# Energy Efficient Optical Burst Switched (OBS) Networks

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***Abstract*—This paper presents an energy saving technique for optical burst switched networks that reduces energy consumption without significantly degrading the quality of service (QoS) and the connectivity of the network. We propose a distributed algorithm using anycasting an communication paradigm, where the wavelength routed nodes (WRNs) adopt a sleep mode cutting the traffic routed through them. This paper also provides a mathematical framework for calculating the energy per bit ($E_{bit}$) across the fiber and the wavelength routed node.**

**Keywords:** Energy management, QoS, OBS 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.

Due to the advances in optical transmission and networking technologies, optical networks were found to provide a cost effective solution for providing high capacity [2]. The energy costs of the network will grow as the amount of data on the network increases [3]. It is predicted that over the coming years, the cost of electricity required to power the network can become a significant component of operational cost [3]. As the network expands in its capacity, energy consumption in the core network is an important concern for the networking industry. Locations where the large capacity routers are situated are called *hot-spots* due to the amount of energy and heat they produce.

The primary reasons for the energy conservation also include increasing cost of electricity and enabling greater deployment of Internet. This indicates a need to reconsider architectures and routing strategies for optical networks to meet the goal of energy efficiency [4]. The possible approaches that can reduce the energy consumption are

- put to sleep some of the wavelength routed nodes and,
- at a network level consider changing routes during low traffic periods.

However these two approaches should be implemented in a manner such that, they do not diminish QoS and the connectivity of the network.

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 [5]. 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) [6].

In this paper we propose a multi-path selection approach to minimize the energy consumption of the optical core network, especially OBS. Our approaches can be applied in optical packet switched (OPS) networks, however we limit our discussion to OBS networks. The 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. By using an efficient optical control management mechanism, network nodes (WRN) can be set to $ON$ or $OFF$ states. During the $OFF$ cycle the nodes, adopt a *sleep mode,* cutting down the traffic routed through them. Thus a node 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 a node 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 wavelength routed node and compute the total energy consumed by each WRN. We discuss the proposed energy-efficient routing algorithm in Section III. We present simulation results in Section IV. Finally in Section V we conclude this paper with possible future extensions.

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## II. ENERGY PER BIT

In this section we calculate the energy required to transmit an optical bit across an WRN shown in Fig. 1. The WRN consists of EDFA amplifiers, multiplexer, demultiplexer and a wavelength cross-connect switch. An WRN 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 consumed and time. There are two different types of energy associated with the optical networks,

1) Energy associated with the transmission of one optical bit over fiber,
2) Energy consumed by a router (WRN) for switching an optical signal.

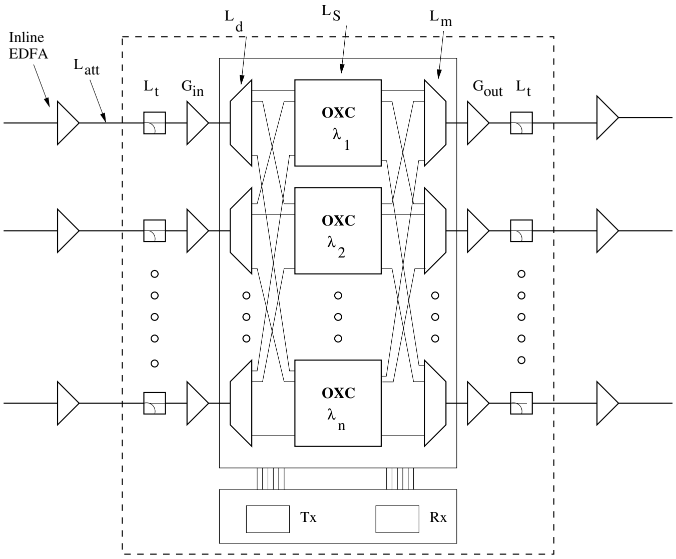

Fig. 1. Wavelength routed node (WRN) used in the network architecture.

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,

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

where $T_{bit}$ is the time to transmit one bit over the fiber ($T_{bit} = 1/B$), $P_d$ is the power consumed. Thus (1) denotes the energy consumption for one optical bit for a distance of $L$ km. We calculate the power consumed $P_d$ by the optical signal to traverse an WRN situated at a distance of $L$ km from the source. The power consumed in an optical network is given by,

$$P_d = P_{\text{signal}} + P_{\text{WRN}} + P_{\text{EDFA}}, \tag{2}$$

where $P_{\text{signal}}$, is the signal power and, $P_{\text{WRN}}$ is the power consumed in the optical crossconnect core router and $P_{\text{EDFA's}}$ is the power consumed in inline EDFA amplifiers. Substituting (2) in (1) we see that energy per bit in an WRN is $P_{\text{WRN}}T_{bit}$ and EDFA's is $P_{\text{EDFA}}T_{bit}$. The energy per bit for a core WRN switch is approximately $E_{bit}^{(WRN)} = 10$ nJ [7]. Similarly the $E_{bit}^{(EDFA)}$ for an optical amplifier such as EDFA is about $0.1$ nJ. Thus we see that if an optical bit traverses $H$ hops, with each hop consisting of $k$ optical inline amplifiers, then the total energy consumed due to WRN and EDFAs is

$$(H+1)E_{bit}^{(WRN)} + kHE_{bit}^{(EDFA)} \; (H > 1) \tag{3}$$

Optical signal and ASE powers vary according to the loss in the signal power and the number of amplifiers used. We calculate the energy per bit required to transmit an optical bit across the WRN based on the network architecture shown in Fig. 1.

### A. Calculation of $P_{\text{signal}}$ and $P_{\text{ASE}}$

- If $L_n$ is the physical distance between the nodes $\langle n, n+1\rangle$, $l$ is the distance between two amplifiers, then $a$, the number of amplifiers used between $\langle n, n+1\rangle$ is given by,

  $$a_n = \left\lceil \frac{L_n}{l} \right\rceil - 1. \tag{4}$$

  We define $l_n$ as the distance of fiber which is not been compensated by the in-line amplification and is given by

  $$l_n = L_n - a_n \times l. \tag{5}$$

- $L_{att}(n) = e^{-\alpha l_n}$ is the loss due to the attenuation in the fiber, where $\alpha$ is the attenuation of the fiber.
- $L_d$, $L_m$, and $L_t$ are defined as demultiplexer, multiplexer and tap (coupling) losses, respectively.
- $L_{ins} = 2\log_2 N L_s + 4L_w$ is insertion loss of the OXC switch [8], where $L_s$ is switch element insertion loss and $L_w$ is waveguide or coupling loss and $N$ is number of fibers, which is equal to number of input/output ports of the switch.
- $G_{in}$ and $G_{out}$, are gains of the input and the output EDFA 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 $\bar{G} = e^{\alpha l}$.

Here we derive recursive power relations similar to [8], [9] in-order to calculate $E_{bit}$ for each hop. The output power at node $n$, $P(n)$, is given by,

$$\begin{aligned} P(n) &= G_{in}G_{out}L_dL_mL_t^2L_{ins}L_{att}(n)P(n-1) \\ &= G_TL_kL_{att}(n)P(n-1), \\ &= G_TL_T(n-1)P(n-1), \end{aligned} \tag{6}$$

where $L_k = L_dL_mL_t^2L_{ins}$; a constant for any node and $L_T(n-1) = L_kL_{att}(n)$.

$$\begin{aligned} P_{ase}(n) = \; & P_{ase}(n-1)L_T(n-1)G_T + P'L_T(n-1) \times \\ & [G_{in}-1]\,G_{out}/L_t + P'L_tL_{att}(n)\,[G_{out}-1] + \\ & P'[\bar{G}-1]a_nL_{att}(n), \end{aligned} \tag{7}$$

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 (7) represents the ASE noise along the fiber, and the first two terms represent the ASE noise due to EDFAs inside the node.The amount of ASE determines the signal power needed for a given SNR level. Therefore ASE directly dictates the transmit power needed and the laser cooling power needed.

Using (2), (3), (6) and, (7) the energy per bit $E_{bit}$ across the fiber of length $L_n$ between the nodes $\langle n, n+1\rangle$ is given by,

$$E_{bit}(n) = E_{bit}^{(WRN)} + a_n E_{bit}^{(EDFA)}, \tag{8}$$

where the two terms indicate the energy per bit in an WRN and the inline EDFAs respectively, for a single hop. The last term indicates the energy consumed in the EDFAs between the two nodes. We neglect the powers due to cross-talk and polarization mode dispersion (PMD) in the noise factor calculation. Hence (8) gives a lower bound for $E_{bit}$. We calculate the energy per bit for each hop the in National Science Foundation (NSF) network. The topology for this network is shown in Fig. 4. Fig. 2 shows the energy per bit in nJ for the longest hop distance in NSF. From Fig. 2 we observe that NSF consumes approximately 13 nJ of energy to transmit an optical bit across the fiber (one hop). It should be noted in Fig.2 that the major contribution to the energy consumption is due to the WRN of each hop ($\sim$ 10 nJ). Hence the only way to significantly decrease the energy consumed is to switch the WRN into sleep mode and cut the traffic routed through it.

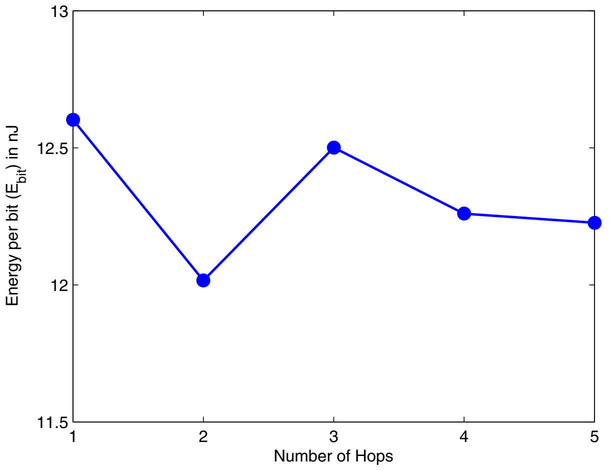

Fig. 2. Energy dissipation along the shortest path route between nodes $\langle 2, 8\rangle$ in NSF.

The energy required to transmit an optical bit across $H$ hops is the sum of the energy spent across each hop and hence the total energy is given by,

$$E_{bit}^{(t)}\langle s, d\rangle = \sum_{H} E_{bit}(n) \tag{9}$$

TABLE I

PARAMETERS USED FOR COMPUTATION OF $E_{bit}$

| Parameter | Value |
|---|---|
| Bit Rate ($B$) | 10 Gbps |
| Electrical Bandwidth ($B_e$) | $0.7B$ |
| Optical Bandwidth ($B_o$) | 70 GHz |
| 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 Attenuation Coefficient | 0.3 dB/km |
| Gain of EDFA in OXC ($G_{in}$, $G_{out}$) | 22 dB, 16 dB |
| ASE factor ($n_{sp}$) | 1.5 |
| Planks Constant $h$ | $6.63 \times 10^{-34}$ J-s |
| Carrier frequency $f_c$ | 193.55 THz |
| $P'$ in (7) | $2n_{sp}hf_cB_o$ |
| Spacing between the amplifiers ($l$) | 70 km |
| $q_{th}$ | 6 |
| Number of fibers/link ($N$) | 2 (bi-directional) |

## III. ENERGY EFFICIENT ROUTING (EER) ALGORITHM

In this section, we describe the proposed energy efficient routing algorithm. This algorithm also helps to provide the necessary QoS for the established route. We propose an *Anycasting* routing technique to minimize the energy consumption in the optical network. 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 [10], [11], [12]. 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. It should be noted that an anycasting application is assumed. Anycasting can serve as a viable communication paradigm especially for many emerging distributed applications, such as Grid computing.

A sleep cycle is defined as the time duration in which an WRN cuts off the traffic routed through it and adopts an $OFF$ state. Sleep cycles can reduce the energy consumption costs. WRNs are partially turned off; transient traffic is not allowed but the source to destination traffic is handled. There can be a degradation in the quality of service (QoS) in terms of bit-error-rate and propagation delay due to these sleep cycles. If the BER and propagation delay incurred during optical transmission, are more than the required bounds set by the user, then a session 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 service [12].

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 $\eta_i$ is the noise factor and $\tau_i$ the propagation delay for the link $i$.

The noise factor is related to the BER [11], [12]. 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,

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

*Definition 2:* Based on the NEV information, the control plane should choose a path that is within the SLA of the job. So we define the threshold parameters for a service ($\theta$) as,

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

Thus $NEV_R$ should satisfy the following condition [10],

$$\begin{aligned} &\eta_R \le \eta_{th} \text{ and } \tau_R \le \tau_{th} \\ &\implies NEV_R \preccurlyeq \top^{(\theta)} \end{aligned} \tag{13}$$

When these conditions are valid, then we say that the route $R$ is within the threshold requirements of the service.

The pseudo-code for the proposed algorithm is shown below. When a session is initiated, 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 that 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: 5-6. The next-hop node ($n_k$) for the present source $n$ is obtained from the routing table. If this $n_k$ belongs to the set of nodes that are in the $OFF$ state ($C_{OFF}$), then all the destinations corresponding to $n_k$ are removed as given by the Line: 10 of the algorithm. Since $n_k$ can be an intermediate node for destination(s) $d_i \in D_n$ and $n_k$ is in the $OFF$ mode at the time of the anycast request, $D_n$ set is updated by removing all the destinations that cannot be reached through $n_k$. If $n_k \in C_{OFF}$ is the only child node for all the destinations in $D_n$ then the anycast request is dropped. This is indicated in Lines:11-13.

If $n_k \in C_{ON}$ then the corresponding link to the node $n_k$, i.e., $\langle n_k, n_{k+1} \rangle$ is checked for wavelength availability as given in Lines:18-19. Since the burst traverses paths that are at longer hops, the QoS parameters tend to degrade. A session can be established on a longer hop path only if the required SLA is meet. This is indicated in Line: 21. The Boolean operation $\circ$ used in Line: 20 of the algorithm performs multiplication on the noise factor and addition of the propagation delay. The operator $\circ$ performs the function $(\times, +)$. The updated NEV is compared with the threshold requirement using (13) and is given in Line: 21.

Lines: 2-3 ensure that if the source node $n$ is a member in $D_n$ then the burst is successfully sent to a destination. There can be a situation in which the destination node, ($n \in D_n$) is in a sleep mode. In such a case we do not consider the burst to be dropped since, the WRN can use its receiver circuitry even in its sleep mode. The energy consumed by the receiver circuitry is very small and can be neglected.

| | | | | |
|---|---|---|---|---|
| **Burst ID** | **Source Node (n)** | **Destination Set ($D_n$)** | $\top^{(\theta)}$ | **NEV** |

Fig. 3. Burst header packet fields used in the EER algorithm [10], [12].

Nodes in the network are partitioned as the two disjoint sets $C_{ON}$ and $C_{OFF}$, as given by

$$\begin{aligned} n &\in C_{OFF} \text{ if } 0 < x < 0.5, \\ &\in C_{ON} \text{ if } 0.5 \le x < 1. \end{aligned} \tag{14}$$

We model the network as a graph $G(V, E)$, with a set of vertices $V$ corresponding to the number of nodes $N$, and unidirectional edges $E$. In (14) $n \in V$, and $x \sim U[0, 1]$.

Line: 1 initializes every new burst entering the network with NEV to $[1, 0]^T$ and assigns a source and a destination set. The assigned source is always selected from $C_{ON}$. This step is skipped if the burst is old which consists of modified anycast request. A unique burst ID number is maintained in the Burst Header Packet (BHP), which remains the same until the burst reaches one of the destinations. This ID helps the control plane for deciding to assign source and a destination set. This is more explained in BHP signaling in Section III-B.

### A. *Time Complexity*

The described EER algorithm is distributed (or decentralized) since it uses local network information (NEV) to forward the burst. Hence the time complexity of the algorithm is the time complexity of the network node. For a network of size $|V|$, Line: 5 requires the time-complexity of $O(E + |V| \log(|V|))$, and the sorting in Line: 6 using merge-sort requires $O(|D_n| \log(|D_n|))$.

### B. *Burst Header Packet Signaling*

Burst Control Packet (BCP) or Burst Header Packet (BHP) can be used to maintain the NEVs and update them as they traverse each network element (NE), in this case WRN. The BHP used for EER algorithm is shown in Fig. 3. 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 depending on threshold requirement. In this paper we consider one-way reservation protocol, such as just-enough-time signaling (JET) [13] where a data burst is scheduled using BHP without waiting for the acknowledgment.

## IV. PERFORMANCE EVALUATION

In this section we validate our proposed algorithm with the help of simulations. The National Science Foundation (NSF) network topology is considered for our simulation study. The topology shown in Fig. 4 consists of bi-directional links, each

**Algorithm 1** Energy Efficient Routing (EER) Algorithm

```
Input: $\top^{(\theta)}$, $NEV[n-1,n]$, $(n, D_n)$.
Output: Updated Anycast request and $NEV$.
Initialization: $NEV_{ini} = [1,0]^T$, $(s, D_s)$
if $n \in D_n$ then
    exit;
else
    $\forall\ d \in D_n$, $h_{min} = SHORTEST\_PATH[n,d]$;
    $D'_n \leftarrow SORT\{D_n\}$;
    $d' \in D'_n$; /* where $d'$ is the destination that is at a minimum-hop distance from $n$. */
    $NEXT\_HOP\_NODE[n,d'] = n_k$; /* $n_k$ is calculated from the shortest path. */
    if $n_k \in C_{OFF}$ then
        Update the destination set $D' \leftarrow D' \backslash \{d'\}\ \forall C_{OFF}$; /* where $C_{OFF}$ is the set of nodes that in $OFF$ mode. */
        if $D_n = \emptyset$ then
            Drop the burst;
            exit; /* Burst loss due to the sleep mode of the intermediate WRN. */
        else
            continue;
        end if
    else
        Check the wavelength availability of the next-hop link; /*$n_k \in C_{ON}$.*/
        if link $\langle n_k, n_{k+1} \rangle$ is available then
            $NEV[n-1,n_k] \leftarrow NEV[n-1,n] \circ NEV[n,n_k]$;
            if $NEV[n-1,n_k] \preccurlyeq \top^{(\theta)}$ then
                continue;
            else
                Drop the burst; /* Burst loss due violation of SLA. */
            end if
        else
            Drop the burst; /* Burst loss due to contention. */
        end if
    end if
end if
```

carrying data at a rate of 10 Gbps. We assume that there is no wavelength conversion and regeneration capability for the network. Burst arrivals follow a Poisson process with arrival rate $\lambda$ bursts per second. The length of the burst is exponentially distributed with an expected service time of $1/\mu$ seconds. The network load is defined as $\lambda/\mu$. Links in Fig. 4 benefit from in-line Erbium Doped Fiber amplifiers (EDFA) placed 70 kms apart. The source and candidate destinations of a request are evenly distributed among all nodes in the network. We have considered the service threshold vector as $\top^{(\theta)} = [5.7, 10]^T$, i.e., the noise-factor and delay of the established session are upper bounded by 5.7 and 10 ms respectively. The noise factor 5.7 corresponds to BER of $10^{-9}$ [10].

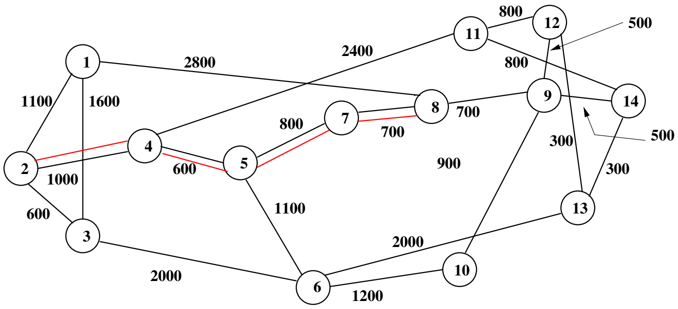

Fig. 4. The NSF network consisting of 14 nodes and 21 bi-directional links.

The network nodes are partitioned as $C_{ON}$ and $C_{OFF}$ using (14). We execute (14) for every random time during the simulation at a given network load $(\lambda/\mu)$. Thus the topology of the network changes after a random interval of time.

Here we compare the performance of the proposed Energy Efficient routing (EER) algorithm with shortest path routing (SPR). We use the traditional SPR without partitioning the network, i.e., in other words $C_{OFF} = \emptyset$. Intuitively one can expect a reduction in energy consumption as the WRN adopts the sleep modes randomly. EER is found to achieve a significant amount of reduction in energy consumption as shown in Fig. 5. We also see from Fig. 5 that in SPR that energy consumption per bit increases linearly with the increase in the network load. For the case of EER the energy consumption fluctuates for varying loads. This is due to randomness in the sleep modes. However at a any given load we observe a decrease in the average energy consumed in the NSF network with the EER algorithm.

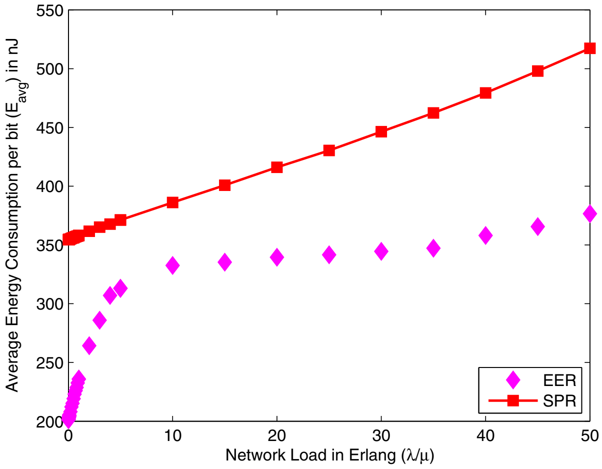

Fig. 5. Comparison of energy dissipation in the NSF network for Shortest Path Routing (SPR) and Energy Efficient Routing (EER), under varying traffic.

The energy reduction shown in Fig. 5 is achieved at the cost of decrease in the quality of service (QoS). Since the bursts have to traverse more hops than the shortest path routes. There is a significant increase in the average delay incurred by the burst as shown in Fig. 6 for EER. However as long as the end-to-end delay incurred by the burst is within the threshold of the SLA, the increase of delay in EER should not be a concern from the user's perspective.

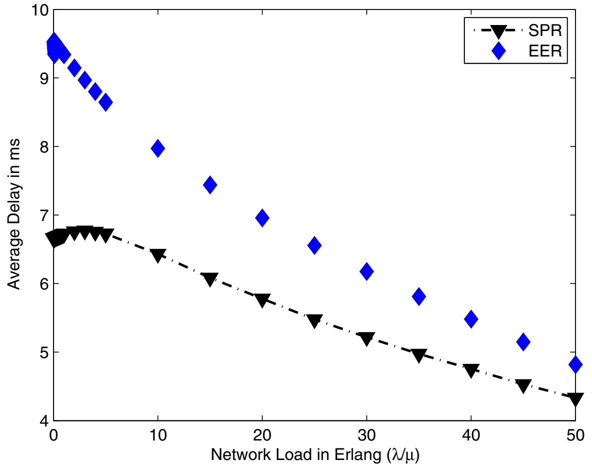

Fig. 6. Comparison of average delay in the NSF network for SPR and EER

Finally we evaluate the performance of EER in terms of the average request blocking as shown in Fig. 7. Request blocking can occur due to channel occupancy (congestion in the link) or violation of SLAs. The number of wavelengths on each single link is considered to be one. From Fig. 7 we observe that there is an increase in the average requests lost for the EER compared to SPR. The connectivity of the network decreases due to the sleep modes of WRN. This results in a larger number of burst drops there by increasing the average request loss. The request blocking can be decreased incorporating more wavelengths along the links (decreasing congestion) or with the use of wavelength regenerators (decreasing the noise factor). However these issues are out of scope of the present paper and could be areas of future work.

For an operator or a carrier the ultimate measure is how much performance is sacrificed versus how much energy saving is achieved. We note in Fig. 6, 7, and 8 at high load (important operating region for energy consumption) of 50 Erlang the energy saved is 40 % while the increase in blocking probability and delay are only 9% and 11% respectively which is a good gain that can be further optimized using our framework.

## V. CONCLUSION

In this paper we have computed the energy required to transmit a bit in an optical channel. We have evaluated the energy consumption based on per hop parameters and node architecture. Using anycasting communication and efficient BHP signaling, we have minimized the energy consumption in optical burst switched networks. This energy saving is obtained without significantly scarifying the QoS. This work can be further enhanced by the using load balancing approaches for sleep modes.

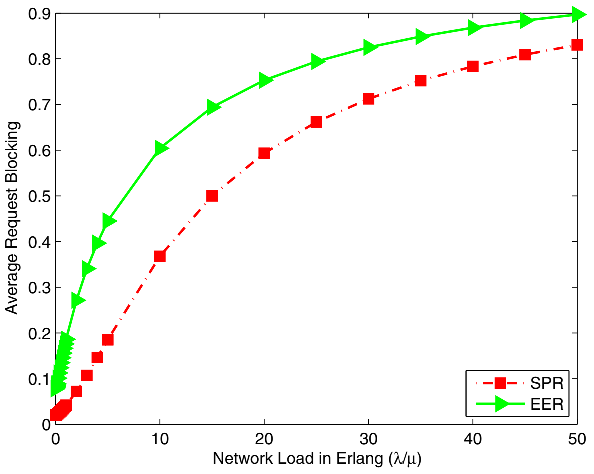

Fig. 7. Comparison of average request loss in the NSF network for SPR and EER

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