Q-based Provisioning for Multicast Connections in Translucent Metropolitan Area Networks

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Abstract—**This paper investigates the problem of identifying the most efficient nodes in translucent metropolitan optical networks to be equipped with 3R regeneration for provisioning multicast calls while taking into account the physical layer impairments via the Q-factor metric and the tree topology of the multicast connections during the regeneration placement procedure. Two regeneration placement heuristics are proposed, namely the Q-based regenerator placement (QbRP) heuristic and the Q-based regenerator placement with path correlation (QbRP) heuristic. Simulations are performed on a number of metropolitan area networks considering a static traffic model for both the proposed heuristics and for a known regeneration placement heuristic, namely the nodal degree first (NDF) algorithm. Results showed that both QbRP and QbRPC outperform NDF while QbRPC performs the best among the three. Furthermore, results showed that the same performance is achieved in a network where only a small percentage of nodes is equipped with regenerators compared to a network with regenerators at all network nodes.**

I. INTRODUCTION

Advances in optical networking have made bandwidth-intensive multicast applications such as HDTV, interactive distance learning, video-conferencing, distributed games, movie broadcasts, etc., widely popular. These applications require point-to-multipoint (PtMP) connections from a source node to several destination nodes in the network. Optical multicasting provides an easy means to deliver messages to multiple destinations by just splitting the optical signal at multicast-capable optical nodes.

Translucent network architectures that support OEO functionality at only some of the network nodes have been proposed as a solution between opaque and transparent (all-optical) networks. Translucent optical networks, exploit the advantages of both transparent optical networks, where connections are switched in the optical domain, and opaque networks where connections are optically terminated at intermediate nodes. On one hand, optical transparency offers considerable bandwidth at low cost, as well as bit-rate, protocol, and modulation format independence. On the other hand, by performing opto-electronic signal regeneration at some of the intermediate nodes, amongst other things, it is possible to recover the signal degradation due to physical layer impairments and avoid end-to-end path engineering [1]. The translucent approach eliminates some of the electronic processing and allows a signal to remain in the optical domain for much of its path, bringing a significant cost reduction due to the removal of electronic equipment (transmitters, receivers, etc) [2]. Thus the objective of this work is to develop a heuristic algorithm that identifies how many and which nodes in a metropolitan area network, have to be equipped with regenerators in order to improve the network performance, considering a static case scenario where a number of known multicast calls have to be established into the network.

Two heuristics are proposed in this work and both aim at improving the network performance by selecting the most appropriate nodes in the network to perform 3R regeneration. To accomplish this, the physical layer impairments (PLIs) are taken into account via the Q-factor metric, assuming the physical layer system modeling proposed in [3]. Assuming that each multicast call is provisioned on the longest wavelength in the network (that yields the worst Q-factor), placement of the regenerators is decided according to the destination nodes with unacceptable Q-factor on each tree. Note that for the evaluation of the Q-factor, the multicast-capable node architecture/engineering with fixed transmitters/receivers presented in [3] is assumed.

Previous work on the regeneration placement problem that takes into consideration the signal quality can be found in [4], [5], for point-to-point connections. In [4] regeneration nodes are decided according to parameter LNMAX, which denotes that a transparent optical signal can traverse at most LNMAX links without having its BER exceed a predetermined threshold. For the evaluation of the LNMAX number the physical distance is used as an approximation of the signal quality. Specifically, every path is inspected starting from the source node and the nodes that lie away from the source more than LNMAX links are the candidate regeneration nodes. Work in [5] showed the sub-optimality of distance-based regeneration placement approaches [4] by introducing impairment-awareness into the problem of dimensioning a WDM network based on selective regeneration. The regeneration placement problem assuming multicast connections has been studied in [6] and is also a distance-based regeneration placement approach.

The proposed heuristics are compared to a known regenerator placement algorithm, namely the nodal degree first (NDF) algorithm which is a network topology based regenerator placement heuristic [4]. Note however that work in [4] considers only point-to-point connections. In NDF, regenerators are decided according to the node degrees in the network and specifically if the allowable number of regenerators in a network is set to z, then the first z nodes with the maximum degree are chosen.

II. NODE ARCHITECTURE/ENGINEERING

As previously mentioned, the multicast-capable node architecture/engineering with fixed transmitters/receivers presented in [3] is assumed for calculating the Q-factor. For the nodes performing 3R regeneration, this architecture is expanded as shown in Fig. 1. Fig. 1 shows a generic node architecture with 3R regeneration consisting of splitters, attenuators, optical switches, amplifiers and fixed transmitters/receivers.

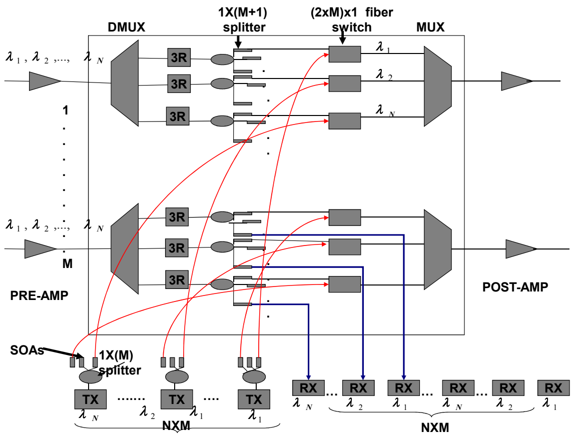

Fig. 1. Node architecture

The figure clearly shows that on the transmitting side an $(1 \times M)$ splitter is needed for each transmitter, followed by M SOAs (functioning as on/off gates), in order to be able to turn the signal off for any unwanted output port. On the receiving side, $(N \times M)$ optical receivers are directly connected to the SOAs inside the node design. $(N \times M)$ 3R regenerators are also added just after the DMUX for regeneration purposes of each signal entering the node.

The signal launched power into the fiber is set to 5 dBm, and each node's EDFA is assigned a realistic noise figure (NF) depending on its gain [3], with the gain of each pre-amplifier compensating for the loss of each preceding fiber span (the fiber attenuation in this analysis is considered to be 0.3 dB/Km). The gain of each post-amplifier compensates for the actual node loss and is engineered based on the worst-case insertion loss through the node. The output powers of the pre- an post-amplifiers are set at $+7$ dBm to further improve the overall node NF. The worst-case insertion loss is limited by the maximum splitting loss. The noise figure of the p-i-n receiver's pre-amplifier is assigned a value of 4.5 dB with a gain that is adjusted so as to bring the signal power to -4 dBm.

III. Q-BASED REGENERATOR PLACEMENT HEURISTICS

Two regeneration placement heuristics are presented that aim at improving the network performance by selecting the most appropriate nodes in the network to perform 3R regeneration. To accomplish this, the physical layer impairments (PLIs) are taken into account. The first heuristic presented is the Q-based Regenerator Placement (QbRP) heuristic that tries to identify a set of candidate regeneration nodes that are as close as possible to the destination nodes with unacceptable Q-factor. The second heuristic is the Q-based regeneration placement with path correlation (QbRPC) heuristic that aims at finding the minimum number of regeneration nodes required by correlating all the paths of the multicast tree, starting from the source node, to every destination node with unacceptable Q-factor. Then the common node/s in these paths are the candidate regeneration node/s of the tree. While both QbRP and QbRPC heuristics return a set of candidate regeneration nodes for each multicast call, one more step is required for choosing the final set of regeneration nodes amongst every candidate regeneration node for every multicast call.

A. Q-based Regeneration Placement (QbRP) Heuristic

The basic idea of the proposed Q-based Regenerator Placement (QbRP) heuristic is briefly described below utilizing the illustrative example of Fig. 2. The heuristic consists of two main steps. The first step is to find an initial set CR of candidate regeneration nodes on tree T and the second step is to try to reduce the number of regenerators in set CR.

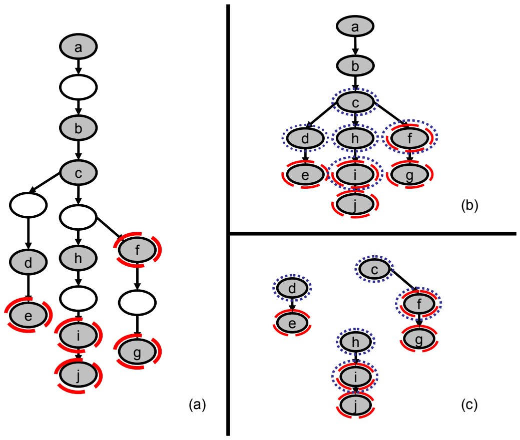

Fig. 2. (a) Tree T with source a and destination nodes $b, c, d, e, f, g, h, i, j$. Destination nodes with a Q-factor below threshold are shown in dashed circles. (b) Graph AG consisting only of the source and destination nodes. Candidate regeneration nodes are marked with dotted circles. (c) Graph AG'.

1) Finding the Initial Set of Candidate Regeneration Nodes CR:

- Calculate the Q-factor for every destination node of multicast tree T assuming that T has been established on the longest wavelength of the working window (that yields the worst Q-factor)

- Identify destination nodes D with a Q-factor below Q-threshold. Fig. 2(a) shows tree T with source a and destination nodes $b, c, d, e, f, g, h, i, j$, where nodes e, f, g, i, j are marked as destination nodes with unacceptable Q-factor.
- Create auxiliary graph AG by first adding the source and every destination node of T and then connecting two nodes in AG if they are connected via a path in T and there is no intermediate node in that path that is a destination node of T. (Fig. 2(b))
- For every destination node $d_j \in D$ identify in AG node r_j that is directly connected to d_j with an outgoing link from node r_j to node d_j. For example, according to Fig. 2(b) if $d_1 = e$ then $r_1 = d$.
- Declare every destination node r_j as a candidate regeneration node and add node r_j into the set of candidate regeneration nodes CR. Thus, according to Fig. 2(b), $CR = \{r_1, r_2, r_3, r_4, r_5\} = \{d, c, h, i, f\}$.

2) Reducing the Number of Candidate Regeneration Nodes in Set CR:

- Declare nodes $d_j \in D$ and $r_j \in CR$ as segmentation nodes of T and every (d_j, r_j) link as segmentation link L_j. Thus, in Fig. 2(b), the segmentation nodes are c, d, e, f, g, h, i, j while the segmentation links are $(d, e), (h, i), (i, j), (c, f)$, and (f, g).
- Create auxiliary graph AG' by first adding to AG' segmentation nodes $d_j \in D$ and $r_j \in CR$. Then add to AG' every segmentation link L_j. Fig. 2(c) illustrates AG' according to segmentation nodes and segmentation links of Fig. 2(b).
- From every candidate regeneration node $r_j \in CR$, find in AG' all shortest paths and count the number k of destination nodes $d_j \in D$ that it can reach. For example, as shown in Fig. 2(c) candidate regeneration node h can reach nodes i and j.
- Associate each candidate regeneration node $r_j \in CR$ with its k number and the destination nodes that it can reach. Specifically, $r_j^k = D', D' \subseteq D$, and denotes that candidate regeneration node $r_j^k \in CR^k$ can reach the k destination nodes of set D'. Thus, from Fig. 2(c), since $r_1 = d, r_2 = c, r_3 = h, r_4 = i$, and $r_5 = f$, then $r_1^1 = \{e\}, r_2^2 = \{f, g\}, r_3^2 = \{i, j\}, r_4^1 = \{j\}$, and $r_5^1 = \{g\}$ respectively.
- Sort regeneration nodes in CR^k according to number k in such a way that the regeneration node reaching the maximum number of destination nodes is placed first on the list. Then, according to Fig. 2(c), $CR^k = \{r_2^2, r_3^2, r_1^1, r_4^1, r_5^1\} = \{c, h, d, i, f\}$.
- Starting from the top of the sorted CR^k list, add regeneration node $r_w \in CR$ to the list of regeneration nodes R^k if at least one of its destination nodes in set $r_w^k \in CR^k$ is not included in sets that were previously inspected in CR^k. According to the above, in our example, node c is added to list R^k as it is the first node in list CR^k. Node h is also added to R^k since nodes i, j are not reached by node c. Similarly, node d is also added, since node e is not reached by either node h or c. Node i is rejected since node j is reached by node h already added into set R^k, and likewise node f is also rejected. According to the above, the candidate regeneration nodes of T (Fig. 2) are nodes c, h, and d. Thus, $R^k = \{c^2, h^2, d^1\}$. Note that the initial number of candidate regeneration nodes in this example is five (5) and the heuristic reduces this number to three (3).

B. Q-based Regenerator Placement with Path Correlation Heuristic

A second regenerator placement heuristic that considers for the PLIs, namely the Q-based regenerator placement with path correlation (QbRPC) heuristic, is presented here that aims at further improving the number of candidate regeneration nodes for each light-tree compared to the QBRP heuristic. As previously described in the example of Fig. 2, QbRP returns three candidate regeneration nodes; nodes d, c, h. However, by inspecting Fig. 2(b), it can be seen that node c can reach every affected destination node, and although further away from some destination nodes, it can still be close enough to cover every affected destination. Thus, the proposed QbRPC heuristic is developed in such a way that in the example of Fig. 2 will return as candidate regeneration node only node c, thus effectively trying to minimize the number of candidate regeneration nodes for each light-tree.

The basic idea of QbRPC is to find the destination node that is common to every affected destination, by correlating every path in a multicast tree T starting from the source and ending at every destination node. For example, multicast tree of Fig. 2(b) consists of five paths: $P_1 = \{a, b, c, d, e\}$, $P_2 = \{a, b, c, h, i\}$, $P_3 = \{a, b, c, h, i, j\}$, $P_4 = \{a, b, c, f\}$, $P_5 = \{a, b, c, f, g\}$. Obviously, nodes a, b and c are the common nodes amongst every path. However, node a is the source and thus cannot be declared as a regeneration node. Amongst the two remaining nodes it is best to choose node c as the candidate regeneration node as it is closer to every affected destination node.

In the above example we try to identify a single regeneration node. However, it is possible that the minimum number of candidate regeneration nodes is more than one. This situation may arise when the source node of the affected tree has a degree greater that one. In that case, instead of correlating together all the paths from the source to every affected destination, several groups of paths are created for correlation according to the second node in paths P_j. Specifically, a P_j path is added to a group of paths if the second node in every path in that group is the same. If k groups of paths are created then k is the minimum number of regeneration nodes the algorithm seeks to find. The basic steps of the QbRPC heuristic are given below utilizing the illustrative example of Fig. 3.

- Calculate the Q-factor for every destination node of multicast tree T assuming that T has been established on the longest wavelength of the working window (that yields the worst Q-factor).

- Identify destination nodes D with a Q-factor below Q-threshold. Fig. 3(a) shows tree T with source a and destination nodes $b, c, d, e, f, g, h, i, j$, where nodes c, f, g, i are marked as destination nodes with unacceptable Q-factor.
- If k is the number of destination nodes in set D, then identify k paths P_i, where $i = 1, 2, ...k$, starting from the source node and ending at every node in set D. According to Fig. 3(a) four paths are created; $P_1 = \{a, k, b, c\}$, $P_2 = \{a, d, e, l, f\}$, $P_3 = \{a, d, e, l, f, g\}$, and $P_4 = \{a, d, h, m, i\}$.
- Update every path P_i into P'_i by removing from P_i every node that is not a destination node of T and every node that belongs to set D. Thus, according to the illustrative example, $P'_1 = \{a, b\}$, $P'_2 = \{a, d, e\}$, $P'_3 = \{a, d, e\}$, and $P'_4 = \{a, d, h\}$.
- Create an auxiliary graph AG according to paths P'_i. The AG of the illustrative example is shown in Fig. 3(b).
- Find the degree d of the source node in AG. In our example $d = 2$.
- Update paths P'_i into P''_i by removing from each path the source node. Thus, $P''_1 = \{b\}$, $P''_2 = \{d, e\}$, $P''_3 = \{d, e\}$, and $P''_4 = \{d, h\}$.
- Create group G_j, where $j = 1, 2, ..., d$ according to the first node in paths P''_i, where $i = 1, 2...., k$. Specifically, the paths P''_i with the same first node belong to the same group. In our example two groups of paths are created; $G_1 = (P''_1)$ and $G_2 = (P''_2, P''_3, P''_4)$.
- For each group G_j perform operation $r^k_j = \bigcap G_j$ where r^k_j is the regeneration node for the j^{th} group of paths and k is the number of affected destination nodes it can reach. Specifically, k is evaluated for the j^{th} regeneration node by counting the set of paths in group G_j. In case there are more than one nodes that are common amongst the paths in a certain group G_v, then the one that is closest to the affected destination nodes is selected.
- The set of regeneration nodes is given by $R^k = \bigcup r^k_j$ where $j = 1, 2, .., d$. In the example, $R^k = \{b^1, d^3\}$.

C. *Finding the Final Set of Regeneration Nodes R_f*

For both regenerator placement heuristics presented above, one more step is required for choosing the final set of regenerators amongst every candidate regenerator for every multicast call. As pointed out, in this work a static case scenario is examined in which case T_i trees, where $i = 1, 2, 3, ..n$, request to be established into the network. According to the QbRP heuristic a candidate set of regenerators is evaluated for each T_i. The final set of regenerators R_f is then decided amongst the candidate regenerators in sets R^k_i. Specifically, during the decision procedure, every network node v is explored, and if $v \in R^k_i$ then the k number associated with each candidate regeneration node is added to counter C_v, initially set to zero. For example, if the network graph consists of nodes a, b, c, d, e and three trees are requesting to be established into the network with $R^k_1 = \{a^3, b^1, c^2\}, R^k_2 = \{b^1, c^2\}$, and $R^k_3 = \{d^1, e^1\}$, then according to the above $C_a = 3, C_b = 2, C_c = 4, C_d = 1$, and $C_e = 1$. Thus, the final set of regenerators R_f is decided according to counters C_v and according to the predetermined allowable percentage of regenerators p over the total number of nodes in the network. Specifically, the network nodes are sorted according to counters C_v in such a way that the node serving the maximum number of nodes in the network graph is placed first on the list. Thus, in the previous example, if $p = 0.5$ then $R_f = \{c, a\}$ is the final set of regenerators.

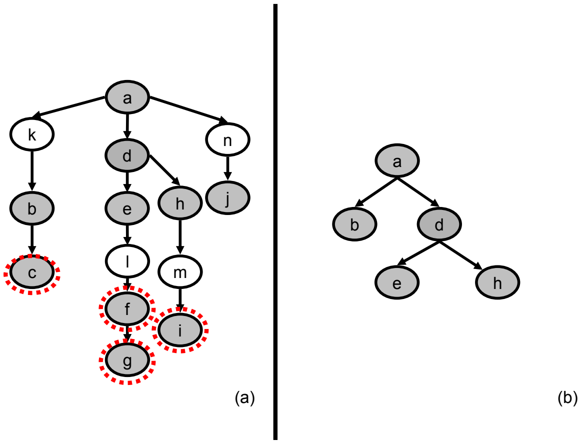

Fig. 3. (a) Multicast tree T with source node a and destination nodes b, c, d, e, f, g, h, i. Destination nodes with a Q-factor below threshold are shown in dashed circles. (b) Auxiliary graph AG.

IV. ROUTING AND WAVELENGTH ASSIGNMENT

In this work a static case scenario is assumed in which n calls of varying multicast group sizes request to be established into the network. The Steiner Tree heuristic is first utilized for calculating on network graph G, n multicast trees T_i $i = 1, ..., n$; one for each multicast call. Then, each call is sorted according to the number of links each tree T_i is utilizing. Specifically, the tree with the maximum number of links is placed first in the list, as paths utilizing a larger number of links are generally harder to be accommodated in the network. Once the set of regenerators R_f is decided, the next step is to break the trees into subtrees according to R_f. Specifically, in each T_i, regenerators are identified and the tree is decomposed at the regeneration nodes into the appropriate independent subtrees T^j_i, where $j = 1, 2, ..., (m + 1)$ if the number of regeneration nodes in T_i is m. For example, Fig. 4 shows how tree T of Fig. 2(a) is decomposed into four subtrees.

After each tree is decomposed into the appropriate subtrees, the wavelength assignment (WA) procedure follows. Starting from the tree placed first on the list, a WA heuristic is utilized that seeks to find a wavelength to accommodate each subtree in such a way that the Q-factor at every destination node is above the predetermined Q-threshold. Furthermore, for the chosen wavelengths for every subtree, an additional check has to be made that there are available transmitters and receivers to accommodate the multicast connection. Wavelengths are searched for availability in a sequential manner and each

TABLE I
NETWORK STATISTICS.

	A	B	C
Number of Nodes	50	21	32
Number of Links	98	56	142
Average Distance (Km)	60	75	74
Maximum Distance (Km)	100	100	100
Minimum Distance (Km)	20	51	50
Average Node Degree	3.92	5.33	8.87
Minimum Node Degree	3	3	5
Maximum Node Degree	6	8	15
Diameter (Km)	305	248	250
Diameter (hops)	6	4	3
Maximum Multicast Group Size	24	10	15
Number of Wavelengths	64	32	32
Blocking Probability ($p = 1$)	0	0	0
Blocking Probability ($p = 0$)	0.09	0.099	0.097

subtree is established into the first available wavelength, according to the first-fit wavelength assignment technique [7]. A multicast call is blocked if there is no wavelength assignment possible with acceptable Q-factor or if there are no available TXs/RXs for at least one of its subtrees.

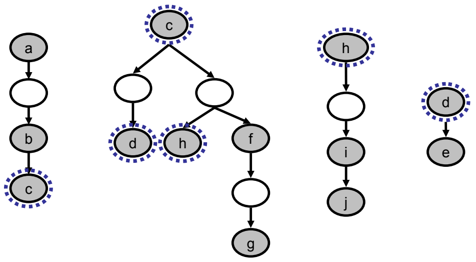

Fig. 4. Tree T of Fig 2(a) is decomposed into four subtrees according to regeneration nodes c, d, and h.

V. PERFORMANCE EVALUATION

Simulations are performed on several metropolitan area networks considering each time a different allowable percentage of regeneration nodes p over the total number of nodes in the network. The QbRP and QbRPC heuristics are compared to a known regenerator placement algorithm, namely the nodal degree first (NDF) algorithm which is a network topology based regenerator placement heuristic (for point-to-point connections) [4]. A static traffic model is used, where multicast sessions of mixed group sizes request to be established into the network. In this work, a Q-threshold of 9dB is assumed, corresponding to a BER of 10^{-15}. In order to determine the Q-value for every destination node of each multicast call, a baseline system Q-value is first calculated based on the signal and noise terms, assuming 10 Gbps bit rate, a pre-amplified p-i-n photodiode, and a WDM system with the wavelengths spaced at 100 GHz. The number of wavelengths is chosen for each network in such a way that the blocking probability is only due to the PLIs and not due to the unavailability of resources (wavelengths). Details regarding the networks utilized, denoted as networks A, B, and C can be found in Table I. Specifically, Table I shows information regarding the number of nodes and links, the average, minimum, and maximum distance between the nodes, the maximum, minimum, and average nodal degree, and the diameter of each network. Furthermore, information is included on the number of wavelengths utilized for achieving a blocking probability equal to zero assuming that all nodes are equipped with regenerators ($p = 1$), as well as for achieving a blocking probability that is limited by the PLIs assuming that there are no regenerators ($p = 0$) in the network. Finally, the maximum allowable multicast group size for each network is given. For example, for network topology A, the maximum allowable multicast group size is 24 and thus, for the simulations multicast sessions were randomly generated between the integer numbers 1 and 24.

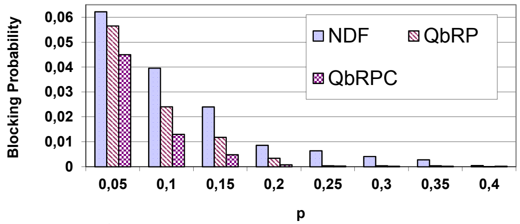

Fig. 5. Network A: Blocking probability versus p.

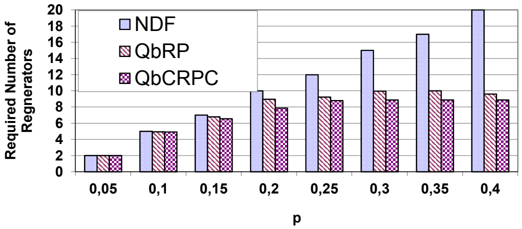

Fig. 6. Network A: Number of Required Regenerators versus p.

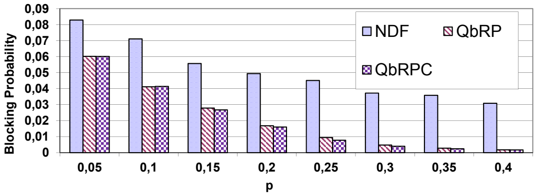

Fig. 7. Network B: Blocking Probability versus p.

Figs. 5, 7, and 9 show the blocking probability versus the allowable regenerator percentage p for network topologies A, B, and C respectively. The number of regenerators required over p for each network topology A, B, and C is shown in Figs. 6, 8 and 10, respectively. Note that 100 requests were generated for each simulation point, and the results

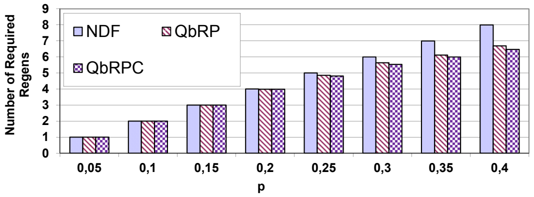

Fig. 8. Network B: Number of Required Regenerators versus p.

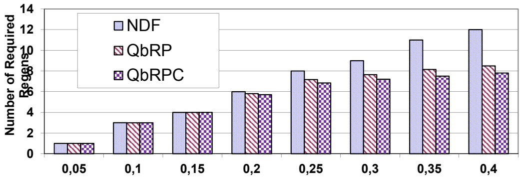

Fig. 10. Network C: Number of Required Regenerators versus p.

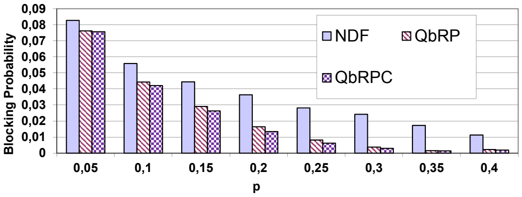

Fig. 9. Network C: Blocking probability versus p.

were averaged over 100 runs. Results in Figs. 5, 7, and 9 show that both QbRP and QbRPC outperform NDF as the blocking probability of both heuristics is for every p and for every network examined lower than that of NDF. Furthermore, the QbRPC heuristic outperforms QbRP in both network performance (Figs. 5, 7, and 9) and cost savings (Figs. 5, 8, and 10); an indicator that finding the minimum number of regeneration nodes in a multicast tree is more important than finding the regeneration nodes that are as close as possible to the affected destinations.

Specifically, results for network topology A show that if $p = 0.25$ (Fig. 5) then both QbRP and QbRPC achieve a blocking probability close to zero, which is also achieved when assuming that every node in the network is equipped with a regenerator; something that with NDF is achieved with $p = 0.4$. Furthermore, Fig. 6 for network topology A, shows that with QbRP no more than 10 regenerators are required to achieve the lowest blocking probability, which corresponds to just the 20% of the overall network nodes in the network while with QbRPC no more than 9 regenerators are required which corresponds to just 17% of the overall network nodes. NDF however, requires 20 regeneratorss which corresponds to 40% of the overall network nodes. Similar results can be deducted for network topologies B and C. For example, by inspecting Figs. 7 and 8 for network B, we can see that with QbRPC if 30% of the overall network nodes is equipped with regenerators then the lowest blocking probability is achieved. Likewise, by inspecting Figs. 9 and 10 for network C and for the QbRPC heuristic, if 25% of the overall network nodes is equipped with regenerators then a blocking probability close to zero is achieved. Thus, QbRP and QbRPC, which consider for the PLIs and the tree topology of multicast calls, outperform NDF in terms of both network performance and cost savings, while QbRPC outperforms QbRP.

VI. CONCLUSION

The performance of regenerator placement heuristics is examined over a number of network topologies. Specifically, two regenerator placement heuristics are proposed, namely the Q-based regenerator placement (QbRP) heuristic and the Q-based regenerator placement with path correlation (QbRP) heuristic, that account for the PLIs and the tree topology of multicast calls during the placement of regeneration nodes in the network. QbRP and QbRPC are compared to the NDF heuristic that is a network topology based regenerator placement heuristic and was initially proposed for point-to-point connections. Results showed that both QbRP and QbRPC outperform NDF for every network topology examined in both network performance and cost savings. Between the two, QbRPC performs the best. In the best network scenario it was found that if the regenerator placement is decided according to the QbRPC scheme, then only 17% of the overall network nodes need to be equipped with regenerators in order to achieve the same network performance as in the case where every network node is a regeneration node.

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