Constraint-Based Anycasting Over Optical Burst Switched Networks

Balagangadhar G. Bathula and Jaafar M. H. Elmirghani

***Abstract*—We present a communication paradigm called "anycasting," which is defined as delivering traffic from a source node to any one destination among a set of recipients in the network. An anycasting message finds an appropriate server that can meet the service requirements of the client effectively. We discuss the mathematical framework to provide quality of service (QoS) for anycasting over optical burst switched networks. These QoS parameters include resource availability, reliability, propagation delay, and quality of transmission. With the help of link-state information available at each network element (NE), the bursts are scheduled to their next link. This decentralized way of routing helps to provide optimal QoS and hence decreases the loss of grid jobs due to multiple constraints. We compare the performance of our proposed algorithm with the shortest-path algorithm. Using simulation results performed on different network topologies, we show that the service-aware anycasting paradigm introduced decreases the number of bursts lost.**

***Index Terms*—All-optical networks; Multicast; Network survivability.**

I. Introduction

The enormous bandwidth capability of optical networks helps the network user community to realize many distributed applications, for example, grid computing. These emerging interactive applications require a user-controlled network infrastructure [1]. This has led many researchers to investigate control plane architectures for optical networks. A comprehensive review of the optical control plane for the grid community can be found in [2]. Quality of service (QoS) policies implemented in an IP network do not work in an optical network, as the store-and-forward model does not exist [3]. We thus see the need for an intelligent control plane in the optical network, which can provide the required QoS.

Revised January 14, 2009; accepted January 15, 2009; published June 18, 2009 (Doc. ID 103565).

The authors are with the School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK (e-mail: b.bathula@leeds.ac.uk).

Digital Object Identifier 10.1364/JOCN.1.000A35

With the advent of many new switching techniques, researchers were able to tap the huge bandwidth capacity of the fiber. Fast and dynamic connection establishments using optical burst switched (OBS) networks have been achieved at much lower switching costs. The Open Grid Forum is a community that aims to develop standards, protocols, and solutions to support OBS-based grid networks [1]. A general layered grid architecture and the role of OBS networks is discussed in [4]. Delivering a grid application effectively involves many parameters, such as design of efficient control plane architectures, algorithms for routing, and providing QoS and resilience guarantees.

"Anycast" can be defined as a variation on unicast, with the destination not known *a priori* [5,6]. Anycasting is similar to deflection routing (DR), except for the fact that different destinations can be selected instead of routing the burst to the same destination by using an alternative path. Routing can be accomplished by a label-based control framework [7] using optical core networks, such as OBS.

Anycasting communication is applicable to many emerging Internet-based distributed applications such as grid computing, distributed interactive service, peer-to-peer networking, and content distribution networks. Anycasting allows the flexibility for the grid job to effectively identify the destination that meets the QoS parameters. Constraint-based anycasting helps provide the necessary QoS to these future Internet applications. Incorporating an intelligent control plane and with the use of efficient signaling techniques, anycasting can provide a viable communication paradigm in grid applications.

Anycast can be used by a client to find an appropriate server when there are multiple servers for the same kind of service in the network. For example, in grid computing, a client requires necessary computing resources to be found from a set of multiple servers. The established route between the client and the server should meet the QoS standards. Hence providing QoS under a set of constraints becomes an important issue in anycasting.

The rest of the paper is organized as follows: in Section II we describe the notation used in the paper. The

1943-0620/09/020A35-9/$15.00

QoS parameters used for burst scheduling are also discussed in Section II. The mathematical framework for ordering the destinations, based on lattice theory, is discussed in Section III. We explain this mathematical framework with the help of a simple network example in Subsection IV.A, and simulation results are presented in Section V, with conclusions and further work in Section VI.

II. Notation

An anycast request can be denoted (s,D), where s denotes the source, D is the destination set, and one of the destinations has to be chosen from set D. This notation is a generalization of manycast [8]. Let $m=|D|$, denote the cardinality of the set. Each grid job has a service class, and we hence define the service class set as $\mathbb{S}=\{S_1,S_2\ldots S_p\}$. There is an associated threshold requirement for which the QoS parameters should not exceed this condition. We define this threshold parameter as $T^{(S_i)}$, where $S_i\in\mathbb{S}$.

Service Parameters. Anycasting allows the flexibility for the grid job to effectively identify the destination that meets the QoS parameters. We define w_j, η_j, γ_j, and τ_j as the residual (or unused) wavelengths, noise factor, reliability factor, and end-to-end propagation delay for link j, respectively.

In wavelength-routed optical burst switched networks, the connection requests arrive at a very high speed, while the average duration of each connection is only of the order of hundreds of milliseconds [9]. To support such bursty traffic, it is always advisable to choose the path with the largest number of free wavelengths (least congested path). w_j indicates the number of free (or residual) wavelengths available on link j. We consider an all-optical network architecture, where there is no wavelength conversion, resulting in a wavelength-continuity constraint (WCC). Let $\mathbb{W}_i$ and $\mathbb{W}_j$ be the two free wavelength sets available on links i and j, respectively. Without loss of generality we assume that $\mathbb{W}_i\cap\mathbb{W}_j\neq\emptyset$. We propose to select a path toward the destination, with more free wavelengths. We use an operation $|\cap|$ that gives the common number of wavelengths on each link. If we assume that each unidirectional link can support five wavelengths, then $|\mathbb{W}_i\cap\mathbb{W}_j|$ is an integer $\leqslant 5$. The number of free wavelengths on the route is given by

$$w_R=\left|\bigcap_{\forall i\in R}\mathbb{W}_i\right|, \tag{1}$$

where R denotes the route and w_R represents the number of free wavelengths available. If $w_R=0$, then the destination is said to be not reachable due to contention.

The noise factor is defined as the ratio of input optical signal to noise ratio ($\mathrm{OSNR}_{i/p}\equiv\mathrm{OSNR}_i$) and output optical signal to noise ratio ($\mathrm{OSNR}_{o/p}\equiv\mathrm{OSNR}_{i+1}$); thus we have

$$\eta_j=\frac{\mathrm{OSNR}_{i/p}}{\mathrm{OSNR}_{o/p}}, \tag{2}$$

where OSNR is defined as the ratio of the average signal power received at a node to the average amplified spontaneous emission noise power at that node. The OSNR of the link and q factor are related as

$$q=\frac{2\sqrt{\dfrac{B_o}{B_e}}\mathrm{OSNR}}{1+\sqrt{1+4\ \mathrm{OSNR}}}, \tag{3}$$

where B_o and B_e are optical and electrical bandwidths, respectively [10]. The bit-error rate is related to the q-factor as follows:

$$\mathrm{BER}=2\ \mathrm{erfc}\left(\frac{q}{\sqrt{2}}\right). \tag{4}$$

In our proposed routing algorithm, we choose a route that has a minimum noise factor. Thus the overall noise factor is given by

$$\eta_R=\prod_{\forall i\in R}\eta_i. \tag{5}$$

The other two parameters considered in our approach include the reliability factor and the propagation delay of the burst along the link. The reliability factor of the link j is denoted η_j. This value indicates the reliability of the link, and its value lies in the interval (0,1]. The overall reliability of the route is calculated as the multiplicative constraint and is given by [8,11]

$$\gamma_R=\prod_{\forall i\in R}\gamma_i. \tag{6}$$

The propagation delay on the link j is denoted τ_j, and the overall propagation delay of the route R is given by

$$\tau_R=\sum_{\forall i\in R}\tau_i. \tag{7}$$

III. Mathematical Framework

In this section we provide the mathematical formulation for selecting the destination based on the above-mentioned service parameters. We define a network element vector (NEV) that maintains information about the QoS parameters at each network element (NE). This information is contained in the optical control plane. In the distributed routing approach, current GMPLS routing protocols can be modified to implement the service information [12,13]. A global traffic engineering database at each optical control plane maintains an up-to-date picture of the NEV.

Definition 1. *We designate the network element vector for a link i as*

$$\mathrm{NEV}_i = \begin{pmatrix} w_i \\ \eta_i \\ \gamma_i \\ \tau_i \end{pmatrix}. \tag{8}$$

The NEV maintains information about the QoS parameters. This NEV is maintained by the optical-control plane (OCP) as shown in Fig. 1. A path is established on a link-by-links basis. The burst header packet (BHP) or burst control packet (BCP) used by the control plane maintains the information of the NEV, the core node (optical cross-connect or NE) routes the optical burst based on the signaling instructions from the control plane. The optical cross-connect node has no intelligence in maintaining the information about the wavelength occupancy of the next hop link.

Definition 2. *Let* NEV_i *and* NEV_j *be the two network element information vectors of links i and j , respectively; then we define a comparison* $\preccurlyeq$ *given by*

$$\begin{pmatrix} w_i \\ \eta_i \\ \gamma_i \\ \tau_i \end{pmatrix} \preccurlyeq \begin{pmatrix} w_j \\ \eta_j \\ \gamma_j \\ \tau_j \end{pmatrix}. \tag{9}$$

The above equation implies that,

$$(w_i \geqslant w_j) \wedge (\eta_i \leqslant \eta_j) \wedge (\gamma_i \geqslant \gamma_j) \wedge (\tau_i \leqslant \tau_j). \tag{10}$$

Equation (10) is chosen such that the path toward the destination has more residual wavelengths, a lower noise factor, higher reliability, and a lower propagation delay. This ensures that the QoS requirement for a particular service are meet effectively.

Definition 3. *Two NEVs are said to be incomparable in a multidimensional vector space if at least one of the inequalities in Eq. (10) is not satisfied. That* NEV_i *and* NEV_j *are two incomparable vectors is denoted* $\mathrm{NEV}_i \| \mathrm{NEV}_j$.

In other words, we have $(w_i < w_j)$ and/or $(\eta_i > \eta_j)$ and/or $(\gamma_i < \gamma_j)$ and/or $(\tau_i > \tau_j)$. The Hasse diagram [14] shown in Fig. 2 explains an example of the ordering $\preccurlyeq$.

Definition 4. *The overall service information of a destination* $d_n \in D$, $1 \leqslant n \leqslant m$ *along the shortest-path route* $R(d_n)$ *is given by*

$$\mathrm{NEV}_{R(d_n)} = \mathrm{NEV}_{R(d_n)}[s,h_1] \bigcirc \ldots \bigcirc \mathrm{NEV}_{R(d_n)} \times [h_i,h_{i+1}] \bigcirc \ldots \bigcirc \mathrm{NEV}_{R(d_n)}[h_k,d_n], \tag{11}$$

$$\mathrm{NEV}_{R(d_n)} = \begin{pmatrix} \left| \bigcap_{\forall i \in R(d_n)} \mathbb{W}_i \right| \\ \prod_{\forall i \in R(d_n)} \eta_i \\ \prod_{\forall i \in R(d_n)} \gamma_i \\ \sum_{\forall i \in R(d_n)} \tau_i \end{pmatrix}, \tag{12}$$

where in Eq. (11) h_i represents the next hop node along the shortest path. The operation $\bigcirc$ performs $|\cap|$ on wavelengths sets, multiplication on the noise factor, multiplication on reliability, and addition on propagation delay. Equation (12) represents the overall QoS information vector for the destination d_n.

Definition 5. *A destination* d_n *is said to be feasible for a given service requirement* $T^{(S_i)}$ *if*

$$\mathrm{NEV}_{R(d_n)} \preccurlyeq T^{(S_i)}, \tag{13}$$

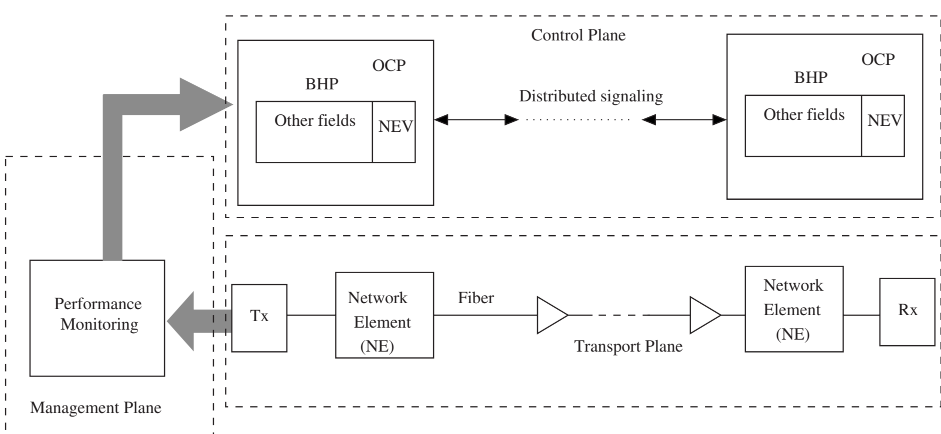
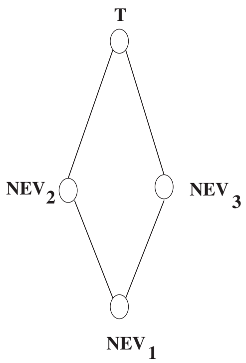


Fig. 1. Structure of the control plane for the distributed signaling.



$\mathrm{NEV}_1 \npreceq \mathrm{NEV}_2$	$\mathrm{NEV}_1 \npreceq \mathrm{NEV}_3$
$w_1 \geqslant w_2$	$w_1 \geqslant w_3$
$\eta_1 \leqslant \eta_2$	$\eta_1 \leqslant \eta_3$
$\gamma_1 \geqslant \gamma_2$	$\gamma_1 \geqslant \gamma_3$
$\tau_1 \leqslant \tau_2$	$\tau_1 \leqslant \tau_3$

Fig. 2. Hasse diagram used to explain ordering $\preccurlyeq$.

where $T^{(S_i)}$ *is given by*

$$T^{(S_i)} = \begin{pmatrix} w_{\min}^{(S_i)} \\ \eta_{\max}^{(S_i)} \\ \gamma_{\min}^{(S_i)} \\ \tau_{\max}^{(S_i)} \end{pmatrix}. \tag{14}$$

The comparison of two multidimensional vectors using $\preccurlyeq$ follows from the notion of lattices [15]. Using this ordering technique, bursts can be scheduled to a destination that satisfies the service requirement if it is the best among the given set of destinations. In the next section we explain the proposed algorithm with the help of a network example.

IV. QoS-Aware Anycasting Algorithm (Q3A)

The pseudocode for the proposed algorithm is explained in this section. As we have considered service-differentiated scheduling, the threshold parameters of the particular service are known *a priori*.

This is completely decentralized, with each network node executing this algorithm. Input to the algorithm is the NEV information from the previous node and anycast requests for a particular burst. When the burst enters the network from the IP/ATM or GMPLS switch, it is tagged with the anycast request (s, D_s), and the NEV is initialized. Each burst will be assigned a label or an ID number, and this remains unaltered until the burst reaches its destination or is blocked. The output for this algorithm is the new NEV and anycast request.

In the initialization step, we consider the cardinality of the free wavelengths as the number of wavelengths the fiber can support. Other service parameters are considered to be 1 for multiplicative and 0 for additive, as indicated in line 1 of the algorithm.

When n is one of the destinations D_n, then the burst is said to have satisfied the anycast request, and the algorithm exits, as shown in lines 2–3. Thus the burst is successfully scheduled to one of its destinations. If the condition in line 2 is not met, then all the destinations are sorted in nondecreasing order of hop distance. Hop distance is calculated along the shortest path from node n to d, $\forall d \in D_n$. Let d' be the destination that is at the minimum hop distance from n. The shortest-path (or minimum-hop) distance in line 5 is calculated by using Dijkstra's algorithm, with the time complexity being $O(p^2)$ for a network with p nodes. Sorting these destinations can be done in a constant time $O(1)$.

The next hop node to the destination d' is selected from the unicast routing table as shown in line 8. The NEV is updated by using information available from the previous link (NEV$[n-1,n]$) and the NEV of the next hop (NEV$[n,n_k]$) as shown in line 9. The threshold condition is validated as given in line 10, similar to Eq. (13). If the condition in line 9 is true, then the path up to n_k is marked as a feasible path, and the destination can be conditionally reachable. A new shortest-path tree is computed with n_k being the source node and D_{n_k} the set of intended destinations that can be reached through n_k (line 12) ($D_{n_k} \subseteq D'$). This algorithm is repeated until a destination is reached. If the condition in line 10 is not satisfied, then all the destinations for which n_k is the intermediate node are removed, and the destination set is updated as given in line 14. If the cardinality of the updated destination set D' is zero, then the anycast request is said be blocked or lost (line 17).

QoS-Aware Anycasting Algorithm (Q3A)

Input: $T^{(S_i)}$, NEV$[n-1,n]$, (n, D_n)
Output: Updated anycast request and NEV
1: Initialization $\mathrm{NEV}_{\mathrm{init}} = [w_{\max}, 1, 1, 0]^T$
2: **if** $n \in D_n$ **then**
3: exit;
4: **else**
5: $\forall d \in D_n$, $h_{\min}$=SHORTEST_PATH$[n,d]$
6: $D'_n \leftarrow$SORT$\{D_n\}$
7: $d' \in D'_n$ {where d' is the destination that is at a minimum hop distance from n}
8: NEXT_HOP_NODE$[n,d']=n_k$ {n_k is calculated from the shortest path}
9: NEV$[n-1,n_k] \leftarrow$ NEV$[n-1,n] \bigcirc$ NEV$[n,n_k]$
10: **if** NEV$[n-1,n_k] \preccurlyeq T^{(S_i)}$ **then**
11: The path $[n-1,n_k]$ is a feasible path and destination d' can be reached
12: New NEV $\leftarrow$ NEV$[n-1,n_k]$ and anycast request (n_k, D_{n_k})
13: **else**
14: Update the destination set $D' \leftarrow D' \setminus \{d'\}$
15: Since route to d' does not satisfy the QoS requirement of the service S_i}
16: **end if**
17: If $|D'| = \emptyset$, then anycast request is blocked or lost
18: **end if**

This Q3A approach can be implemented in a distributed way with the help of a signaling approach as shown in Fig. 1 [12]. A burst control packet or burst header packet can be used to maintain the NEVs and update them as they traverse each NE. At each NE, a traffic engineering database is used to maintain the traffic engineering (TE) and can be modified to maintain the NEV. The BHP used for Q3A is shown in Fig. 3. A burst entering the network is assigned a unique identifier (burst ID). This ID is deleted when it reaches a destination. The source, destination set, and NEV fields are updated at each network element. The updated NEV is compared with the threshold field, and the bursts are scheduled or dropped if the threshold requirement is met.

A. Network Example

In this section we discuss the Q3A with the help of an example to show the effectiveness of the algorithm in comparison with

1. shortest-path routing (SPR),
2. deflection routing (DR),
3. source-initiated routing (SIR).

In SPR the intended destination set (D) is sorted in the nondecreasing order of shortest hop distance and destination (say $d_{\min}$), where the minimum hop distance is selected and the burst is routed. This routing is not dynamic, and if the condition for threshold is not met, then the request will be lost or blocked. SPR gives the upper bound for average blocking. DR is similar to the SPR, expect that if the $d_{\min}$ is not within the QoS requirement along the shortest path, then a secondary path is chosen to the same destination and the burst is routed. Finally, in SIR, we assume that the source has *a priori* knowledge about the QoS parameters on each link, and the NEVs are computed, sorted, and the best destination (if available) is selected. One can intuitively understand that SIR results in the lowest blocking, since the source has information of the QoS parameter.

In this paper we have compared our baseline algorithm (Q3A) against the most commonly used routing algorithms, like SPR, DR, and SIR. The traditional SPR do not take the QoS into account; however, we show the performance of SPR under QoS-aware routing. This results in an upper bound on the average blocking. DR, on the other hand, is an alternative routing strategy employed to decrease the burst loss due to contention. The bursts are deflected and routed to the same destination, but on longer paths. Hence the QoS attributes, such as BER and delay, will degrade. However, if the elements in NEV are within the threshold requirement, a path can still be established. This results in a decrease of the average blocking probability. However this is not the optimal value. In SIR, the source (or client) knows the QoS attributes prior to the establishment of the path, and NEVs are calculated and reordered. Based on the algebra, a destination with minimum NEV is chosen. Hence SIR results in the lower bound on the blocking probability. SIR is not practical to realize, since the source will not be aware of the service attributes before it sends the burst.

Burst ID	Source Node (n)	Destination Set (D_n)	$\top(S_i)$	**NEV[n−1,n]**

Fig. 3. Burst header packet fields used in the algorithm.

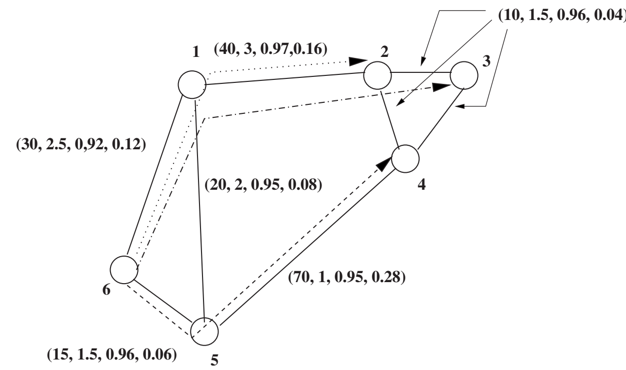


Fig. 4. Network example used to explain the proposed algorithm. The weights on the links indicate distance, noise factor, reliability, and propagation delay.

Consider the network shown in Fig. 4 with the anycast request as (6,{2,3,4},1). The dotted lines in Fig. 4 represent the shortest-path distance from source node 6 to the respective destination. Let the threshold requirement of service S_i be $[1,10,0.7,10]^T$. The weights on each link represent fiber distance in kilometers, noise factor, reliability factor, and propagation delay in milliseconds. Table I shows the set of free wavelengths on the links at the time of the anycast request.

TABLE I
WAVELENGTHS AVAILABLE ON NETWORK LINKS IN FIG. 4 (SNAPSHOT)

No.	Link $(i \to j)$	Available Wavelengths $\mathbb{W}(i,j)$
1	$6 \to 5$	$\{\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5\}$
2	$5 \to 4$	$\{\lambda_1,\lambda_3,\lambda_5\}$
3	$6 \to 1$	$\{\lambda_1,\lambda_2,\lambda_5\}$
4	$1 \to 2$	$\{\lambda_3\}$
5	$2 \to 3$	$\{\lambda_3,\lambda_4,\lambda_5\}$
6	$1 \to 5$	$\{\lambda_3,\lambda_5\}$
7	$2 \to 4$	$\{\lambda_5\}$

When the anycast request arrives, node 2 is selected from the set of destinations $D_n=\{2,3,4\}$ as given in line 7 of the algorithm. The next-hop node along the shortest path to node 2 is node 1. Thus the NEV at node 1 is given by

$$\mathrm{NEV}[6,1] = \mathrm{NEV}_{\mathrm{init}} \bigcirc \mathrm{NEV}[6,1] = \begin{pmatrix} |\mathbb{W}| \\ 1 \\ 1 \\ 0 \end{pmatrix} \bigcirc \begin{pmatrix} |\mathbb{W}(6,1)| \\ 2.5 \\ 0.92 \\ 0.12 \end{pmatrix} = [3,2.5,0.92,0.12]^T. \tag{15}$$

Since the WCC is not satisfied on the link $1\rightarrow 2$, the threshold condition in line 10 is not met, and hence all the destinations that can be reached through node 1 are removed as given in line 14. Hence the new anycast request becomes (1,{4}) with the NEV given in Eq. (15). This algorithm will be repeated with this updated anycast request, and the NEV. (The initialization step in the algorithm is executed only when the burst ID is new.)

B. Shortest-Path Routing (SPR)

For the anycast request (6,{2,3,4},1), the sorted destination set is $D'=\{2,4,5\}$. Node 2 is at a shortest-hop distance from node 6. The next-hop node from source 6 to destination 2 is node 1, and the $\mathrm{NEV}[6,1] = [|\mathbb{W}(6,1)|,2.5,0.92,0.12]^T$. From Table I we see that on link $1\rightarrow 2$ the only free wavelength available is λ_3, and hence the NEV does not satisfy the required service threshold. Thus the anycast request is not met, and the burst is said to be lost. This kind of routing results in high average burst blocking.

C. Deflection Routing (DR)

From Section IV.B we see that link $1\rightarrow 2$ was not feasible, and hence the burst is routed along a disjoint path. The burst follows the route $1\rightarrow 5\rightarrow 4\rightarrow 2$. The overall NEV thus becomes

$$\mathrm{NEV}[6,2] = \mathrm{NEV}[6,1] \bigcirc \mathrm{NEV}[1,5] \bigcirc \mathrm{NEV}[5,4] \bigcirc \mathrm{NEV}[4,2] = \begin{pmatrix} 1 \\ 7.5 \\ 0.79 \\ 0.52 \end{pmatrix}. \tag{16}$$

From Eq. (16) we see that the QoS is within the threshold requirement of the service, and hence the anycast request is satisfied.

D. Source-Initiated Routing (SIR)

This routing calculates all the NEVs to each destination node assuming the network to be static and that the source has knowledge about all NEVs. The equations below show the ordering technique used in selecting the final anycast destination:

$$\mathrm{NEV} = \{\mathrm{NEV}_{R(d_1)}, \mathrm{NEV}_{R(d_2)}, \ldots, \mathrm{NEV}_{R(d_p)}\} \quad (1 \leqslant p \leqslant n), \ (\text{unsorted}) \tag{17}$$

$$= \{\mathrm{NEV}_{R(d_1')}, \mathrm{NEV}_{R(d_2')}, \mathrm{NEV}_{R(d_p')}\} \ (\text{sorted}) \tag{18}$$

$$\mathrm{NEV}_{R(d_1')} \leqslant \mathrm{NEV}_{R(d_2')} \leqslant \ldots \leqslant \mathrm{NEV}_{R(d_p')} \leqslant T^{(S_i)}. \tag{19}$$

From Eq. (19) d_1' is the best destination from D that can meet the service requirement of S_i effectively. The NEVs for each destination can be calculated as given below:

$$\mathrm{NEV}_{R(2)} = \begin{pmatrix} |\mathbb{W}(6,1)| \\ 2.5 \\ 0.92 \\ 0.12 \end{pmatrix} \bigcirc \begin{pmatrix} |\mathbb{W}(1,2)| \\ 3 \\ 0.97 \\ 0.16 \end{pmatrix} = [|\mathbb{W}(6,2)|,7.5,0.89,0.28]^T = [0,7.5,0.89,0.28]^T. \tag{20}$$

The free wavelengths on each link are obtained from Table I, and the cardinality of the common wavelengths is repesented in Eq. (20). This ensures the WCC in the all-optical networks, where there is an absence of wavelength converters. As the route toward destination 3 shares the common path until node 2, the NEV is given by

$$\mathrm{NEV}_{R(3)} = \mathrm{NEV}_{R(2)} \bigcirc \begin{pmatrix} |\mathbb{W}(2,3)| \\ 3 \\ 0.97 \\ 0.16 \end{pmatrix} = \begin{pmatrix} |\mathbb{W}(6,2)| \\ 7.5 \\ 0.89 \\ 0.28 \end{pmatrix} \bigcirc \begin{pmatrix} |\mathbb{W}(2,3)| \\ 1.5 \\ 0.96 \\ 0.04 \end{pmatrix} = [0,11.5,0.85,0.32]^T, \tag{21}$$

$$\mathrm{NEV}_{R(4)} = \begin{pmatrix} |\mathbb{W}(6,5)| \\ 1.5 \\ 0.96 \\ 0.04 \end{pmatrix} \circ \begin{pmatrix} |\mathbb{W}(5,4)| \\ 1 \\ 0.95 \\ 0.28 \end{pmatrix}$$
$$= [3, 1.5, 0.91, 0.32]^T. \tag{22}$$

From Eqs. (20)–(22), we observe that destination 4 has optimal QoS parameters. This confirms the benefits of specifying the service requirements, whereby a destination can be chosen rather than selecting it at random.

V. Simulation Results

In this section we validate our proposed algorithm with the hep of discrete-event simulation. The National Science Foundation (NSF) and the Italian Mesh networks are considered for our simulation study. The topologies shown in Figs. 5 and 6 consist of bidirectional links, each carrying data at a rate of 10 Gbits/s. We assume that there is no wavelength conversion and regeneration capability for the network. Burst arrivals follow a Poisson process with an arrival rate of λ bursts/s . The length of the burst is exponentially distributed with the expected service time of $1/\mu$ s. The network load is defined as λ/μ. Links in Figs. 5 and 6 benefit from in-line erbium-doped fiber amplifiers (EDFAs) placed 70 km apart. The calculation of the noise factor is based on linear impairments such as attenuation, mux/demux loss, tap loss, and amplified spontaneous emission noise [16,17]. There are no optical buffers, and hence the burst that finds the channel occupied will be dropped or lost. The reliability factor of the link indicates that the reliability is affected by damage caused by faults, fiber cuts, and catastrophic effects. This factor is computed based on a uniformly distributed random variable $\sim U[0.8,1]$ [8].

We have considered three intended destinations from which the destination can be selected based on the QoS requirement of the service. (However, different values of intended destinations can also be considered for the analysis.) The two service classes considered for analysis include data service (DS) and real-time service (RTS). Data services call for certain service guarantees. Applications include storage area

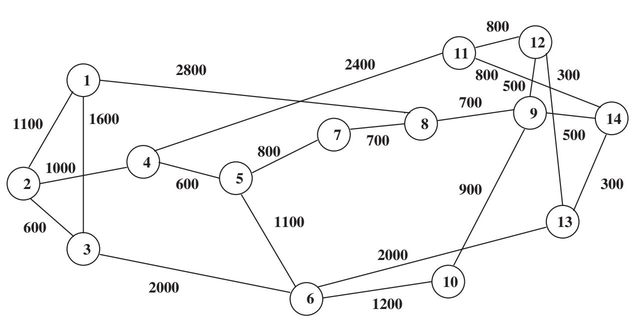


Fig. 5. Network topology of NSF network, consisting of 14 nodes and 21 bidirectional fiber links.

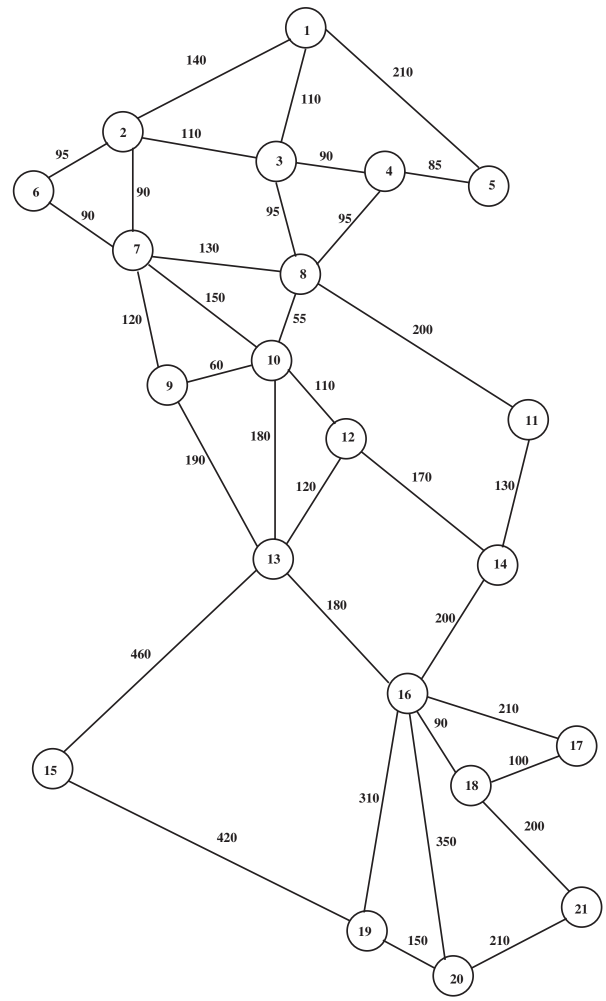


Fig. 6. Topology for Italian high-capacity network, consisting of 21 nodes and 36 bidirectional links.

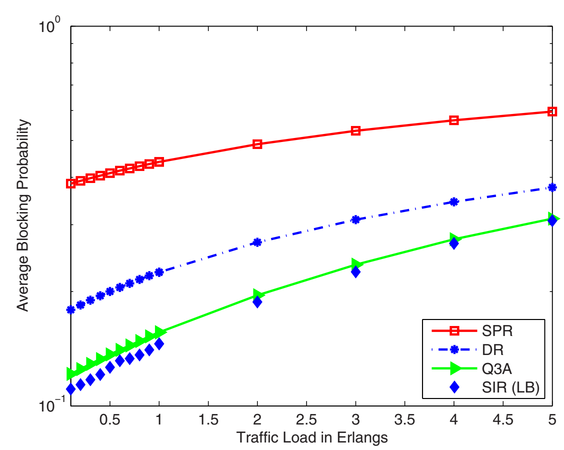


Fig. 7. (Color online) Performance comparison of NSF network for data services.

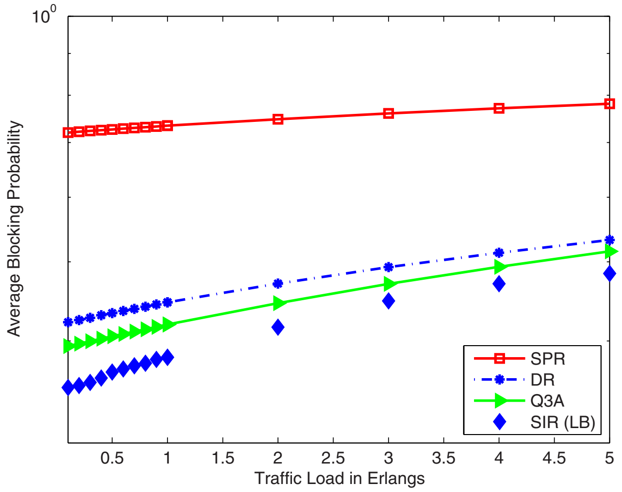


Fig. 8. (Color online) Performance comparison of NSF network for real-time services.

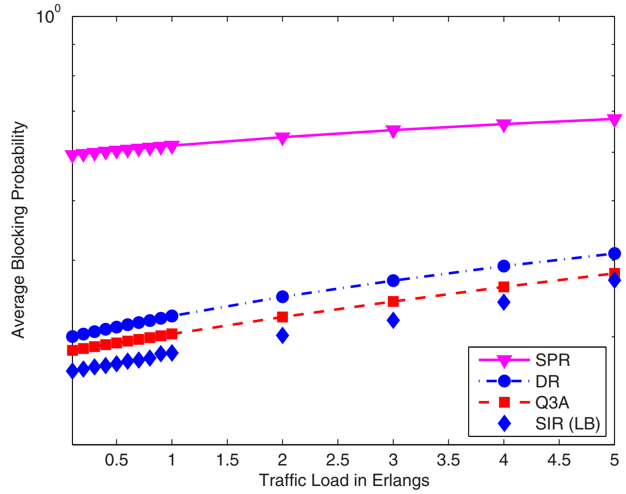


Fig. 10. (Color online) Performance comparison of Italian mesh network for real-time services.

networks, content-distribution networks, and peer-to-peer networking. We have set the threshold requirement for data traffic as

$$T^{(\mathrm{DS})} = [1, 5.7, 0.7, 20]^T. \qquad (23)$$

In Eq. (23) the noise factor (η) from source to destination is within 5.7, the reliability of the overall path is more than 70%, and the burst propagation delay along the path cannot exceed 20 time units. In Eq. (23) we have considered one wavelength to be free on all the links of the path, thereby ensuring the WCC. Another important and predominant traffic in the present Internet is real-time traffic. Applications include video conferencing, Internet gaming, video on demand, and distributed interactive simulations. The real-time service threshold conditions can be much higher than the data service thresholds, in terms of noise factor, delay, and reliability. Hence we have considered the threshold conditions for real-time service as

$$T^{(\mathrm{RTS})} = [1, 4, 0.8, 10]^T. \qquad (24)$$

Figure 7 shows the performance of the anycasting under the different routing strategies discussed in Section IV. Our proposed algorithm has a significant reduction in the average blocking when compared with deflection routing. This is mainly because deflection routing routes the packet to the same destination, but along disjoint paths. This causes the service attributes to exceed the threshold requirement, thus increasing the burst loss. We also observe from Fig. 7 that the performance of our algorithm is very close to the lower bound. SIR gives the best possible solution, as the source has *a priori* knowledge of the network. However, in practice the dynamics of the network vary, and hence it is not always possible to know the values of the service attributes beforehand. The proposed Q3A algorithm is completely decentralized and takes the dynamics of the network into account without compromising the performance.

Figure 8 shows the performance of Q3A under the real-time service threshold. We observe that under low network loads, i.e., (0,1], Q3A performs slightly above the optimal lower bound (SIR). However, at medium network loads, our proposed algorithm is very near the optimal lower bound.

We have verified the performance of the Italian mesh network for data service and real-time service. Our results in Figs. 9 and 10 show that Q3A improves the performance of the network in terms of a decrease in the burst blocking probability. From all of the above results we observe that there is an approximately 33% reduction in average blocking probability for multiple services such as data and real-time.

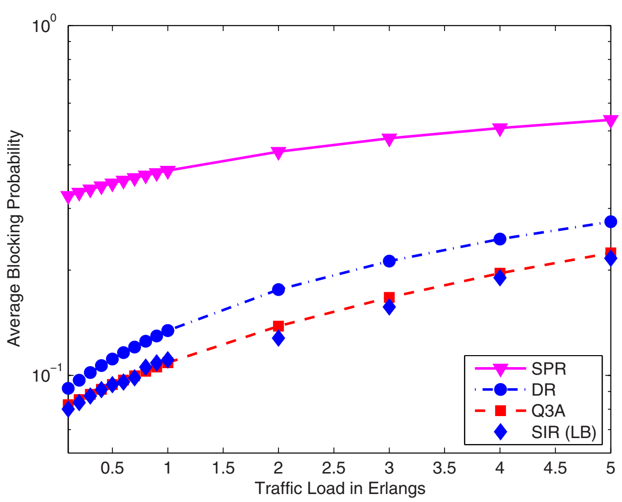


Fig. 9. (Color online) Performance comparison of Italian mesh network for data services.

VI. Conclusion

In this paper we discuss the provisioning of QoS for anycasting in OBS networks. By using the information vectors available at each NE, QoS parameters are computed. We have considered parameters that can be additive or multiplicative. Providing QoS to anycast communication allows the applications to choose a candidate destination according to its service requirements. This flexibility helps realize a user-controlled network. We have compared our baseline algorithm (Q3A) against the most commonly used routing algorithms, such as shortest-path routing (SPR), deflection routing (DR), and source-initiated routing (SIR). We have shown that with the help of using local network information, Q3A performs close to the lower bound (SIR). Our proposed algorithm also helps in service-differentiated routing.

References

[1] R. Nejabati, "Grid optical burst switched networks (GOBS)," www.ogf.org, 2006.

[2] A. Jukan and G. Karmous-Edwards, "Optical control plane for the grid community," *IEEE Commun. Surv. Tutorials*, vol. 9, no. 3, pp. 30–44, 2007.

[3] A. Kaheel, T. Khattab, A. Mohamed, and H. Alnuweiri, "Quality-of-service mechanisms in IP-over-WDM networks," *IEEE Commun. Mag.*, vol. 40, no. 12, pp. 38–43, Dec. 2002.

[4] F. Farahmand, M. D. Leenheer, P. Thysebaert, B. Volckaert, F. D. Turck, B. Dhoedt, P. Demeester, and J. P. Jue, "A multi-layered approach to optical burst-switched based grids," in *Proc. IEEE Int. Conf. on Broadband Communications, Networks, and Systems*, New York, NY, 2005, pp. 1050–1057.

[5] M. D. Leenheer, D. Chris, S. Tim, D. Bart, P. Mario, and D. Piet, "Design and control of optical grid networks," in *Proc. IEEE Int. Conf. on Broadband Communications, Networks, and Systems*, New York, New York, 2007, pp. 107–115.

[6] M. D. Leenheer, F. Farahmand, K. Lu, T. Zhang, P. Thysebaert, B. Volckaert, F. D. Turck, B. Dhoedt, P. Demeester, and J. P. Jue, "Anycast algorithms supporting optical burst switched grid networks," in *Proc. IEEE Int. Conf. on Networking and Service*, New York, NY, 2006, pp. 63–69.

[7] K. Lu, T. Zhang, and A. Jafari, "An anycast routing scheme for supporting emerging grid computing applications in OBS networks," in *Proc. IEEE Int. Conf. on Communications*, New York, NY, 2007, pp. 2307–2312.

[8] B. G. Bathula, "QoS aware quorumcasting over optical burst switched networks," Ph.D. thesis, Indian Institute of Science, 2008.

[9] M. Duser and P. Bayel, "Analysis of dynamically wavelength-routed optical burst switched network architecture," *J. Lightwave Technol.*, vol. 20, pp. 574–585, 2002.

[10] R. Ramaswami and K. N. Sivarajan, *Optical Networks*, San Francisco, CA: Morgan Kaufmann, 2004.

[11] A. Jukan and G. Franzl, "Path selection methods with multiple constraints in service-guaranteed WDM networks," *IEEE/ACM Trans. Netw.*, vol. 12, pp. 59–72, 2004.

[12] R. Martinez, F. Cugini, N. Andriolli, L. Wosinska, and J. Comellas, "Challenges and requirements for introducing impairment-awareness into management and control planes of ASON/GMPLS WDM networks," *IEEE Commun. Mag.*, vol. 44, no. 12, pp. 76–85, 2006.

[13] A. Farrel and I. Bryskin, *GMPLS, Architecture and Applications*, San Francisco, CA: Morgan Kaufmann, 2006.

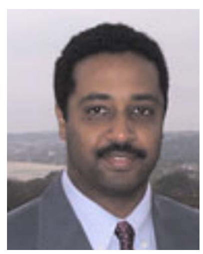
[14] B. A. Davey and H. A. Priestley, *Introduction to Lattices and Order*, New York, NY: Cambridge U. Press, 2002.

[15] A. B. Przygienda, "Link state routing with QoS in ATM LANs," Ph.D. thesis, Swiss Federal Institute of Technology, 1995.

[16] B. G. Bathula, V. M. Vokkarane, and R. R. C. Bikram, "Impairment-aware manycasting over optical burst switched networks," in *Proc. IEEE Int. Conf. on Communications*, New York, NY, 2008, pp. 5234–5238.

[17] B. G. Bathula, R. R. C. Bikram, V. M. Vokkarane, and S. Talabattula, "Impairment-aware manycasting algorithms over optical burst switched networks," in *Proc. IEEE Int. Conf. on Computer Communications and Networks*, New York, NY, 2008, pp. 1–6.

Balagangadhar G. Bathula (S'08) was born in Pithapuram, A.P., India. He received his Ph.D. in electrical communication engineering from the Indian Institute of Science. He has obtained the M.Tech. in opto-electronics and laser technology from Cochin University of Science and Technology, Cochin, India, in 2004. From August 2007 to May 2008 he was a Visiting Scholar in the Department of Computer and Information Science, University of Massachusetts, Dartmouth, MA. Presently he is a Post-Doctoral Research Associate at the School of Electronic and Electrical Engineering, University of Leeds, United Kingdom. His research interests include performance modeling of optical networks and grid over optical networks.



Jaafar M. H. Elmirghani is a Fellow of the IET, a Fellow of the Institute of Physics, a Senior member of IEEE, and the Director of the Institute of Integrated Information Systems within the School of Electronic and Electrical Engineering, University of Leeds. He joined Leeds in 2007 and prior to that founded, developed, and directed the Institute of Advance Telecommunications at the University of Wales Swansea. He has provided outstanding leadership in a number of large research projects over the past 5 years and led a number of multisite collaborative projects funded by the Engineering and Physical Sciences Research Council (EPSRC), the Department of Trade and Industry/the Technology Strategy Board (DTI)/(TSB), and the EU. He was a PI in the following ERDF projects: Institute of Advanced Telecommunications, IRIS, and REACH. He was/is co-PI/WP leader in the EPSRC/DTI projects HIPNet, TINA, VESEL, and INSTANT, as well as EU FP6 PHOSPHOROUS. These projects involved him forming important industrial links with Laing O'Rourke, British Airports Authority (BAA), Motorola, Ericsson, Red M, Boeing, Tyco, Zinwave, Innovision, Arup (TINA); Ericsson, Freescale, and Emerson (HIPNet); Motorola and O2 (Vesel, IRIS); BT and Agilent (REACH); ALPS and Xyratex (INSTANT); and Hitachi and Nortel (PHOSPHOROUS). He received the IEEE Communications Society Hal Sobol Award for achievements in communications, the IEEE Comsoc Chapter Achievement Award for excellence in chapter activities (both in international competition in December 2005), and the University of Wales Swansea Outstanding Research Achievement Award in 2006. He has published over 300 journal and conference papers, his work is currently used by major industrial players including BT, Ericsson, Motorola, and O2, and it has been incorporated into ITU standards. He has research interests in communication systems and networks.