Hybrid Multicast Traffic Grooming in Transparent Optical Networks with Physical Layer Impairments

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***Abstract*—This paper investigates the problem of multicast traffic grooming in transparent optical networks utilizing a novel grooming approach that is based on routing/grooming of multicast calls on hybrid graphs. The proposed approach exhibits improved performance when compared to existing grooming schemes especially when the physical layer impairments are taken into account.**

I. INTRODUCTION

The emergence of Wavelength Division Multiplexing (WDM) technology provides the capability for increasing the bandwidth of an optical network, by grooming low-speed traffic streams onto high-speed wavelength channels [1]. Traffic grooming in mesh WDM optical networks has received considerable attention from the research community [2]–[7]. However, in these studies, only unicast traffic was considered while only a smaller number of studies have been performed on grooming multicast traffic [8]–[10]. As next generation networks are expected to support both unicast and multicast applications, such as multiparty conferencing, software and video distribution and distributed computing, it is important to design and dimension networks in order to be able to support traffic of the multicast type, while grooming sub-wavelength traffic demands. To support multicasting, optical splitters can be used in network nodes to split the incoming signal to multiple outputs, thus enabling the establishment of connections with multiple destinations [11]. Finding the multicast tree corresponds to solving the Steiner Minimum Tree (SMT) problem that is NP-complete, and therefore several heuristics have been developed to approximately solve the problem [12], [13].

This paper investigates the problem of multicast traffic grooming in transparent optical networks utilizing a novel grooming approach that is based on routing/grooming of multicast calls on hybrid graphs (HGs). HGs are constructed dynamically upon the arrival of each multicast call, in such a way that are consisting of both the available physical links and the logical links with available free capacity. For building the HGs, a novel heuristic approach is proposed, namely the maximum overlapping light-tree first (MXOF) while for routing/grooming on HGs a novel hybrid Steiner tree heuristic (HST) is presented. The proposed routing/grooming approach exhibits improved performance when compared to existing multicast grooming approaches that route/groom multicast calls by considering physical and logical links separately [9]. Note that while attempts for solving the traffic grooming problem jointly have been made in [6], [7], in these works only unicast connection requests were assumed. Also, in [7] full wavelength conversion at every node is present and the problem of multiple links between two nodes is not considered. Additionally, this work considers for the first time in the multicast traffic grooming problem the impairments introduced by the physical layer (utilizing the Q-factor parameter) during the provisioning phase of the new sessions. While the Bit Error Rate (BER) of the system is the main performance indicator in a fiber-optic digital communication system, the required system Q-factor for a target BER is derived using Eq. (1) [17], as the BER is a difficult parameter to evaluate.

$$BER = \frac{1}{2}erfc\Big(\frac{Q}{\sqrt{2}}\Big) \approx \frac{e^{\frac{-Q}{2}}}{Q\sqrt{2\pi}} \tag{1}$$

The physical layer system modeling used for the calculation of the Q-factor for a target BER, during the multicast routing/grooming and wavelength assignment algorithm is presented in detail in [14]. In this work, a Q-threshold of 8.5 dB is assumed which corresponds to a BER of 10^{-12}. In general when increasing the BER of a system, more calls are expected to be dropped.

II. NODE ARCHITECTURE/ENGINEERING FOR MULTICAST TRAFFIC GROOMING

A grooming-capable node, must be able to switch and pack lower-speed traffic streams into higher-speed streams. In order to support multicast traffic, data must be copied and duplicated using electronic hardware (opaque node architectures), or the optical signal may split at a node to several outgoing fibers utilizing optical splitters (transparent node architectures), or a combination of both (translucent node architectures). As the cost of passive optical splitters is considerably less than the cost of electronic line terminal equipment (LTE), it is more cost efficient to duplicate the incoming traffic in the optical domain. However, electronic devices are still needed if traffic needs to be groomed to wavelength channels. Therefore, in this work we assume the translucent node architecture shown in Fig. 1 that implements both optical light splitting and sub-lambda grooming. This architecture is an extension of the node architecture with passive optical splitters and fixed TXs/RXs first proposed in [16], in which a traffic grooming fabric (GF) is added to support multicast traffic grooming.

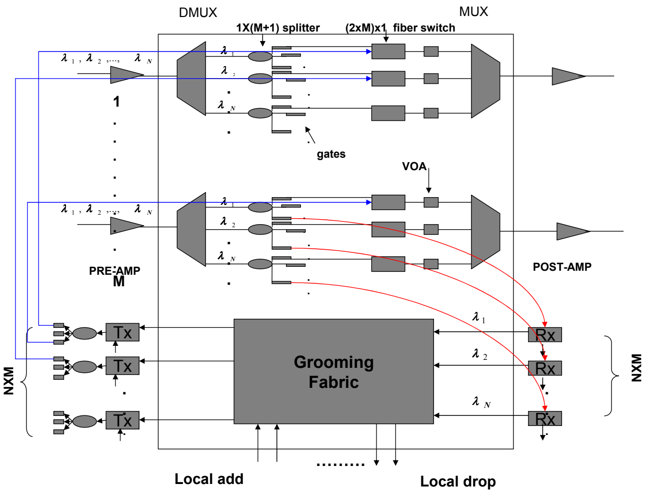

Fig. 1. Grooming- and multicast-capable node architecture.

The architecture of Fig. 1 can provide all-optical bypass for light-trees passing through the node without any electronic processing. Alternatively, a light-tree can be dropped if the node is the final destination of all the traffic carried by the light-tree or otherwise the light-tree is dropped to the GF where other traffic can be multiplexed (groomed) onto this light-tree to increase the bandwidth efficiency of wavelength channels. Upon grooming, the traffic is switched to a corresponding optical splitter to split the incoming signal to multiple output ports. Note that this allows for traffic to be forwarded from one light-tree to another on its way to its ultimate destinations. This is referred to as multicast multihop grooming. Note that according to Fig. 1, grooming is not possible at destination nodes that are intermediated nodes for a light-tree, as at these nodes the signal is dropped but not retransmitted. A portion of the signal is dropped to the destination nodes, and the rest passes through the node transparently to reach its next destination. However, the signal at the destination nodes can be dropped to the grooming switch, if the signal carries traffic for different connections, in order to allow for part of the traffic to be dropped locally and to allow for the rest of the traffic to be groomed to another light-tree if needed.

The node architecture of Fig. 1 is engineering for a $+5$ dBm optical power launched into the system. Each node's EDFA is assigned a typical noise figure which depends on its gain as described in [16]. The gain of each pre-amplifier compensates the loss of each preceding fiber span with a fiber loss of 0.3 dB/Km and both pre- and post-amplifiers are engineered for bringing back the power to the value of $+7$ dBm. Variable optical attenuators (VOAs) are responsible for attenuating the total power to a prescribed value when needed, according to the worst-case scenario. The worst-case scenario is defined here as the maximum insertion loss experienced when the signal passes through the maximum degree node. The insertion loss is calculated assuming the component losses described in [16], considering passive splitters, and the amplifier gain is set for the worst-case scenario as well. Controllable semiconductor optical amplifiers (SOAs) are also introduced as gates to block the power at outputs where the signal is not destined for. All gates are controlled together in an intelligent manner to avoid clashing at the same output port and/or same wavelength of the switch. At the destination nodes, p-i-n photodiodes are used in conjunction with RX pre-amplifiers that have a noise figure of 4.5 dB. The number of TXs/RXs in this architecture is assumed to be equal to the number of wavelengths times the degree of the node [16].

III. EXISTING MULTICAST TRAFFIC GROOMING HEURISTICS

The authors in [9] investigated the dynamic multicast traffic grooming problem for which two heuristic approaches, namely the Logical First Hybrid Routing (LFHR) and the Physical First Sequential Routing (PFSR) heuristics were proposed amongst others. For both heuristics, the physical and logical layers of the network are treated separately. Specifically, upon the arrival of a multicast call, the PFSR heuristic first tries to find a new light-tree from the source to the destinations and only if this fails, existing (single or multihop) logical routes are inspected. Unlike PFSR, LFHR first seeks existing light-tree(s) to provision the request or part of the source/destination nodes in the request, and if it fails or only part of the request is accommodated, a new light-tree is created. According to the above, both heuristics are decomposed into the physical provisioning phase and the logical provisioning phase and depending on the heuristic followed, the two phases are performed sequentially.

A. Logical Provisioning

During the logical provisioning phase, the maximum overlapping light-tree (MOL) heuristic is implemented, initially described in [15]. The MOL heuristic aims at minimizing the session blocking probability by grooming each multicast call onto the maximum overlapping light-tree. Each time a multicast call arrives into the network, MOL computes a list L consisting of the already established light-trees with free capacity equal to or greater than the rate of the new call. Then each light-tree in L is compared to the new multicast call, and the light-tree that can serve the maximum number of source/destination nodes is chosen for grooming the new call. The maximum number of logical hops that MOL is allowed to perform is constrained by a parameter h.

B. Physical Provisioning

During the physical provisioning phase, the Impairment-Aware Multicast Routing and Wavelength Assignment (IAMC-

RWA) algorithm is implemented for a multicast set [16]. The IAMC-RWA algorithm first solves the multicast routing subproblem and then assigns a wavelength for the multicast tree found based on the *first-fit* algorithm. The entire multicast set is accepted, if:

- A multicast tree and a wavelength assignment is possible.
- The Q-factor for each path on the multicast tree is above the predetermined Q-threshold.
- There are available TXs/RXs for that connection.

If the physical impairments are not met, a new wavelength assignment is implemented and the heuristic is repeated until no new wavelength assignment is possible. Note that for the LFHR approach the Steiner Tree (ST) heuristic [11] is used for the routing subproblem. However, for the PFSR approach the ST heuristic is slightly modified to the Sub-Steiner tree (SST) heuristic to allow for feasible sub-light-trees to be established, in case the entire light-tree is not feasible. Destination nodes not reached by the physical layer, either due to insufficient Q-factor or unavailability of resources, have a chance of been reached by the logical layer by removing from the initial multicast set the destination nodes already reached by the physical layer, before moving to the MOL heuristic. Algorithm 1 describes in detail the SST heuristic proposed that takes into account the physical layer impairments (PLIs) during the construction of the multicast tree.

IV. GROOMING ON HYBRID GRAPHS

A novel hybrid routing heuristic is proposed aiming at improving the session blocking probability by performing routing/grooming on pre-calculated HGs consisting of both the available physical links and logical light-trees with free capacity.

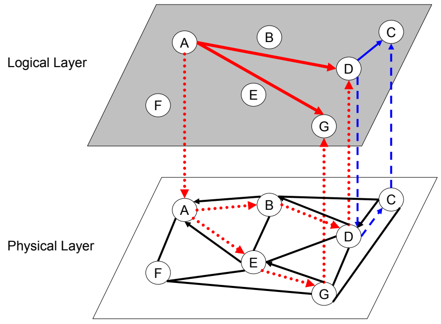

Fig. 2. Physical and logical layer graphs.

Fig. 3 is used as an illustrative example of a HG created by the combination of logical and physical layers shown in Fig. 2. In this example it is shown that the two light-trees already established in the network do not overlap in the logical layer, which makes the combination of the two layers trivial. In other systems however, more than one logical links may be present, originating from the same source and reaching the same destination node(s). The problem that arises then, concerns the creation of the HG in which case only one logical link must be chosen for the connection of any two nodes in the HG. This is done in order to save resources and eventually reduce the blocking probability in the network. Thus, a heuristic approach is developed, namely the maximum overlapping light-tree first (MXOF), that gives priority to the logical light-trees that serve the maximum number of source/destination nodes to be placed first on the HG. By doing so, the routing algorithm tries to utilize those logical light-trees that serve the maximum number of source/destination nodes in the request, aiming at reducing the number of logical hops utilized by the request, and consequently the blocking probability in the network.

Algorithm 1 Sub-Steiner Tree (SST) heuristic

Input: A graph $G = (V, E)$ representing the network, a source node $s \in V$, a destination set $D = [d_1, d_2, ...d_n] \subseteq V$, link weights representing the physical distance assigned to each edge $e \in E$ and a Q-threshold q.

Output: A tree T spanning the set $[s, D']$ where $D' \subseteq D$, and the set $D_r \subseteq D$, where $D_r = D - D'$.

```
begin
$k \leftarrow 0$
$D_r \leftarrow \emptyset$
Find set $D'' \subseteq D$, of the destination nodes for which receivers are not available in the network. Let $r$ be the number of destination nodes in $D''$.
$D = D - D''$, $n = n - r$ and $D_r = D_r + D''$.
if $n > 0$ then
  $T \leftarrow s$
  while $k < n$ do
    Calculate all shortest paths from nodes $\in T$ to destination nodes $\in D$
    if At least one shortest path can be created from nodes $\in T$ to a destination node $\in D$ then
      Choose the shortest path amongst them and add it to tree $T$.
      Identify node $d_j \in D$ last added to tree $T$
      Calculate Q-factor $q_j$ of $d_j$.
      if $q_j < q$ then
        Remove shortest path last added to $T$.
        Remove destination node $d_j$ from $D$.
        Add destination node $d_j$ to $D_r$.
        $k \leftarrow k + 1$
      else
        Remove destination node $d_j$ from $D$
        $k \leftarrow k + 1$
      end if
    else
      $D_r = D_r + D$
    end if
  end while
end if
return $T$ and $D_r$
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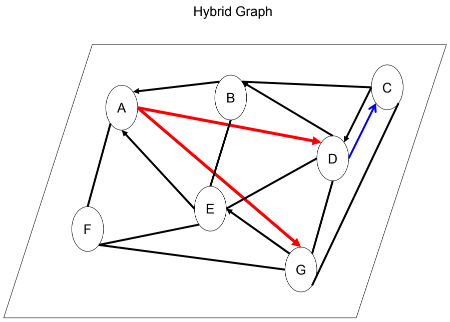

Fig. 3. Hybrid graph based on physical and logical layer graphs of Fig. 2.

A. Maximum Overlapping Light-Tree (MXOF) Heuristic for Building the Hybrid Graph

Given a network G, hybrid graph HG is created on wavelength λ_i by first adding to HG all nodes of graph G and then adding to HG all the arcs with full wavelength capacity on wavelength λ_i. Then the light-trees already established in the network are examined and the light-trees with free capacity less than the rate of the arriving request are rejected. The rest of the light-trees are placed in a sorted list which is created according to the MXOF scheme. Specifically, in the MXOF scheme the light-tree that has the maximum number of same source/destination nodes with the arriving multicast call is placed first on the list. Figs. 4, 5, and 6 are used as an illustrative example of the MXOF scheme. Figure 4 shows the state of the network G upon the arrival of the multicast call $R = \{b, c, g, i\}$ requesting 2 units of capacity. Note that in a multicast set, the first letter denotes the source node while the rest denote the destinations. Fig. 6 shows information regarding the wavelength, the overlapping degree, the free capacity and the logical links for each multicast set already established in the network. Since the arriving request requires 2 units of capacity then none of the already established light-trees is rejected and based on the MXOF scheme, light-trees of Fig. 6 are placed in the table in decreasing order according to their overlapping degree. Note that in case of a tie in the overlapping degree, light-trees are sorted according to their free capacity in decreasing order.

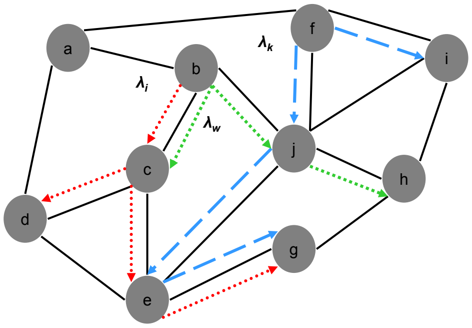

Fig. 4. Current network state.

According to the above, the HG for wavelength λ_i is created by first copying G to HG and then removing from HG all the physical links that are occupied by λ_i (Fig. 5). Then the logical links for each light-tree shown in Fig. 6 are added sequentially in the HG. During this procedure, if two nodes are found to be already connected in HG, either via a logical or via a physical link, then every logical link included in the colliding light-tree is neglected. For example, Fig. 6 shows that λ_i and λ_w have a common link. However, since logical link (b, c) of λ_i is added first on HG then none of the logical links of λ_w are included in HG. The final HG is shown in Fig. 5.

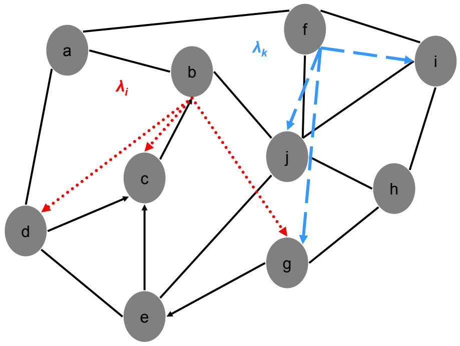

Fig. 5. Hybrid graph HG.

Lambda	Multicast Group	Overlapping Degree	Free Capacity	Logical Links
λ_i	R_i={b,c,d,g}	3	3	(b, c) (b, d) (b, g)
λ_k	R_k={f,j,g,i}	2	4	(f, j) (f, g) (f, i)
λ_w	R_w={b,c,h}	2	3	(b, c) (b, h)

Fig. 6. Information for already established light-trees according to arriving multicast call $R = \{b, c, g, i\}$.

B. Hybrid Steiner Tree Heuristic

The Hybrid Steiner Tree (HST) heuristic is developed for routing on the HGs, as known multicast routing algorithms cannot be applied directly on a HG. The reason for this is that logical links belonging to the same logical light-tree are grouped together and cannot be separated. Due to transparency and the lack of wavelength conversion in the networks examined, light-trees originating from the same transmitter have to reach every destination node of the light-tree first established for that specific transmitter. Thus, the Steiner Tree (ST) heuristic [11] is modified, resulting in the Hybrid Steiner Tree (HST) heuristic, to account for the inseparability of logical links belonging to the same light-tree. Specifically, the HST heuristic differs from the ST heuristic in that it finds the hybrid multicast tree HT by adding in the currently constructed tree HT the path that leads to the destination node that is more closer to HT, but each time a new path is added, it has to identify if any of the newly added links corresponds to a logical link. For the newly added links that do correspond to a logical link it identifies their logical light-trees and adds the corresponding logical links to the HT. In each iteration the multicast set is updated by removing from the set all destination nodes added to the HT. The heuristic terminates when every destination node of the multicast call is added to the HT.

C. Multicast Connection Provisioning on Hybrid Graphs

For each multicast call, the Impairment-Aware Hybrid Multicast Routing and Wavelength Assignment (IA-HMC-RWA) algorithm builds k hybrid graphs HGs, one for each of the k wavelengths in the network. The wavelength assignment subproblem is solved based on the *first-fit* algorithm while for the hybrid multicast routing subproblem the HST heuristic is used. Multicast requests are accepted into the network if:

- A hybrid tree exists onto one of the k HGs,
- The Q-factor on each destination node of the newly created light-trees is above the predetermined Q-threshold
- There are available TXs/RXs for every newly created light-tree.

If the physical impairments are not met, a new wavelength assignment is implemented, in the sense that the assignment of the request is attempted on the next HG according to the sorted list of wavelengths, and the heuristic is repeated until no new wavelength assignment is possible.

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed techniques simulations were performed on a metro network consisting of 50 nodes and 98 links (196 arcs), with an average node degree of 3.92 and an average distance between the nodes of 60 Km. We used a dynamic traffic model where multicast sessions arrive at each node according to Poisson process and the holding time is exponentially distributed with a unit mean. Thirty-two (32) wavelengths per link were utilized with each wavelength utilizing 10 units of capacity. The rate of each call was randomly generated between the set of integer numbers 1 to 10. For each simulation point, 5000 requests were generated and the results were averaged over five simulation runs. A Q-threshold of 8.5 dB is assumed corresponding to a BER of 10^{-12} while the node architecture and engineering design first proposed in [16] and extended here to include a grooming fabric is assumed.

Results were evaluated for both the proposed HST heuristic in conjunction with the MXOF scheme for the creation of the HGs, as well as for the PFSR/LFHR heuristic algorithms [9]. For the PFSR/LFHR heuristics, it is assumed that only one hop can be performed in the logical layer due to the fact that for our network topology and traffic engineering, more hops tend to increase the blocking probability. This is clearly demonstrated in Fig. 7 that shows the blocking probability versus the multicast group size for the PFSR heuristic when different number of logical hops (h) is allowed by the MOL heuristic. Results show that the case $h = 1$ results in the best blocking probability while when $h = 2$ the blocking probability is worst than the case where no grooming techniques were considered which is indicated by $h = 0$. Note that results of Fig. 7 correspond to a traffic load of 100 Erlangs.

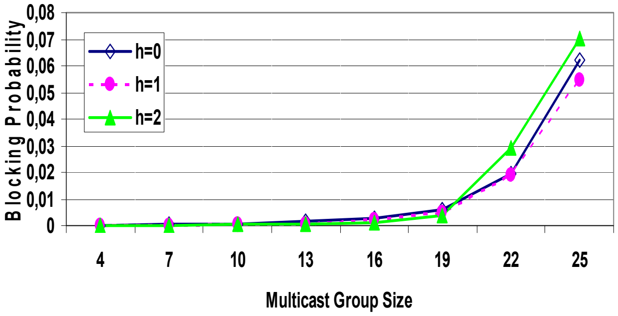

Fig. 7. Blocking Probability versus the multicast group size for PFSR heuristic for different values of h.

Figs. 8 and 9 show the blocking probability versus the load in Erlangs when the PLIs are not considered and when the PLIs are taken into account respectively. For each simulation point, requests of mixed group sizes were randomly generated between the set of integer numbers $[2, 40]$. Hence, multicast as well as unicast requests randomly arrived into the network with 40 being the maximum multicast group size. Note that the multicast group size is defined as the number of nodes included in the multicast set $R = \{s, D\}$, where s denotes the source node and set D denotes the set of destination nodes. Results of Fig. 8 show that the HST heuristic in conjunction with the MXOF scheme slightly outperforms the other schemes only for heavy loaded networks. However, when the PLIs are also considered (Fig. 9) the HST heuristic clearly outperforms the other grooming schemes developed for comparison purposes (again for heavy loads). The reason for this is that when the PLIs are considered, newly established light-trees are constrained in the sense that fewer resources are utilized by each light-tree since now only destination nodes with an acceptable Q-factor can be included in the light-trees. Hence, the creation of constrained light-trees results to the better utilization of the available logical and physical resources by the HST heuristic. Increased blocking probability for the PFSR/LFHR heuristics in both cases is caused due to the fact that available physical and logical resources are treated separately and sequentially. Although physical or logical resources may exist to serve the new call, these resources are either not able to be utilized by PFSR/LFHR or cannot be combined in the most efficient way. In the hybrid approach, however, the HST heuristic can have global information about the availability of the physical and the logical links as well as of their connectivity, thus making it possible for the resources to be combined in a more efficient way.

When observing both Figures 8 and 9, it seems that in general the PLIs do not seem to affect significantly the performance of grooming approaches. This is due to the fact

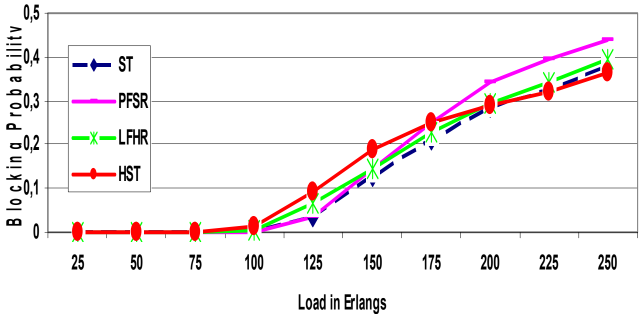

Fig. 8. Blocking Probability versus the load in Erlangs when the PLIs are not considered.

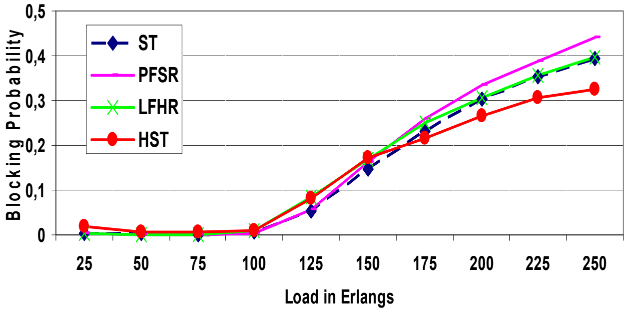

Fig. 9. Blocking Probability versus the load in Erlangs when the PLIs are considered.

that the grooming procedure manages to handle these effects at least for the network topology and engineering scenario examined here. Increased blocking probability is observed only for the ST heuristic (as clearly shown when comparing Figures 8 and 9), since in that case grooming techniques are not considered.

VI. CONCLUSION

In this work, the multicast traffic grooming problem under physical layer constraints is examined. A hybrid routing algorithm is proposed, namely the hybrid Steiner tree (HST) heuristic that routes multicast calls on hybrid graphs, consisting of both the available physical and logical links. The MXOF heuristic is proposed for building the HGs that prioritizes the logical light-trees according to the number of similar source/destination nodes to the arriving multicast call.

Results show that HST in conjunction with the MXOF heuristic outperforms existing approaches that were developed here for comparison purposes, especially when the PLIs are also considered. In general, increased blocking probability for the existing PFSR/LFHR heuristics is caused due to the fact that available physical and logical resources are treated separately and sequentially and although physical or logical resources may exist to serve the new call, these resources are either not able to be utilized by PFSR/LFHR or cannot be combined in the most efficient way. In the hybrid approach, however, the HST heuristic can have global information of the availability and connectivity of physical and logical links, thus making it possible for the resources to be utilized in a more efficiently way.

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