Impairment-Aware Manycast Algorithms Over Optical Burst-Switched Networks

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***Abstract*— We discuss the effect of physical impairments on manycasting service over optical burst-switched (OBS) networks. Signal quality degradation in manycast networks is an important issue and it can occur due to fiber attenuation, splitter switch, and amplified spontaneous noise in EDFA. These physical layer impairments causes the signal quality to be weak at the receiver and hence burst may not be detected. Our objective is to select the manycast destinations based on resource unavailability and the quality of signal received. We propose three impairment-aware algorithms that take into account of the physical layer impairments. Using extensive simulation results we compute average burst loss probability, both due to contention and signal degradation. These simulation results are verified by the analytical model. We have also compared our results with random destination selection using Binomial model and observe that our methods perform better than the random selection method.[1]**

Keywords: Manycast, OBS, Impairments, BER, and OSNR, Blocking Probability.

I. Introduction

Optical burst switched (OBS) network is a promising candidate to support high bandwidth Internet applications. These networks were proposed to overcome the technological constraints imposed by optical packet-switched networks. There has been recent emergence of many distributed applications that require high-bandwidth, such as grid computing, content distribution, and storage area networks. OBS networks have all the ingredients to support these applications. These applications require multiple destinations to be co-ordinated with a single source, and thus it seems multicasting is the way to implement these distributed applications. However in multicasting the destination set is fixed and the dynamic behavior of the network cannot be implemented. A variation in this is to dynamically vary the destinations depending on the status of the network. Hence in distributed applications, first step is to identify potential destination candidates and then select the required number. This is called *manycasting* and the problem is defined as follows: given a network $G(V, E)$, with V nodes and E edges, edge cost function is given by $g : E \rightarrow R^+$, an integer k, a source s, and the subset of candidate destinations $D_c \subseteq V$, $|D_c| = m \geq k$, where $|D_c|$ is the cardinality of the set D_c. If $k = 1$, one destination is chosen from the set D_c and this is called *anycasting*.

In an OBS network, multiple packets to the same egress edge node are packed together in the form of single data burst at the ingress nodes. A control information for this data burst is transmitted ahead on separate channel and is called *burst header packet (BHP)*. BHPs are processed electronically at each intermediate node to reserve network resources before the data burst arrives at the node. After a certain offset time data burst is transmitted all-optically through the network.

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Data loss in OBS network can occur either due to burst contentions or impairments in the fiber. *Burst contention* is a special issue in OBS networks, which occurs due to burstiness of IP traffic and the lack of optical buffering. Contention occurs when multiple bursts contend for the same outgoing port at the same time. Many schemes have been proposed to resolve burst contentions [1]. However all of these assume that the underlying physical fiber media is ideal. In other words, the burst that is allocated a wavelength is consider to be delivered error-free. But in practice this not the case. Bursts are transmitted all-optically in the fiber; they traverse through many optical components, such as fiber, multiplexer, demultiplexer, splitters and optical amplifiers. This causes the quality of the signal to degrade. Received signal have amplified spontaneous emission (ASE) noise due to optical amplifiers in the network [3]. The common metric to characterize the signal quality is optical-signal-to-noise ratio (OSNR), defined as the ratio of power of signal received to power of the ASE noise [4]. Multicast capable switches cause optical power to split depending on number of output ports. The power will be reduced as the signal propagates towards destination, thus decreasing OSNR. Bit error rate (BER) of the signal is related to OSNR. Decrease in OSNR causes an increase in BER. Thus a burst scheduled on a wavelength can be lost due to high BER of the signal. BER of the signal can be computed through q-factor [4]. If signal has low q, then BER of the signal is high and vice-verse. Thus a burst successfully scheduled on a wavelength, can be lost due to a low q. These impairments studies have been done extensively in past. Recent challenges are to develop impairment-aware routing algorithms before scheduling the data transmission [2]. As the first step toward implementing the impairment-aware manycasting, in this paper we consider only the OSNR constraint. Therefore there is need to develop policies that implement manycasting considering both *burst contention* and *optical impairments*.

Our previous work [11] discusses performance of the impairment-aware manycasting and average blocking probability computed using discrete-event simulation model. In this paper we extend our previous work to manycasting algorithms and also present an analytical loss model for the proposed IA-manycasting algorithms. We also compare performance of different algorithms in the presence of impairments. The rest of the paper is organized as follows: Section II discusses issues of supporting manycasting over OBS networks. Section III defines the problem and obtains a measure to characterize the quality of signal. In Section IV we describe the proposed impairment-aware manycasting algorithms. Section V discusses the analytical model for the proposed manycasting algorithms. Results are presented in Section VI where we compare our analytical results with simulation results. Finally Section VII concludes the paper.

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II. Manycasting Service

A manycast request is simply denoted by (s, D_c, k). We have to send the burst to k destinations out of m ($|D_c| = m$) possible candidate destinations. But due to the burst loss that occurs due to burst contention and/or signal degradation, there is no guarantee that exactly k destinations receive the burst. In general most multicasting solution approaches of are largely applicable to manycasting. Networks that can support optical multicast can also support optical manycasting. Thus, manycasting can be implemented by multicast-capable optical cross-connect (MC-OXC) switches [11]. Now when it comes to routing the burst, shortest-path tree (SPT) can be computed, as given below:

- *Step 1*: Find the shortest path from source s to all the destinations in D_c. Let $D_c = \{d_1, d_2, \dots d_{|D_c|=m}\}$ and minimum hop distance from s to d_i, where $1 \le i \le m$ is $\mathbb{H}^{(s)} = \{h_1, h_2, \dots h_m\}$.
- *Step 2*: All the destinations in D_c are sorted in the non-decreasing order according to the shortest distance from source s to the destinations. Let D'_c be the new set in this order given by $\{d'_1, d'_2, \dots d'_m\}$.
- *Step 3*: Select the first k destinations from D'_c.

However it is not necessary that along the shortest-path optical signal will have minimum degradation. In the following sections we propose manycast algorithms aware of physical-layer impairments.

III. Problem Statement

In this section we discuss the data loss due to physical impairments by computing q-factor. We first discuss the network architecture consisting of optical components that a signal traverses from source to destination in Section II-A. We then discuss the impairments, in such network, in Section II-B. We compute the quality factor of the signal on per hop basis in Section II-C. The parameters used for the computation of q-factor can be found in [11].

A. Network Architecture

MC-OXC architecture for multicast-optical cross-connect (MC-OXC) using Splitter-and-Delivery (SaD) switch can be found in [11]. As optical signal traverses from source to destination, it encounters losses due optical switches, multiplexer, demultiplexer, and fiber. Power loss can be compensated either by incorporating optical amplifiers or by increasing signal power at source. Fiber in-line amplification provided by the cascaded Erbium doped fiber amplifiers (EDFA), compensate the power loss due to attenuation in the fiber. However they increase the ASE noise in the channel, which in turn increases the BER. In this paper, we consider in-line amplification of signal, and hence the effect of ASE noise on the signal quality is used for the computation of BER. An $N \times N$ SaD switch proposed in [5] is used in the architecture for manycasting. These switches are assumed to be configurable and hence can be instructed to split the incoming signal to any of $i = 1, 2, \dots N$ output ports [6].

B. Calculation of q-factor on per-hop basis

Below recursive power relations can be used to compute OSNR which is in turn related to the q-factor. All the notations used in below equations maintain consistency with that used in [11].

Recursive Power Relations: Here we derive recursive power relations similar to [3]. However the only difference, is that we consider in-line amplification and we use SaD switch instead of OXC. The output power at the Node n, $P(n)$ and is given by,

$$\begin{aligned} P(n) &= G_{in} G_{out} L_d L_m L_t^2 L_{ins} L_{att}(n) L_{sp}(n-1) \times \\ &\quad P(n-1), \\ &= G_T L_k L_{att}(n) L_{sp}(n-1) P(n-1), \\ &= G_T L_T(n-1) L_{sp}(n-1) P(n-1), \end{aligned} \quad (1)$$

where $L_k = L_d L_m L_t^2 L_{ins}$, this loss is a constant for any node and $L_T(n-1) = L_k L_{att}(n)$.

$$\begin{aligned} P_{ase}(n) &= P_{ase}(n-1) L_T(n-1) G_T + P_n L_T(n-1) \times \\ &\quad [G_{in} - 1]/L_t + P_n L_t [G_{out} - 1] + \\ &\quad P_n [\bar{G} - 1] a_n, \end{aligned} \quad (2)$$

where $P_n = 2 n_{sp} h f_c B_o$ with typical values given [11]. Due to in-line amplification of the signal using EDFA, there will be ASE noise along the route. Hence the last term in Eq. (2) represents the ASE noise along the fiber, and the first two terms represent the ASE noise due to EDFAs inside the node. We assume that this is as constant, when the wavelengths are centered around f_c. In the system of cascade amplifiers, the notion of sensitivity is not very useful when signal reaching the receiver has already added lot of noise [4]. In this case two parameters that are measured are, the average received signal power, $P(n)$ and received optical noise power $P_{ase}(n)$. The optical signal to noise ratio (OSNR) at node n is given by $OSNR(n) = P(n)/P_{ase}(n)$. By neglecting the receiver thermal noise and shot noise, the relationship between the q-$factor$ and OSNR is given by [4],

$$q(n) = \frac{2\sqrt{\frac{B_o}{B_e}}\mathrm{OSNR}(n)}{1 + \sqrt{1 + 4\mathrm{OSNR}(n)}}, \quad (3)$$

where $q(n)$ is defined as the quality factor of the link between nodes $\langle n, n+1 \rangle$. Bit error rate of link n is given by,

$$BER(n) = 2 \ \mathrm{erfc}\left(\frac{q(n)}{\sqrt{2}}\right), \quad (4)$$

where, $erfc(x)$ is called complementary error function. Assumptions used in computation of BER remain same as in [11]. Online Evaluation of q-factor using Burst Header Packet (BHP) Signaling can be done using above recursive equations. Initially, the q-field is set to a high value, and once BHP reaches the next node q value is updated using the recursive Eqs. (1,2,3). At every intermediate node, the BHP updates the q and checks the condition, $q > q_{th}$. If this is true the BHP proceeds further, else the burst is dropped. Burst loss due to signal impairment is defined as *optical-layer blocking* [11].

IV. Impairment-Aware Manycasting Algorithms

In this section we ensured the manycasting algorithms proposed in [1] to consider the signal degradation due to impairments in the fiber. In order to consider impairment-awareness during burst transmission, we modify the manycast request as $(u, D'_u, k_u, P(u), P_{ase}(u))$, where the last two tuples indicate signal and noise power respectively. u can be a source s or an intermediate node, with sorted destination set D'_u and intended number of destinations k_u. In all the algorithms considered, we have

1) **Input:** The manycast request (u, D'_u, k_u) arrives at the source node with a candidate destination set D'_u, along with k intended destinations. The power inputs for this manycast request are $(P(u), P_{ase}(u))$. Hence we have $(u, D'_u, k_u, P(u), P_{ase}(u))$.
2) **Output:** Manycast request to the next-hop node after satisfying the BER constraint.
3) **Initialization:** At the source node, the manycast request is of the form $\big(s, D'_s, k_s, P(s), P_{ase}(s)\big)$. For every new burst entering the network, this manycast request is tagged to it. All other sets are initialized to null.

A. Impairment-Aware Shortest Path Tree (IA-SPT)

IA-SPT algorithm uses a pre-computed shortest path tree. Based on the three steps mentioned in Section-II, the tree is constructed for each manycast request. Recursive power relations in Section III-B can be used to compute the OSNR of the optical signal along its path. If the link from the source node to one of the child nodes is free, then q is computed. If the q-factor is above the threshold value, q_{th}, then the channel is scheduled for burst transmission. Hence, the successful reception of the burst at the destination node guarantees that signal is error-free. This continues until k destinations are reached. If the burst reaches $< k$ destinations, then the manycast request is said to be blocked. As the IA-SPT is implemented on the pre-computed routing tree, it does not consider the dynamic nature of the network. This algorithm suffers from high burst loss, due to fixed routing along the shortest path tree and this is verified by simulation results. Other algorithms proposed, decrease the burst loss in the presence of optical layer impairments. In the pseudo-code lines 2-3 ensure that if the current node is the destination node then the destination set (D'_u) and intended number of destinations (k_u) are updated. These lines remain same for all the three algorithms used. Child nodes or the next-hop node set for Node u, are calculated using lines 5-8. For all child nodes the channel availability is checked using Line 10. Using recursive power relations described in Section-III, q-factor is computed and if the threshold condition is met, then we say that all the destinations corresponding to the child node n_j can be reached and this set is given by $S_D(n_j)$. $S_D(n_j) = k_u$ only when there is one child node for all the destination in D'_u. The new manycast request is thus formed at the child node n_j as given in Line 15. $\mathbb{D}$ is the set of all destinations that can be reached from node u. If $|\mathbb{D}| < k_u$, then the request is said to be blocked and probability of the request blocking is given by $1 - |\mathbb{D}|/k_u$.

Consider the example given in Fig. 1, in the case of IA-SPT, we select first $k_u = 3$ from $D'_c = \{5, 6, 8, 9\}$, i.e., $\{5, 6, 8\}$. As both the conditions in lines 10 and 14 are met, we have $S_D(2) = \{5, 8\}$ and $\mathbb{D} = \{5, 8\}$ and the new manycast request at $n_j = 2$ becomes $(2, \{5, 8\}, 2, P(2) = 0.4, P_{ase}(u) = 0.011)$. When $i = 2$, we have $n_j = 3$ and if the conditions are met then we have $S_D(3) = 6$ and $\mathbb{D} = \{5, 8\} \cup \{6\}$, that implies $|\mathbb{D}| = k_u$ and hence request $\big(1, \{5, 6, 8, 9\}, 3, P(1) = 1, P_{ase}(1) = 0.0042\big)$ is successful.

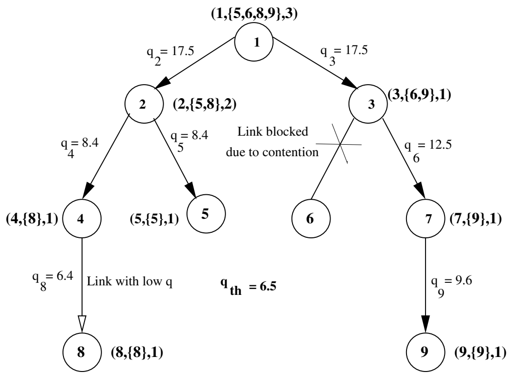
Impairment Aware Shortest Path Tree (IA-SPT) Algorithm

```
1   if u ∈ D'_u
      ▷ Update D_u and k_u
2     D'_u ← D'_u \ {d'_j}
3     k_u ← k_u − 1
      ▷ Destination set D'_u is the non-decreasing order of
       the hop distance
4   else
5     for j ← 1 to k_u
6       n_j ← SPT[u, d'_j]
         ▷ Next hope node or child node is obtained from
         shortest path tree
7       N = N ∪ {n_j}
8     end
9     for i ← 1 to |N|
10     if (⟨u, n_i⟩ = FREE)
11      P(n_i) ← POW_SIGNAL(P(u), |N|)
12      P_ase(n_i) ← ASE_SIGNAL(P_ase(u))
13      q(n_i) ← Q_FACTOR(P(v_i), P_ase(v_i))
14      if (q(n_i) > q_th)
         D_{n_i} ← D_{n_i} ∪ {S_D(n_i)}
         ▷ S_D(n_i) is the set of all destinations (⊆ {d'_1, ..., d'_{k_u}}) that
         can be reached through child node n_i. |S_D(n_i)| ≤ k_u
15       Output: Manycast request to the next hop node will be
         (n_i, D_{n_j}, |S_D(n_i)|, P(n_i), P_ase(n_i))
16       𝔻 ← 𝔻 ∪ S_D(n_i)
17      else
18      end
19     else
20     end
21    end
```

B. Impairment-Aware Static Over Provisioning (IA-SOP)

IA-SOP algorithm is similar to IA-SPT except that here we will not limit the number of destinations to k, but we send the burst to $k + k'$ destinations, where k' is such that $0 \le k' \le m - k$. With $k' = 0$, IA-SOP is similar to IA-SPT, i.e., no over-provisioning. In this algorithm, first $k + k'$, destinations are selected from the set D'_c. Sending the burst to more than k destinations ensures that it reaches at least k of them. However by doing over-provisioning the fan-out of the splitter increases, which increases BER. In spite of decrease in the contention loss, there is no significant improvement in the overall loss. From the simulation results we see that IA-SOP shows better performance than IA-SPT. The algorithm for IA-SOP is similar to that of IA-SPT, but with k_u replaced with $k_u + k'$. Thus the probability of request blocking is given by $1 - \min(|\mathbb{D}|, k_u)/k_u$. This is because if all the $k_u + k'$ are free then the burst is sent to more destinations than intended (i.e., k_u), but from the user perspective we have only k_u to be reached. If $|\mathbb{D}| > k_u$ implies $\min(|\mathbb{D}|, k_u) = k_u$, then the request blocking ratio is zero.

Consider the example shown in the Fig. 1, if we select $k'_u = 1$, then we have first $k_u + k'$ of D'_c as $\{5, 6, 8, 9\}$ and at two child nodes $2, 3$ the manycast requests are $\big(2, \{5, 8, 9\}, 2, P(2) = 0.4, P_{ase}(2) = 0.011\big)$, $\big(3, \{6, 9\}, 2, P(3) = 1, P_{ase}(3) = 0.011\big)$, respectively (assuming links $\langle 1, 2\rangle$, $\langle 1, 3\rangle$ are free and the q-factor is greater than the required threshold). Thus the request is successful.



Node	P(n)=Signal Power (mW)	P_{ase}(n)=ASE Power (mW)	Splits
1	1.00	0.0042	2
2	0.40	0.0110	2
3	0.40	0.0110	1
4	0.16	0.0160	1
5	0.16	0.0160	–
6	–	–	–
7	0.32	0.0160	1
8	0.12	0.020	–
9	0.25	0.020	–

Fig. 1. For a manycast request we show how the three proposed algorithms works. Thus we see that in spite of having no congestion on the link $\langle 4, 8\rangle$, the manycast request is not meet due to the low q-factor.

C. Impairment-Aware Dynamic Membership (IA-DM)

IA-DM takes the dynamic network status into consideration. Instead of selecting the destinations before the burst is transmitted, we dynamically add members as possible destinations, depending on contention and quality of the link. IA-DM will work with a distributed version of SPT. The set of k-destinations is tentatively set up at the source node. We do not discard the remaining $m-k$ destinations, but instead keep them as child branches at the source node. This algorithm is explained in [11]. We compare our results with IA-DM and show that IA-DM performs better in terms of reduced burst loss.

V. Analytical Model

In this section, we present the analytical model for the manycasting scenario. We use $M/M/c/c$ queuing model for modeling blocking probability for the proposed impairment-aware manycasting, where c is the number of wavelengths per link used in the network. Let us define $\mu = 1/E[L]$, where $E[L]$ is the expected (or average) value of the burst length and λ be the arrival rate. Then the unicast load is given by $\rho = \lambda/\mu$. In manycasting, there are k intended destinations that have to be selected from m. We keep k to be the majority of the group, so we have $k \geq \lceil m/2 \rceil$. We define over-provisioning factor $\beta = k'/k$. β lies in the interval $0 < \beta < 1$ as long as we take $k \geq \lceil m/2 \rceil$. Hence the effective manycast load for IA-SPT and IA-SOP is given by,

$$\begin{aligned}\rho_m &= \lambda/(k\mu) \text{ for IA-SPT and} \\ &= \lambda\beta/(k\mu) \text{ for IA-SOP.} \end{aligned} \quad (5)$$

The manycast request blocking probability due to the contention in the network is given by Erlang-B model [10] as

$$B_C = \frac{\rho_m^c/c!}{\sum_{i=1}^{c} \rho_m^i/i!}. \quad (6)$$

Bursts are scheduled once the links along its path to the destination are available. However, all the scheduled burst do not meet the BER requirement of the network. So some of the bursts will be dropped in spite of occupying a free channel. This blocking is referred to as *optical layer blocking* blocking and can be defined as,

$$\begin{aligned} B_Q &= \frac{\text{\# manycast requests dropped due to high BER}}{\text{\# manycast requests that find a free channel}} \\ &= \frac{\text{\# bursts dropped due to high BER } (q < q_{th})}{\text{\# bursts that find a free channel}}. \end{aligned} \quad (7)$$

Thus the overall blocking probability including *contention* and *optical layer blocking* is given by,

$$\begin{aligned} B_{total} &= B_C + B_Q - B_C B_Q \\ &= B_C + (1 - B_C) B_Q. \end{aligned} \quad (8)$$

In the Eq. (8) we have considered blocking due to contention and insufficient BER are independent.

IA-DM adds and removes candidate destinations depending on whether or not the link is contention free. We use Poisson splitting to evaluate the blocking probability for IA-DM manycasting. Each burst carries the information about the destination set and the intended destinations k. If a particular child branch toward the destination in k of D'_c is blocked then, that destination is removed and a new destination is added from first $m-k$ thus maintaining total intended destination to be k (this is unlike the deflection routing where the burst is sent to the same destination, but through an alternative route). First k are selected from D'_c, i.e., $\{d'_1, \ldots, d'_k\}$. We define this destination set as *primary destinations* (D'_p). If any of the d'_i, $1 \leq i \leq k$ is blocked (with probability say $\widehat{q}$), then to satisfy the manycast request a destination is selected from the other $m-k$ destination set, i.e., $\{d'_{k+1}, \ldots, d'_m\}$ and we define this set as *secondary destinations* (D'_s). Secondary destinations are only used when at least one of the primary destination cannot be reached through its child nodes. Having partitioned D'_c into two disjoint sets, we model the arrival process using *Poisson splitting*. Let λ be the unicast arrival rate into the network. These arrivals are split into primary and secondary arrivals as independent arrivals based on the outcome of the Bernoulli trial with probability $\widehat{q}$, given by

$$\widehat{q} = \frac{(\lambda/\mu)^c/c!}{\sum_{i=1}^{c} (\lambda/\mu)^i/i!}. \quad (9)$$

This is similar to probability $\widehat{q}$ of failure in a Bernoulli trial, referred as *randomization* or *Poisson split* [10]. However note that split of arrival processes into two Poisson processes is valid only when each arrival is independent of assignment of other arrivals. We assume that we have, an estimate for contention blocking as $\widehat{q}$ and split the traffic based on the outcome of an experiment. Let us define X_r be a random variable which takes either 0 or 1. Thus we have,

$$X_r = \begin{cases} 1 & \text{if } d'_j \in D'_p,\ 1 \le j \le k, \text{ w.p. } (1-\widehat{q}) \\ 0 & \text{if } d'_j \in D'_s,\ k+1 \le j \le m, \text{ w.p. } \widehat{q}. \end{cases} \quad (10)$$

Hence we have two independent Poisson processes with arrival rates $\lambda_p = \lambda(1-\widehat{q})$ and $\lambda_s = \lambda\widehat{q}$ for primary and secondary destination sets, respectively. Thus the manycast load in case of IA-DM is given by,

$$\rho_m = \begin{cases} \lambda_p/k\mu & (\equiv \rho_m^{(p)}) \text{ for } D'_p \\ \lambda_s/(m-k)\mu & (\equiv \rho_m^{(s)}) \text{ for } D'_s. \end{cases} \quad (11)$$

In $\rho_m^{(s)}$, the denominator is the cardinality of D'_s i.e., $m-\ k$. Thus the overall manycast request blocking for IA-DM is given by,

$$B_{total}^{(IA-DM)} = B_{total}^{(p)} + (1 - B_{total}^{(p)})B_{total}^{(s)}, \quad (12)$$

where $B_{total}^{(p)}$ and $B_{total}^{(s)}$ are blocking probabilities of primary and secondary destinations, respectively, obtained from Eq.(8), with manycast loads as given by Eq.(11). *IP Manycasting:* Selection of k destinations out of m by the IP layer is similar to the *random algorithm* in [8], we also present a simple analytical model for the manycasting with random selection of k destinations. Our results show that random selection of destinations has poor performance, hence supporting manycasting at the OBS layer is necessary. A manycast request is said to be blocked if the burst reaches less than k destinations. Hence given there are k destinations, probability that at least one of them is blocked is given by,

$$B_C^{(bino)} = \sum_{i=0}^{k-1} \binom{k}{i} (B_C)^i (1-B_C)^{k-i}. \quad (13)$$

Hence the total blocking is,

$$B_{total}^{(bino)} = B_C^{(bino)} + (1 - B_C^{(bino)})B_Q. \quad (14)$$

VI. Numerical Results

In this section we present our simulation and analytical results. We consider *average request blocking* as performance metric. We define average request blocking ratio as given by [1]. Let f be the total number of requests used in the simulation. Consider a manycast request (s, D_c^f, k). Let $\mathbb{D}$ be the set of destinations which actually receive the data. Then *average request blocking* is given by,

$$B_{total}^{(Sim)} = \sum_f \left[1.0 - \min(|\mathbb{D}|, k)/k\right]/f. \quad (15)$$

We use notation m/k, which means $|D_c| = m$ and k intended destinations. As in [8] [9], we consider the candidate destinations set D_c at small, medium, and large sizes, and the intended destinations is a majority of the group. Three typical configurations, $3/2$, $7/4$, $11/6$ were used, however only results for $7/4$ are shown in this paper and all other

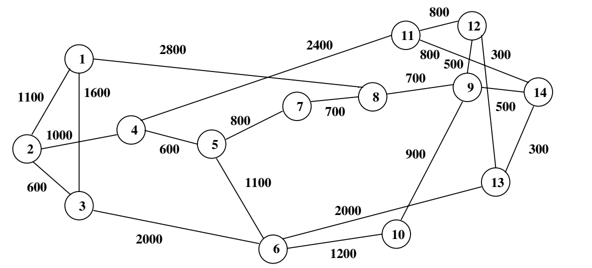


Fig. 2. The NSF network consisting of 14 nodes and 21 bi-directional links. The numbers on the links indicate the distance between the nodes in kilometers. These links consists of in-line EDFAs spaced 70 kms apart (not shown in the figure for clarity).

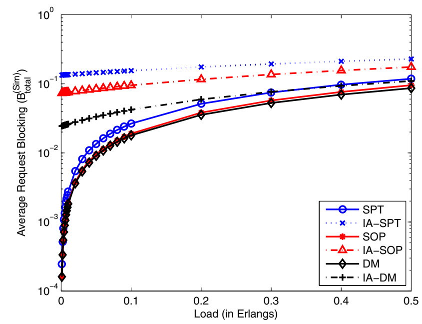


Fig. 3. Comparison of algorithms with and without impairment awareness.

were found to perform similar. We use NSF network as shown in the Fig. 2 for our simulation studies. All the links in the network are bi-directional and have same transmission rate of 10 Gb/s. Burst arrivals follow Poisson process with an arrival rate of λ bursts per second. The length of the burst is exponentially distributed with expected service time of $1/\mu$ seconds. The unicast network load is then defined as λ/μ. The source and candidate destinations of a manycast request are evenly distributed among all the nodes. There are no optical buffers or wavelength converters in the network. We consider a single wavelength plane and hence $c = 1$ in Eq. (6),(9). The physical layer parameters used in the simulation model are shown the Table I. For all graphs, x-axis indicates unicast load.

Using discrete-event simulations we compute $B_{total}^{(Sim)}$ using Eq. (15) and compare our results for without impairment-awareness, as given in [1]. Fig. 3 show the comparison of impairment-aware average request blocking to regular algorithms. From these graphs we observe there is significant difference in $B_{total}^{(Sim)}$ under low load conditions. This is because under low load conditions, contention blocking will be less and hence regular algorithms used in [1] does not provide the correct estimate of blocking. From the Fig. 3 we also observe that IA-DM has lower blocking than IA-SPT and IA-SOP and thus, impairment-aware manycasting over OBS, can be improved by using IA-DM. Our simulation results show that even under high loads IA-DM is better than the other two as shown in Fig. 4.

We validate our simulation results with the analytical model explained in Section V. Fig. 5 shows that our model is accurate for IA-SPT. This graph also indicates that random

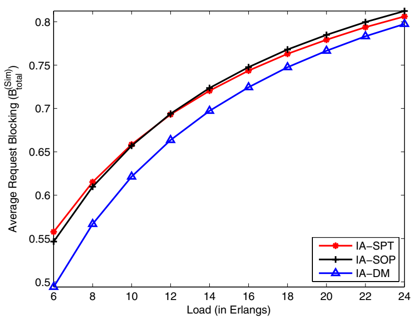


Fig. 4. The blocking performance comparison between IA-SPT, IA-SOP and IA-DM for manycast configuration $7/4$ under High load.

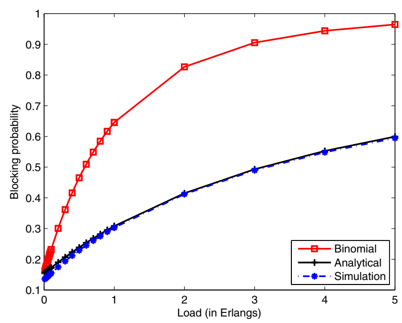


Fig. 5. Comparison of Binomial, Analytical and Simulation results for overall blocking probability for IA-SPT under low load.

selection of k destinations from D_c (IP-Manycasting) has poor performance compared IA-SPT. Significant reduction in the blocking can be achieved by using IA-SPT.

From Fig. 6 we observe that our analytical model over-estimates the blocking probability of IA-SOP at low loads. This is due to the size of intended destinations. In our case we have $k' = 3$, which is equivalent to multicasting. However at high loads these results converge.

Finally we validate our simulation results for IA-DM using Poisson-splitting. From Fig. 7 we observe that Poss ion split model slightly over-estimates the blocking probability than simulation. This is because of the Eq. (15) does not distinguish between primary and secondary destinations as in Poisson split. However the difference being very small, it provides

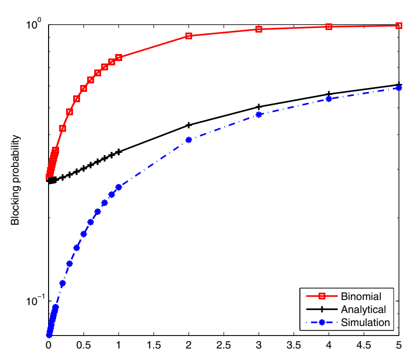


Fig. 6. Comparison of Binomial, Analytical and Simulation results for overall blocking probability for IA-SOP with $k' = 3$ under low load.

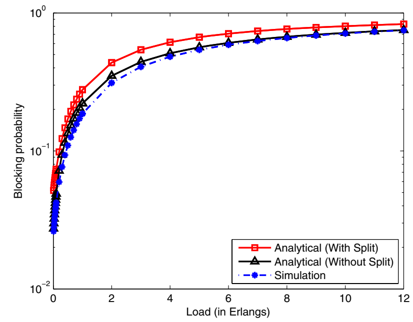


Fig. 7. Comparison of Analytical (with and without Poss ion split) and Simulation results for overall blocking probability for IA-DM under low load.

a good estimate for the impairment-aware manycasting. Also by using Poisson-splitting we maintain the arrival process to secondary destinations as Poisson distribution and this makes analysis computationally efficient. In the Fig. 7 we also compare our results without split, which clearly validate our simulation results.

VII. Conclusion

In this paper, we discuss issues of impairment-aware many-casting service over OBS networks. Supporting manycasting over OBS improves the network performance. We indicate that BER based signaling using BHP has significant impact in calculating data loss in OBS networks. We propose three impairment-aware algorithms IA-SPT, IA-SOP and IA-DM. Through extensive simulation and numerical analysis, we show that IA-DM has better performance for supporting manycast-ing over OBS.

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