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Abstract

This paper introduces the Multi-Server Multicast (MSM) approach for Content Delivery Networks (CDNs) delivering services offered by a set of Data Centers (DCs). All DCs offer the same services. The network is an Elastic Optical Network (EON) and for a good performance, routing is performed directly at the optical layer. Optical switches have heterogeneous capacities, that is, light splitting is not available in all switches. Moreover, frequency slot conversion is not possible in any of them. We account for the degradation that optical signals suffer both in the splitting nodes, as well as across fiber links to compute their transmission reach. The optimal solution of the MSM is a set of light-hierarchies. This multicast route contains a light trail from one of the DCs to each of the destinations with respect to the optical constraints while optimizing an objective (*e.g.,* minimizing a function). Finding such a structure is often an NP-hard problem. The light-hierarchies initiated from different DCs permit delivering the multicast session to all end-users with a better utilization of the optical resources, while also reducing multicast session latencies, as contents can be delivered from such DCs closer to end-users. We propose an Integer Linear Programming (ILP) formulation to optimally decide on which light-hierarchies should be setup. Simulation results illustrate the benefits of MSM in two reference backbone networks.

Keywords: Data Centers, Elastic Optical Networks, Multicast Session Planning, Physical Layer Impairments, Degree-Constrained Steiner Problem, Light-Hierarchy, ILP.

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1. Introduction and Motivation

Cloud computing and networking are nowadays very popular and real possibilities for enterprises and end-users. In the last few years, the Data Center (DC) industry has played a key role in the development of the IT sector. Indeed, the total capacity of DCs is growing by 5 percent per year. In 2016, for example, approximatively 1710 important DC locations in North America and 1400 in Europe were counted. Providers (*e.g.,* CenturyLink, Cogent Communications, Equinix, NTT, Tiscali, TELEHOUSE, AT&T, etc.) offer services in several continents (for more details, *cf.* http://www.datacentermap.com/).

Content Delivery Networks (CDNs) are distributed, server set based systems. They can be composed of dedicated replica servers located at DCs across the network, providing replication of some contents. Such a geographic distribution of servers eventually offering the same content facilitates and accelerates service delivery to end-users, as contents can be delivered to them from their closest replica server, thus minimizing network resources and experienced latencies. The latest CISCO traffic forecasts [1] highlight the key role that CDNs will most probably play in the short-term future, carrying up to 71% of all global Internet traffic by 2021. Therefore, to cope with such a huge amount of traffic, it seems natural that CDNs will have to operate over ultra-high capacity network infrastructures. Service providers provide a large number of profiles, including data storage, server hosting, integrated services, voice and data communications, video and content distribution, different cloud-based solutions, etc. Each service may have a special requirement, and require a more or less rigorous QoS level or security.

To connect DCs to end-users for an effective service delivery, routing may involve unicast but also anycast and multicast communications. Multicast communication technique is important to save network resources when several end-nodes are involved in the communication. Typically, big data-related broadcasting, stock information, results of environment measurements, data collected from IoT segments (traffic, meteorology, etc.), news, collaborative applications, multimedia applications, video, TV broadcasting, and games are examples of multicast-based applications. Data transfers between DCs can also be based on multicast. The required bandwidth can be very different for these applications, typically 1-10 Mbps for simple voice, 10-100 Mbps for video and TV streaming, and some Gbps for data transfers between DCs. When end-users are scattered across the network, a single route to reach them all can require a substantial amount of resources and also a high latency, a crucial figure toward successful 5G services. In this paper, we focus on the case where several equivalent servers are available in the network. This enables to organize multicast sessions based on a set of servers: Multiple Server Multicast (MSM) in contrast to the Single Server Multicast (SSM), leveraging the content replication in CDNs.

Current multicasting in CDNs is based on IP. However, IP multicasting is not scalable and the multicast implemented in the application layer introduces delays and additional traffic load. Over the last decade, Network Virtualization and Software Defined Networking (SDN) have emerged as new solutions to facilitate distributed systems like CDNs. Abstractions in virtual networks permit network services to be developed and deployed independently from underlying physical infrastructure. SDN is a solution where data forwarding and control planes are separated. Generally, routing decisions are taken from a central control entity and the data follows the computed routes. SDN and virtualization are closely related to each other. Virtualization permits the coexistence of networks on a shared physical infrastructure; it can be used to perform SDNs. SDNs find viable applications in not only network virtualization but also in the optical networking domain [2]. We propose a potential SDN-based multicasting directly at optical layer.

One of the most promising solutions for implementing backbone networks is all optical networking using optical switches. Specifically, Wavelength Division Multiplexing (WDM) is the legacy solution for circuit switching in all-optical networks. Circuits are trivial elements for virtual networks and can be computed by an SDN controller. In all optical networks the used technology involves additional constraints (uniqueness of carriers in fibers, wavelength continuity, physical impairments, degree constraints in the traversed switches, etc.).

With the advent of Elastic Optical Networks (EONs), the flexibility of optical channels permits managing network resources in a more efficient manner when supporting connections at multiple bit-rates [3]. To solve the (multicast) routing at the optical layer, the decision should entail the route computation jointly with the assignment of the frequency slots and modulation format used in the transmission, which is known as the Routing, Modulation level and Spectrum assignment (RMSA) problem. In the network, we assume heterogeneous switches and sparse splitting capability. Consequently, we focus on adequate optimal solutions corresponding to light-hierarchies (*cf.* Section 4.1). In the Multi-Server Multicast (MSM) approach, a set of light-hierarchies allows from multiple DCs to serve all end-users. In this way, better utilization of the resources can be achieved, while also reducing latencies, as contents can be delivered from DCs closer to end-users.

In summary, we are interested in the design of DC-based content distribution. We consider heterogeneous EONs. The network interconnects DC servers to destinations in an end-to-end fashion, taking IPTV CDNs as reference scenario. There are several DCs, which can distribute simultaneously the same content. The destinations are EON switches connecting eventual sub networks and users. The distribution uses optical multicasting for different sets of destinations. The optical multicast routes can be computed by an SDN controller or a Path Computation Element (PCE) and should satisfy the physical constraints. The objective is the optimal organization of this content delivery.

The paper presents the optimal route (which is a set of light-hierarchies and not always a set of light-trees) and proposes an Integer Linear Programming (ILP) formulation to find this set. That is, the ILP decides from which DCs routes will be started, as well as their structure to reach a specific sub-set of end-users. Moreover, the effect of the physical layer impairments on the eventual transmission reach of the optical signals is accounted in the ILP. For this, we propose the extension of a model widely accepted for unicast routing to multicasting. Once the ILP is presented, we use it to disclose some illustrative results of the benefits achievable by MSM versus SSM.

Our paper is organized as follows. In the following section the most related works are presented. Section 3 gives the definition of the problem. Section 4 briefly presents the proposed graph model and some relevant related concepts. The design of the exact ILP formulation is in Section 5 and the computation results can be found in Section 6. Conclusions and perspectives remarks close our study.

2. Related Work

Today, several cloud based CDNs are emerging [4]. Often audio and video streams, stock data, big meteorologic data bases are delivered [5]. With the arrival of DCs some networking paradigms need to change: *1)* particular networks may be needed inside DCs to link several thousand machines in a reliable and economic manner [6] [7] *2)* access to (DC based) services must be ensured with variable and often high bandwidth and must be reliable (*cf.* a survey in [8]) *3)* sub-sets of DCs (*e.g.,* DCs of a company, CDNs, etc.) must be inter-connected with high capacity connections for data exchanges [9]. To ensure more efficient network management, virtualization of network functions and SDN have been deeply changing the network control and data planes. The counterpart of this evolution is that more complex problems should be solved (*e.g.,* in routing, load balancing, security, etc). SDN enables more complex and precise network management. Often in SDN, the routing decisions are taken by a central entity (for example PCE) that configures the switches for data forwarding [10]. Openflow is one of the most widely used protocol for the communication between the controller and routers. Openflow supports multicast by default [11]. The structure of the network is essential for the services. In [4] an overview of DCNs for cloud computing is presented. The wide relation between SDN and optical networks is analyzed in a large survey [12].

In an invited paper of IEEE Proceedings ([13]), authors suppose that optical network based cloud computing becomes the key element of future services. Moreover as it is indicated, multicast is a good candidate for efficient communication between different DCs and users for the distribution of experimental or collected data and related results for highly expensive computing and further analysis and interpretation. Another trivial use case for multicast is IPTV where the TV is broadcased for several distributors, sites, users. The Internet-Draft "Multicast in the Data Center Overview" proposes IPTV service providers to use multicast to deliver content from the DC to end users. Redundant servers are sending multicast streams into the network and the network is forwarding the data across diverse paths [14].

As presented in [15], EONs provide significant benefits toward spectrum-efficient service provisioning (the multi-path routing is also analyzed, which can be efficient but is out of scope of our recent study). In [9] the elastic optical inter-DC network problem is analyzed. In this study, the requests are sporadic, highly dynamic anycast type requests where any DC can satisfy any request.

Both the offline and online routing and spectrum assignment (RSA) problems are formulated as ILPs and heuristics are also proposed.

In a CDN over EON scenario, when a specific content is simultaneously requested by a set of end-users, the standard anycast solution establishes one light-path from any one of the multiple DCs for each end-user (*e.g.,* as in [16]). Instead, using multicast, the requested content can be provided from any one of the multiple DCs to all end-users together. This can be performed by setting up a light-tree [17] or a light-hierarchy [18], being the latter the optimal solution under splitting constraints. We refer to this approach as Single Server Multicast (SSM).

Different exact formulations of the related problems exist in the literature. An ILP for manycast (unicast, multicast and anycast) routing using a set of DCs in EON has been formulated in [19]. This RSA problem tries to minimize the energy usage. An additional adaptive modulation format selection can be found in [20]. Optical multicasting in EON has been analyzed in several works (*e.g.,* [21]). Co-joint optimization of unicast and multicast is discussed in [22]. Physical impairments should be taken into account in the route computation. For unicast communications it can be modeled by means of the well-known GN-model [23], extending it for multicast ones. In [24] the optimization of multicast routing in EON (where all network nodes are equipped with multicasting) is discussed. The requests are satisfied by light-trees. The spectrum requirements are determined using the distance-adaptive transmission (DAT) principle[1]. The authors formulate two ILP models, one of them with a previous computation of candidate trees and also propose a heuristic method. A DAT based impairment- and splitting-aware cloud-ready single source multicast provisioning is presented in [25]. It is important to notice that all these works are based on light-trees and the optical switches are assumed to be multicast capable and server replications are not taken into account.

3. The Multi-Server Multicast Routing Problem in EON

We assume an EON represented as a directed topology graph $G_t = (V_t, A_t)$, where V_t is the set of nodes (*i.e.* Bandwidth Variable Optical Cross Connects, BV-OXCs) and A_t the set of arcs corresponding to unidirectional optical fiber links. Two unidirectional fiber links in opposite directions are assumed between each connected node pair. The spectrum of each fiber is discretized as an ordered set $F = \{f_1, f_2, \cdots, f_{|F|}\}$ of Frequency Slots (FS). We assume heterogeneous switches and consequently sparse splitting in the EON, namely, only a subset $MC \subseteq V_t$ have multicast capability in the network (*e.g.,* nodes having B&S ROADM and Non-broadcast&S architectures). In contrast, the set $MI = V_t \setminus MC$ represents the multicast incapable nodes (*e.g.,* R&S nodes with basic FlexGrid WSSs) [26]. We denote as R_t the set of DCs where CDN replica

[1] DAT consists in selecting the most effective modulation s.t. the maximal source-destination distance does not exceed the modulation transmission range.

servers are located. Each $r \in R_t$ is co-located with one EON node $v \in V_t$. Without loss of generality, we consider that all DCs replicate the CDN content to be delivered to end-users.

Bandwidth Variable Transponders (BV-TXPs) equipped at EON nodes can operate at a set of possible bit-rates B and employ a set of modulation formats M at any bit-rate $b \in B$. Therefore, the number of adjacent FSs required for a request using a given modulation format can be computed (*cf.* Section 5.1). Moreover, as we do not consider spectrum conversion in the EON, the same selected contiguous FS block will have to continuously allocated from source to destination nodes.

To decide RMSA in the EON, a controller is implemented (a PCE or an SDN controller). Although a request will generally be necessary to ask for a multicast session to the controller. In case of acceptance, the traffic will be from the DCs to the end-users. Multicast requests are served upon arrival, taking the current state of the network resources into account and trying to meet an optimization criteria. The state of the network is given by the set of available (and occupied) frequency slots in each fiber link.

To serve a multicast session request, different strategies could be employed:

- Single Server-based Multicast (SSM): The DC from which the multicast contain is delivered is chosen in an anycast fashion, taking the specific optimization criteria into account. In this case a single light-hierarchy is setup in the network.
- Multi-server-based Multicast (MSM): In this case, multiple light-hierarchies (initiated from different DCs if needed) can be setup to deliver the video content to all end-users of the request. The DCs from which the light-hierarchies are initiated can be: *1)* chosen in an anycast fashion, taking a specific optimization criteria / clusterization of destinations into account *2)* given by a unique joint optimization. In this paper, we propose this second MSM solution; the classification of destinations is useless applying our solution.

In both aforementioned SSM and MSM strategies, it is mandatory to deliver the requested content with the requested quality to all end-users of the request. However, we could also think about still accepting (slightly) degraded requests if they can be served given the current state of network resources, instead of directly blocking them. Such degradation could happen in terms of the number of end-users served and/or the quality of the delivered content. The optimization of the eventually limited, degraded services is a very promising subject but it is out of scope of our actual study.

Let us define our problem more precisely.

Problem 1. Multi-Server Multicast problem (MSM) *The MSM problem aims at finding a set of optical multicast routes rooted at some DC corresponding to an objective, while satisfying optical constraints, such as the availability of the FSs at fiber links, the spectrum contiguity and continuity along the communication imposed by the EON, the limited transmission reach of the optical* *signals (depending on the employed modulation format) and, finally, the splitting capacity constraint in the switches.*

Different objectives can be followed to compute the optimal routes. Without being exhaustive, the most frequently used objectives for routing in EONs follow.

1. Minimization of the used resources (modeled by an additive cost)
2. Minimization of the highest index of FSs used permitting more possibilities for ulterior routing demands
3. Optimization of some QoS parameters (*e.g.,* latency, etc)
4. Minimization of the energy, ...

The optimization can be mono-objective or several objectives can be combined and a multi-objective optimization can serve the routing.

In this paper, we consider the objective of minimizing the highest index of the slots used and also the number of FSs used. The solution to this problem is a set $\mathcal{H}_l = \{H_i, i = 1, \ldots, |\mathcal{H}_l|\}$ of directed light-hierarchies H_i covering the destination set. They can use different modulation formats and FS blocks. The solution must contain at least one feasible light-trail from a DC node to each destination. Since the solution minimize the used resources, finding the optimum is NP-hard even if there is only one server [18]. The mathematical formulation is in the next section.

4. Proposed Models and Solutions

At first, we demonstrate that the optimal multicast route is not mandatorily a (set of) light-tree(s) but a (set of) light-hierarchy(ies). Then, we propose an adequate graph model for the computation.

4.1. Hierarchies

Without loss of generality, let us suppose there is a single source (DC) for multicasting. Usually, *p*artial spanning trees (*i.e.* connected sub-graphs without cycles) are considered as the minimum cost solutions for multicast routing. However, they have some limitations. Trees can not always satisfy the constraints on node degrees representing the splitting capacity of nodes and, in some cases, there is no tree-based solution. As demonstrated in [27] a more flexible solution is a connected, graph related structure called *hierarchy.* A hierarchy is defined as follows.

Definition 1 (Hierarchy)**.** *Given an arbitrary graph $G = (V, E)$ and a tree $T = (W, F)$, let $x : W \to V$ be a homomorphism which associates a node $v \in V$ to each node $w \in W$.*[2] *The application (T, x, G) defines a hierarchy in G.*

[2] A homomorphism preserves the adjacencies of nodes; $w_1 \in W$ and $w_2 \in W$ can be adjacent iff the corresponding nodes $v_1 \in V$ and $v_2 \in V$ are also adjacent

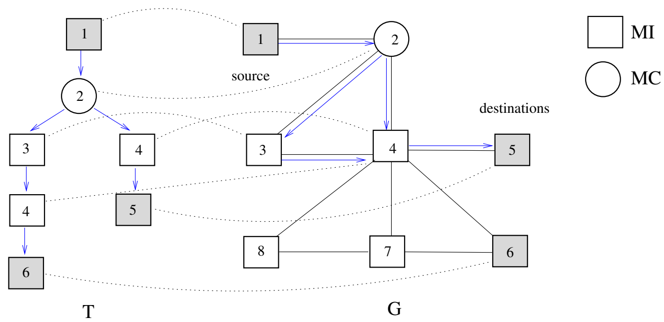

Figure 1: Example of a light-hierarchy

Notice that a hierarchy is not a sub-graph, but it generates a sub-graph of G. This sub-graph is the *image* of the hierarchy and may contain cycles. Even if there is no spanning tree to cover the nodes to span and satisfying a set of degree constraints, such a hierarchy can exist. In some other cases, spanning hierarchies give better solutions than trees.

For optical multicast data forwarding, the route is rooted at the source and we consider rooted directed hierarchies (the tree T is rooted and directed). The solution will be detailed by the computational model in the next section. Here we propose the extension of light-hierarchies to EONs presented in [18] for WDM techniques.

Definition 2 (Light-hierarchy in EON)**.** *A light-hierarchy is a directed rooted hierarchy, which use the same frequency slots from the source to the destinations.*

Figure 1 illustrates a light-hierarchy. The graph G is the topology graph of the network and the tree $T = (W, F)$ represents the routing information (the succession of nodes in the route). The splitting constraints are respected by the light-hierarchy (remember MI nodes haven't splitters).

Theorem 1. *The optimal multiple server multicast route (e.g., with minimum cost, or with minimum highest index of FSs used, etc.) in EONs under the optical constraints is a set of light-hierarchies covering the destination set. Each of these directed hierarchies is rooted at one of the DC nodes. They can use different frequency slot blocks.*

Proof. The optimal (*e.g.,* minimum cost,etc.) route is a set of directed connected multicast routes. Trivially, each route of the set is directed from one of the DC nodes to a sub set of destinations. We should prove that this set of multicast routes corresponds to a set of directed hierarchies. That is, a directed graph T_i can be associated with the component (route) r_i of the solution. This graph T_i should be connected (it should contain a directed trail from the source to each destination). If the associated connected graph T_i is not a tree (the route is not a hierarchy), there is at most one *useless* cycle in T_i and the route r_i can not be optimal.

To avoid conflicts using a same arc in G by several light-hierarchies, they can use different, non-overlapping frequency slot blocks. □

In the following, the complexity of the optimization is shortly discussed. Let us suppose the routing can use a given FS block and a modulation associated with. The directed topology graph of available links is $G_s = (V, A_s)$ and the source s and the destination set D are given. The modulation implicates a maximal transmission range TR for unicast communication. To simplify, suppose that TR limits the longest light-trail in the solution. Since hierarchies include trees, we are searching for light-hierarchies and the following question can be formulated.

Is there a light-hierarchy directed from s to D in G_s respecting the maximal transmission range and the degree constraints imposed by the set of MI nodes? This question can be seen as the existence problem of a radius and degree constrained directed partial spanning hierarchy.

Lemma 1. *It is NP-complete to decide if G_s contains a partial spanning hierarchy respecting the degree and the radius constraints.*

Proof. The problem is in NP, since it is easy to verify, if a hierarchy respects the constraints or not.

To prove the hardness, let us focus on the degree constraints. In a particular case, the set MC is empty and the degree bound of nodes is equal to two. That is, the solution is a walk (the tree T in the hierarchy definition is a path). The question is: is there a directed walk from the source and covering the destinations with limited total length. This problem corresponds to the directed traveling salesperson walk problem, which is NP-complete [28]. □

The interest of the light hierarchies for multicast routing can be illustrated as follows. To simplify, let us suppose that a request needs one FS from the source a to the destinations e and g in the network indicated in Fig. 2/a). Let us suppose that two FSs ($FS1$ and $FS2$) are partially available for this routing as it is indicated in Fig. 2/b and Fig. 2/b) respectively. Let us suppose that $index\ of\ FS1 < index\ of\ FS2$. Using $FS1$ we obtain a light-hierarchy and using $FS2$ we have a light-tree as the figure indicate them with dotted lines. If the objective is the minimization of the maximal index of the FSs, the light-hierarchy using $FS1$ is better. It is not true for the costs, the light-hierarchy uses 7 arcs whereas the light-tree uses only 4 arcs.

4.2. Graph Model

To compute the optimal solution corresponding to a set of light-hierarchies, we propose some simple considerations to construct an auxiliary layered graph.

1. Since, a source can inject the light simultaneously into several fibers, DC nodes in R can be considered as MC-nodes.

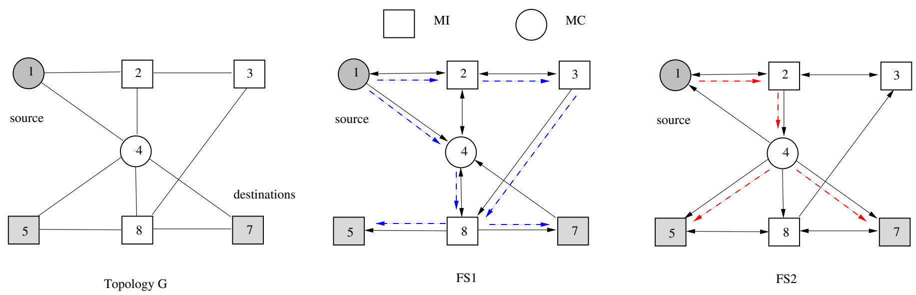

Figure 2: Interest of a light-hierarchy vs. a light-tree

2. To take into account all combinations of modulation formats and FSs that can participate in the routing, a layered auxiliary graph can be used similarly to the proposition in [29]. In our model, this layered graph is generalized to support a set of modulation formats. For each modulation format e, the capacity ns_e in number of FS blocks needed for the request can be determined. Then a set of sub-graphs is generated whose cardinality is $|F| - ns_e + 1$. A sub-graph $G^k = (V^k, A^k)$ is generated for each possible contiguous FS subset $SB^k = \{b_k + i, i = 0, \dots ns_e - 1\}$. For each node $v \in V_t$ corresponds a node $v^k \in V^k$. An arc $a^k \in A^k$ is present in G^k iff the subset SB^k is available in the corresponding arc $a \in A_t$: $f^a_{k+i} = 1, i = 0, \dots ns_e - 1$.
3. In any valid optimal solution of our problem, there is no return to a DC, therefore incoming arcs of the data centers can be deleted.
4. An artificial source node can be added to the graph such that this source is connected to the copies of DC nodes in R by zero cost arcs having all frequencies available in the homogeneous frequency spectrum F in the network.
5. If a sub-graph G^k does not contain any directed path from the source to a destination, the sub-graph is deleted.
6. Since a destination should be spanned in at least one light-hierarchy but this light-hierarchy and its associated slot block can be arbitrary, the nodes d^k in the different sub-graphs corresponding to the same destination d can be connected to a virtual destination d' in the auxiliary graph. In this manner, the virtual destinations should be covered. To avoid the multiple spans of a virtual destination, the incoming arcs of these virtual destinations must have the same positive costs.

The auxiliary graph is illustrated in Figure 3 and can be the target of additional practical reductions (*cf.* Section 5).

In this graph a directed light-hierarchy H^* is computed from the artificial source to all virtual destinations. By construction, sub-hierarchies of the source pass obligatory by some DC-nodes. After deleting the artificial source and the virtual destinations, a disconnected set $\mathcal{H}^*$ of sub-hierarchies is remained. Each

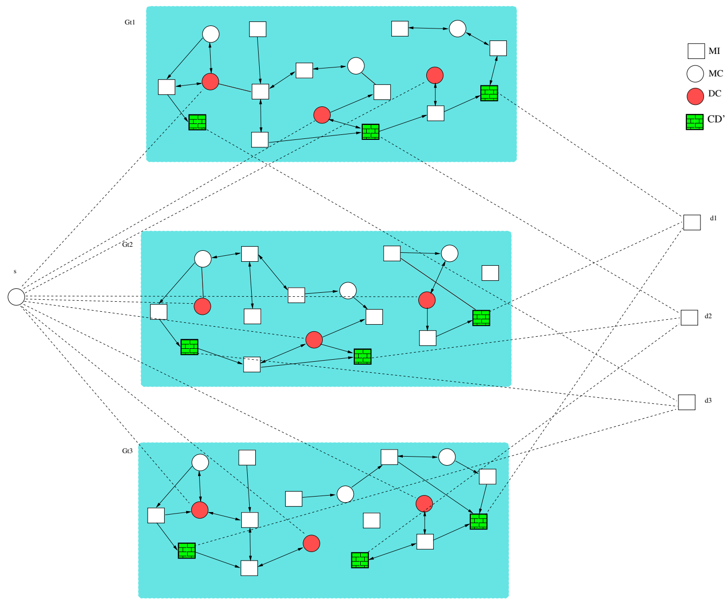

Figure 3: The directed auxiliary graph with the virtual destinations

sub-hierarchy is a light-hierarchy rooted at one of the DC-node. Let us suppose that H^* is optimal: *e.g.,* with the minimum highest index of FSs. Since the artificial arcs have unlimited capacities, the remained set $\mathcal{H}^*$ is also optimal.

An important property of our auxiliary graph is that each sub-graph G^k corresponds to a modulation format and a slot block. Consequently, an arc of the auxiliary graph can be used in the solution at most once and its usage implicates the usage of the associated modulation format and slot block. This property simplifies the mathematical formulation in Section 5.

4.3. Transmission reach estimation for multicast

In order to account for the physical degradations experienced by optical signals along the routes, we propose to rely on the well-known Gaussian Noise (GN)-Model proposed in [23], whose reliability for nonlinear fiber propagation has been proven in most cases of interest. Nonetheless, the GN-Model does not account for the additional noise that would be introduced when amplifying optical signals after splitting them at network nodes, which degrades their eventual transmission reach. Therefore, we assume in this work that no optical signal splitting occurs at MI nodes, whereas they are split at MC ones only when strictly needed to construct the light hierarchy (or light tree).

Under these considerations, we firstly obtain the worst-case transmission reach values using the GN-Model, what we refer to as the unicast transmission reach. For this, we assume the "Link 1" scenario in [23], similarly to as in [30], from which we get different transmission reach values depending on the modulation format employed. A particularity of the GN-model is that, given a specific modulation format and spectral efficiency, the nonlinear interference is independent of the number of channels, that is, it is independent of the symbol rate used in the communication.

To account for the multicast nature of the communications, we rely on the fact that the transmission reach values in the GN-Model depend on the number of spans (amplification stages that introduce noise) along the route. Therefore, if an optical signal is split and amplified at an MC node, its transmission reach is reduced by a span length (L_{span}) as a worst-case. Hence, if $TR_e^m(l)$ denotes the transmission reach value over the route from the source to leaf node l, and TR_e denotes the unicast transmission reach value provided by the GN-Model, we can relate them as:

$$TR_e^m(l) = TR_e - n_{MC}(l) * L_{span} \tag{1}$$

where $n_{MC}(l)$ is the number of MC nodes crossed in the route where splitting is performed (referred to as branching nodes). To respect the QoT at the destinations, it is sufficient to verify, for each leaf node l, that the distance from the source to it does not exceed $TR_e^m(l)$. Again, we would like to point out that this is a worst-case estimation of the transmission reach estimation for multicast communications. Nonetheless, given its linearity, it is very convenient for considering it in an ILP formulation as the one in the following section.

5. Exact Solution

Before the design of the hierarchy computations, a pre-computation step is proposed. Then we present the computations using an ILP. The notations and network parameters are summarized in Table 1. Let us notice that some parameters are the same for all arcs in a given sub-graph of the auxiliary graph. An example is the contiguous set of frequency slots available in the arcs (it is the same for all arcs in a given sub-graph). To reduce the number of parameters, the homogeneous parameters of a sub-graph are associated with the first artificial arc from the artificial source to the given occurrence of a DC node.

5.1. Pre-computation

The objective of this step is to compute the auxiliary graph, and to reduce the search space by some simplifications.

a. A sub-graph corresponds to a modulation format and a slot block capable of satisfying the multicast request. The number ns_e of slots needed to satisfy the required capacity C using modulation efficiency m_e is

$$ns_e = \left\lceil \frac{\frac{C}{m_e} + w_{GB}}{w_{FS}} \right\rceil \tag{2}$$

where w_{FS} and w_{GB} indicate the width of the slots and guard bands respectively. The slot interval F contains $nbsb_e = |F| - ns_e + 1$ slot blocks with

Table 1: Network parameters and notations

$G_t = (V_t, A_t)$	The directed topology graph.
$G = (V, A)$	The directed auxiliary graph.
$R \subset V$	The set of DCs in the auxiliary graph.
$r \in R \subset V$	A DC node in the auxiliary graph.
$MC \subset V$	The set of MC-switches in the auxiliary graph.
$MI \subset V$	The set of MI-switches in in the auxiliary graph.
$s \in V$	The artificial source.
$D \subset V$	The set of nodes in G corresponding to the destinations in G_t.
$D' \subset V$	The set of virtual destinations in the auxiliary graph G.
$D^d \subset V$	The set of (duplicated) destinations connected to d'.
B	the required capacity (in Gbps) of the multicast request.
C	the capacity (in Gbps) of an FS when using BPSK as modulation format.
$(u, v) \in A$	The arc from node u to node v.
$l(u, v)$	The length of the arc (u, v).
$Out(v)$	Extremities of the outgoing arcs from node v.
$In(v)$	Extremities of the incoming arcs to node v.
$Deg^-(v)$	The in-degree of node v.
$Deg^+(v)$	The out-degree of node v.
F	The set of frequency slots supported in the network.
f_i	A slot $f_i \in F$.
$f_i(u, v)$	It is 1 when the slot f_i is available in arc $(u, v) \in A$
m_e	The modulation efficiency of the modulation format e $e = 1, \ldots, 4$, in bits/s/Hz
TR_e	The maximal transmission range for unicast transmission corresponding to the modulation format e.
L_{span}	The distance equivalent with power loss caused by a traversed splitter.
ns_e	The requested capacity in number of slots corresponding to the modulation format e.
SB_e	The set of contiguous slot blocks with capacity ns_e.
SB	The set of contiguous adequate slot blocks, $SB = \cup_{e=1,\ldots,4} SB_e$
sb_k	The k^{th} slot block, $sb_k \in SB$.
G^k	Sub-graph associated with slot block sb_k.
$b(s, r)$	The index of the highest frequency slot in the sub-graph rooted at r (associated with arc (s, r)).
$L(u_t, v_t) \subset A$	The set of arcs in G corresponding to $(u_t, v_t) \in A_t$.

ns_e contiguous slots in each. A slot block set SB_e is then computed for each modulation. The entire available slot block set is $SB = \cup_e SB_e$ and contains $nbsb = \sum_e nbsb_e$ blocks. For each slot block $sb_k \in SB$ a sub-graph G^k is generated. An arc (u, v) is present in G^k, iff the subset sb^k is available in (u_t, v_t): $f_{k+i}(u, v) = 1, i = 0, \ldots ns_e - 1$.

b. The artificial (virtual) source and the set of virtual destinations are created and connected to the sub-graphs.

c. The nodes for which the shortest path from the source is longer than the maximum transmission reach and the nodes without incoming arc are deleted.

d. If a sub-graph G^k does not contain a path from the source to any destination, the sub-graph is deleted. (Notice these verifications may be done in polynomial time by using a simple shortest path computation.)

The solution is computed by an ILP in the auxiliary graph.

5.2. ILP formulation

Our ILP is based on flows associated to destinations. The following variables are used in the ILP.

$x(u, v)$	Binary variable that indicates whether the arc (u, v) is used
$y^d(u, v)$	Commodity flow variable. Equal to 1 if the flow from s to virtual destination $d \in D'$ passes by arc (u, v).
s_i	Binary variable that is equal to 1 if the frequency slot f_i is used in the solution
$mc(u)$	Binary variable that is equal to 1 if the MC node u is branching node in the solution
$mc(u)^d$	It is equal to 1 if the MC node u is a branching node to virtual destination $d \in D'$
w	Integer variable that is the highest index of the used FSs.

The ILP follows the main lines of the formulation in [18], which computes light-hierarchies (and not only light-trees) in WDM networks. Our formulation adapts the ILP to compute light-hierarchies using convenient FSs.

To avoid to produce highly congested links that could prevent the allocation of future demands, in this study we consider as first objective the minimization of the highest FS index used in the route. We also consider the minimization of the number of FSs. We should allocate routes using the fewer amount of resources (number of FSs) as possible.

Objective:

We minimize the maximal index of the FSs used first, then try to minimize of the number of FSs.

$$\min(\Delta \cdot w + \sum_{i=1}^{|F|} s_i) \tag{3}$$

Δ should be large enough to ensure the priority of the first part, so we set $\Delta = |F|$. Trivially w should be at most equal to the highest indexes in the different sub-graphs:

$$b(s, r_k) \cdot x(s, r_k) \leq w \qquad \forall k = 1, \ldots, nbsb \tag{4}$$

This objective is subject to the following constraints (5 − 22). In these constraints, we use $\forall d$, $\forall i$, and $\forall(u, v)$ to imply $\forall d \in D'$, $\forall i = 1, \ldots, |F|$, and $\forall(u, v) \in A$, respectively.

5.2.1. Light-Hierarchy Constraints

The number of outgoing links at the source is limited by the number of destinations.

$$1 \leq \sum_{v \in Out(s)} x(s, v) \leq |D| \tag{5}$$

Each destination should be spanned by one incoming arc of the solution.

$$\sum_{v \in In(d)} x(v, d) = 1 \qquad \forall d \tag{6}$$

Constraints (7), (8) guarantee that an MC node u has at most one input arc and the number of used output arcs is at most $Deg^+(u)$ (it can be 0, when there in no input for the node).

$$\sum_{v \in In(u)} x(v, u) \leq 1 \qquad \forall u \in MC \tag{7}$$

$$\sum_{v \in Out(u)} x(u, v) \leq Deg^+(u) \cdot \sum_{v \in In(u)} x(v, u) \quad \forall u \in MC \tag{8}$$

For MI type nodes, which do not correspond to any destination, the number of output arcs is limited by the number of input arcs.

$$\sum_{v \in Out(u)} x(u, v) \leq \sum_{v \in In(u)} x(v, u) \qquad \forall u \in MI \setminus D \tag{9}$$

If the MI type node corresponds to a destination, the related virtual destination can be reached from a given occurrence of the node.

$$\sum_{v \in Out(u)} x(u, v) \leq \sum_{v \in In(u)} x(v, u) + x(u, d) \quad \forall u \in MI \cap D, \forall d \tag{10}$$

For the non destination nodes, the following constraint is held.

$$\sum_{v \in Out(u)} x(u, v) \geq \sum_{v \in In(u)} x(v, u) \qquad \forall u \notin D' \tag{11}$$

5.2.2. Spectrum Non-overlapping Constraints

In a fiber corresponding to an arc (u_t, v_t) of the topology graph, a slot can be used at most once. The following constraint guarantees that two overlapping slot blocks can not be used in a same arc.

$$\sum_{(u,v) \in L(u_t, v_t)} x(u, v) \cdot f_i(u, v) \leq 1 \; \forall (u_t, v_t) \in A_t, \forall i \tag{12}$$

A slot s_i is used in the solution iff it is used in some arc $(s, r), r \in R$.

$$f_i(s, r) \cdot x(s, r) \leq s_i \qquad \forall i, \forall r \in R \tag{13}$$

$$s_i \leq \sum_{r \in R} (f_i(s, r) \cdot x(s, r)) \qquad \forall i \tag{14}$$

5.2.3. Flow Conservation Constraints

$$\sum_{v \in In(u)} y^d(v, u) - \sum_{v \in Out(u)} y^d(u, v) = \begin{cases} -1, & u = s, \\ 1, & u = d, \\ 0, & \textit{otherwise}. \end{cases} \qquad \forall d \tag{15}$$

Eq. (15) ensures that if a virtual destination node d is covered in the solution, it can only be served in one light-hierarchy, and there is a single path/trail from s to d on it.

5.2.4. Maximum Transmission Reach Constraint

Each path and trail from the source to the destinations should satisfy the constraint on the maximum transmission reach of optical signals. Following Eq. (1):

$$\sum_{u \in MC} mc^d(u) \cdot L_{span} + \sum_{(u,v) \in A} y^d(u,v) \cdot l(u,v) \le TR_e \, \forall d \tag{16}$$

To compute the variable $mc(u)^d$, first we compute $mc(u)$ by the following constraints.

$$mc(u) \le \max(0, \sum_{v \in Out(u) \setminus D'} x(u,v) - \sum_{v \in In(u)} x(v,u)) \, \forall u \in MC \tag{17}$$

$$\sum_{v \in Out(u) \setminus D'} x(u,v) - 1 \le Deg^+(u) \cdot mc(u) \quad \forall u \in MC \tag{18}$$

Eqs. (17) and (18) ensure that a node u is a branching node if it is in MC and there are at least two outgoing arcs (except the arc leading to an eventual virtual destination).

The variable $mc(u)^d$ expresses the fact that a branching node u is in the light-trail to the destination d. Its value can be computed from $mc(u)$ as follows:

$$mc(u)^d = mc(u) \cdot \sum_{v \in Out(u) \setminus D'} y^d(u,v) \qquad \forall u \in MC, \forall d \tag{19}$$

$$mc(u)^d = 0 \qquad \forall u \in MC, \forall d \in Out(u) \cap D' \tag{20}$$

Moreover, there are trivial relations between the flow variables and the arc usages.

$$x(u,v) \ge y^d(u,v) \qquad \forall (u,v), \forall d \tag{21}$$

$$x(u,v) \le \sum_{d \in D'} y^d(u,v) \qquad \forall (u,v) \tag{22}$$

Note that the two non-linear equations (17) and (19) are transformed to linear forms in the implementation.

The result is an optimal hierarchy. After the deletion of the virtual nodes, the remaining set corresponds to the set of optimal light-hierarchies.

6. Performance Evaluation of the Solutions

The ILP formulation presented in Section 5.2 computes the MSM solution based on light-hierarchies (LH), so we call it MSM-LH. Furthermore, it can also be extended to compute an SSM solution, even employing light-trees (LTs) in any of these two approaches, with some appropriate additional constraints. Particularly, to compute SSM solutions, each sub-graph G^k should have at most one incoming arc from the virtual source, whereas to compute solutions based on LTs, there is at most one incoming arc to every node for every sub-graph. In other words, constraint (7) should be applied for all the nodes (not just MC nodes). With these considerations, we can easily evaluate 4 different models with the presented ILP formulation, namely, MSM-LH, MSM-LT, SSM-LH and SSM-LT, that is, MSM an SSM, either over LHs or LTs.

Moreover, the presented ILP considers one input request, which is suitable for a dynamic network scenario. However, we should point out that running an ILP program in dynamic scenarios is not realistic, given its high complexity and long execution time. We consider two main routing scenarios: *incremental* and *single request*. In an *incremental* scenario, a set of demands are incrementally loaded into the network, and the ILP is called to serve one demand after another. We assume infinite demand holding times, *i.e.* previous multicast demands are not released. In the *single request* scenario only one route is computed.

The load can start by an *empty network state* where all FSs are available for use (mainly for incremental network loading), or by an arbitrary *random network state* where some FSs are used for previously allocated communications.

In the *random network state* scenario, the availability of the FSs in the links was generated using the following algorithm. Specifically, the availability of the first two-third FSs (whose indices are from 0 to $2/3 \times |FS|$) are set randomly, while the last one-third FSs are all available.

Let $A[k, i]$ the value indicating the availability of the FS of index i on arc k. Let FS_Set1 be the set of the first two-third FSs.

Random Network State Generation

For all arcs k:

For the FSs of index i in FS_Set1:

$A[k, i]$ = *a random value from* $\{0, 1\}$ *(the probability of* 1 *is proportional to the index i, consequently the availability of FSs of higher index is more probable)*

For the FSs of index i not in FS_Set1:

$A[k, i] = 1$ *(FSs are always available)*

Although the ILP formulation can work with multiple modulation formats, due to its complexity, we selected only two representative ones for the computations: PM-QPSK and PM-16QAM, whose transmission reaches are $TR_e = \{9000, 2000\}km$, respectively. Moreover, the span length is set to $L_{span} = 85km$. Using it, we assume the same scenario as "Link 1" in [23].

A multicast request is given by a triplet (s, D, C) where s is the source, D is the set of destinations and C is the requested capacity. In the different scenarios, we used *randomly generated requests* changing from one instance to another, or *fixed request sets*, where the same randomly generated requests are presented for different states and models. This latter permits a more accurate comparison of the models.

The simulation settings and results are detailed in the following.

6.1. Simulation Settings

A key question for the design of the simulations is the expected execution time to compute the exact solution. Due to the hardness of the problem and the exponential complexity of the ILP formulations, only small instances can be tested. Therefore we used two relatively small topologies: the 14-node NSF network and the 28-node US Longhaul topology (*cf.* Figs. 4a and 4b in [31]). The size of the computation in the latter network, in which there are 90 arcs is briefly illustrated as follows. Let us suppose that there are 30 FSs in the fibers (it is not realistic but enough for the proposed computations without blocking). Supposing a small capacity demand and only one modulation format, the number of implicated layers (duplications) in the auxiliary graph is equal to 54. The number of arcs in the layered graph (without the artificial arcs) is equal to 9720. The number of decision variables is proportional to this value. Naturally, the number of constraints also strongly depends on the dimension of the problem. For this reason, the capacity of each fiber link in the simulations is limited to 20 or 30 FSs, whose bandwidth granularity is 12.5 GHz, and the guard band is set to 10 GHz. Supposing four modulation formats, the number of variables and constraints can be four times larger.

Since the diameter of the networks is small regarding the number of hops, we select no more than 3 DC nodes in MSM scenario.

To simulate EON networks with sparse splitting, we set the number of MC nodes relatively small, *i.e.* in the NSF topology $|MC| \in \{0, 3\}$ and in the US Longhaul network $|MC| \in \{0, 2, 4, 6, 8\}$. Notice that DC nodes are all assumed to have full multicast capacity. All the remaining nodes are MI.

We generate $|MR|$ multicast requests in a random way as follows. For each request, the desired number of destination nodes is selected discarding those nodes where a DC is co-located. The requested capacity for the multicast communication is set randomly between 10 and 100 GHz.

To evaluate the performances of the different aforementioned models with different metrics, we ensure that no request gets blocked. The detailed parameter settings can be found for each experiment in the following sub-sections.

We ran the four ILP programs using CPLEX 12.5 on a machine with Intel Core i7, 3.4GHz processor and 16GB of RAM.

6.2. Runs and Results

In the following, we present the experimentation of the exact model in the two referenced backbone networks. The optimal solutions are investigated in scenarios of incremental requests and single requests. Moreover, the effect of distance adaptive modulation selection using two modulations, and the influence of MC nodes are presented. The following notations are used in the presented tables and figures:

FS max	the index of the last FS used in the computed multicast route (it corresponds to the first objective of the minimization)
Number of FSs	the number of FSs used in the computed multicast route
Total FSs	the total number of FSs used in all links (it represents the total allocated resources)
Spectrum gaps	the sum of the number of free slots until the last allocated one in the used links; it characterizes the fragmentation
Ex. time	CPU time consumed by the route computation (in seconds)

If a computation concerns a set of requests (for example, incremental requests or several single random requests in the same state of the network), the average values are indicated.

6.2.1. Incremental Requests

In the NSF network topology, we conducted 30 instances for each model. The resulted values are averaged for each metric of interest corresponding to the objective function and they are shown in Table 3 for two cases of MC nodes. The parameters used for the computation are summarized in Table 2.

Table 2: Parameter setting for incremental requests in the NSF network

DC nodes	MC nodes	Network state	$\|MR\|$ per model	Modulations
3 randomly selected	0 or 3 randomly selected	empty	30	PM-QPSK

Table 3: Results for incremental requests in the NSF network

Number of MCs	Model	FS max	Number of FSs
0	MSM-LH	7,2370	2,5006
	MSM-LT	7,3911	2,6060
	SSM-LH	7,8006	2,7837
	SSM-LT	7,8092	2,9355
3	MSM-LH	6,7949	2,4019
	MSM-LT	7,1792	2,4722
	SSM-LH	7,4631	2,6638
	SSM-LT	7,4724	2,6753

In the 14-node NSF network the hop distances are very limited. A second experimentation was organized in the US Longhaul network topology. In these experiments 20 random requests were generated and loaded in an incremental manner from an initial random network state (*cf.* the parameters in Table 4).

Table 4: Parameter setting for incremental requests in the US Longhaul network

DC nodes	MC nodes	Network state	$\|MR\|$ per run	Modulations
{9, 15, 27}	0, 2, 4, 6 or 8 randomly from {7, 8, 9, 10, 13, 17, 26, 27}	randomly generated	20	PM-QPSK PM-16QAM

Table 5 shows the results. The values are the averages of 10 runs and in each run 20 requests were incrementally loaded. In addition to the optimized values, the table shows the total number of FSs, the spectrum gaps at the end of the new allocations (characterizing the fragmentation), and the execution time.

Table 6 details the performance gap of the three other strategies over MSM-LH in the series obtained in the NSF network. As seen, MSM outperforms SSM, and LH is better than LT. Specifically in this series, the performance tendency of the four strategies from best to worst is: MSM-LH, MSM-LT, SSM-LH and SSM-LT. MSM-LH achieves the lowest maximal FS index used and consumes the least

Table 5: Average values for 20 incremental requests in the US Longhaul network

Model	FS max	Number of FSs	Total FSs	Spectrum gaps	Ex. time (sec)
MSM-LH	27,0	24,0	348,2	112,100	1201
MSM-LT	28,2	25,2	352,0	94,800	1322
SSM-LH	27,2	25,2	353,8	128,668	379
SSM-LT	28,8	26,8	368,8	148,000	559,8

number of FSs. It is better than its counterpart MSM-LT, while outperforming SSM solutions. Accordingly to the results, MSM-LH outperforms SSM-LH by saving up to 11.3% FSs, while it is slightly better than the traditional light-tree based MSM-LT by reducing 4.2% FSs used. The combination of MSM with light-hierarchies is by far better than the traditional SSM combined with light-trees, which can achieve up to 17.4% resource saving. We also observe a similar performance comparison in terms of the maximal FS used shown in the table.

Table 6: Performances of the models versus MSM-LH (comparison of the results obtained using the NSF network)

	Number of MCs	MSM-LT vs. MSM-LH(%)	SSM-LH vs. MSM-LH(%)
FS max	**0**	2,1	7,8
	3	5,7	9,8
Number of FSs	**0**	4,2	11,3
	3	2,9	10,9

The values observed in the US Longhaul network confirm the findings. MSM outperforms SSM, and LH is better than LT. Notice that the MSM routing produced less not used spectrum gaps, however its execution time is more important (2-3 times more than for SSM).

The above results are reasonable. On one hand, MSM can use all possible DC nodes as sources of the multicast routes, hence it can exploit all available FSs in each slot block to reach all the destinations; whereas SSM can use only one DC as its multicast source, it may rely on multiple FS blocks to do the same. Consequently, MSM uses less FSs and lower maximal FS index than SSM. Moreover, by using SSM the FS budget gets exhausted more quickly to serve the same amount of demands compared to using MSM. On the other hand, light-hierarchies have been proved to be able to produce better solutions than light-trees as shown in previous work [18, 31] in sparse splitting optical networks. In our case, light-hierarchies can allocate some available FS blocs which can not used in a tree (because a needed branching node of the tree is an MI node). When $|MC| = 0$ in the first series, all strategies consume more resources. This is reasonable and aligned with the widely adopted consensus that all-optical multicasting is better with more MC nodes (*cf.* more elements in the sub-section 6.2.4).

The following route computations focus on the single request scenarios.

6.2.2. Single Requests

In this series, 250 single requests were executed for each model using the US Longhaul network topology. Different randomly generated sets of MC nodes and five previously and randomly generated initial network states were used to compute the routes for randomly generated requests (*cf.* Table 7).

Table 7: Parameter setting for random single requests in the US Longhaul network

DC nodes	MC nodes	Network state	$\|MR\|$ per random state
{9, 15, 27}	0, 2, 4, 6 or 8 randomly from {7, 8, 9, 10, 13, 17, 26, 27}	5 random states	50

For each run, the total number of the allocated FSs, the index of the last FS, the spectrum gaps (the fragmentation) and the execution time were collected. Table 8 gives the average values and illustrates the difference between the proposed models.

Table 8: Random single request in the US Longhaul network

Model	FS max	Number of FSs	Total FSs	Spectrum gaps	Ex. time (sec)
MSM-LH	16,0600	1,7333	15,0467	52,0600	148,380
MSM-LT	16,2000	1,7333	15,0800	52,6333	180,140
SSM-LH	16,5200	1,7333	15,9867	58,2667	43,880
SSM-LT	16,6867	1,7333	15,7733	58,3533	57,086

The average values of 250 computations illustrate the finding in the previous series of incremental requests and meet our exceptions. MSM delivery outperforms the SSM configurations and the light-hierarchies can be better than light-tree despite the fact, that the average of the total number of allocated FSs is less for light-trees than for light-hierarchies in the single server configuration. It is understandable because the first objective is the minimization of the maximal index of the allocated slots. The light-hierarchies can produce the optimum, even if the number of arcs in them may be higher than in light-trees. Moreover, the number of spectrum gaps is less using light-hierarchies and the MSM solution.

Notice that the results of another series performed in the NSF network for a set of single requests and using the possibility of the distance-adaptive modulation are presented in the next sub-section.

6.2.3. Distance-Adaptive Modulation

The first computations were performed using the NSF network for 30 randomly generated single requests. For the 4 models, the same requests were loaded to a random (but fixed) state of the network. Here we assumed that there is no MC node in the NSF network and two configurations of the available modulation formats were examined. At first, only the modulation PM-QPSK was available, while in the second series PM-16QAM modulation was also used. The parameter setting is as follows (Table 9).

Table 9: Parameter setting for single requests in the NSF network

DC nodes	MC nodes	Network state	$\lvert MR \rvert$ per fixed state	Modulations
{1, 5, 12}	$\emptyset$	5 random states	30	PM-QPSK PM-16QAM

The measured values are summarized in Table 10.

Table 10: Random single request in the NSF network

Modulations	Model	FS max	Number of FSs	Total FSs	Spectrum gaps	Ex.time (sec)
PM-QPSK	MSM-LH	17,1333	2,2666	15,5333	46,8333	6,200
	MSM-LT	17,2000	2,1333	15,2667	48,1333	6,200
	SSM-LH	17,5333	2,1333	19,8333	64,7333	3,300
	SSM-LT	17,6000	2,1333	18,7667	61,5333	2,900
	Average	17,3667	2,1666	17,3500	55,3083	4,650
PM-QPSK and PM-*16QAM*	MSM-LH	15,1304	1,7391	11,7826	37,1739	59,300
	MSM-LT	15,2273	1,7273	11,1364	36,4091	25,500
	SSM-LH	16,0435	1,7392	12,7391	44,0000	13,200
	SSM-LT	16,1818	1,7273	11,9091	43,0909	12,500
	Average	15,6458	1,7332	11,8918	40,1685	27,625

According these results an important gain can be seen in favor of the distance-adaptive modulation even if only two different formats are used. The maximal index and also the number of allocated FSs are significantly less with two modulations than with only one. There are less spectrum gaps using the distance-adaptive modulation but the computation of the exact solution with two modulations is more expensive.

In the following sequence we examined the effect of multiple modulations in the US Longhaul network and we found similar advantages of the modulation format adaptation with multiple formats. In the US Longhaul network topology using 3 DCs, 2 MC nodes and 5 different random network states, the routes for 50 random multicast requests were computed (10 requests for each network state). The same initial states and multicast requests were loaded at first using only the modulation PM-QPSK, and in the second case supposing two available modulations (PM-QPSK and PM-16QAM). Remember that we limited our experimentation to two modulations, since the size of the auxiliary layered graph is duplicated for each modulation format.

Table 11: Parameter setting to compare the case of single modulation to the case of two modulations in the US Longhaul network

DC nodes	MC nodes	Network state	$\|MR\|$ per state	Modulations
{9, 15, 27}	{8, 26}	5 random states	10	PM-QPSK PM-16QAM

Table 12 resumes the observed measurements in the Longhaul network.

Table 12: Performances of the distance-adaptive modulation

Modulations	Model	FS max	Number of FSs	Total FSs	Spectrum gaps	Ex. time (sec)
PM-QPSK	MSM-LH	18,1800	2,3600	22,0200	68,0600	11,400
	MSM-LT	18,4800	2,3600	20,4000	66,0200	19,700
	SSM-LH	18,7000	2,3600	24,1600	78,9400	3,300
	SSM-LT	19,0600	2,3600	23,2000	80,3400	4,200
	Average	18,6050	2,3600	22,4450	73,3400	9,650
PM-QPSK and PM-*16QAM*	MSM-LH	14,8000	1,7600	14,8400	50,5400	263,800
	MSM-LT	15,2800	1,9000	14,9800	52,2600	159,100
	SSM-LH	15,1600	1,7600	16,6000	59,2200	57,300
	SSM-LT	15,6400	1,7600	15,1600	56,6800	49,400
	Average	15,2200	1,7950	15,3950	54,6750	132,400

In addition to the results presented above (namely the performance of the light-hierarchies and the multiple servers in the content delivery), the advantages of the adaptive choice of the modulation are important. The selection of the more efficient PM-16QAM modulation, if it can be used, significantly improves the quality of the routing: there is less FSs used, and the average of the maximal index is also lower. Moreover, the number of spectrum gaps responsible for the fragmentation is less using the distance-adaptive modulation. The counterpart of these advantages is the more important execution time when using the two formats.

6.2.4. Effect of the MC nodes

The first illustration of the effect of MC nodes on the multicast route can be found in Table 3 in the sub-section 6.2.1. A second series in the larger US Longhaul netwok gives more elements. Several runs were organized for various MC node sets using single routing requests and random network states. In this section we present one series. For the 4 models the same network state and the same 30 random multicast requests were used. The set of multicast nodes was varied as the parameter setting shows it.

The computed values are presented in Table 14. Each value is the average of 30 runs. In this configuration (network topology, DC set, network link state and 30 randomly generated but fixed requests) the effect of MC nodes is minimal.

Table 13: Parameter setting to examine the routing regarding the MC nodes

DC nodes	MC nodes	Network state	$|MR|$ per state	Modulations
{9, 15, 27}	∅, {8, 26}, {8, 10, 17, 26}, {7, 8, 10, 13, 17, 26}, {7, 8, 9, 10, 13, 17, 26, 27}	one random state	30	PM-QPSK PM-16QAM

Table 14: Averages for single requests with different MC node sets in the US Longhaul network

Number of MCs	Model	FS max	Number of FSs	Total FSs	Spectrum gaps	Ex. time (sec)
0	MSM-LH	16,5000	2,1333	21,0000	61,4333	92,500
	MSM-LT	16,9000	2,1333	19,3333	59,5000	156,700
	SSM-LH	17,4667	2,1334	22,8333	71,8667	43,800
	SSM-LT	18,0667	2,7334	20,2000	67,9667	36,000
2	MSM-LH	16,5000	2,1333	21,2000	62,8667	150,500
	MSM-LT	16,8667	2,1334	19,6333	59,8000	185,000
	SSM-LH	17,3333	2,1333	22,8000	70,9333	32,100
	SSM-LT	17,9333	2,1333	20,6000	68,5333	71,830
4	MSM-LH	16,5000	2,1333	21,0667	62,0000	190,400
	MSM-LT	16,8667	2,1334	19,8333	61,0000	165,100
	SSM-LH	17,3333	2,1333	22,1000	68,1667	56,900
	SSM-LT	17,9333	2,1333	20,1333	65,9333	55,500
6	MSM-LH	16,5000	2,1333	21,0000	61,4333	161,000
	MSM-LT	16,8000	2,1333	19,9667	61,2333	183,900
	SSM-LH	17,3333	2,1333	22,3000	68,2667	43,500
	SSM-LT	17,8667	2,1334	20,3000	66,1000	58,400
8	MSM-LH	16,5000	2,1333	21,0000	61,5333	147,500
	MSM-LT	16,8000	2,1333	20,2667	62,2000	210,000
	SSM-LH	17,3333	2,1333	22,3000	68,2667	43,100
	SSM-LT	17,8667	2,1334	20,7000	67,1333	63,700

The optimized values (the maximal index of the used FSs and the total number of FSs) diminish when increasing the MC node set. Trivially, if all the nodes are MC, the optimal solution is a set of light-trees. The number of MC nodes slightly affects the results when the objective is the minimization of the maximal index of FSs. Even if longer routes (long trees and hierarchies with less branching nodes) are found, the maximal index of the allocates FSs can be more preferable and it is not directly correlated to the length of the routes. Probably, the influence of MC nodes can be important when the goal is the cost minimization. Moreover, similarly to the other cases, the MSM model is always better than the SSM and light-hierarchies outperform light-trees.

7. Conclusions and Perspectives

In this paper the multi-server multicast approach for CDNs over EONs with sparse splitting constraints is investigated. We proposed an ILP formulation to compute the optimal multicast route as a set of light-hierarchies from multiple DCs to deliver a multicast content to all end-users. Unlike simple previously proposed models, the ILP, which is based on an auxiliary layered graph, takes into account the signal degradation caused not only by the EON fiber impairments but also the splitting, so as to impose precise limitations on their transmission reach. The computation also adapts to a set of different modulations. The results revealed that the MSM approach can achieve better resource utilization compared to the traditional SSM approach. In particular, the obtained results suggest that under sparse splitting constraints, light-hierarchies should be used to optimize MSM performance. Moreover, our experiments demonstrated the interest of the usage of multiple modulation formats in the multicast routing in EONs suporting CDNs. Due to the hardness of the problem, the computation of the exact solution is expensive and not scalable. Therefore, good heuristics to realize the MSM-LH approach in larger network settings will be main targets in our future work.

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