical network. This mode of transmission allows sending a message from a source node to several destination nodes [3, 7, 8]. In transparent optical networks, an optical structure must be created to serve a multicast request [9-12]. An optical splitter divides the incoming signal into multiple outputs, which makes it possible to establish an optical path toward multiple destinations [13-15]. In practice, only a few nodes in a network may have optical splitters. These optical nodes are called "multicast capable" (MC) nodes; the rest of the optical nodes are called "incapable multicast" (MI) nodes (nodes that do not have the capability of splitting) [16]. To support WDM multicasting function, a switch (optical cross-connects, OXCs) node should be equipped with splitter, which can divide the incoming signal into multiple output signals [17-19].

Wavelength converter is a special device which shifts a wavelength arriving at an input switch port to another wavelength. Thanks to this wavelength converter, different wavelengths can be used along a single optical path, and so the wavelength continuity constraint is relaxed. If no wavelength converters are used in the WDM network, the same wavelength must be used on all the optical links of each optical structure [20]. Authors in [21] show that adding wavelength converters to optical networks minimizes the blocking probabilities, supports higher loads and enhances the network throughput. Therefore, a wavelength converter is introduced in the optical nodes to reduce the probability of blocking. Thus, different wavelengths can be used in a single optical path.

In an optical network, establishing communication between the optical nodes first requires determining the path to be taken, then assigning the wavelength on each optical link. This problem is called Routing and Wavelength Assignment (RWA) [22, 23]. Several researchers have proposed approaches for the problem of multicast routing and allocation of wavelengths in WDM optical networks with different objectives. In [24], authors carry out comparisons between lightpath and light-tree schemes in dynamic multicast traffic grooming process. The results show that, in most cases, the lightpath-based schemes outperform the light-tree based ones, typically with only a slightly higher consumption of resources. Many heuristics have been proposed to approximate the solution. In [25], a new heuristic algorithm, called Sparse Splitting Multicast Routing Heuristic was presented. Performance results show that the proposed approach achieves an important reduction on the average cost of the calculated multicasting trees compared to the most efficient multicast routing algorithms for sparse networks. In [24, 25], authors presented an ILP formulation and heuristic algorithms in sparse splitting networks. However, the sparse wavelength conversion and the hierarchical structure were not addressed. So, in comparison with [24, 25], we studied the routing and wavelength allocation problem with sparse wavelength converters using a hierarchical structure.

In [26] authors introduce a generalised optical tree called "hierarchy". In this new optical structure one node can be visited more than once. In [27], a new multicast routing structure called light-hierarchy is proposed for all-optical network. This optical structure permits cycles introduced by the Cross Pair Switching (CPS) capability of MI nodes. MI node could be visited more than once to switch a light signal towards several destinations with only one wavelength through different input and output port pairs. Zhou, Molnar, and Cousin, in [27], proposed an integer linear programming (ILP) model. This model allows finding a set of optical hierarchies connecting the source and a set of destination nodes. They solved this model with the aim of reducing the number of wavelengths and the cost of the optical links. Recently, multicast routing in elastic optical networks (EONs) has received lots of attention in the literature [28, 29]. In [28], authors presented an integer linear programming (ILP) model to perform multicast routing and spectrum assignment. In addition to this model a heuristic algorithms is proposed for large networks. In [29], authors studied the design of data-center based on content distribution. An ILP model is also presented to compute the multicast route and optimally decide on which light-hierarchies should be set up in elastic optical networks. However, in [26-29]wavelength conversion is not considered, only the sparse splitting and the hierarchical structure were taken into account.

An all-optical network where all nodes are equipped with optical splitters is expensive. So, to reduce the cost of an optical network, only a few nodes may have a splitter, also known as sparse splitting network [30-32]. In this paper, we consider the case where only some nodes of the network are equipped with wavelength converter and optical splitter, this is known as sparse wavelength conversion and sparse splitting [33]. In the case of a tree structure, the problem of multicast routing with sparse wavelength conversion has been studied [33]. It has been shown that sparse wavelength conversion can get the most benefit of full wavelength conversion [34], and sparse splitting can achieve most benefit of full optical splitting [30-32]. In [30-34], only the sparse splitting and the sparse wavelength conversion were taken into account but the hierarchical structure was not addressed.

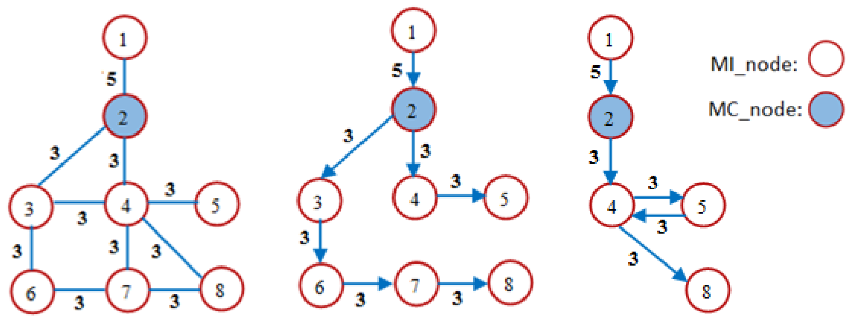
In this paper, we study the routing and wavelength allocation problem with sparse wavelength converters and sparse splitting using a tree structure and a hierarchical structure. In comparison with [26-29], we use a new optical structure and we have taken into consideration the optical constraints coming from the wavelength converters in WDM network. Our main contribution consists of the introduction of the optical constraints coming from the wavelength converters within a hierarchical structure. The introduction of this device allows a light path to use different wavelengths along the optical links. In other words, it removes the wavelength continuity constraint. The objective is to focus on the benefits and performance of using wavelength converters in a WDM network. In this paper, the problem is to find a set of optical structures with the minimum overall link cost and number of wavelengths.

The article is organized as follows. In Section 2, we show the advantages of the hierarchical structure compared to the tree structure. In Section 3, we propose an ILP formulation of the problem. Section 4 presents the simulation results and Section 5 presents the conclusion.

## 2. The hierarchical structure

The example below ( Fig. 1 taken from [35] ) shows the advantage of the hierarchy structure compared to the tree structure in terms of the overall link cost. Overall link cost is defined by the set of optical links constituting the optical structure.

In the first example, consider the $G(V, E)$ topology, where $V$ is the set of nodes, and $E$ is the set of bidirectional optical link representing physical connectivity between the nodes. We assume that each fiber supports a set of wavelengths $W > 2$. All the nodes are $MI$ nodes (nodes that do not have the capability of splitting) except node 2. We consider that the source of the multicast session is node 1, and destination set is $\{5, 8\}$. The overall link cost calculated by the hierarchy-based solution in order to cover all destination nodes is (5+3+3+3+3=17). However, the overall link cost calculated by the tree-based solution structure in order to cover all destination nodes is (5+3+3+3+3+3+3=23). In the second example, consider the COST-239 topol-




(a) $G(V, E)$ topology (b)Tree structure (c)Hierarchical structure

Figure 1: Hierarchical solution versus tree structure solution

ogy. The number of splitting-capable nodes ( $MC_{(G)}$ nodes) is set at 2 nodes (node 5 and node 9). They represent 18% in COST-239 topology. We consider that the source of the multicast session is node 2, and destination set is $\{3, 8, 9, 10\}$. The overall link cost calculated by the hierarchy-based solution in order to cover all destination nodes is (3+3+3+3+3+3=18, Fig. 3(a)). However, the overall link cost calculated by the tree-based solution structure in order to cover all destination nodes is (3+3+3+3+3+3+3=21, Fig. 3(b)). Moreover the tree-based solution uses two wavelengths (one path using wavelength $\lambda_1$ and another path using wavelength $\lambda_2$) to cover all destinations. However, hierarchy-based solution uses just a single wavelength using wavelength $\lambda_1$ to cover all destinations thanks to cycling between nodes 9 and 10. We concluded that the hierarchical structure is better than the tree structure as a function of

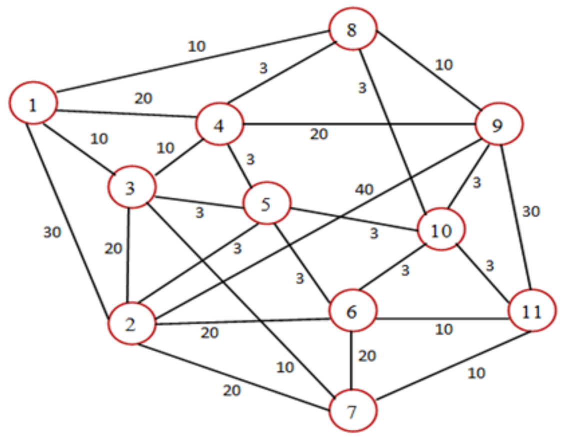
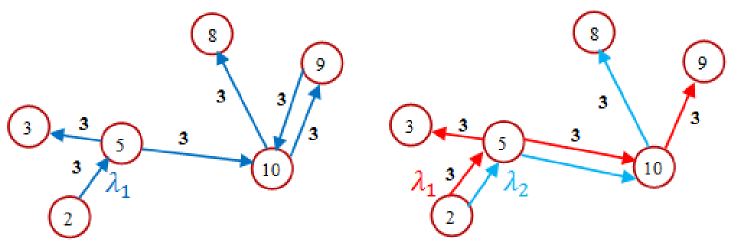



Figure 2: COST-239 topology




(a)Hierarchical structure (b) Tree structure

Figure 3: Hierarchical solution versus tree structure solution

overall link cost and number of wavelengths.

## 3. Problem definition and formulation

A WDM network is modeled as a connected undirected graph $G(V, E)$, where $V$ is the set of nodes (optical cross connects), and $E$ is the set of bidirectional optical link representing physical connectivity between the nodes. Each fiber supports a set of wavelengths $W$. Given a multicast session denoted by $ms = (s, D)$, the problem consists in finding a set of optical structures which connect a source s to a set of destination nodes $D$. Our objective is to minimize the overall link cost of the set of optical structures. We consider two cases. In the first case, we assume that the WDM network has sparse splitting and no wavelength converter. Then, we compare the performance of the hierarchical structure to the tree structure in terms of the overall link cost and number of wavelengths . In the second case, we assume that the WDM network has sparse splitting and sparse wavelength converter. Constraints produced by the absence or presence of wavelength converters in some nodes are introduced in WDM network. The objective of the second case is to focus on the benefits and performance of adding wavelength converters in a WDM network when sparse splitting and multicast optical structure are considered. The mathematical model to minimise the cost in the WDM optical network is set out below:

### *3.1. Notations and network parameters*

The network parameters are:

$G$: Graph of the optical network, formed on $V$ and $E$

$V$: Set of optical nodes

$E$: Set of optical links

$E_{m,n}$: Direct optical link between node $m$ and node $n$, $E_{m,n} \in E$

$l_{m,n}$: The optical link length $E_{m,n}$, in $km$

$W$: Set of wavelengths in an optical link $E_{m,n}$

$In_{(m)}$: Set of incoming links to the node $m$

$Out_{(m)}$: Set of outgoing links of node $m$

$MI_{(G)}$: Set of nodes of $G$ that do not own a splitter, included in $V$

$MC_{(G)}$: Set of nodes of $G$ that owns a splitter, included in $V$ (and $MC_{(G)} = V - MI_{(G)}$)

$M$: a constant, uses as a bound and which can be set as $|W| \times max_{n \in V}\{degree(n)\}$

$ms(s, D)$: Multicast request from the source node to the set of destination $D$

$N_{conv}$: Total number of wavelength converters

$A_{m,n}$: Number of amplifiers in the optical link $E_{m,n}$. If we are given the span distance between each neighboring amplifiers $L(e.g., 80km)$, the number of in-line amplifiers for a fiber link $E_{m,n}$ is given by $A_{m,n} = \left[\frac{l_{m,n}}{L} - 1\right] + 2$, where 2 is used to count pre- and post-amplifier.

$C_a$: The cost of an amplifier

$Cl_{m,n}$: The cost of the optical link $E_{m,n}$

$C_{m,n}$: The overall link cost $E_{m,n}$, where $C_{m,n} = (Cl_{m,n} + A_{m,n} \times C_a)$

*3.2. ILP Variables:*

$L_{m,n}(\lambda)$: Binary variable. Equals 1 if the multicast request $ms(s,D)$ uses the wavelength $\lambda$ in the optical link $E_{m,n}$ and equals 0 otherwise.

$F_{m,n}(\lambda)$: This variable indicates the number of destinations served by the optical link $E_{m,n}$ for wavelength $\lambda$.

$S(\lambda)$: Binary variable. Equal to 1 if wavelength $\lambda$ is used in the optical structure (hierarchical or tree)and equals 0 otherwise.

$\Phi_n$: Indicator of wavelength conversion capability. Equals to 1 if node n is capable of wavelength conversion and equals 0 otherwise.

*3.3. ILP Formulation*

The solution to this problem is to find an optimal set of optical structures covering a multicast session and minimizing its cost. The objective function is defined as follows: Min $(\sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda) \times C_{n,m})$
the primary objective to be achieved is to minimize the overall link cost in the set of optical structures. In this article, two models are implemented: the first model deals wit he hierarchical structure with or without wavelength converters. The second one addresses the tree structure with or without wavelength converters.

*3.3.1. Hierarchical structure with or without wavelength converters*

- Connectivity constraints of the set of optical structures

  Source constraint:

$$\sum_{\lambda \in W} \sum_{n \in Out(s)} F_{s,n}(\lambda) = |D| \tag{1}$$

  Constraint (1) indicates that the value of the set of optical flow emitted by the source must be equal to the number of destinations $|D|$ in the multicast session.

  Destination constraint:

$$\sum_{\lambda \in W} \sum_{n \in In(d)} F_{n,d}(\lambda) = \sum_{\lambda \in W} \sum_{n \in Out(d)} F_{d,n}(\lambda) + 1, \forall d \in D \tag{2}$$

$$\sum_{n \in Out(d)} F_{d,n}(\lambda) \leq \sum_{n \in In(d)} F_{n,d}(\lambda) + |D| \times \Phi_n, \forall d \in D, \forall \lambda \in W \quad (3)$$

$$\sum_{n \in Out(d)} F_{d,n}(\lambda) + |D| \times \Phi_n \geq \sum_{n \in In(d)} F_{n,d}(\lambda) - 1, \forall d \in D, \forall \lambda \in W \quad (4)$$

Equations (2)-(4) ensure that only the terminal nodes consume an optical flow. When the destination is not a terminal node, the flow enters and exits to power one or more other destinations.

Non-member nodes constraint with converters:

$$\sum_{\lambda \in W} \sum_{n \in In(m)} F_{n,m}(\lambda) = \sum_{\lambda \in W} \sum_{n \in Out(m)} F_{m,n}(\lambda), \quad \forall m \in V \setminus (s \cup D), \forall \lambda \in W \quad (5)$$

$$\sum_{n \in In(m)} F_{n,m}(\lambda) \leq \sum_{n \in Out(m)} F_{m,n}(\lambda) + |D| \times \Phi_n, \quad \forall m \in V \setminus (s \cup D), \forall \lambda \in W \quad (6)$$

$$\sum_{n \in In(m)} F_{n,m}(\lambda) + |D| \times \Phi_n \geq \sum_{n \in Out(m)} F_{m,n}(\lambda), \quad \forall m \in V \setminus (s \cup D), \forall \lambda \in W \quad (7)$$

Equations (5)to(7) indicate the conservation of flows at the intermediate nodes, excluding the destination node and the source node.

Non-member nodes constraint without converters:

$$\sum_{n \in In(m)} F_{n,m}(\lambda) \doteq \sum_{n \in Out(m)} F_{m,n}(\lambda), \quad \forall m \in V \setminus (s \cup D), \forall \lambda \in W \quad (8)$$

Equation (8) indicates the conservation of flows at the intermediate nodes, excluding the destination node and the source node.

$$F_{m,n}(\lambda) \geq L_{m,n}(\lambda), \forall m, n \in V, \forall \lambda \in W \quad (9)$$

$$F_{m,n}(\lambda) \leq \mid D \mid \times L_{m,n}(\lambda), \forall m, n \in V, \forall \lambda \in W \quad (10)$$

Equations (9) and (10) ensure that if a link $E_{m,n}$ is used in the optical structure, the number of flows $F_{m,n}(\lambda)$ that go through this link is not equal to zero and should not exceed the total flow emitted by the source node.

- Constraints of the optical hierarchical structure

$$\sum_{\lambda \in W} \sum_{n \in In(s)} L_{n,s}(\lambda) = 0 \tag{11}$$

$$1 \leq \sum_{\lambda \in W} \sum_{n \in Out(s)} L_{s,n}(\lambda) \leq \mid D \mid \tag{12}$$

Constraint (11) ensures that the number of incoming links to the source node is equal to 0. Constraint (12) ensures that the number of outgoing links from the source node must be greater than or equal to 1 and less than or equal to the number of destinations $|D|$ .

Destination constraint:

$$1 \leq \sum_{\lambda \in W} \sum_{n \in In(d)} L_{n,d}(\lambda) \leq \mid D \mid, \forall d \in D \tag{13}$$

Constraint (13) ensures that each destination node must be reached at least once and at most $|D|$ optical structures are used.

$$S(\lambda) \geq L_{m,n}(\lambda), \forall m, n \in V, \forall \lambda \in W \tag{14}$$

Equation (14) shows that the wavelength $\lambda$ is used by the optical structure if the multicast request $ms(s, D)$ uses the wavelength $\lambda$ in the optical link $E_{m,n}$.

Non-member nodes constraint:

  - $MC_{(G)}$ node ( without conversion)

$$\begin{gathered} \sum_{n \in In(m)} L_{n,m}(\lambda) \leq 1, \forall \lambda \in W, \\ \forall m \in MC_{(G)}, \text{and } m \text{ is not s} \end{gathered} \tag{15}$$

$$\sum_{n \in Out(m)} L_{m,n}(\lambda) \leq Out_{(m)} \times \sum_{n \in In(m)} L_{n,m}(\lambda), \quad \forall \lambda \in W, \forall m \in MC_{(G)}, \text{and } m \text{ is not s} \tag{16}$$

Constraint (15) ensures that the number of incoming links to an optical splitter must be less than or equal to 1. Equation (16) indicates that if an optical splitter without wavelength conversion participates in the optical structure, the number of outgoing links of this optical splitter must be between 1 and $Out\,(m)$.

– $MC_{(G)}$ node ( with conversion)

$$\sum_{\lambda \in W} \sum_{n \in Out(m)} L_{m,n}(\lambda) \leq Out_{(m)} \times \sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda) \tag{17}$$

$$, \forall \lambda \in W, \forall m \in MC_{(G)}, \text{and } m \text{ is not s}$$

Equation (15) is same in both cases ( $MC_{(G)}$ node with or without wavelength conversion). Equation (17) indicates that if an optical splitter with wavelength conversion participates in the optical structure, the number of outgoing links of this optical splitter must be between 1 and $Out\,(m)$.

– $MI_{(G)}$ node ( without conversion)

$$\sum_{n \in Out(m)} L_{m,n}(\lambda) \leq \sum_{n \in In(m)} L_{n,m}(\lambda), \quad \forall \lambda \in W, \forall m \in MI_{(G)}, \text{and } m \text{ is not s} \tag{18}$$

For all $MI_{(G)}$ nodes other than the source node, constraint (18) verifies that the number of outgoing links is equal to or less than the number of incoming links.

$$\sum_{n \in Out(m)} L_{m,n}(\lambda) \geq \sum_{n \in In(m)} L_{n,m}(\lambda), \quad \forall m \in V, \text{and } m \text{ is not an element of D} \tag{19}$$

Apart from the destination nodes, constraint (19) ensures for all the other nodes that the number of outgoing links is greater than or equal to the number of incoming links.

– $MI_{(G)}$ node ( with conversion)

$$\sum_{\lambda \in W} \sum_{n \in Out(m)} L_{m,n}(\lambda) \leq \sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda), \quad \forall \lambda \in W, \forall m \in MI_{(G)}, \text{and } m \text{ is not s} \tag{20}$$

For all $MI_{(G)}$ nodes other than the source node, constraint (20) ensures that the number of outgoing links is equal to or less than the number of incoming links.

$$\sum_{\lambda \in W} \sum_{n \in Out(m)} L_{m,n}(\lambda) \geq \sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda), \quad \forall m \in V, \text{and } m \text{ is not an element of D} \tag{21}$$

Apart from the destination nodes, constraint (21) ensures for all the other nodes that the number of outgoing links is greater than or equal to the number of incoming links.

### *3.3.2. Tree structure with or without wavelength converters*

The set of constraints (1-17) are the same for the two optical structures.

- Constraints of the optical tree structure

  Non-member nodes constraint:

  – $MI_{(G)}$ node ( without conversion)

$$\sum_{n \in In(m)} L_{n,m}(\lambda) \leq 1, \forall \lambda \in W, \forall m \in MI_{(G)}, \text{and } m \text{ is not s} \tag{22}$$

For all $MI_{(G)}$ nodes other than the source node, constraint (22) ensures that the number of incoming links is equal to or less than 1.

$$\sum_{n \in Out(m)} L_{m,n}(\lambda) \leq 1, \forall m \in V, \text{and } m \text{ is not an element of D} \tag{23}$$

Apart from the destination nodes, constraint (23) ensures for all the other $MI_{(G)}$ nodes that the number of outgoing links is equal to or less than 1.

– $MI_{(G)}$ node ( with conversion)

$$\sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda) = \sum_{\lambda \in W} \sum_{n \in Out(m)} L_{m,n}(\lambda),$$

$$\forall m \in MI_{(G)} \setminus (s \cup D) \quad (24)$$

Equations (22) and (23) are the same in both cases of $MI_{(G)}$ node with or without wavelength conversion, but equation (24) is added to $MI_{(G)}$ node with wavelength conversion. Equations (22) and (23) indicate that the tree structure does not allow a cycle. Equation (24) ensures that the number of incoming links equals the number of outgoing links in the case of $MI_{(G)}$ node including the wavelength conversion capability.

## 4. Simulation results

In the first sub-section (4.1), the performance of the hierarchical structure (HS) and the tree structure (TS) are compared in the case of multicast routing without wavelength converters. This comparison is made in terms of the overall link cost. Then, in the second sub-section (4.2), the comparison is done between a WDM network with sparse wavelength converters and WDM network without wavelength converters using the hierarchical structure. The objective of the second sub-section is to focus on the benefits and performances of using the wavelength converters in WDM networks in terms of the overall link cost and the number of wavelengths.

The simulations are run on the PC with 1.7 GHz CPU and 4 GB of RAM. For the implementation of the ILP model, we use the C ++ language with Cplex packages. The results are obtained by considering the well-known COST-239 and USA Longhaul network topology. Each fiber supports a set of wavelengths $W$=4 [1], the links are bidirectional (each link is made of two fibers; each fiber is used in one direction), and wavelength converter is present in the network. For the COST-239 network topology, the number of $MC_{(G)}$ nodes is set at 2 nodes and the number of converters nodes is set at 3 nodes. For the USA

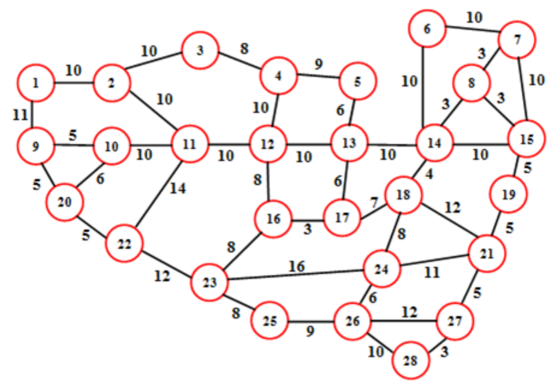



Figure 4: USA Longhaul network

Longhaul network topology, the number of $MC_{(G)}$ nodes is set at 5 nodes and the number of converters nodes is set at 9 nodes. $MC_{(G)}$ nodes and converters nodes were distributed randomly in the network (uniform distribution). The number of destinations $|D|$ is given by the graph topology. Destinations are drawn randomly (uniform distribution) and we randomly generate 100 multicast sessions. Then, we run the model to find the optimal solution generated for each session. Then, we compute, over 100 sessions, the average values of the overall link cost constituting the optical structure and the number of wavelengths used for each number of destinations. Two metrics are taken into account; these are defined as follows:

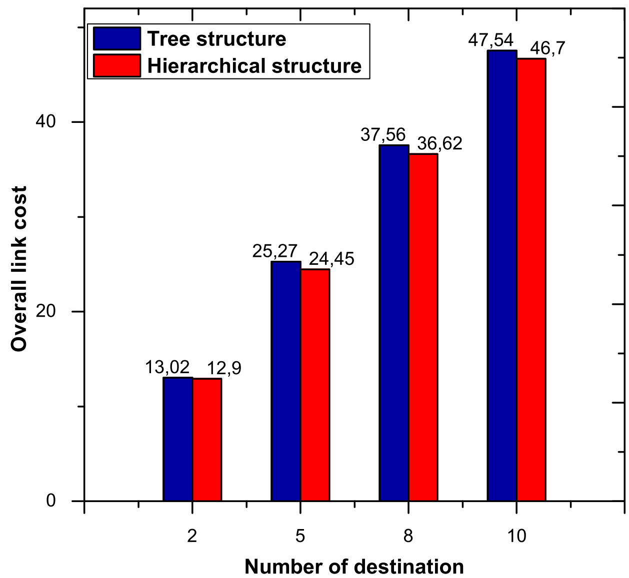
(1) The cost of the set of optical links constituting the optical structure (overall link cost): $CL = \sum_{\lambda \in W} \sum_{n \in In(m)} L_{n,m}(\lambda) \times C_{n,m}$

(2) The number of wavelengths used by the optical structure: $TC = \sum_{\lambda \in W} S(\lambda)$

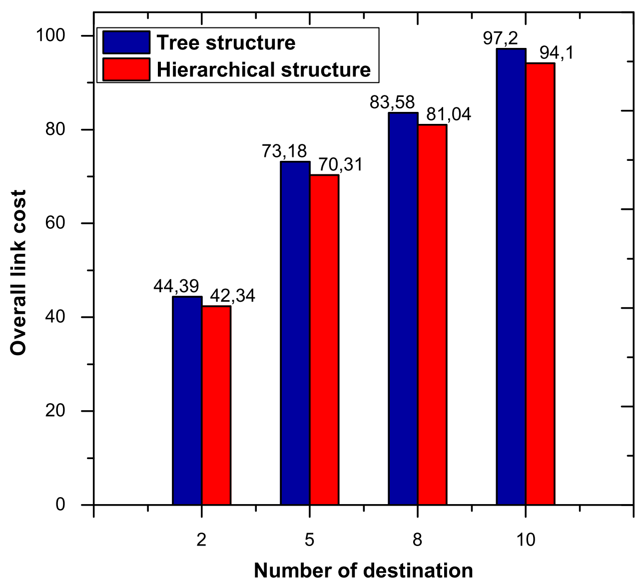
Based on the experimental results obtained from the well-known COST-239 network topology, we make the following observations in the two sub-sections.

### *4.1. Performance of the hierarchical structure (HS) versus the tree structure (TS)*

In the first sub-section, Fig. 5 presents the overall link cost as a function of the number of destinations in the case of the hierarchical structure versus

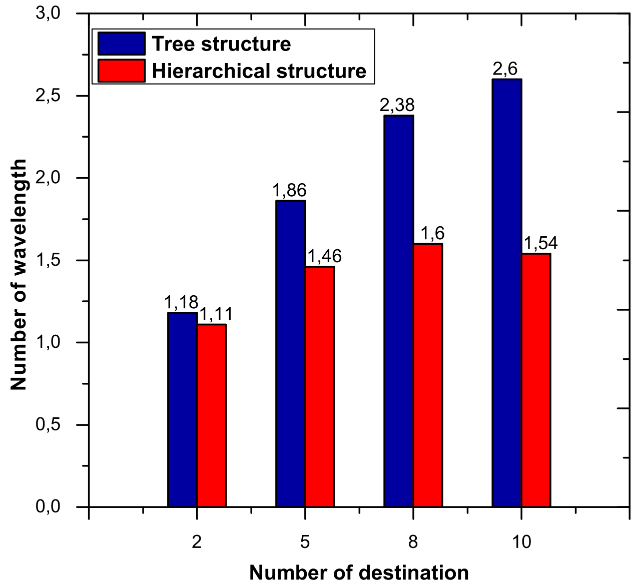



(a)

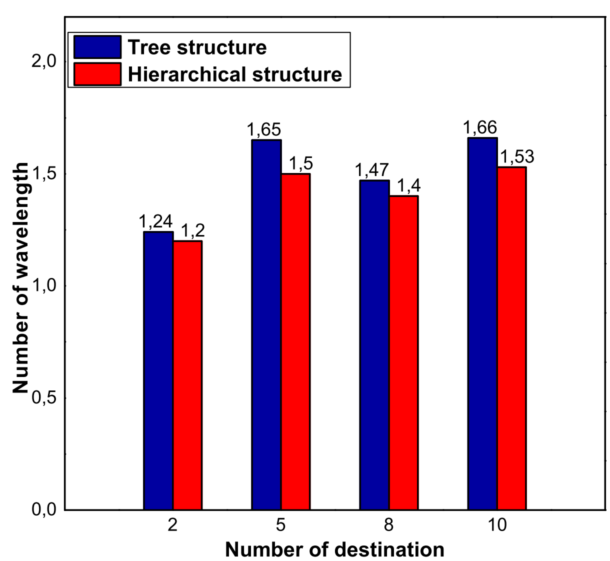



(b)

Figure 5: Overall link cost in the optical structure as a function of the number of destinations: (a) COST-239 network wth sparse splitting; (b) USA Longhaul network with sparse splitting




(a)



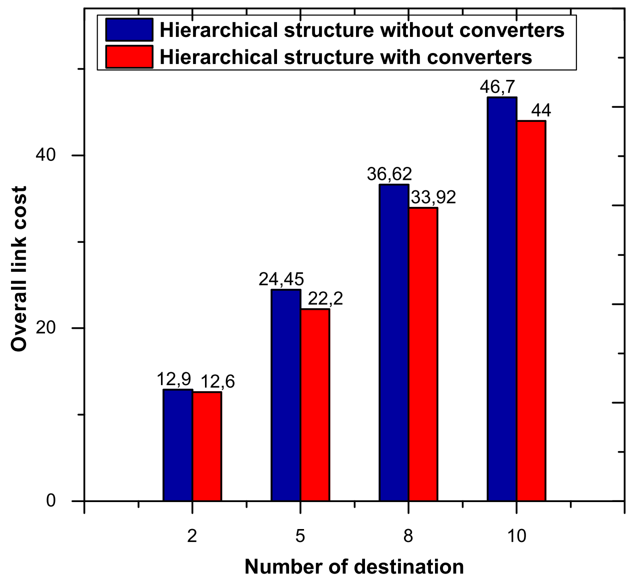

(b)

Figure 6: Number of wavelengths used by the optical structure as a function of the number of destinations: (a) COST-239 network with sparse splitting; (b) USA Longhaul network with sparse splitting

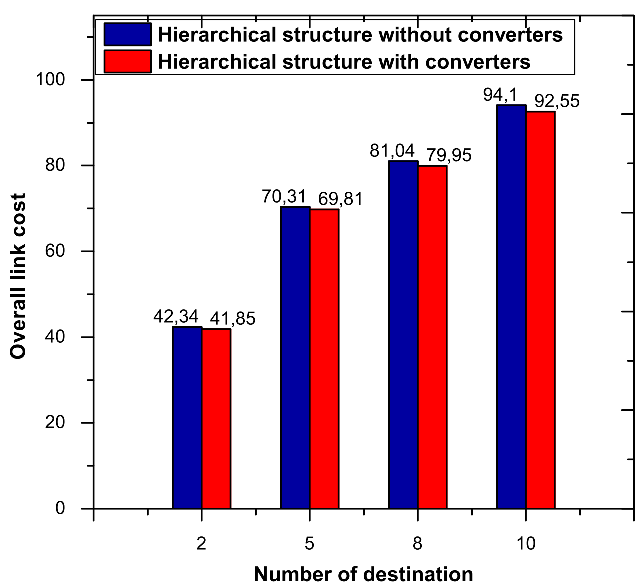
the tree structure. Fig. 5(a) shows that the overall link cost decreases by 1.67% to 6.27% in the case of COST-239 network. In the case of USA Longhaul network, Fig. 5(b) shows that the overall link cost decreased by 3.04% to 4.62%. Fig. 6 shows the number of wavelengths used as a function of the number of destinations in the case of the hierarchical structure versus the tree structure. The use of a hierarchical structure instead of a tree structure makes it possible to considerably reduce the number of wavelengths in the optical network. Indeed, Fig. 6(a) indicates that the number of wavelengths is reduced by 13.67% to 44.77% in the case of COST-239 network. Then, in the case of USA Longhaul network, Fig. 6(b) shows that the number of wavelengths decreased by 3.23% to 9.1%. This is measured using the number of times that an optical path of a multicast session passed more than once on the same optical node for the set of 100 generated sessions: 7 times for a multicast session with two destinations and up to 44 times for 5 destinations in the COST-239 topology.

*4.2. Benefits of using wavelength converters in a WDM network*

In the second sub-section, Fig. 7 presents the overall link cost as a function of the number of destinations in the case of the hierarchical structure without converters (HS) versus the hierarchical structure with converters (HSC). In the case of COST-239 topology, Fig. 7(a) indicates that the overall link cost was reduced by 2.68% to 10.15%. Then, in the case of USA Longhaul topology, Fig. 7(b) shows that the overall link cost decreased by 2.32% to 9.2%. Fig. 8 shows the number of wavelengths as a function of the number of destinations in the case of the hierarchical structure without converters versus the hierarchical structure with converters. Fig. 8(a) indicates that the number of wavelengths was reduced by 5.83% to 33.17% in the case of COST-239 topology. Then, in the case of USA Longhaul topology, Fig. 8(b) shows that the number of wavelengths decreased by 3.6% to 27.92%. Table 1 indicates the average execution time of the hierarchical structure in a WDM network with or without wavelength converters.

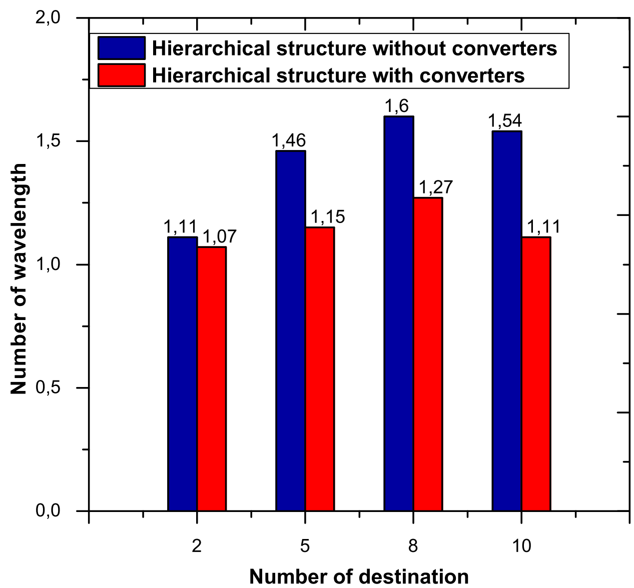



(a)

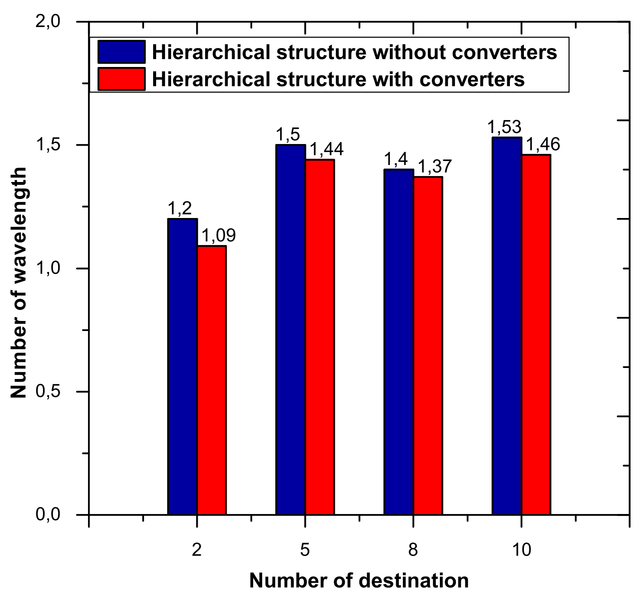



(b)

Figure 7: Overall link cost in the optical structure as a function of the number of destinations: (a) COST-239 network with sparse splitting; (b) USA Longhaul network with sparse splitting




(a)




(b)

Figure 8: Number of wavelengths used by the optical structure as a function of the number of destinations: (a) COST-239 network with sparse splitting; (b) USA Longhaul network with sparse splitting

| Average computation time in second (s) | | | | |
|---|---|---|---|---|
| $\|D\|$ | 2 | 5 | 8 | 10 |
| HSC | 0.37 | 0.51 | 0.62 | 0.72 |
| HS | 0.37 | 0.63 | 0.88 | 0.79 |

Table 1: Average computation time for one session of the hierarchical structure in a WDM network with or without wavelength converters (HSC or HC) in the case of COST-239.

## 5. Conclusion

In this article, we presented the routing and wavelength allocation problem with sparse wavelength converters and sparse splitting using a tree structure and a hierarchical structure. An ILP formulation is presented where the objective is to minimize the overall link cost constituting the optical structure required by the multicast session. Our main contribution consists of the introduction of the optical constraints coming from the wavelength converters within a hierarchical structure. The objective is to focus on the benefits and performance of using wavelength converters in a WDM network.

In the first part, the results of the simulations show that the hierarchical structure is better than the tree structure in terms of overall link cost and the number of wavelengths. In fact, the overall link cost decreases by 1.67% to 6.27% in the case of COST-239 network. In the case of USA Longhaul network, the overall link cost decreased by 3.04% to 4.62%. The fact that the hierarchical structure allows to pass more than once on the same optical node this permits a greater choice of paths and therefore potentially the possibility of finding more efficient paths.

In the second part, optical wavelength converters constraints are introduced into the model to study their benefits in WDM networks. Simulation results confirm that the hierarchical structure gives better results in the case of WDM network with wavelength converters than WDM network without wavelength converters, in terms of the overall link cost and the number of wavelengths. In fact, in the case of the COST-239 network, the cost of optical link decreased by 0.92% to

3.24%. In the case of USA Longhaul network, the overall link cost decreased by 2.32% to 9.2%. The introduction of wavelength converters allows a light path to use different wavelengths along the optical links. In other words, it removes the wavelength continuity constraint. As a consequence, it allows for a greater choice of paths and therefore the possibility of finding more efficient ones.

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