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 policies. 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-OBDS) [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...
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.

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,

\[ E_{\text{bit}} = P_T T_{\text{bit}}, \]  

(1)

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

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

\[ \text{BER} = Q \left( \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \right), \]  

(2)

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

(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 \( R \) is the responsivity of the photodetector, then \( I_1 = R P_1 \) and \( I_0 = R P_0 \). The variance of the photocurrent are given by,

\[ \sigma_1^2 = 2qI_1 B_e + 4k_B T B_e / R_L, \]

\[ \sigma_0^2 = 2qI_0 B_e + 4k_B T B_e / R_L, \]

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,

\[ I_1 = R (L_t P_T). \]  

(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,

\[ L_t = e^{\alpha l} L_{\text{max}} L_{\text{sw}} L_{\text{demux}}, \]  

(5)

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

\[ \text{BER} = Q \left( \frac{\mathcal{R} e^{\alpha l} L_{\text{max}} L_{\text{sw}} L_{\text{demux}} P_T}{\sigma_0 + \sqrt{2 q R (L_t P_T)} B_e + 4k_B T B_e / R_L} \right). \]

(6)

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

\[ E_{\text{bit}} = \frac{\left( \frac{2 R L_t B}{\gamma \sigma_0} \right) + \frac{2 q R L_t B B_e}{\sigma_0^2}}{\left( \frac{R L_t B}{\gamma \sigma_0} \right)^2}. \]

(7)

where \( T_{\text{bit}} = 1/B \). 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 \( E_{\text{bit}} \) 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 (\( \gamma \)). We observe from the graph that for a BER of \( 10^{-12} \) which corresponds to \( \gamma = 7 \) we require an energy of \( \sim 1.3 \) 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 \( E_{\text{bit}} \) 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. 1. Optical Cross-connect (OXC) switch used in the network architecture.

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

Fig. 3. Energy versus Bit error rate (BER) and q-factor for OOK.
7 is the source \( s \)

\[ q_{- \text{factor}} \]

\[ 6.8 \]

\[ 6.6 \]

\[ 20 \]

\[ 10 \]

\[ 1 \]

\[ 1 \]

\[ 0.2 \text{ dB/km} \]

\[ 6.63 \times 10^{-34} \text{ J-s} \]

\[ 1.55 \mu \text{m} \]

\[ 2 \text{ (bi-directional)} \]

\[ 2 \log_2 2N L_s + 4L_w \]

\[ 70 \text{ km} \]

\[ 7 \]

\[ 1.25 \text{ A/W} \]

\[ 3.312 \times 10^{-22} B_e A^2 \]

\[ \frac{4k_B T_e R_e}{R_L} \]

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Rate (( B ))</td>
<td>( B/2 )</td>
</tr>
<tr>
<td>Electrical Bandwidth (( B_e ))</td>
<td>( \text{10 Gbps} )</td>
</tr>
<tr>
<td>Input power of the signal</td>
<td>( 1 \text{ mW (0 dBm)} )</td>
</tr>
<tr>
<td>Loss of Multiplexer/Demultiplexer</td>
<td>( 4 \text{ dB} )</td>
</tr>
<tr>
<td>Switch element insertion loss (( L_s ))</td>
<td>( 1 \text{ dB} )</td>
</tr>
<tr>
<td>Waveguide fiber coupling loss (( L_w ))</td>
<td>( 1 \text{ dB} )</td>
</tr>
<tr>
<td>Fiber Attenuation Coefficient</td>
<td>( 0.2 \text{ dB/km} )</td>
</tr>
<tr>
<td>Planks Constant ( h )</td>
<td>( 6.63 \times 10^{-34} \text{ J-s} )</td>
</tr>
<tr>
<td>Wavelength (( \lambda ))</td>
<td>( 1.55 \mu \text{m} )</td>
</tr>
<tr>
<td>Number of Fibers/link (( N ))</td>
<td>( 2 ) (bi-directional)</td>
</tr>
<tr>
<td>Switch ( (N \times N) ) loss (( L_{sw} ))</td>
<td>( 2 \log_2 2N L_s + 4L_w )</td>
</tr>
<tr>
<td>Length of the fiber (( l ))</td>
<td>( 70 \text{ km} )</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>( 7 )</td>
</tr>
<tr>
<td>Responsivity (( R ))</td>
<td>( 1.25 \text{ A/W} )</td>
</tr>
<tr>
<td>( \sigma_{\text{thermal}} )</td>
<td>( 3.312 \times 10^{-22} B_e A^2 )</td>
</tr>
</tbody>
</table>

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,

\[ E_{\text{OXC}} = P_{\text{OXC}} T_{\text{ON}} = (P_{\text{max}} + P_{\text{WXC}} + P_{\text{demax}} + P_{\text{TR}}) T_{\text{ON}} \]

where \( P_{\text{OXC}} \) is the power consumed by the optical and electronic devices used in Fig. 1, and \( T_{\text{ON}} \) is the time for which the router is in the ON state (out of sleep cycle). \( P_{\text{OXC}} \) 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,

\[ E_T = E_{\text{bit}} + E_{\text{OXC}}. \]

**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 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. 3. Energy versus Fiber length for OOK.](image1)

![Fig. 4. Energy versus q-factor and Fiber Length for OOK.](image2)
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 (BN) in each cluster are shown. The network example given in Fig. 6 is composed of three clusters: C1, C2, and C3. The weights on the links between the boundary nodes in each cluster are shown in the table below. The weights are bi-directional. Consider a computer cluster consisting of a set of servers connected to the network via OXCs. The weight of each link represents the 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 (\( \theta \)) as,

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

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 \( \tau^{(\theta)} \). 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 \((D_n)\) 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.

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 define the network element vector for a link \( i \) as,

\[
NEV_i = \left[ \begin{array}{c} \eta_i \\ \tau_i \end{array} \right]. \tag{10}
\]

where \( \eta_i \) is the noise factor and \( \tau_i \) 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 (\( \theta \)) as,

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\tau^{(\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.
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 sacrificing the QoS. We will consider dynamic sleep-cycles for the clusters based on the traffic conditions in our future work.

**REFERENCES**


