Quality-of-Transmission-Aware Manycasting Over Optical Burst-Switched Networks

Balagangadhar G. Bathula, Rajesh R. C. Bikram, Vinod M. Vokkarane, and Srinivas Talabattula

***Abstract*—Many next-generation distributed applications, such as grid computing, require a single source to communicate with a group of destinations. Traditionally, such applications are implemented using multicast communication. A typical multicast session requires creating the shortest-path tree to a fixed number of destinations. The fundamental issue in multicasting data to a fixed set of destinations is receiver blocking. If one of the destinations is not reachable, the entire multicast request (say, grid task request) may fail. Manycasting is a generalized variation of multicasting that provides the freedom to choose the best subset of destinations from a larger set of candidate destinations. We propose an impairment-aware algorithm to provide manycasting service in the optical layer, specifically OBS. We compare the performance of our proposed manycasting algorithm with traditional multicasting and multicast with over provisioning. Our results show a significant improvement in the blocking probability by implementing optical-layer manycasting.**

***Index Terms*—Multicast; Manycast; OBS; BER; ASE; OSNR.**

I. Introduction

With the advent of many Internet-based distributed applications, there is a continued demand for a high-capacity transport network. Networks based on wavelength division multiplexing (WDM) are deployed to tackle the exponential growth in the present Internet traffic. WDM networks include optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS). In OCS a lightpath is set up by the user for the entire duration of the data transfer. In OPS the user data is transmitted in optical packets that are switched entirely in the optical domain. In OBS the user data is transmitted all-optically as bursts with the help of an electronic control plane. One of the primary issues with OCS is that the link bandwidth is not utilized efficiently in the presence of bursty traffic. On the other hand, many technological limitations have to be overcome for OPS to be commercially viable. OBS networks overcome the technological constraints imposed by OPS and the bandwidth inefficiency of OCS networks [1]. In this paper, we focus on the optical transport network being OBS. Most of the discussed algorithms can easily be modified to work for OCS and OPS networks.

There has been recent emergence of many distributed applications that require high-bandwidth, such as video conferencing, telemedicine distributed interactive simulations (DIS), grid computing, storage area networks (SANs), and distributed content distribution networks (CDNs). Certain grid applications, such as computational grids, DIS, e-Science applications, and real-time remote visualization require a stringent constraint on delay. These delay constraints can be met effectively by using OBS as the transport paradigm. These distributed applications require a single source to communicate with a group of destinations. Traditionally, such applications are implemented using multicast communication. A typical multicast session requires creating the shortest-path tree to a fixed number of destinations. The fundamental issue in multicasting data to a fixed set of destinations is receiver blocking. If one of the destinations is not reachable, the entire multicast request (say, grid task request) may fail. A useful variation is to dynamically select destinations depending on the status of the network. Hence, in distributed applications, the first step is to identify potential candidate destinations and then select the required number. This dynamic approach is called *manycasting*. Manycasting has caught the attention of several researchers during the recent past, due to the emergence of many of the distributed applications described above [2–9]. Manycasting has also been found an attractive and viable communication paradigm for providing fault tolerance for defense information infrastructures in the battlefield [3,10].

The manycasting problem is defined as follows: given a network $G(V,E)$, with V the set of vertices and E edges, an edge cost function given by $g:E\rightarrow R^{+}$, an integer k, a source s, and the subset of candidate destinations $D_s \subseteq V$, $|D_s|=m \geqslant k$, where $|D_s|$ is the cardinality of the set D_s, find a minimum cost tree spanning the best k destinations in D_s [2–11]. If $k=1$, one destination is chosen from the set D_s and this is called *anycasting*.

In an OBS network multiple packets to the same egress node are assembled together to form a data burst at the ingress. Control information for this data burst is transmitted

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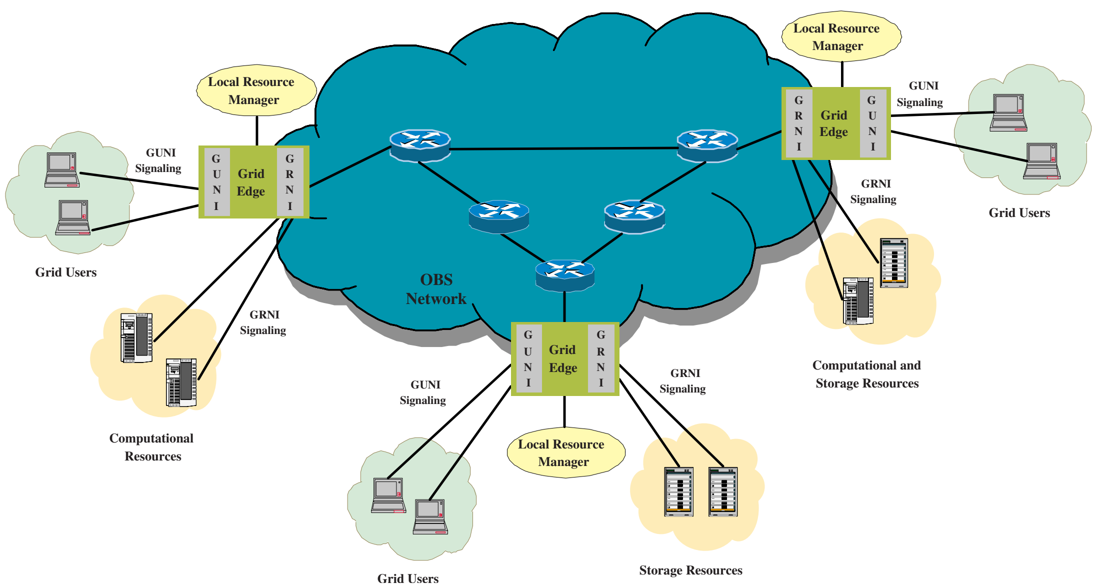


Fig. 1. (Color online) Grid over OBS network architecture.

ahead on a separate channel and is called the *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 the data burst is transmitted all-optically through the network.

Data loss in the 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 bursty 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 [12]. However, all of these assume that the underlying physical fiber media is error free, but in practice this is not the case. Bursts are transmitted all-optically in the fiber; they traverse through many optical components, such as fiber, multiplexers, demultiplexers, splitters, and optical amplifiers. This causes the quality of the signal to degrade. Received signals have amplified spontaneous emission (ASE) noise due to optical amplifiers in the network [13]. The common metric to characterize the signal quality is the optical-signal-to-noise ratio (OSNR), defined as the ratio of the power of the signal received to the power of the ASE noise [14]. In addition, multicast-capable switches cause the optical power to split depending on the number of output ports. The power will be reduced as the signal propagates toward the destination, thus decreasing the OSNR. The bit error rate (BER) of the signal is related to the OSNR. A decrease in the OSNR causes an increase in the BER. A burst successfully scheduled on an outgoing wavelength can be lost due to high BER of the signal. The BER of the signal can be computed through the q factor [14]. If the signal has low q, then the BER of the signal is high and vice versa. Thus a burst successfully scheduled on a wavelength can be lost due to a low q. These impairment studies have been done extensively in the past [13,15–18]. Recent challenges have been to develop quality-of-transmission- (QoT-) or impairment-aware (IA)[1] routing algorithms before scheduling the data transmission [15]. As the first step toward implementing impairment-aware manycasting, we consider only the OSNR constraint. We develop algorithms that implement manycasting considering both *burst contentions* and *optical impairments*. Impairment awareness in the burst scheduling algorithms causes more burst loss when compared with algorithms considering an ideal physical layer (i.e., burst loss occurs only due to the contention). Hence there is need to develop suitable burst scheduling algorithms such that overall loss due to contention and optical impairments is minimized.

[1]In this paper, QoT and IA are used interchangeably.

The control plane plays an important role, especially in switched optical networks for supporting dynamic and interactive services. A comprehensive review of the optical control plane for the grid user community can be found in [19]. However, for the sake of completeness, we present the control plane architecture for grid applications over the OBS network as shown in Fig. 1. Control and management mechanisms include *access signaling* and *bandwidth provisioning*. *Access signaling* is responsible for providing an exchange of information between the client and the optical core network. In the case of grid applications these clients can be grid users or computational/storage resources as shown in Fig. 1. Access signaling is of two types: *grid-user network interface* (GUNI) and *grid-resource network interface* (GRNI). Efforts are made to standardize the properties of GUNI and GRNI. *Bandwidth provisioning* is responsible for the path search and the signaling for path setup. These path signaling techniques are called the *network–network interface* (NNI).

OBS routing protocols offer the opportunity to consider the effects of signal impairments as a part of the routing algorithm and grid service offering [20]. The grid service will be established across the path that satisfies the service policy requirements (using NNI signaling) in terms of threshold parameters specific to the service. These threshold parameters are communicated to the edge router and the local resource management (LRM) (as shown in Fig. 1).

The LRM maintains the information of the service. The signaling adopted between the clients and the LRM is based on GUNI or GRNI. In this paper we focus on the NNI signaling, which obtains the information from the LRM.

The rest of the paper is organized as follows: Section II discusses issues related to supporting multicasting and manycasting over OBS networks. Section II defines the problem and obtains a measure to characterize the signal quality. Section III describes the proposed impairment-aware manycasting algorithm. In Section IV, using simulation results we compare the performance of the proposed impairment-aware manycasting algorithms. Section V concludes the paper and lists the areas of future work.

II. Problem Statement

A request denoted by (s, D_s, k) corresponds to a communication between a single source and multiple destinations. In order to configure the connection for this request, a shortest-path tree (SPT) has to be computed, as given below:

- *Step 1*: Find the shortest path from source s to all the destinations in D_s. Let $D_s = \{d_1, d_2, \ldots, d_{|D_s|=m}\}$ and the minimum hop distance from s to d_i, where $1 \leq i \leq m$, is $\mathbb{H}^{(s)} = \{h_1, h_2, \ldots, h_m\}$.
- *Step 2*: All the destinations in D_s are sorted in nondecreasing order of their path distance from source s. Let D_s' be the new set in this order given by $\{d_1', d_2', \ldots, d_m'\}$.
- *Step 3*: Select the first k destinations from D_s'.

For a network of size $|V|$, each step requires the time complexity of $O(E+|V|\log(|V|))$, $O(m \log(m))$, and $O(|V|)$, respectively. If the shortest-path distance to all the destinations are known, then the time complexity of the SPT algorithm reduces to $O(|V|)$. We implement the SPT algorithm in a distributed manner. *Step 1* is implemented by the unicast routing table. *Step 2* sorts the destinations at the source node, in $O(m \log(m))$.

Selecting the first k destinations and sending the burst to these destinations corresponds to a simple multicast communication. If at least one among the k is not reachable, then the request is said to be blocked. In multicast with overprovisioning the burst is sent to more than the required k. In this case, the request is said to be successful, if the burst reaches at least k of them. Finally, in manycasting the burst is sent to first k of them, and, if any one of the destinations is not reachable, then one among the remaining $(|D_s'|-k)$ is selected. In other words, the first destination in the set $\{d_{k+1}', d_{k+2}', \ldots, d_m'\}$ is selected. In general most multicasting solution approaches 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 as shown in Fig. 2.

The well-known OBS signaling protocols for unicast traffic, such as tell-and-wait (TAW), tell-and-go (TAG), just-in-time (JIT), and just-enough-time (JET) [21–23] can be used for multicasting and manycasting. The one-way-based signaling techniques are used to minimize the end-to-end data transfer delay. However, this can lead to high data loss due to contention of data bursts in the OBS core. Two-way-based signaling techniques are acknowledgment based, where the request for a resource is sent from the source to the destination. The acknowledgment message confirming a successful assignment of requested resources is sent back from the destination to the source. The data burst is transmitted only after a connection is established successfully. The primary objective of the two-way-based technique is to minimize packet loss in the core network, but such an objective leads to high data transfer delay due to the round-trip connection setup [24]. Our proposed methods can be modified to work with two-way reservation techniques. However, we restrict our study only to one-way signaling techniques.

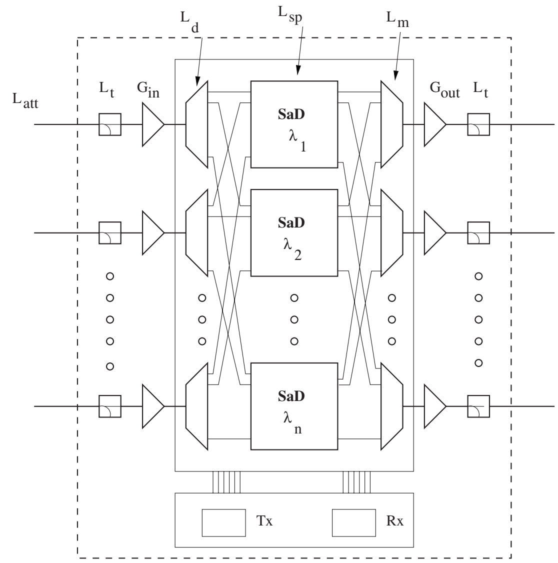


Fig. 2. MC-OXC based on splitter-and-delivery (SaD) architecture.

In all three methods mentioned the shortest-path destinations are selected first and hence the signal degradation along the path will be minimal. However, due to split loss in the MC-OXCs, the signal impairments on the shortest path are not guaranteed to be within the threshold requirement of the q factor. Hence there is a need to further investigate the physical-layer-aware algorithms that will compute the online q factor. The OSNR is estimated based on the ASE noise, which is static and can be computed offline too. However, we consider the online evaluation of the q factor due to the randomness in the location of the power splitting. Also, online computation of the q factor using BHP will be able to accommodate other dynamically changing impairments in the future.

In Subsection II.A, we first discuss the network architecture used for computing the q factor. We then discuss the impairments in such a network and compute the quality factor of the signal on a per-hop basis in Subsection II.B.

A. Network Architecture

Figure 2 shows the architecture for a MC-OXC [13] using the splitter-and-delivery (SaD) switch shown in Fig. 3 [25,26]. As the optical signal traverses from source to destination, it encounters losses due to optical switches, a multiplexer, a demultiplexer, and fiber. Power loss can be compen-

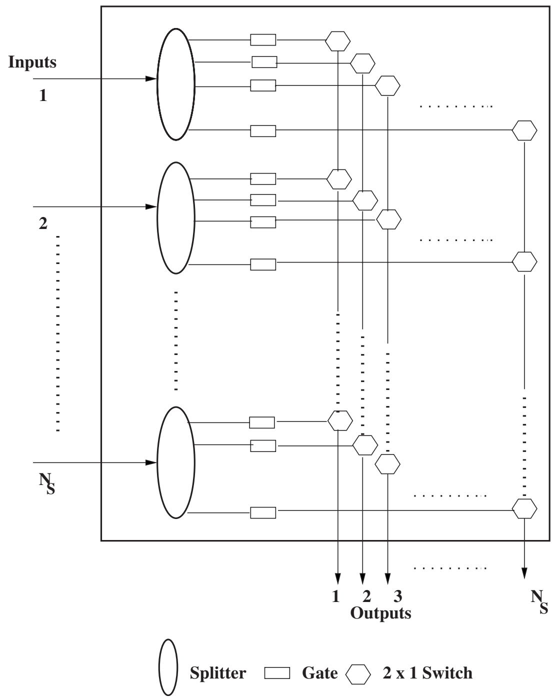


Fig. 3. An $N_s \times N_s$ SaD switch.

sated either by incorporating optical amplifiers or by increasing signal power at the source. Fiber in-line amplification provided by cascaded erbium-doped fiber amplifiers (EDFAs) compensates the power loss due to attenuation in the fiber. However, the EDFAs increase the ASE noise in the channel, which in turn increases the BER. In this paper, we consider in-line amplification of the signal, and hence the effect of ASE noise on the signal quality is used for the computation of the BER. An $N_s \times N_s$ SaD switch proposed in [25] is used in the architecture for manycasting. It consists of N_s power splitters, N_s^2 2×1 optical gates (used to reduce cross-talk), and N_s^2 2×1 photonic switches as shown in Fig. 3. These switches are assumed to be configurable and can be instructed to split the incoming signal to any of $i=1,\ldots,N_s$ output ports [26,27].

B. Calculation of the q-Factor on a Per-Hop Basis

- $L_{sp}(n)=1/sp(n)$ is the loss due to the splitter at node n, where $sp(n)$ is the number of the output ports to which the signal is split, defined as the *fan-out* of the splitter. If $sp(n)=1$, then there is no splitting at the node and hence $L_{sp}(n)=1$.
- L_n is the physical distance between the nodes $\langle n-1,n\rangle$, and l is the distance between two EDFAs. Then a_n, the number of amplifiers used between $\langle n-1,n\rangle$ is given by

$$a_n = \left\lceil \frac{L_n}{l} \right\rceil - 1. \tag{1}$$

We define l_n as the distance of fiber that is not compensated by in-line amplification, given by

$$l_n = L_n - a_n \times l. \tag{2}$$

- $L_{att}(n)=e^{-\alpha l_n}$ is the loss due to the attenuation in the fiber between $\langle n-1,n\rangle$, where α is the attenuation of the fiber.
- L_d, L_m, and L_t are defined as demultiplexer, multiplexer, and tap losses, respectively.
- $L_{ins}=(2\log_2 N_s)L_s+4L_w$ dB is the insertion loss of the SaD switch, where L_s is the switch element insertion loss, L_w is the waveguide or coupling loss, and N_s is the number of input/output ports of the switch. The SaD shown in Fig. 3 consists of an array of directional couplers based on titanium-diffused lithium niobate ($\mathrm{Ti{:}LiNbO_3}$) devices. L_s represents the material absorption and scattering losses as the signal propagates through the length of the $\mathrm{Ti{:}LiNbO_3}$ waveguide [13].
- G_{in} and G_{out} are the gains of the input and the output EDFAs, respectively. Define $G_T=G_{in}G_{out}$ as the total gain provided by the amplifiers at the node.
- $\bar{G}$ is the saturated gain of the in-line EDFA. This gain is set to compensate the fiber loss between consecutive amplifiers given by $\bar{G}=e^{\alpha l}$ [28,29].
- $P(n)$ and $P_{ase}(n)$ are the signal power and ASE noise power inputs to the nth node, respectively, as shown in Fig. 4.
- B_o and B_e are the optical and electrical bandwidths.

Recursive Power Relations: Here we derive recursive power relations similar to [13]. However, the difference is that we consider in-line amplification and we use a SaD switch instead of an OXC. The output power at node n, $P(n)$, is given by

$$\begin{aligned} P(n) &= G_{in}G_{out}L_dL_mL_t^2L_{ins}L_{att}(n)L_{sp}(n-1)\times P(n-1) \\ &= G_TL_kL_{att}(n)L_{sp}(n-1)P(n-1) \\ &= G_TL_T(n)L_{sp}(n-1)P(n-1), \end{aligned} \tag{3}$$

where $L_k=L_dL_mL_t^2L_{ins}$ is a constant for any given node, and $L_T(n)=L_kL_{att}(n)$.

$$\begin{aligned} P_{ase}(n) &= P_{ase}(n-1)L_T(n)G_T + P'L_k\times[G_{in}-1]G_{out}/L_t \\ &\quad + P'L_t[G_{out}-1] + P'[\bar{G}-1]a_n, \end{aligned} \tag{4}$$

where $P'=2n_{sp}hf_cB_o$ with typical values given in Table I. Due to in-line amplification of the signal using EDFA, there will be ASE noise along the route. The last term in Eq. (4) 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 a constant when the wavelengths are centered around f_c. In the system of cascaded amplifiers, the notion of sensitivity is not very useful when the signal reaching the receiver has already added a lot of noise [14]. In this case the two parameters that are mea-

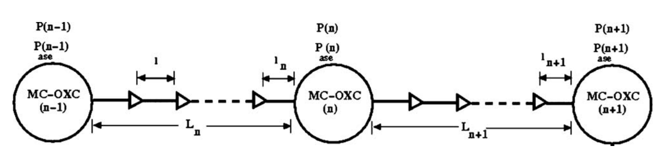


Fig. 4. Illustration of notations used in Eqs. (3) and (4).

TABLE I
PARAMETERS USED FOR COMPUTATION OF THE q FACTOR

Parameter	Value
Channel bit rate (B)	10 Gb/s
Optical bandwidth (B_o)	70 GHz
Electrical bandwidth (B_e)	$0.7\times B$
Input power of the signal	1 mW (0 dBm)
Loss of multiplexer/demultiplexer	4 dB
Switch element insertion loss	1 dB
Waveguide fiber coupling loss	1 dB
Tap loss	1 dB
Fiber loss	0.3 dB/km
Gain of EDFA in MC-OXC (G_{in}, G_{out})	22 dB, 16 dB
ASE factor (n_{sp})	1.5
Plank's constant h	6.63×10^{-34} J-s
Carrier frequency f_c	193.55 THz
P' in Eq. (4)	$2n_{sp}hf_cB_o$
Spacing between the amplifiers (l)	70 km
q_{th}	6.5
Number of fibers/link	2 (bidirectional)

sured are the average received signal power, $P(n)$, and the received optical noise power, $P_{ase}(n)$. The OSNR at node n is given by $\mathrm{OSNR}(n)=P(n)/P_{ase}(n)$. By neglecting the receiver thermal noise and shot noise, the relationship between the q factor and the OSNR is given by [14]

$$q(n)=\frac{2\sqrt{\frac{B_o}{B_e}}\mathrm{OSNR}(n)}{1+\sqrt{1+4\mathrm{OSNR}(n)}}, \tag{5}$$

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

$$\mathrm{BER}(n)=\frac{1}{2}\,\mathrm{erfc}\left(\frac{q(n)}{\sqrt{2}}\right), \tag{6}$$

where $\mathrm{erfc}(x)$ is the complementary error function.

Assumptions

1) In the recursive power relations we have chosen the gain of the amplifiers (input/output) to be a constant, i.e., gain saturation effects of the amplifier are not considered.
2) We have assumed that the q factor is independent of the wavelength chosen. This assumption is valid when the wavelength spacing is less. Hence the carrier frequency f_c is chosen to be the central frequency of the wavelength band.
3) Impairments due to cross-talk, polarization mode dispersion (PMD), and fiber nonlinearity are ignored in the computation of the q factor.
4) The modulation format used is on–off keying (OOK).
5) The thermal noise and shot noise of the receiver are neglected in Eq. (5).
6) We also assume that the received pulses are Gaussian distributed.

C. Online Evaluation of the q Factor Using BHP

Consider the request in the form of (s,D_s,k), with $|D_s|=m$. In order to identify the best set of k destinations, we need to construct the best possible tree, both in terms of load and quality [in other words, high $q(n)$]. Assuming the link to be free, we can route the optical signal. However, the link may have a bad q value, which in turn results in a high BER. If the BER is greater than 10^{-9}, then the signal cannot be recovered. Thus by setting a threshold value for the BER, we ensure that the received signal is acceptable. A high BER corresponds to a low q, so we say the optical signal is lost when q falls below the threshold value, q_{th}. Thus, the burst that was assumed to be transmitted by the OBS layer cannot be recovered by the core node and is actually lost before reaching the *egress* node. The BHP used to reserve the channel for the MC-OXC can also be used to make the MC-OXC aware of the q factor. The BHP can incorporate a new field that stores the current q-factor value. Initially, q is set to a high value, and once the BHP reaches the next node the q value is updated using the recursive Eqs. (3)–(5). At every intermediate node, the BHP updates the q and checks the condition, $q>q_{th}$. If true, the BHP proceeds further; otherwise the burst is dropped. We refer to burst loss due to signal impairments as *optical-layer blocking*.

Successful reception of the optical burst at the *egress* node is based on two issues, contentions and link impairments.

III. IMPAIRMENT-AWARE ROUTING ALGORITHMS

In this section we look at three different approaches to solving the single source to multiple destinations routing with impairment awareness. We first discuss the existing multicasting solution and then discuss a simple multicasting with overprovisioning solution. We then propose the distributed impairment-aware manycasting solution.

The three-tuple request (as explained in Section II) is stored in the BHP and at each node the burst is scheduled on the next-hop link along the shortest path. At every node a request is transmitted (as we see later in this section) only if the next-hop link is available for transmission. However, in order to provide impairment awareness during burst transmission, we modify the request as a five-tuple $(u,D'_u,k_u,P(u),P_{ase}(u))$, where the last two tuples indicate signal power and noise power, respectively. Node u can be the 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 request $(u,D'_u,k_u,P(u),P_{ase}(u))$ arrives at the node u with a candidate destination set D'_u, along with k_u intended destinations. The power inputs for this request are $P(u)$ and $P_{ase}(u)$.
2) **Output:** Request to the next-hop node(s) if the link is contention free and the BER constraint satisfied.

3) **Initialization:** At the source node, the request is of the form $(s, D'_s, k_s, P(s), P_{ase}(s))$. This five-tuple request is created for every new burst entering the network.

These impairment-aware routing algorithms are implemented through JET signaling using a BHP. The BHP fields are modified to contain the information about the five-tuple $(u, D_u, k_u, P(u), P_{ase}(u))$.

A. Impairment-Aware Multicasting

The impairment-aware multicasting (IA-MC) algorithm uses a precomputed shortest-path tree. Based on the three steps mentioned in Section II, the tree is constructed for each multicast request. Recursive power relations in Subsection II.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 the signal is error free. This continues until k destinations are reached. If the burst reaches $<k$ destinations, then the multicast request is said to be blocked. As the IA-MC is implemented on the precomputed 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. In the pseudocode for IA-MC, shown in Algorithm 1, lines 2–5 ensure that, if the current node is the destination node, then the destination set (D'_u) and intended number of destinations (k_u) is updated. These lines remain the same for all three algorithms discussed. Child nodes or the next-hop node set for node u and the set of destinations that can be reached through each next-hop node n_j are calculated using lines 6–10. For all child nodes the channel availability is checked using line 12. Using the recursive power relations described in Section II, the q factor is computed, and if the threshold condition is met, then we say that all the destinations corresponding to the child node n_i can be reached and this set is given by $S_D(n_i)$. $|S_D(n_i)| = k_u$ only when there is one child node for all the destinations in D'_u. The new multicast request is thus formed at the child node n_i as given in line 18. $\mathbb{D}$ 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 the probability of the request blocking is given by $1 - |\mathbb{D}|/k_u$. We assume that all the nodes in the network are equally likely to be chosen as a destination.

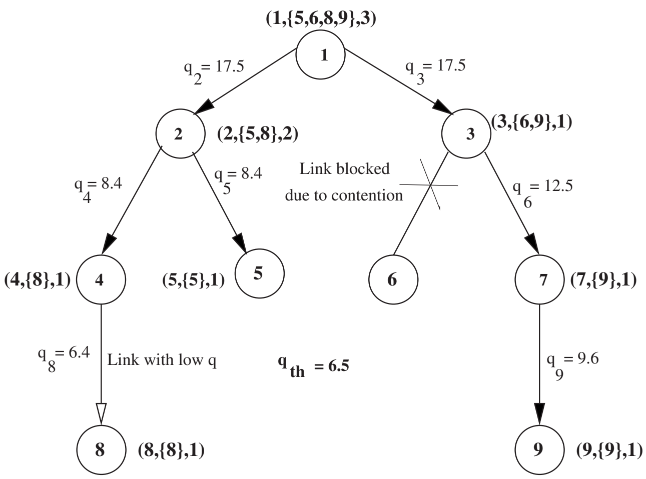
Consider the example given in Fig. 5, in the case of IA-MC, we select first $k_u = 3$ from $D'_c = \{5,6,8,9\}$, i.e., {5,6,8}. As both the conditions in lines 12 and 16 are met, we have $S_D(2) = \{5,8\}$ and $\mathbb{D} = \{5,8\}$ and the new manycast request at $n_i = 2$ becomes (2, {5,8}, 2, $P(2) = 0.4$, $P_{ase}(u) = 0.011$). When $i = 2$, we have $n_i = 3$, and, if the conditions are met, then we have $S_D(3) = 6$ and $\mathbb{D} = \{5,8\} \cup \{6\}$, which implies $|\mathbb{D}| = k_u$ and hence request (1, {5,6,8,9}, 3, $P(1) = 1$, $P_{ase}(1) = 0.0042$) is successful. If the outgoing link corresponding to $\langle 3, 6 \rangle$ is blocked due to contention as shown in Fig. 5, then the request is dropped.

Algorithm 1 Impairment-Aware Multicasting Algorithm

1: **Initialization:** At the source node, the manycast request is of the form $(s, D'_s, k_s, P(s), P_{ase}(s))$. Sets N and $\mathbb{D}$ are assigned to null.
{Update D'_u and k_u.}
2: **if** $u \in D'_u$ **then**
3: $D'_u \leftarrow D'_u \setminus \{u\}$.
4: $k_u \leftarrow k_u - 1$.
{Destination set D'_u is the nondecreasing order of the hop distance}.
5: **else**
6: **for** $j \leftarrow 1$ to k_u **do**
7: $n_j \leftarrow \mathrm{SPT}[u, d'_j]$
{Next hop or child node is obtained from shortest path tree}
8: $N = N \cup \{n_j\}$
9: $S_D(n_j) \leftarrow S_D(n_j) \cup d'_j$
{$S_D(n_j)$ is the set of all destinations $(\subseteq \{d'_1, \ldots, d'_{k_u}\})$ that can be reached through child node n_j. $|S_D(n_j)| \leq k_u$}
10: **end for**
11: **for** $i \leftarrow 1$ to $|N|$ **do**
12: **if** $(\langle u, n_i \rangle = \mathrm{FREE})$ **then**
13: $P(n_i) \leftarrow \mathrm{POW\_SIGNAL}(P(u), |N|)$
14: $P_{ase}(n_i) \leftarrow \mathrm{ASE\_SIGNAL}(P_{ase}(u))$
15: $q(n_i) \leftarrow Q\_\mathrm{FACTOR}(P(v_i), P_{ase}(v_i))$
16: **if** $(q(n_i) > q_{th})$ **then**
17: $D_{n_i} \leftarrow D_{n_i} \cup \{S_D(n_i)\}$
18: $(n_i, D_{n_i}, |S_D(n_i)|, P(n_i), P_{ase}(n_i))$
19: $\mathbb{D} \leftarrow \mathbb{D} \cup S_D(n_i)$
20: **else**
21: $\mathrm{DEST}[n_i] \leftarrow S_D(n_i)$ are not reachable due to high BER.
22: **end if**
23: **else**
24: $\mathrm{DEST}[n_i] \leftarrow S_D(n_i)$ are not reachable due to contention.
25: **end if**
26: **end for**
27: **end if**

B. Impairment-Aware Multicast With Overprovisioning

The impairment-aware multicast with overprovisioning (IA-MO) algorithm is similar to IA-MC except that here we do not limit the number of destinations to k, but we send the burst to $k + k'$ destinations, where k' is such that $0 \leq k' \leq m - k$. With $k' = 0$, IA-MO is similar to IA-MC, i.e., no overprovisioning. In this algorithm, first $k + k'$, destinations are selected from the set D'_c. Sending the burst to more than k destinations improves the probability that the request reaches at least the required k destinations. However, due to overprovisioning the fan-out of the splitter increases, thereby increasing the BER. In spite of the decrease in the contention loss, there is no significant improvement in the overall loss. From the simulation results (refer to Section IV) we see that IA-MO shows slightly better performance than IA-MC. The IA-MO algorithm is similar to that of IA-MC, 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 be-



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. 5. Example used for explaining the proposed algorithms. The distances between all nodes is 70 kms.

cause, 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 Fig. 5, if we select $k'=1$, we then have first k_u+k' of D'_c as {5,6,8,9}. At two child nodes, node 2 and node 3, the new manycast requests are (2, {5,8}, 2, $P(2)=0.4$, $P_{ase}(2)=0.011$), (3, {6, 9}, 2, $P(3)=1$, $P_{ase}(3)=0.011$), respectively (assuming links $\langle 1,2\rangle$ and $\langle 1,3\rangle$, are free and the q factor is greater than the required threshold). At node 2, the target node 5 is the destination node and the request is updated as 5, 5, 1, $P(2)=0.16$, $P_{ase}(5)$. Since node 5 is one of the destinations, the algorithm terminates. However, node 4 is the child node to the destination node 8, and hence the request is updated as 4, 8, 1, $P(4)$, $P_{ase}(4)$. The outgoing link at node 4 has a q factor that is below the threshold value (q_{th}). On the other hand, at node 3, assuming the outgoing link $\langle 3,6\rangle$ is blocked due to contention, the request is dropped. Thus we see that the overprovisioned request fails due to contention and impairments.

C. Impairment-Aware Manycasting

The impairment-aware manycasting (IA-MA) algorithm 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 the contention and quality of the link. IA-MA will work with a distributed version of SPT. k destinations are 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.

Algorithm 2 Impairment-Aware Manycasting Algorithm

1: **Initialization:** At the source node, the manycast request is of the form $(s,D'_s,k_s,P(s),P_{ase}(s))$. Sets $\mathbb{V}$, $\mathbb{Q}_L$, and $\mathbb{C}_L$ are assigned to null.
{Update D'_u and k_u.}
2: **if** $u\in D'_u$ **then**
3: $D'_u\leftarrow D'_u\setminus\{u\}$.
4: $k_u\leftarrow k_u-1$.
{Destination set D'_u is the nondecreasing order of the hop distance.}
5: **else**
6: **for** $j\leftarrow 1$ to $|D'_u|$ **do**
7: $n_j\leftarrow UNI\_CAST[u,d'_j]$
8: **if** $(\langle u,n_j\rangle=FREE)$ **then**
9: $\mathbb{V}\leftarrow\mathbb{V}\cup\{n_j\}$
10: **for** $v_i\in\mathbb{V}$ **do**
11: $P(v_i)\leftarrow POW\_SIGNAL(P(u),|\mathbb{V}|)$
12: $P_{ase}(v_i)\leftarrow ASE\_SIGNAL(P_{ase}(u))$
13: $q(v_i)\leftarrow Q\_FACTOR(P(u),P_{ase}(u))$
14: **if** $(q(v_i)>q_{th})$ **then**
15: $D_{v_i}\leftarrow D_{v_i}\cup\{d(v_i)\}$.
{$d(v_i)$ is the destination to be reached through child node v_i.}
16: **else**
17: $D_{v_j}\leftarrow D_{v_j}\setminus\{d(v_i)\}$
18: $\mathbb{Q}_L\leftarrow\mathbb{Q}_L\cup\{d(v_i)\}$
19: **end if**
20: **end for**
21: **while** $\Sigma_{k=1}^{j}k_{n_k}<k_u$ **do**
22: $k_{n_j}\leftarrow k_{n_j}+1$
23: **end while**
24: **else**
25: $\mathbb{C}_L\leftarrow\mathbb{C}_L\cup\{d_j\}$
26: **end if**
27: **end for**
28: **end if**

The pseudocode for IA-MA given in Algorithm 2 is explained with an example shown in Fig. 5. Consider the manycast request (1, {5,6,8,9}, 3, $P(1)=1$, $P_{ase}=0.0042$) with signal and ASE powers as shown in Fig. 5. The table in Fig. 5 shows the number of splits, input signal power, and ASE power at each node. The output of IA-MA algorithm gives the manycast request at the next-hop node with signal and ASE values. These two values can be used to compute the q factor and thus qualify the outgoing link. $\mathbb{V}$ represents a set of next-hop nodes (or child nodes) for node u, $\mathbb{Q}_L$ represents a set of nodes that have a low q factor, and $\mathbb{C}_L$ represents a set of nodes that are blocked due to contentions. These sets are initialized to null before the start of the algorithm (as given in line 1 of Algorithm 2). When the request arrives, and if $u\in D'_u$, then the burst is received locally and the request is updated as shown in lines 2–5. The set {5,6,8,9} is the sorted set of candidate destinations in the nondecreasing order of hop distance. Assuming link $\langle 1,2\rangle$ is free, $\mathbb{V}$ is updated, and the signal power and ASE power received at node 2 is computed. Note that there is no split ($|\mathbb{V}|=1$) and the q factor is computed using lines 11–13. The condition for threshold is checked and thus the destination set at the next-hop node is updated. Lines 21–23 ensure that the number of destinations at all the child nodes does not exceed k_u, the number of destinations at the current node. The loop in line 6, is executed for all destinations. Hence, the next destination in the order of nondecreasing hop distance is node 6. The child node for the current node 1 is node 3 and hence link $\langle 1,3\rangle$ is checked for contention. If it is free then the split takes place at node 1 and the power is divided equally among nodes 2 and 3 ($|\mathbb{V}|=2$). Note that ASE power remains unchanged. Thus the new power and q values are computed using lines 11–12, as given in Algorithm 2.

As the power of the signal is split at node 1, the new manycast requests at the next hops, node 2 and node 3, become, (2, {5,8}, 2, $P(2)=0.4$, $P_{ase}(2)=0.011$) and (3, {6, 9}, 1, $P(2)=0.4$, $P_{ase}(2)=0.011$), respectively. At node 2 the next-hop nodes are node 4 and node 5, and the burst is scheduled assuming the links $\langle 2,4\rangle$ and $\langle 2,5\rangle$ are available. The new manycast requests are updated accordingly. Because node 5 is a destination node, lines 2–5 in the algorithm ensure that routing of the burst terminates at node 5. Along node 4 the burst continues to be routed toward node 8. As shown in Fig. 5 we see that the q factor at node 8 is less than the required threshold of $q_{th}=6.5$. On the other side of the tree, as link $\langle 3,6\rangle$ is blocked, the burst has to be routed to the other destination, node 9, which is at a longer distance. Assuming all the links leading to node 9 are free, we see that the q factor is much less than at node 6. We observe that in IA-MA destinations can be added or removed dynamically and this decreases the request blocking in comparison with IA-MC and IA-MO.

We observe that the number of child nodes is not fixed and hence power relations need to be recomputed according to the split. Thus the average request delay for IA-MA is more, when compared with IA-MC, as discussed later in the numerical results.

For each manycast request (burst), a corresponding BHP is created with a unique burst ID. When the BHP reaches the next hop, the request gets updated with the source node being the next-hop node (u) and the destination set being all the destinations (D_u) that can be reached through the next hop. k_u in IA-MC and IA-MO is updated to be equal to the cardinality of D_u, whereas in IA-MA lines 21–23 are used to update k_u for the next-hop node. Note that the burst ID remains the same throughout the transmission of a manycast request.

IV. Numerical Results

In this section we present our simulation results using discrete-event simulations. We consider *average request blocking* as the performance metric. Let f be the total number of requests used in the simulation. Let $\mathbb{D}$ be the set of destinations that actually receive the data for each request. Then *average request blocking* is given by

$$B_{total}^{(Sim)} = \sum_{f} [1.0 - \min(|\mathbb{D}|,k)/k]/f. \tag{7}$$

In order to have a good estimate of the average blocking probability, we have used $f=10^6$. The derivation for Eq. (7) can be found in [30].

We use the notation m/k, which means $|D_s|=m$ and k intended destinations. As in [2,31], we consider the candidate destinations set D_s at small, medium, and large sizes, and the intended destinations constitute a majority of the group. Three typical configurations, 3/2, 7/4, and 11/6 were simulated. We use the NSF network as shown in Fig. 6 for our simulation studies. All the links in the network are bidirectional and have the same transmission rate of 10 Gb/s. Burst arrivals follow a Poisson process with an arrival rate of λ bursts per second. The length of the burst is exponentially distributed with the expected service time of $1/\mu$ s. The network load in Erlangs 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 in the network simulations. The physical layer parameters used in the simulation model are shown in Table I.

We compute $B_{total}^{(Sim)}$ using Eq. (7) and compare our results for without impairment awareness. Figure 7 shows the comparison of impairment-aware average request blocking to regular algorithms. From these graphs we observe that 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 the regular algorithms used in [4] do not provide the correct estimate of blocking. From Fig. 7 we also observe that IA-MA has lower blocking than IA-MC and IA-MO, and thus impairment-aware manycasting over OBS can be improved by using IA-MA. From Fig. 7 we also observe that without impairment awareness the performance of all three algorithms is similar. However, in the presence of impairments there is significant reduction in the burst loss when IA-MA is used. Figure 8 shows the performance of the IA-MA for higher network load conditions. From this result we observe that at higher load conditions the blocking probability for the IA-MA converges to IA-MC and IA-MO. This is because at higher loads, most of the bursts are dropped due to contention. IA-MA helps to de-

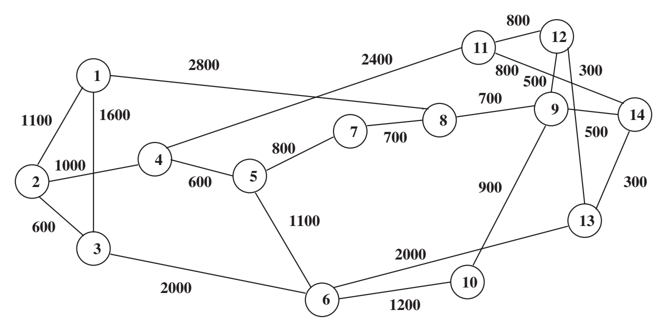


Fig. 6. The NSF network consisting of 14 nodes and 21 bidirectional links. The numbers on the links indicate the distance between the nodes in kilometers. These links consist of in-line EDFAs spaced 70 km apart (not shown in the figure for clarity).

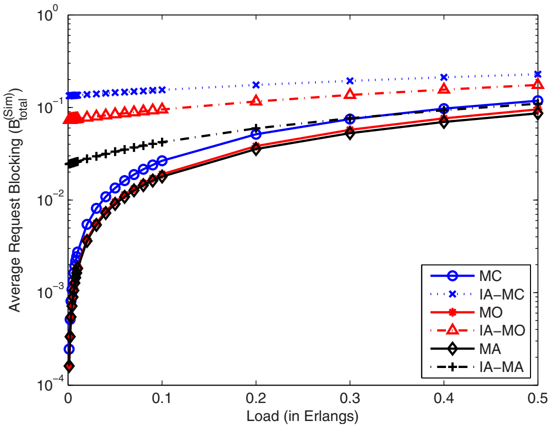


Fig. 7. (Color online) Comparison of algorithms with and without impairment awareness.

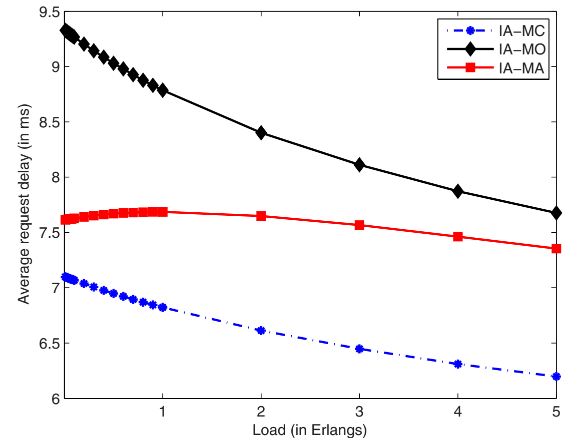


Fig. 9. (Color online) Comparison of average request delay for the proposed algorithms.

crease the burst loss, where the burst loss due to impairments are high (low network load).

We now compare the average request delay for the three proposed algorithms on a 7/4 scenario, as shown in Fig. 9. From Fig. 9 we observe that the average delay for the IA-MA algorithm is more than that of IA-MC. This is because the IA-MC algorithm routes the burst to the shortest destinations (i.e., it creates a SPT). On the other hand IA-MA looks for the destinations that are at a longer distance, causing increased request delay. From Fig. 9 we also observe that the algorithm IA-MO has the highest request delay compared with the other two algorithms at any given network load. This is because, in the case of IA-MO, we have considered the overprovisioning factor $k'=3$, which means that the bursts are sent to all the destinations, causing a significant increase in the delay.

We compare the performance of other manycast scenarios, such as 3/2 and 11/6. Figure 10 shows the average request blocking for the 3/2 manycast configuration. We observe that there has been a significant reduction in the burst loss using IA-MA when compared with the other two algorithms IA-MC and IA-MO. This reduction is attributed to the decrease in the contention loss. Static behavior of the IA-MC and IA-MO causes more requests to be blocked due to contention. In Fig. 10 we also see the performance comparison of these algorithms, without impairments.

Comparison of these algorithms for the 11/6 manycast configuration is given in Fig. 11. In the case of 11/6 the IA-MO and IA-MA algorithms have similar loss performance. However, in the presence of impairments, there is significant decrease in the burst loss for IA-MA when compared with IA-MO and IA-MC for the same given load. We observe that for all manycast configurations IA-MA performs better in terms of request blocking.

We evaluate the performance of IA-MO as shown in Fig. 12. By overprovisioning, the burst may reach a greater number of destinations than necessary. However, due to the increase in power loss at the SaD switch, the BER increases. Thus sending the manycast request to more destinations does not really decrease the blocking. This is observed in Fig. 12 where the slope of the decrease in the burst blocking is small with the increase of k' for a given network load.

Considering 11/6 as the baseline model, which indicates 54% of intended destinations, we simulate the performance of IA-MA in comparison with IA-MC. In Fig. 13, k is varied from $7 \leqslant k \leqslant 10$. We observe from Fig. 13 that as k increases, the blocking probability increases for a given network load. Also we see from this result that for all percentages of num-

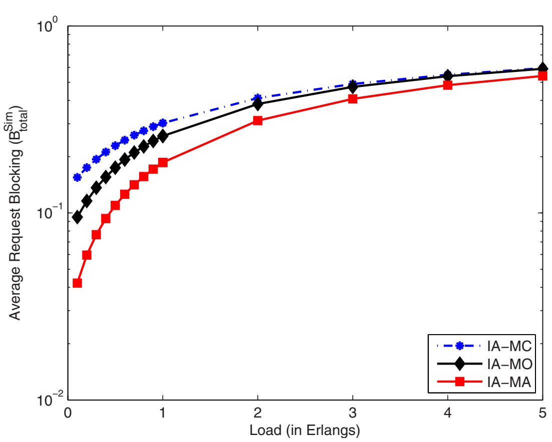


Fig. 8. (Color online) Comparison of algorithms of proposed impairment-aware algorithms at high load.

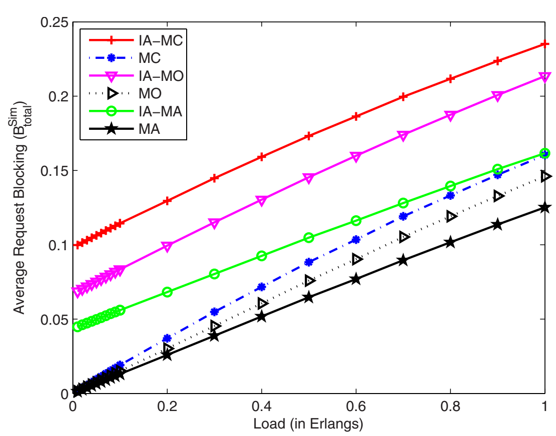


Fig. 10. (Color online) Comparison of algorithms with and without impairment awareness for manycast configuration of 3/2.

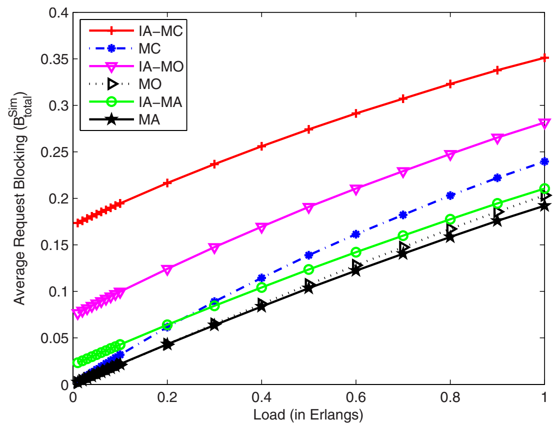


Fig. 11. (Color online) Comparison of algorithms with and without impairment awareness for manycast configuration of 11/6.

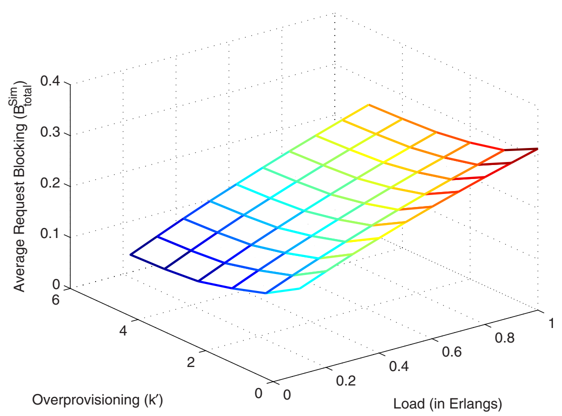


Fig. 12. (Color online) Performance of 10/5 with different levels of overprovisioning.

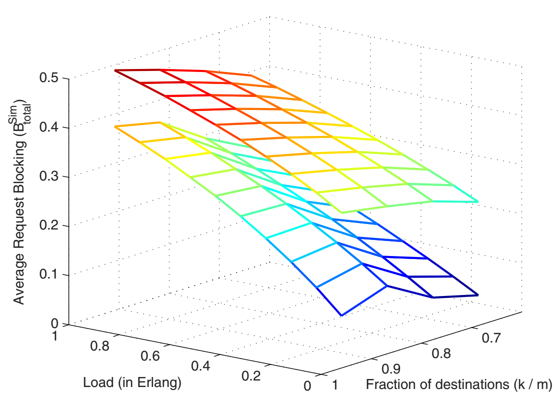


Fig. 13. (Color online) Performance of IA-MC and IA-MA for different percentages of destinations.

ber of destinations, there has been a 33% reduction in blocking in the case of IA-MA for the given load and the number of destinations. This reduction in blocking comes from the fact that in IA-MA destinations join or leave depending on the network congestion.

V. Conclusion and Future Scope

In this paper, we have discussed issues related to optical-layer impairment-aware manycasting service. Supporting manycasting over OBS improves the network performance as compared with OBS multicasting. We proposed a distributed impairment-aware manycasting algorithm for OBS networks. Through extensive simulations, we show that our proposed IA-MA algorithm outperforms IA-MC and IA-MO algorithms in terms of blocking probability. An important area of future work is to implement QoS-based manycasting over OBS networks [30] and also to modify the manycast algorithms to work with other dynamic impairments in all-optical transport networks.

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