Multicast Routing Algorithms Based on Q-Factor Physical-Layer Constraints in Metro

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***Abstract*—We use novel “light-tree balancing techniques” to investigate the problem of provisioning multicast sessions in metropolitan all-optical networks. The Q-factor for every path of a derived light-tree is calculated taking into account several physical layer constraints in the network and using a Q-budgeting approach. Based on the above performance, tree balancing techniques are applied to maximize the number of multicast connections that can be admitted to the network.**

***Index Terms*—Multicasting, Q-factor, routing, impairments.**

I. INTRODUCTION

Multicasting has been investigated since the early days of optical networking [1,2], but has only recently received considerable attention from the service providers, mainly because now many applications exist that can utilize the multicasting feature. Bandwidth-intensive applications and rich multimedia and real-time services are becoming very popular in today’s networks (e.g., video-conferencing, real-time online computer games, etc.) and unicast, multicast and groupcast traffic need to be supported. In these networks, optical splitters can be used to split the incoming signal to multiple output ports thus enabling a source node to establish connections with multiple destinations. In this case, a *light-tree* is created to serve a multicast request, which is a set of lightpaths from the source to all the destination nodes.

In this paper we present novel light-tree routing approaches that use physical layer constraints through the Q-factor. Apart from finding the minimum cost tree, our proposed techniques calculate the physical performance of the system by calculating Q-penalties for impairments and using a Q-budgeting approach [3], to investigate whether a multicast connection should be admitted to the network. The new routing approaches use “tree balancing techniques” for the multicast sessions, aiming at maximizing the multicast connections that can be admitted to the network. The work presented here expands the existing multicast routing techniques that use optical signal power as the main optical layer constraint [4]. We demonstrate that by taking into account the noise contributions in the network and calculating the Q-factor as opposed to just the optical power results in significantly improved blocking probability for multicast connections. A byproduct of the above is that different engineering of the physical layer produces different multicast group blocking, a strong indicator that a more refined interaction between physical and logical layer is needed for multicast connection provisioning.

II. TREE BALANCING ALGORITHMS WITH PHYSICAL LAYER IMPAIRMENTS

Constructing cost-effective light-trees (known as the Steiner-tree problem) along with the wavelength assignment problem for these light-trees is an NP-complete problem [1]. Even though several heuristics exist for solving the multicast routing and wavelength assignment (MC-RWA) problem [2,5-7], these heuristics do not account for the physical layer impairments encountered by the multicast connections. Furthermore, when the physical layer constraints are introduced in solving the MC-RWA problem, only the power budget is considered [4,8]. This paper improves on these MC-RWA algorithms by also including physical layer constraints utilizing the Q-factor.

Initially, the algorithm finds a shortest-path light-tree T that spans the source and the destination nodes for each multicast group. This work then extends the *balanced light-tree* (BLT) approach for power budget constraints [4] by taking into account the Q-factor (*balanced light-tree_Q* [BLT_Q]). Consider a light-tree, and let u denote the node with the minimum Q-factor, and v denote the node with the maximum Q-factor. The idea behind BLT_Q is to delete node u from T, and add it back to the tree by connecting it to node v in the path from source s to node v. This results in an increase of the Q-factor of node u, but it also reduces the Q-factor of all nodes below node v in the tree. Therefore, this pair of delete/add operations is performed *only* if it does not reduce the Q-factor of any node beyond that of node u. Thus, after each iteration of BLT_Q, the Q-factor of the node with the minimum value is increased. The algorithm also ensures that while the Q-factor of some other node(s) is decreased, it does not decrease beyond the previous minimum value. As a result, the difference between the minimum and maximum Q-factor values also decreases with each iteration. The balancing part of the algorithm terminates after a certain number of iterations. Note that if more than a pair of nodes with the same maximum and minimum Q-factor exist, we let U denote the set of nodes with the minimum Q-factor and V denote the set of nodes with the maximum Q-factor. We then select the shortest path amongst all the shortest paths that may exist between any two nodes in sets U and V.

As the BLT_Q algorithm tends to create trees that have more breadth than depth, it decreases the attenuation loss and

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the signals now pass through a smaller number of optical amplifiers. However, it also increases the total number of links in the tree. In order to keep the number of recourses low (small total number of links on the tree, thus less number of wavelengths used), algorithm BLT_$Q_{tolerance}$ is employed (BLT algorithm based on minimum acceptable Q-factor). Considering that the minimum acceptable Q-factor for each path is *q,* this modified algorithm tries to maximize the Q-factor only at those destination nodes where its value is lower than *q*. Thus, if after a number of iterations the minimum Q-value for all destination nodes is higher than *q,* then the balancing algorithm terminates.

The proposed MC-RWA is described as follows: For each multicast request, the algorithm first solves the routing problem by finding a tree that can accommodate the request and then tries to assign a wavelength for that tree based on the *first-fit* algorithm [5]. Multicast requests are blocked if there is no available wavelength for the entire tree. If a wavelength assignment is possible, the Q-factor for each path on the tree is evaluated and the BLT_Q (or BLT_Q_$_{tolerance}$) heuristic is then implemented. The multicast request will now be blocked if there is at least one route on that tree with a Q value that falls below a predetermined threshold value and there is no alternate wavelength assignment possible. Otherwise, a new wavelength assignment is implemented and the BLT_Q (or BLT_Q_$_{tolerance}$) heuristic is repeated.

III.PHYSICAL LAYER SYSTEM MODELING

To evaluate the Q-factor the following equations are used [9]:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \qquad \sigma_i^2 = \sigma_{th}^2 + \sigma_{shot-i}^2 + \sigma_{ASE-ASE}^2 + \sigma_{s-ASE-i}^2 + \sigma_{RIN-i}^2 + \sigma_{ASE-shot}^2$$

where σ_i is the sum of the variances of the thermal noise, shot noise, various components of beat noise, and RIN noise. The above assumes a baseline system with amplified spontaneous emission (ASE) noise from the optical amplifiers. To include other common physical layer impairments such as crosstalk, fiber nonlinearities distortion due to optical filter concatenation, and PMD among others, a simple Q-budgeting approach is utilized as in [3]. We start from the Q-value for the baseline system and budget Q-penalties for the various physical layer impairments present.

The Q-penalty (QdB) associated with each physical layer impairment in a system is commonly expressed in dB and in this work we use the following definition: QdB = 10log (Qlinear). The Q-penalty is calculated as the QdB without the impairment in place minus the QdB with the impairment present [3]. This approach provides a good trade-off between accuracy and computational complexity especially given the fact that thousands of connections are being routed in each iteration and interaction with the physical layer is needed in each one. In a real system this interaction happens during the provisioning phase to decide whether a multicast connection will be admitted to the network or rejected [10].

Our modeling allows for the Q-calculation to be performed for the new call and each affected existing call. If any of these tests fails, meaning the Q for any path on the calculated tree is below a predetermined threshold, the new call will be blocked. In the simulations, a Q-threshold of 8.5 dB is assumed, corresponding to a BER of 10^{-12}. In trying to determine the Q-value for each call, a baseline system Q-value is first calculated based on the signal and noise terms, assuming 10 Gbps bit rate, a pre-amplified photodiode and 32 wavelengths spaced at 100 GHz. 12 dB insertion loss is assumed for the add/drop channels and 14 dB for the through channels at each network node. A generic node architecture is used (Fig. 1).

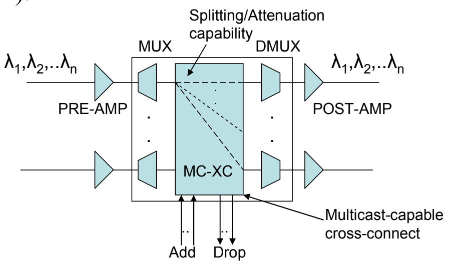

Figure 1.Multicast-Capable Cross-Connect (MC-XC) node architecture consisting of splitters, optical switches, attenuators and amplifiers.

These nodes are engineered in three different ways: (1) each node's Erbium Doped Fiber Amplifier (EDFA) is assigned a 7 dB noise figure with the gain of each pre-amplifier in Fig. 1 assumed to be compensating the loss of each preceding fiber span, whereas each post-amplifier has a gain of 14 dB resulting in a signal launched power into the fiber of 0 dBm; (2) Signal launched power into fiber is now increased to +3 dBm and the gain of the post-amplifiers is reduced to 12 dB as more gain is shifted to the pre-amps (to improve the overall node noise figure) which now compensate the loss of the preceding fiber and have a total output power of 20 dBm. In addition, the noise figure of each EDFA is adjusted depending on its gain and varies from 5.5 dB to 7 dB; (3) the node parameters of (2) are used and in addition in-line amplifiers are introduced on each network span that exceeds 40 km thus improving the Q-performance of each link. Each scenario is then simulated in the multicast algorithms above by subtracting a Q-penalty for each impairment from the baseline Q-value as described before. As a result, a typical signal will traverse 10 optical filters and collect 35 common channel crosstalk terms (5 nodes times 7 signals based on average node degree of 8) each at a level of -50 dB which is assumed for the switch fabric of Fig. 1. Incoherent common channel crosstalk penalty is then budgeted at 0.8 dBQ based on a model presented and Fig. 12 of [3]. The penalty due to optical filter narrowing is budgeted at 0.4dB according to work in [3,11]. PMD is budgeted at 0.2 dBQ based on the analytical model presented in [3] and references therein. Fiber nonlinearities are factored at 1 dBQ, typical for a metro network [3], and a safety margin of 1 dBQ is included into the budgeting model for component aging. It must also be pointed out that amplifier gain control is assumed [12] and that no polarization dependent gain/loss (PDG/PDL) or amplifier ripple are present, thus precluding power instabilities.

IV.RESULTS

In order to evaluate the average performance of the balanced light-tree routing algorithms we simulated multicast connections on a metro/regional network consisting of 50 nodes and 196 links, with an average node degree of 7.84 and an average distance between the links of 70 km. We used a dynamic traffic model where multicast sessions arrive at each node according to a Poisson process and the holding time is exponentially distributed with a unit mean. In each simulation 5,000 requests were generated for each multicast group size (number of destinations for the multicast tree) for a total of 40,000 multicast requests, and the results were averaged over five simulation runs. Thirty-two wavelengths per link were utilized to evaluate the blocking probability versus the multicast group size for a network load of 100 Erlangs. Figures 2-3 demonstrate the network performance in terms of blocking probability for the three different engineering scenarios discussed. For all three results, there was less than ±1% variation between the maximum and the minimum values obtained between simulation runs, with this variation decreasing to less than ±0.5% for large multicast group sizes.

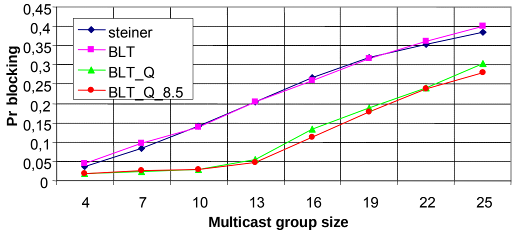

Figure 2. Blocking probability versus multicast group size for node engineering scenario 1.

Fig. 2 shows the simulation results for the blocking probability versus the multicast group size when a number of multicast algorithms are used assuming node engineering scenario 1. The Steiner tree heuristic (multicast tree with the minimum cost based on shortest-path calculations) and the BLT algorithm that only takes power budget constraints into consideration have much higher blocking probability than the BLT_Q and BLT_$Q_{tolerance}$ algorithms. For instance, a typical multicast group of 13 (25% of the network nodes are destination nodes) shows improvement of 15% in blocking with the proposed algorithms. This is the case since with the new algorithms trees tend to become "shallower" which means that the Q threshold is not exceeded. Figure 3(a) shows the simulation results for engineering scenario 2. Better node engineering improves blocking by another 4% for BLT_Q and BLT_$Q_{tolerance}$ assuming multicast group of 13. The BLT_$Q_{tolerance}$ algorithm generally provides better performance results than BLT_Q. This is due to the fact that with improved Q-performance BLT_$Q_{tolerance}$ which creates trees with not so much breadth compared to BLT_Q utilizes resources better. If in-line optical amplifiers are also used (scenario 3), the Steiner tree and the BLT_$Q_{tolerance}$ algorithms perform better than BLT_Q (that tends to use a larger number of wavelength channels) with the Steiner tree giving the best results for large group sizes as Q-performance greatly improves with this engineering scenario and blocking is now mostly due to limited resources (Fig. 3(b)). Using the Q-factor as the figure of merit for the physical layer part of the algorithms as opposed to optical power allows for the inclusion of ASE noise in the calculations. As a result, node/system engineering becomes important and the inclusion of these in the light-tree multicast algorithms affects the results as shown in Figs. 2-3.

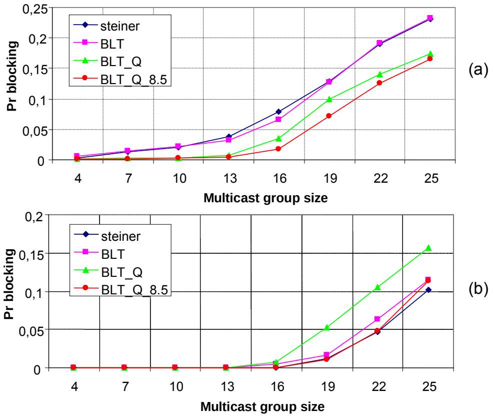

Figure 3. Blocking probability vs. Multicast group size for (a) engineering scenario 2, (b) engineering scenario 3.

V. CONCLUSIONS

This paper improves on MC-RWA algorithms which are becoming critical in the provisioning of multicast services in optical networks by including physical layer constraints utilizing the Q-factor. Modified BLT algorithms are designed and their performance is tested on a 50-node network. Results show that the blocking probability is improved significantly (15% for multicast group size of 13 and more for higher sizes) compared to both the Steiner heuristic and the BLT algorithm that only takes the power budget into consideration. Blocking probabilities are actually now more realistic for optical networks. Accounting for PDL/PDG will generate different Q-performance for each path of a light-tree and thus affect the balancing mechanisms. This is the subject of our future work.

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