Green Networks: Energy Efficient Design for Optical Networks

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Abstract—**In this paper we discuss new energy efficient paradigms for optical networks. With the increasing number of high bandwidth applications, devices used in backbone networks such as optical networks increase. Energy consumption of optical networks is an important issue that has to be addressed. In this work we propose novel routing algorithms for decreasing the energy consumption of optical networks. We propose sleep cycle protocols for use in the network nodes. Energy-Aware optical network protocols can impact the Quality of Services (QoS) such as bit-error-rate (BER) and delay. Our proposed algorithm maintains a trade-off between energy consumption and the QoS.**

Keywords: Energy management, QoS, Grid networks.

I. Introduction

Information and communication technology (ICT) has a profound impact on the economy and the environment. A study estimated that the Internet equipment consumed roughly 8 % of the total energy (i.e. electricity) in the United States with the prediction of growth to 50 % within a decade [1]. The development of faster communication links is likely to contribute to the demand for faster computers, which is likely to increase energy consumption. In addition computer networks at present, require additional power demanding equipment, such as servers, amplifiers, routers, filters, storage devices and communication links. These communication components consume significant amounts of energy. With the ever-increasing demand for bandwidth, these communication components tend to increase and hence energy efficiency is an important issue.

WDM networks can provide a huge amount of bandwidth for present and future Internet applications. These networks are deployed in large scale to form the backbone network. Dynamic optical capabilities in WDM can be achieved with the advent of optical-cross connect (OXC) nodes, which can switch the wavelengths completely in the optical domain. Optical networks are evolving into a complex interconnection of circuit-switched networks due to the continued growth in high-bandwidth applications. The *E-Science* community is a fine example of such applications, which has already started using optical networks as the backbone network to support multi-giga bit connectivity. These developments led to research in the area of intelligent optical control plane [2].

Using intelligent optical control planes lightpaths, (or wavelength channels) can have dynamic route selection polices. All-optical networks (AON) have to maintain a wavelength continuity constraint. Lightpaths established in wavelength routed networks can be maximized with the help of dynamic wavelength discovery paths [3]. Constraint-based path selection policies help to meet the QoS demands of the service effectively. Contention resolution schemes such as deflection routing are used in wavelength routed optical burst switched networks (WR-OBS) [4].

In this paper we propose a multi path selection approach to minimize the energy consumption of the optical core network. These wavelength routed paths may have to forgo minimum distance paths and choose a path which is at a larger distance. This tends to degrade the QoS like BER and delay. Given the service requirement conditions, we propose to select the paths such that the overall energy consumed by the optical network decreases and at the same time maintain the service threshold conditions. We propose a clustered node architecture similar to the one proposed in [5]. It has to be noted however that in [5] the clustering approach was proposed to reduce packet loss, here we utilize a similar approach with a different objective: energy minimization. The selection of these clusters can be static or dynamic. Dynamic cluster partitioning of the core network can be based on network load or load balancing. However we restrict our study only to the static case. By using an efficient optical control management mechanism, these clusters can be set to ON or OFF states. During the OFF cycle the nodes that belong to the cluster, adopt a *sleep mode,* cutting down the traffic routed through them. Thus a cluster isolates itself from the network. The energy reduction achieved due to a sleep cycle is at the cost of decrease in QoS. Hence the traffic that is by-passed from the cluster during its OFF cycle should be aware of the service threshold conditions. Thus there is a need to develop an intelligent and efficient control plane and associated algorithms for the implementation of Energy-Aware Optical networks (EAON).

The remainder of the paper is organized as follows: in Section II we explain the optical cross-connect (OXC) node and compute the total energy consumed by each OXC switch. In Section III we describe the network architecture for Energy Efficient Optical networks (EEON). We discuss the proposed energy-efficient routing algorithm with the help of a network example in Section IV. Finally in Section V we conclude this paper with possible future extensions.

II. Energy Consumed in Optical Networks

In this section we calculate the energy required to transmit an optical bit and the energy spent by each OXC shown in Fig. 1. The OXC consists of mux/de-mux and a wavelength cross-connect switch. An OXC can also have the functionality to add/drop channels, using the transmitter and receiver array shown in Fig. 1. Energy is defined as the product of power and

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time. There are two different types of energy associated with the optical networks, (1) Energy associated with transmission of one optical bit and, (2) Energy consumed by a router (optical-cross connect switch) during its ON state.

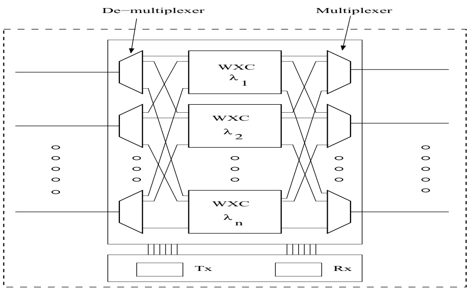

Fig. 1. Optical Cross-connect (OXC) switch used in the network architecture.

A. Energy per Bit

The average time to transmit 1 (optical) bit over a channel (fiber) is the inverse of the average bit rate (B). The energy associated with the transmission of 1 bit can be expressed as,

$$E_{bit} = P_T T_{bit}, \tag{1}$$

where T_{bit} is the time to transmit one bit over the fiber ($T_{bit} = 1/B$), P_T is the average transmit power. Thus (1) denotes the energy consumption for one optical bit. We now derive a relationship between E_{bit} and BER for ideal On-Off keying (OOK).

The bit error rate (BER) in an OOK detection scheme is given by [6],

$$BER = Q\left(\frac{I_1 - I_0}{\sigma_1 + \sigma_0}\right), \tag{2}$$

where $Q(x)$ is given by,

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-y^2/2}dy \tag{3}$$

I_1 is the mean photocurrent for the received optical power P_1, when a 1 bit is transmitted. Similarly P_0 and I_0 are the corresponding quantities for a zero bit. If $\mathcal{R}$ is the responsivity of the photodectector, then $I_1 = \mathcal{R}P_1$ and $I_0 = \mathcal{R}P_0$. The variance of the photocurrent are given by,

$$\begin{aligned}\sigma_1^2 &= 2qI_1B_e + 4k_BTB_e/R_L,\\ \sigma_0^2 &= 2qI_0B_e + 4k_BTB_e/R_L.\end{aligned}$$

where q is the electronic charge, B_e is the electrical bandwidth, k_B is the Boltzmann constant (J/K), T is the temperature in K and R_L is the load resistor. For ideal OOK P_0 and I_0 are zero and,

$$I_1 = \mathcal{R}(L_t P_T). \tag{4}$$

The received optical power P_1 is product of the transmitted optical power (P_T) and the loss incurred by the signal during the transmission denoted by L_t. From Fig. 1 we see that the loss factor for one-hop is given by,

$$L_t = e^{\alpha l} L_{mux} L_{sw} L_{demux}, \tag{5}$$

where α is the attenuation loss of the fiber km^{-1}, l is the fiber length in km. L_{mux}, L_{sw} and, L_{demux} are the multiplexer, demultiplexer and switch loss respectively. Hence using (4), (5) we have,

$$BER = Q\left(\frac{\mathcal{R}e^{\alpha l}L_{mux}L_{sw}L_{demux}P_T}{\sigma_0 + \sqrt{2q\mathcal{R}(L_tP_T)B_e + 4k_BTB_e/R_L}}\right). \tag{6}$$

Let $\gamma = Q^{-1}(.)$, substituting (1) in the above equation and solving for E_{bit} we get,

$$E_{bit} = \frac{\left(\frac{2\mathcal{R}L_tB}{\gamma\sigma_0}\right) + \left(\frac{2qR_LBB_e}{\sigma_0^2}\right)}{\left(\frac{RL_tB}{\gamma\sigma_0}\right)^2}, \tag{7}$$

where $T_{bit} = 1/B$. Equation (7) gives the energy required to transmit an optical bit over a fiber channel (wavelength) for a distance of l km. The parameters used for computing E_{bit} are tabulated in Table II-A. Any decrease in the energy of an optical bit is achieved at the cost of more bit-error rate. Fig. 2 shows the energy versus BER and q-factor (γ). We observe from the graph that for a BER of 10^{-12} which corresponds to $\gamma = 7$ we require an energy of ~ 1.3 nJ. Hence for transmitting low BER optical signals more energy is required. Thus there is a trade-off between energy and BER. The energy consumed by the optical bit is also dependent on the length of the fiber. From Fig. 3 we see that for fiber lengths exceeding 100 km, 20 nJ per bit are required. However in most of the cases, in-line fiber amplifiers placed at a distance of 70 km compensate the fiber loss due to attenuation. Thus the effective un-compensated length of the fiber becomes $<$ 70 km, for which the energy consumption is $\sim$ 1 nJ as seen from Fig 3. Note that this does not take into account the optical amplifier noise and beat terms.

From (7) we see that E_{bit} is dependent on the q-factor and loss L_t. The optical loss incurred during the signal transmission as given in (5) is dependent on the length of

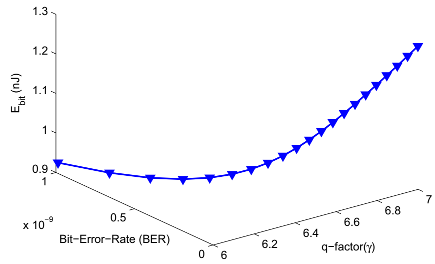

Fig. 2. Energy versus Bit error rate (BER) and q-factor for OOK.

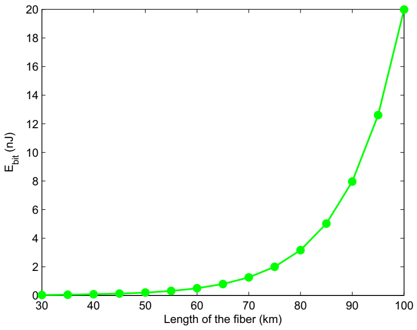

Fig. 3. Energy versus Fiber length for OOK.

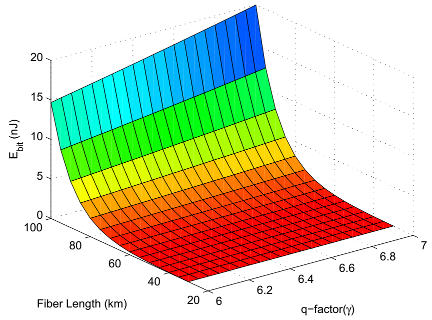

Fig. 4. Energy versus q-factor and Fiber Length for OOK.

TABLE I
PARAMETERS USED FOR COMPUTATION OF E_{bit}

Parameter	Value
Bit Rate (B)	10 Gbps
Electrical Bandwidth (B_e)	$B/2$
Input power of the signal	1 mW (0 dBm)
Loss of Multiplexer/Demultiplexer	4 dB
Switch element insertion loss (L_s)	1 dB
Waveguide fiber coupling loss (L_w)	1 dB
Fiber Attenuation Coefficient	0.2 dB/km
Planks Constant h	6.63×10^{-34} J-s
Wavelength (λ)	1.55 μm
Number of Fibers/link (N)	2 (bi-directional)
Switch ($N \times N$) loss (L_{sw})	$2\log_2 2NL_s + 4L_w$
Length of the fiber (l)	70 km
γ	7
Responsivity ($\mathcal{R}$)	1.25 A/W
$\sigma^2_{thermal} = 4k_BTB_e/R_L$	$3.312 \times 10^{-22} B_e$ A^2

the fiber. Variation of energy with the q-factor and the length of the fiber is shown in Fig. 4.

B. Energy spent by OXC

In the previous section we have computed the energy required to transmit an optical bit over a fiber channel. Apart from the transmitting energy, the optical routers (OXC's) consume energy during their operation. In traditional optical core networks, these routers remain in the ON state indefinitely and hence consume significant energy. The energy consumption of an OXC depends on its architecture and the number of devices used. Considering the OXC shown in Fig. 1, the energy consumed is given by,

$$
\begin{aligned}
E_{OXC} &= P_{OXC}T_{ON} \\
&= (P_{mux} + P_{WXC} + P_{demux} + P_{TR})T_{ON} \quad (8)
\end{aligned}
$$

where P_{OXC} is the power consumed by the optical and electronic devices used in Fig. 1, and T_{ON} is the time for which the router is in the ON state (out of sleep cycle). P_{OXC} is the sum of electronic circuitry powers consumed by the optical devices. Using (7) and (8), the total energy consumed to transmit a bit through an OXC situated at a distance l km is given by,

$$E_T = E_{bit} + E_{OXC}. \quad (9)$$

III. ENERGY EFFICIENT OPTICAL NETWORKS

In this section we describe the proposed energy efficient routing algorithm for optical networks in a clustered node architecture as shown in Fig. 5. We propose an *Anycasting* routing technique to minimize the energy consumption in optical networks. Anycasting is defined as the communication paradigm, in which the user has the ability to choose a probable destination from a group of possible destinations unlike deciding it a-priori as in unicast [7], [8], [9]. An Anycast request is denoted as a two-tuple (s, D_s), where s is the source node initiating a session and D_s is set of probable destinations. Anycasting can serve as a viable communication paradigm especially for many emerging distributed applications, such as Grid computing. In this paper we use anycasting over a clustered node architecture in a Grid computing scenario.

In Fig. 5 the optical network is partitioned into clusters C1 through C5. These clusters are interconnected to each other by the boundary nodes (BNs). The network shown in Fig. 5 is an example of a grid computing application, which consists of resources such as computing and storage. Consider a computer connected to the access network of cluster C4 that would like to initiate a grid application requiring a large amount of computation resources such as memory and storage. Examples of such type of grid application can be the High Energy Particle Physics (HEP) community experiment at CERN's Large Hadron Collider [10]. This experiment involves petabytes of data to be analyzed, which are stored in different parts of the network.

A computer situated in Cluster C4 sends an anycast request for a Grid job. The requested computational resource (CR) for the grid job can be obtained from clusters C1, C2 and C3, as shown in Fig. 5. The nearest CR to C4 being C1, using the shortest-path algorithm, a session can be established. However anycasting allows the flexibility to choose any destination from clusters C1, C2 and C3.

In order to bring energy efficiency into optical networks, we for the first time propose *Sleep Cycles* for these clusters. A sleep cycle is defined as the time period for which a particular cluster switches off its functionality. Sleep cycles can be implemented by the management and control plane. In the case of deterministic sleep cycles these clusters toggle between OFF and ON modes with the help of signaling from the control plane. Let us consider for example clusters C1 and C2 to be in the OFF mode. A Grid session initiated by the user in cluster C1 gets routed to its BN, and the BN has options

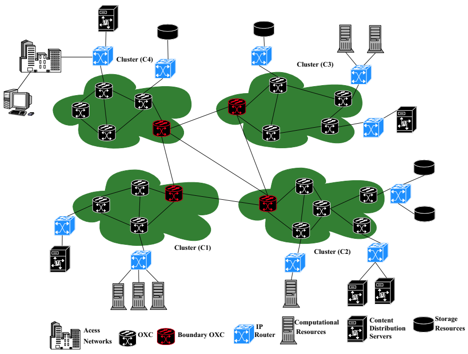

Fig. 5. Network showing Cluster architecture of nodes connected to the different resources.

to route the job to any of three clusters available. Since C1 and C3 are in the off state, the next hop node for BN of cluster C4 is the BN of cluster C2. Thus we can achieve a significant reduction in energy due to introducing OFF states in clusters C1 and C3. Dynamic sleep cycles can be achieved based on the traffic load conditions of the clusters. If the traffic generated by a clusters is not significant, it can choose to shut down its functionality and all the grid jobs can be rerouted to other clusters which are in the ON state. However in this paper we restrict our study only to the static case and will consider dynamic sleep cycles in future work.

Sleep cycles can reduce the energy consumption costs. From the previous example we have already seen that cluster C2 was chosen for the grid job, which was at a longer distance. So there can be a degradation in the quality of service (QoS) in terms of bit-error-rate and propagation delay. If the BER and propagation delay incurred during optical transmission, are more than the required bounds set by the user, then a grid job cannot be accomplished. An anycast session established should be within the service level agreement (SLA) of the user. It is the function of the control plane to check, whether the session is within the threshold requirements of the grid job [9].

IV. Energy Efficient Routing (EER) Algorithm

In this section, we describe the proposed energy efficient routing algorithm in anycasting. This algorithm also helps to provide the necessary QoS for the established route. Before we describe the routing algorithm, we first discuss the mathematical notation used. We define the network element vector (NEV) as,

Definition 1: We denote the network element vector for a link i as,

$$NEV_i = \begin{pmatrix} \eta_i \\ \tau_i \end{pmatrix}. \tag{10}$$

where η_i is the noise factor and τ_i propagation delay for the link i.

The noise factor is related to the BER [8], [9]. The NEV given in Def. 1 is used to keep the updated picture for the QoS parameters. The overall NEV for a route can be computed as the product of the noise factors and the sum of the propagation delay of the individual links. Thus the overall NEV for a route R, consisting of links $\{i, i+1, \ldots, j-1, j\}$ is given by,

$$NEV_R = [\eta_R, \tau_R]^T = \left[\prod_{k=i}^{j} \eta_k, \sum_{k=i}^{j} \tau_k\right]^T. \tag{11}$$

Based on the NEV information, the control plane should choose a path that is within the SLA of the grid job. So we define the threshold parameters for a grid job (θ) as,

$$\top^{(\theta)} = [\eta_{th}, \tau_{th}]^T. \tag{12}$$

Thus NEV_R should be such that $\eta_R \leq \eta_{th}$ and $\tau_R \leq \tau_{th}$. When these conditions are valid, then we say that the route R is within the threshold requirements of the grid job.

The pseudo-code for the proposed algorithm is shown below. When the grid session is initiated by the user, the service threshold requirements are set by the user and are given by the vector $\top^{(\theta)}$. NEV is initialized to $[1, 0]^T$. An anycast request is created by the application layer as denoted by (n, D_n). It is an iterative algorithm and repeats until a destination ($\in D_n$) is reached. It is a distributed routing algorithm with every node maintaining the information about the NEV. We use shortest-path routing in the algorithm, and sort the destinations in non-decreasing order of hop-distance h_{min} as given in Lines: 4-6. The next-hop node (n_k) for the present source n is obtained from the routing table. During this iterative process the next-hop node will be the boundary node of other clusters say C_j (C_j is a cluster different from the cluster in which the user who initiated the grid session is located). If this BN, n_k belongs to the set of BN's that are in the OFF state ($BN(C_{OFF})$), then all the destinations corresponding to these clusters are removed as given by the Lines: 8-9 of the algorithm.

If n_k is the boundary node of a cluster that is in the ON mode, then NEV is updated using (11). The Boolean operation $\circ$ used in Line: 11 of the algorithm performs multiplication on the noise factor and addition of the propagation delay. This updated NEV is compared with the threshold requirement given in Line: 12. The inequality given in Line: 12 performs $\eta_R \leq \eta_{th}$ and $\tau_R \leq \tau_{th}$. If this inequality is not met, then another BN from a different cluster that is in the ON mode is chosen (Line: 15).

A. Network Example

In this section we explain the proposed EER algorithm proposed in Section IV with an example shown in Fig. 6. We use the same network given in Fig. 5, but it is shown here again for clarity. The weights on the links between the boundary nodes of the cluster ($BN(C_i)$) indicate the distances in km. All the fiber links are bi-directional. Consider a computer situated in cluster C_4 that initiates a grid session requiring computational and storage resources. The application layer sets the SLA or service level threshold on the QoS parameters: BER and propagation delay. Let this be $\top^{(\theta)} = [5.7, 5]^T$. This implies that, the noise-factor for the session is upper-bounded by 5.7 (a.u) and the propagation delay should be within 5 (t.u). A noise factor of 5.7 corresponds to a BER of 10^{-9} [7]. At

Input: $\top^{(\theta)}$, $NEV[n-1,n]$, (n, D_n)
Output: Updated Anycast request and NEV

```
1: if n ∈ D_n then
2:   exit
3: else
4:   ∀ d ∈ D_n, h_min = SHORTEST_PATH[n, d]
5:   D'_n ← SORT{D_n}
6:   d' ∈ D'_n /*where d' is the destination that is at a minimum-hop distance from n */
7:   NEXT_HOP_NODE[n, d'] = n_k, /* n_k is calculated from the shortest path */
8:   if n_k ∈ BN(C_OFF), /* where C_OFF is the set off-clusters */ then
9:     Update the destination set D' ← D'\{d'} ∀C_OFF
10:  else if n_k ∈ BN(C_ON) /* n_k is the nearest next-hop BN among all the ON clusters. */ then
11:    NEV[n−1, n_k] ← NEV[n−1, n] ∘ NEV[n, n_k]
12:    if NEV[n−1, n_k] ≼ ⊤^(θ) then
13:      continue
14:    else
15:      Choose C_j ∈ C_ON /*We assume that at least two clusters are always ON |C_ON| ≥ 2*/
16:    end if
17:  else
18:    continue
19:  end if
20: end if
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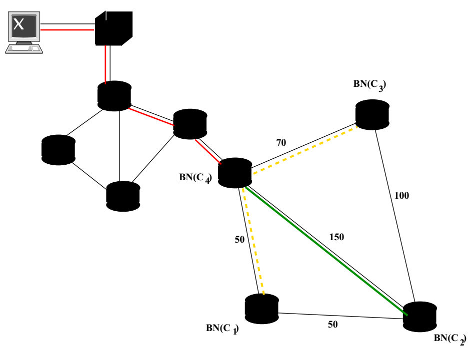

Fig. 6. Example used in explaining the proposed EER algorithm.

the time of session initiation, let the clusters C_1 and C_3 be in the OFF state.

The IP router (shown as square-shape in Fig. 6) now creates an anycast request, say $(1, \{d_{c_1}, d_{c_2}, d_{c_3}\})$, where $s = 1$ is the source node of the session and d_{c_i} are the boundary nodes of cluster C_i. The IP router also initializes the $NEV_{ini} = [1, 0]^T$. Thus we have all the required inputs for the EER algorithm. The First two lines of the algorithm are executed only when the next-hop node itself is the destination node, where the algorithm terminates. We sort the destinations in an increasing order with respect to their shortest-path distance from the IP-router that initiated the grid session. For the boundary node of C_4, the sorted destination set is $D' = \{d_{c_1}, d_{c_3}, d_{c_2}\}$. The closet being $BN(C_1) \equiv d_{c_1} \equiv n_k$ in Line: 7. However cluster C_1 is in the OFF state, and since the new destination set is updated as given by Line: 9 (similarly for C_3), we have $D' = d_{c_2} \equiv BN(C_3)$. Now the condition for the threshold is calculated as,

$$\begin{aligned} NEV[1, BN(C_2)] &= NEV_{ini} \circ NEV[BN(C_4), BN(C_2)] \\ &= [1, 0]^T \circ [4.5, 0.5]^T \equiv [4.5, 0.5]^T \end{aligned}$$

Since the $NEV[1, BN(C_2)] \preccurlyeq \top^{(\theta)}$, SLA is valid and the session is established. We assume that during routing in intra-clusters the SLA agreements are always met. This assumption is justified since the nodes in the clusters are close to each other and have low BER and propagation-delay. Also in most of the cases the BN's have additional functionality such as wavelength conversion and regeneration.

We thus see that it is possible to obtain energy saving due to the sleep-cycle of clusters C_1 and C_3, without compromising the QoS. It is also clear that the cluster node architecture helps to classify the nodes based on certain metrics (such as traffic) and according to traffic and utilization choose to adopt a particular sleep cycle.

V. Conclusion and Future Scope

In this paper we have computed the energy required to transmit a bit in an optical channel. An empirical relationship between, energy, BER and length of the fiber has been derived for OOK modulation. Using anycasting communication on a new clustered-node architecture, we have minimized the energy consumption. This energy saving is obtained without scarifying the QoS. We will consider dynamic sleep-cycles for the clusters based on the traffic conditions in our future work.

References

[1] A. Plepys, "The grey side of ICT," *Journal of Environmental Impact Assessment Review*, vol. 22, no. 5, pp. 509–523, 2002.

[2] A. Jukan and G. Karmous-Edwards, "Optical control plane for the grid community," *IEEE Communications Surveys and Tutorials*, vol. 9, no. 3, pp. 30–34, 2007.

[3] A. Jukan and G. Franzl, "Path selection methods with multiple constriants in service-guaranteed WDM networks," *IEEE/ACM Transactions on Networking*, vol. 12, no. 1, pp. 59–72, 2004.

[4] C. F.Hsu, T. L. Liu, and N. F. Huang, "Performance analysis of deflection routing in OBS networks," in *Proc. IEEE INFOCOM-'02*, New York, USA, June 2002, pp. 66–73.

[5] A. Stavdas, T. G. Orphanoudakis, H. C. Leigou, K. Kononakis, C. Matrakidis, A. Drakos, J. D. Angelopoulos, and A. Lord, "Multidomain optical networks: Issues and challenges-dynamic CANON: A scalable multidomain core network," *IEEE Communications Magazine*, vol. 46, no. 6, pp. 138–144, 2008.

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

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

[8] B. G. Bathula and J. M. H. Elmirghani, "Providing QoS for anycasting over optical burst switched grid networks," in *Proc. LNICST, GridNets-2008*, Beijing, China, Oct. 2008.

[9] ——, "Constraint based anycasting over optical burst switched (OBS) networks," *to appear in IEEE/OSA Journal of Optical Communication and Networks*, 2009.

[10] G. Karmous-Edwards, "Global E-Science collaboration," *IEEE Computing in Science and Engineering*, pp. 2–27, 2005.