Load-Aware Anycast Routing in IP-over-WDM Networks

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Abstract—In this work we propose anycast routing methods to improve the performance of reconfigurable WDM networks under the variations in the IP traffic. We first investigate anycast communication via impairment-aware anycast routing (IAAR); our simulation results show significant improvement in the blocking probability. We also investigate the proposed load-aware anycast routing (LAAR) for the varying traffic model. From the results we observe that LAAR minimizes the lightpath request loss, by dynamically choosing the anycast configuration based on the network load.

Keywords: IP-over-WDM, RWA, anycast, unicast, transmission impairments.

I. INTRODUCTION

Wavelength division multiplexed (WDM) networks comprise a promising solution for meeting the Internet's increasing bandwidth demands. Connection provisioning in WDM networks is realized via *lightpaths* (LPs). Lightpaths are computed using routing and wavelength assignment (RWA). RWA algorithm evaluates the route for a given source-destination pair and assigns a wavelength that is available on all the links along the route. The wavelength continuity constraint (WCC) requires the availability of the same wavelength along all the links. A request for the lightpath could be blocked if the WCC is not satisfied. Thus the performance of the WDM network is limited by the number of wavelengths the network can support. WDM networks equipped with wavelength converters (WCs) will decrease the number of LP requests dropped due to WCC, however at increased network cost. In the present work, we consider the network without wavelength converters.

In practice the WDM network is non-ideal, and the request blocking can also occur due to transmission impairments in the optical systems. The major impairments that reduce the optical-signal to noise ratio (OSNR) of a LP operating within data rates of 10 Gb/s are amplified spontaneous emission (ASE) noise present in the amplifiers and crosstalk (XT) generated in the wavelength switches.

Thus, the performance of WDM networks is, limited by the WCC and impairment constraint. Impairment or Quality of Transmission (QoT)-aware routing algorithms reduce the number of LP requests blocked due to insufficient optical signal quality. Thus, the LP loss with impairment aware routing (IAR) is approximately equal to that of an ideal network [1].

In this work, we propose anycast communication for transparent WDM networks. The anycast communication paradigm is a variation of unicast, where the source node has a choice of selecting a destination from the candidate set. IP-anycast [2] provides a means to discover the appropriate service location from a candidate set of locations, implying a user can communicate using the IP-anycast addressing format to retrieve the data from the nearest replica. IP-anycast has also been proposed as an infrastructure for multicast routing [3].

Supporting anycast routing on a WDM network has been investigated in the past. RWA algorithms for anycast communication was addressed in [4]. Anycasting over optical burst-switched (OBS) networks has been studied in [5]. Performance of grid applications over OBS networks using anycast communication is addressed in [6]. Sleep modes are proposed using anycast communication for achieving energy minimization for OBS networks [7].

The remainder of this paper is structured as follows: we first describe the IP-over-WDM network architecture in Section II. Section III defines the problem and the functionality of the optical control plane (OCP). In Section IV, the proposed anycast routing algorithms are described. Section V discusses the simulation results. Finally, we conclude in Section VI.

II. IP-OVER-WDM

IP-over-WDM networks consist of two layers as shown in Fig. 1. IP routers are connected to the optical cross-connect switches (OXCs). Electronic traffic from IP layer is modulated into optical data stream at each WDM transponder shown in Fig. 1. The core optical layer provides the huge bandwidth pipe between the IP routers. OXCs are connected via physical fiber links that consist of inline amplifiers, multiplexers, and demultiplexers. The OXC switch could be a static switch that is not reconfigurable and hence requires no intelligence. However, due to the advances in optical networking technology, the OXC switch could be made reconfigurable using an add-drop multiplexer (ADM). This allows the IP router to establish dynamic connection between different IP-ports. A connection between the IP routers is established using lightpath, creating a virtual topology for the IP layer. There are two possible ways to implement IP-over-WDM networks: i.e., lightpath non-bypass and bypass. Under lightpath non-bypass, all the lightpaths incident to a node must be terminated, i.e. all the data carried by the lightpaths is processed and forwarded by electronic IP routers. In contrast, the lightpath bypass approach allows IP traffic, whose destination is not the intermediate node, to directly bypass the intermediate router via a cut-through lightpath [8]. This requires the OXC to have intelligence that could enable the optical bypass. In this work, we consider a reconfigurable WDM network with optical bypass.
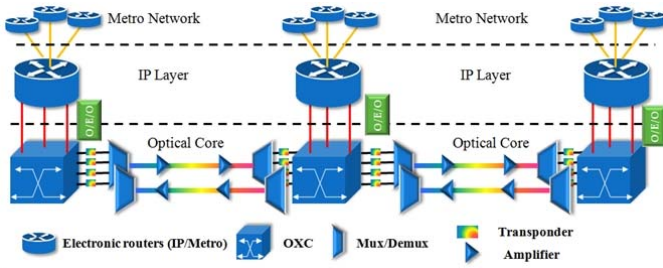
Fig. 1.   IP-over-WDM.

III. PROBLEM DEFINITION

For a given source node s and the candidate destination set $D_m = \{d_1, d_2, \ldots, d_m\}$ with a cardinality $|D_m| = m$, anycast is defined as communication in which a source node s can choose any one among m destinations. We denote such an anycast configuration as $m/1$. In the case of unicast, $m = 1$ and is denoted as $1/1$. The algorithms proposed in this paper use source initiated routing (SIR); the OCP (described in Section. III-A) at the source node chooses a destination based on given threshold requirement for impairments. Request blocking and the delay involved with connection provisioning are related to the destination set size. For example, choosing a large candidate destination set can decrease the request blocking; however, this involves a large overhead on the control plane and causes delay in connection provisioning. Having large m might also cause problems maintaining replicas (or resources) in many candidate destinations across the network. Thus, we see trade-offs that would be essential in choosing the value of m, such that the connection provisioning could be done at fly.

Given a network, $G(V, E)$, where V is the set of vertices and E is the set of edges, an edge cost function given by $g : E \rightarrow R^+$, a source s, and the subset of candidate destinations $D_m \subset V, |D_m| = m$, where $|D_m|$ is the cardinality of the set D_m, then the anycast request is denoted by $(s, D_m, 1)$.

Impairments, such as attenuation along the fiber and ASE noise from the amplifiers remain static, and are directly proportional to the physical distance on the route between any source-destination pair. Crosstalk among the wavelength switches is dynamic, so impairments on the lightpath configured with shortest-distance will not necessarily lead to minimum impairments. Thus, we observe a need to search for alternate paths for a given source-destination pair. The anycast routing algorithm does not chose an alternative path, but instead computes the LP to a different destination if WCC and the OSNR constraints are not satisfied. This type of communication is particularly useful for distributed applications, such as storage-area networks (SAN), content distribution networks (CDN), and grid computing. IP anycast request from an source IP router (in Fig. 1) is communicated via the OCP, and then wavelength-switches (OXCs) are configured accordingly.

A. Optical Control Plane (OCP)

Control management in WDM networks can be centralized [9] or distributed [10]. In this work we use a centralized control plane similar to the one proposed in [9]. Fig. 2 shows the control plane between an IP-router and an OXC switch. OCP

box has been implemented using a NetFPGA [11] to control optical components, such as an OXC and amplifiers, and has been demonstrated in [12].

When the connection between two IP routers must be established, the optical ADM (OADM) is configured via a control signal from the OCP to the respective OXC router. RWA algorithm calculates the route based on heuristics (Section IV) for a source-destination pair and assigns the wavelength. The bit-error-rate (BER) estimator evaluates the QoT for the LP (wavelength). If the OSNR along the path for the assigned wavelength is within the threshold, the connection is provisioned. Thus, the control plane first estimates the transmission quality and then configures the switch fabrics along the path. In the case of anycast communication, the OCP will evaluate the RWA and BER for other destinations in the candidate set only if the path to the closest destination on all wavelengths exceeds the OSNR threshold.
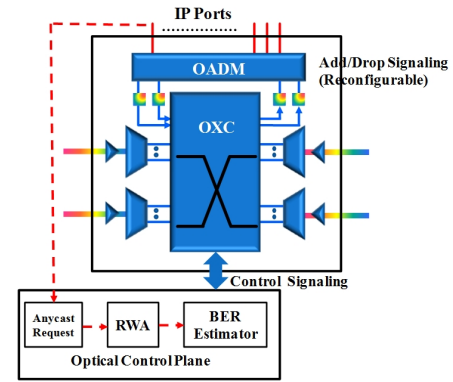

Fig. 2.   Architecture for IP-over-WDM with optical control plane (OCP).

IV. ANYCAST ROUTING ALGORITHMS

In anycast algorithms, selecting a destination from a given set can be done randomly. However, we propose heuristics based on weights of the edges in the network. The given destination set is first sorted based on shortest distance (or hop) from the source node. Selecting a destination (from the sorted set) closest to the source may minimize the parameters, such as impairments (not necessarily), delay, etc. Thus, there is high probability of successfully provisioning LP connection to such a destination. These heuristics can also help reduce the algorithm execution time.[1]

In this section, we propose anycast routing algorithms based on minimum-distance (MD) and minimum-hop (MH) heuristics as described in Algorithms 1 and 2. The following are the steps involved with sorting the destinations in the anycast request $(s, D_m, 1)$,

- *Step 1*: Find the shortest distance (or hop-count) from source s to all the destinations in D_m. Let $D_m = \{d_1, d_2, \ldots, d_{|D_m|=m}\}$ and distance (or hop-count) from s to d_i, where $1 \leq i \leq m$ is $\mathbb{P}^{(s)} = \{p_1, p_2, \ldots, p_m\}$ ($\mathbb{H}^{(s)} = \{h_1, h_2, \ldots, h_m\}$ for hop-count heuristic), where p_i (or h_i), is the shortest distance (minimum hop-count) for a $\langle s, d_i \rangle$.

[1] Results for random destination selection are not shown in this paper.

- *Step 2*: All the destinations in D_m are sorted in the non-decreasing order according to the shortest distance (or hop-count) from the source. Let D'_m be the new set in this order given by $\{d'_1, d'_2, \ldots, d'_m\}$.

A. Impairment-Aware Anycast Routing (IAAR)

The input to Algorithm 1 will be an anycast request in the form $(s, D_m, 1)$. The destination set in the request is first sorted based on the MH or MD heuristic as described in Step 1 and Step 2 above (shown in line 2). The first destination (d'_i) in the ordered set D'_m is chosen. The set of all the available wavelengths that satisfy the WCC for the calculated path (based on MD or MH) is denoted by Λ_A. A random wavelength $\lambda_k \in \Lambda_A$ is selected. Random wavelength assignment is found to minimize the impairments due to XT [13], [14]. The lines 7-10 describe the BER estimator used in the Fig. 2. Power (PWR), ASE and XT are calculated recursively [15] as given in lines 8-10 at each node (h) in the route. $ASE.SW$ and $XT.SW$ represent the ASE noise and the XT at the node h. The calculated OSNR is compared to the threshold requirement as indicated in line 12. If the required threshold condition is met the anycast request is said to be successful and the LP is configured along the wavelength-switches (λ_k) on the $\langle s, d'_i \rangle$ path. If the threshold condition is not met, then the set Λ_A is updated (line 18) and another wavelength is randomly chosen from the set. When all the wavelengths are exhausted $(\Lambda_A == \emptyset)$, the destination set is updated as indicated in line 20. The anycast request is said be to blocked if the LP cannot be configured to any destination on any wavelength $(D'_m == \emptyset)$.

B. Load-Aware Anycast Routing (LAAR)

In Algorithm 1, the destination cardinality (m) is fixed. Having a fixed value of m for network with static traffic may be a good solution. However the IP traffic flowing on a WDM network does not remain static, and having a fixed value of m may not yield an optimized solution. Choosing a high (static) value for $m(= |V|-1)$ to accommodate the peak traffic might cause a significant latency in provisioning the connection even during the low network load. This undesirable effect on the control plane at low network loads can be partially mitigated if size of the destination set is chosen based on the network load.

In this work we use a sinusoidal model IP traffic [16] on the WDM network as shown in Fig. 3. The load on the WDM network is measured in Erlangs, defined as the ratio of the connection arrival rate to the departure rate. From Fig. 3 we observe that the network load reaches a peak during the day and decreases at night. The modeled network load at time t is given by,

$$\rho(t) = \frac{0.6\gamma_p + 0.4\gamma_p \sin(\pi t/12)}{\mu}, \qquad (1)$$

where γ_p is the peak value of the arrival rate and μ is the departure rate. In this paper we assume a constant departure rate of the anycast connection requests. We also assume that the load on the WDM network reaches 20% during the off-peak. The LAAR algorithm is evaluated using the traffic pattern shown in Fig. 3, where $\gamma_p = 100$ and $\mu = 1$ in (1) and thus $\rho_p = \gamma_p = 100$ Erlangs.

Algorithm 1: Impairment-Aware Anycast Routing (IAAR).

Input : Anycast Request: $(s, D_m, 1)$ = $(s, \{d_1, d_2, \ldots, d_m\})$

Output : Request Successful: $TRUE/FALSE$

1 **begin**
2    $D'_m \leftarrow SORT[D_m]$
3   **while** $D'_m \neq \emptyset$ **do**
4      $\langle s, d'_i \rangle$ where $d'_i \in D'_m$; $1 \leq i \leq |D'_m|$
5      $(ROUTE\langle s, d'_i \rangle, \lambda_k) \leftarrow RWA$
6   **while** $\Lambda_A \neq \emptyset$ **do**
7   **for** $h \in ROUTE\langle s, d'_i \rangle$ **do**
8          $PWR(h, \lambda_k) \leftarrow PWR(h-1, \lambda_k) - LOSS(h, \lambda_k)$
9          $ASE(h, \lambda_k) \leftarrow ASE(h-1, \lambda_k) + ASE.SW(\lambda_k)$
10          $XT(h, \lambda_k) \leftarrow XT(h-1, \lambda_k) + XT.SW(\lambda_k)$
11        $OSNR(d'_i, \lambda_k) = \frac{PWR(d'_i, \lambda_k)}{(ASE(d'_i, \lambda_k) + XT(d'_i, \lambda_k))}$
12   **if** $OSNR(d'_i, \lambda_k) \geq OSNR_{th}$ **then**
13          $CONFIG.SD\langle s, d'_i \rangle$
14          $REQUEST\ (s, D_m, 1) \leftarrow TRUE$
15   exit   /* exit the algorithm */
16
17   **else**
18          $\Lambda_A \leftarrow \Lambda_A \backslash \{\lambda_k\}$
19   **if** $\Lambda_A == \emptyset$ **then**
20        $UPDATE.DES: D'_m \leftarrow D'_m \backslash \{d'_i\}$
21   **if** $D'_m == \emptyset$ **then**
22          $REQUEST\ (s, D_m, 1) \leftarrow FALSE$
23          $DROP.OSNR \leftarrow DROP.OSNR + 1$
24   **else**
25          $CREATE.SD: \langle s, d'_{i+1} \rangle$
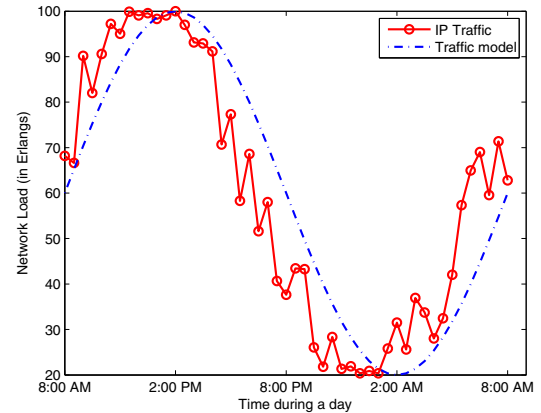

Fig. 3. IP-traffic model used in this paper.

The pseudo-code for the proposed load-aware anycast routing (LAAR) is given in Algorithm 2. When the connection request arrives, the cardinality of the candidate destination set is determined based on network load at time t as given by (2). We evaluate the algorithm for large $(m_L(t))$ and small $(m_s(t))$ destination set sizes. $m_L(t)$ in (2) can have a maximum value of $|V|-1$, when $\rho(t) = \rho_p$ and on the other hand $m_s(t)$ at peak is $\lceil |V|/2 \rceil - 1$. Fig. 4 shows the variation of destination size with IP-traffic for the National Science Foundation network (NSFNET) shown in Fig. 5. From Fig. 4 we observe that the maximum destination size at peak network load for NSFNET topology is 13 for $m_L(t)$ and 6 for $m_s(t)$ according to (2).
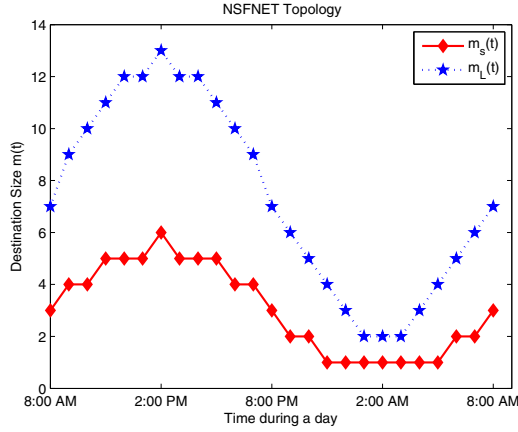
Fig. 4. Variation of anycast request destination set size with varying IP-traffic.

When the connection request arrives, $m(t)$ is calculated according to (2) and then an anycast request $(s, D_{m(t)}, 1)$ is created as indicated in line 3 of Algorithm 2. The $D_{m(t)}$ represents all the possible destinations, where the replica (or resource) can be present. Destinations are then sorted based on MD (or MH) as described in Section IV. The remainder of the algorithm is similar to IAAR, where lines 7-10 in Algorithm 1 are replaced with the BER estimator given in line 10 of the LAAR algorithm.

Algorithm 2: Load-Aware Anycast Routing (LAAR).

Input   : Anycast connection request
Output   : Request Successful: $TRUE/FALSE$
1 **begin**
2
$$m(t) = \begin{cases} \lfloor \frac{(|V|-1)\rho(t)}{\rho_p} \rfloor & \text{for } m(t) = m_L(t) \\ \lfloor \frac{(\lceil |V|/2 \rceil - 1)\rho(t)}{\rho_p} \rfloor & \text{for } m(t) = m_s(t) \end{cases} \quad (2)$$

3   Anycast request: $(s, D_{m(t)}, 1)$
4    $D'_{m(t)} \leftarrow SORT[D_{m(t)}]$
5   **while** $D'_{m(t)} \neq \emptyset$ **do**
6        $\langle s, d'_i \rangle$ where $d'_i \in D'_{m(t)}$; $1 \leq i \leq |D'_{m(t)}|$
7   **while** $\Lambda_A \neq \emptyset$ **do**
8            $(ROUTE\langle s, d'_i \rangle, \lambda_k) \leftarrow RWA$
9   **for** $h \in ROUTE(s, d'_i)$ **do**
10               $OSNR(d'_i, \lambda_k) \leftarrow$ BER Estimator
11   **if** $OSNR(d'_i, \lambda_k) \geq OSNR_{th}$ **then**
12               $CONFIG.SD\langle s, d'_i \rangle$
13               $REQUEST (s, D_{m(t)}, 1) \leftarrow TRUE$
14   exit   /* exit the algorithm */
15
16   **else**
17               $\Lambda_A \leftarrow \Lambda_A \setminus \{\lambda_k\}$

18   **if** $\Lambda_A == \emptyset$ **then**
19           $UPDATE.DES$: $D'_{m(t)} \leftarrow D'_{m(t)} \setminus \{d'_i\}$
20   **if** $D'_s == \emptyset$ **then**
21               $REQUEST (s, D_{m(t)}, 1) \leftarrow FALSE$
22               $DROP.OSNR \leftarrow DROP.OSNR + 1$
23   **else**
24               $CREATE.SD$: $\langle s, d'_{i+1} \rangle$

V. SIMULATION RESULTS

In this section, we evaluate the performance of the anycast algorithms proposed in Section IV on the NSFNET shown in Fig. 5. We have scaled the distances to the order of hundreds of km (as opposed to the actual thousands of km). This scaling will decrease the impact of ASE noise and fiber attenuation throughout the network, such that the impairments will be primarily dominated by XT. We use discrete event simulations wherein requests arrive dynamically according to a Poisson process with exponential departure times. The parameters used for the OSNR calculation are shown in Table I. The OSNR threshold in the table corresponds to a q-factor of 6 ($BER = 0.5 \times \text{erfc}(q/\sqrt{2})$). Each fiber link supports 8 wavelengths with 100-GHz spacing (0.8 nm) in the C-band. We compare our proposed algorithms with various anycast scenarios $m/1$, where $1 \leq m \leq |V|-1$. However in this paper we show the results for $m \leq 7$. The blocking probability is calculated as the ratio of the number of anycast requests blocked to the total number of requests.

We first evaluate the performance of IAAR under static network load for various anycast configurations. The results for IAAR using MD heuristics are shown in Fig. 6. We compare the anycast configurations $m/1$, $2 \leq m \leq 7$ against the baseline $1/1$ (unicast) IAAR. From Fig. 6 we observe that the blocking probability decreases with an increase in the destination size. The performance of MH heuristics for IAAR is shown in Fig. 7. Comparing the results in Fig. 6 and Fig. 7, we observe that MH:IAAR routing results in lower blocking than MD:IAAR for a given $m/1$ configuration. This is because of the fact that, the request loss due to the WCC and impairments is lower than MD:IAAR. However, the propagation delay[2] (directly proportional to the distance) will be higher in MH:IAAR. OCP can choose to provision the connection based on MD instead of MH if delay is the primary concern for the IP-layer.
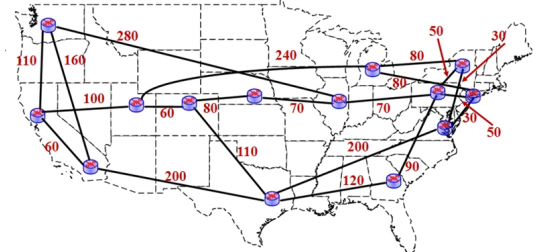

Fig. 5.   Scaled NSFNET topology.

TABLE I
PARAMETERS USED FOR COMPUTATION OF OSNR.

Parameter	Value
Channel bit rate	10 Gb/s
Optical bandwidth	7 GHz
Electrical bandwidth	10 GHz
Input signal power	1 mW (0 dBm)
Switch crosstalk ratio	25 dB
OSNR threshold for BER 10^{-9}	7.4 dB
Number of requests	10^6
Amplifier gain (pre, post, and inline)	22,16, and 14 dB.
Starting Wavelength	1542.6 nm

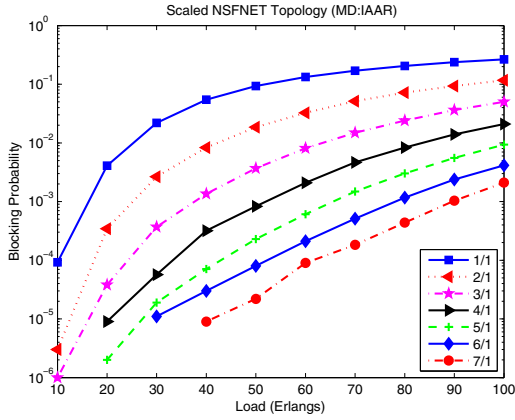[2]The results for delay are not shown in this paper due to the page limit.

Fig. 6. Performance of various anycast scenarios under MD routing.

Fig. 8. Variation of anycast destination set size with blocking probability for a fixed network load.

In Fig. 8, we show the variation of destination set size versus blocking probability at a given network load. At 50 Erlangs of network load, the MD:IAAR and MH:IAAR diverge. This is due to the fact that, at low network load there is no blocking for configurations with $m \geq 7$. However at higher network loads (100 Erlangs), the improvement (decrease) in the blocking probability with an increase in the size of the destination set is significantly small (slope tends to infinity in Fig. 8). Thus, having a large destination set ($m \approx |V| - 1$) at higher loads is not an optimal choice, as it increases the algorithm running time.
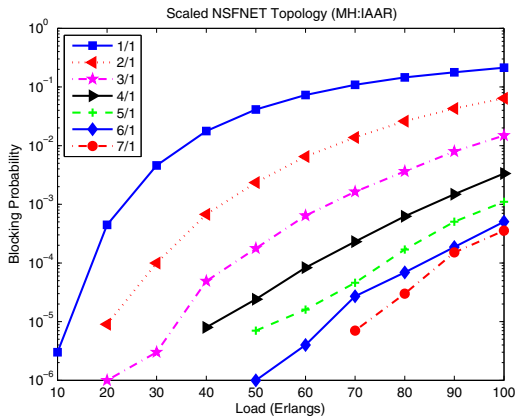

Fig. 7. Performance of various anycast scenarios under MH routing.

The performance of MD:IAAR and MH:IAAR for unicast ($m = 1$) is evaluated for the time-varying IP traffic shown in Fig. 3. At higher network load all the routing methods converge, since the request loss is primarily dominated by the WCC. However at low loads, we observe a significant difference in blocking probability for unaware and aware routing.

Ideal Network: In an ideal WDM network not equipped with wavelength converters, the request loss is caused due to the WCC (assuming no transmission impairments). From Fig. 9, we observe that the loss due to MH routing is lower than MD routing for a random wavelength assignment.

Impairment-Unaware: In such routing methods [15], the requests are successful only if impairments along the route on an assigned wavelength are within the threshold condition.
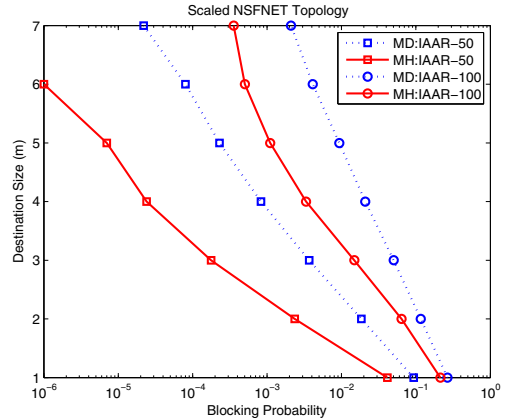
Due to the BER threshold constraint and the WCC, the blocking probability is much higher in these routing methods. From Fig. 9, we see that MH routing results in lower blocking. This is again due to the lower WCC loss for MH routing.

Impairment-Aware: Impairment-aware RWA (IARWA) algorithms [1] reduce the request loss significantly and the performance of such methods is nearly equal to that of an ideal network. In IARWA, impairments are evaluated for a chosen wavelength (randomly) on a given route. If the impairment threshold is not met, then another wavelength is chosen from the available set as described in Algorithms 1 and 2. Since the loss due to impairments is dependent on the number of wavelengths that meet the WCC, MH routing shows a lower loss than MD routing as seen in Fig. 9.
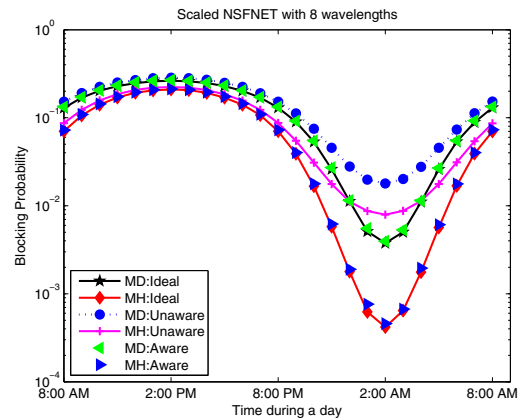

Fig. 9. Comparison of blocking probability under the modeled IP-traffic with unicast MD and MH routing.

Finally, we evaluate the performance of LAAR for MD and MH on an IP traffic shown in Fig. 3. In this routing method the cardinality of the destination set is chosen based on network load. The centralized OCP will have knowledge of the network load and creates a destination set using (2). In Fig. 10, we compare the LAAR with the unicast IAAR ($m = 1$). We have already seen that anycast communication improves blocking probability as compared to unicast. Hence using anycast communication with an optimized destination set can improve the blocking at higher network loads. Fig. 10

shows the results obtained for $m_s(t)$ and $m_L(t)$ with MD and MH routing. From Fig. 10, we observe that using $m_L(t)$ decreases the request blocking. Using $m_s(t)$, we observe from Fig. 10 that during the increasing half-cycle of network load the blocking probability for MD:LAAR and MH:LAAR is maintained nearly a constant value at 10^{-2} and 10^{-3}, respectively. At the low traffic period, LAAR with $m_s(t)$ adapts unicast communication $(m_s(t) = 1)$ and hence the graphs for LAAR overlap with unicast IAAR. In the case of MH:LAAR routing with $m_L(t)$, we observe that the blocking probability is nearly same as that of $m_s(t)$ at peak network load (100 Erlangs). Unlike $m_s(t)$, the blocking probability for $m_L(t)$ is found to increase with the network load (traffic between 8 AM to 2 PM).

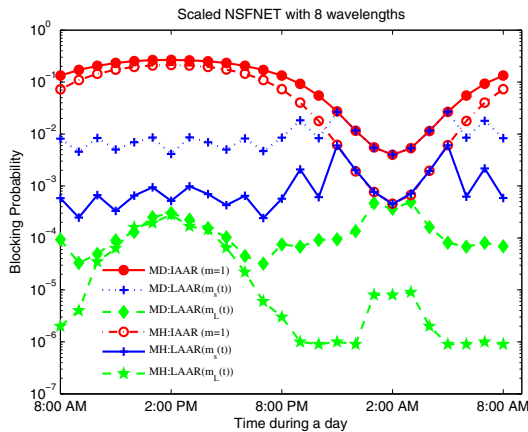Fig. 11. Comparison of normalized execution time for IAAR and LAAR with distance and hop heuristics.

Fig. 10. Comparison of blocking probability for IAAR and LAAR with distance and hop heuristics.

The normalized execution time for each request in unicast IAAR and LAAR with $m_s(t)$ and $m_L(t)$ is shown in Fig. 11. The execution time is nearly a constant for unicast IAAR and varies linearly with the cardinality of the destination for LAAR. We also observe from Fig. 11 that MD and MH routing methods take approximately the same amount of time.

From Fig. 10 and Fig. 11, we observe that the decrease in blocking probability for $m_L(t)$ is achieved with an increase in connection provisioning time. LAAR with $m_L(t)$ can be used, if latency involved with connection provisioning is not a constraint. Also using $m_L(t)$ under such constraint can cause an increase in the request blocking compared to using $m_s(t)$.

VI. CONCLUSION

We show that the load-aware anycast routing (LAAR) decreases the blocking probability, by choosing the candidate destination set size optimally based on the network load. Minimum distance and hop heuristics are proposed for selecting the destinations in the set. LAAR results are compared against the unicast IAAR and we show a decrease in the blocking at peak IP-traffic. Trade-offs between connection provisioning latency and request blocking can be achieved using LAAR. We plan to extend this network model to a test-bed and experimentally demonstrate in the future.

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