Energy Efficient Architectures for Optical Networks

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Abstract— In this paper we study the energy consumption in optical networks. We propose a cluster based architecture for minimizing the energy consumed in transparent optical networks. The network topology is partitioned as disjoint clusters and nodes in the clusters adopt sleep cycles. Using anycast routing, we obtain a trade-off between the energy consumption and the average requests lost due to the sleep cycles.

1 Introduction

In the recent past, the research community has recognized the importance of the Internet's energy consumption. The US network infrastructure requires about 5 and 24 TWh/year [1], which is equivalent to a cost of $ 0.5-2.4 B/year. Although the networking equipment consumes only a small fraction of the total energy used for the information technology, it is important to consider the methods to cut the energy costs. A study also estimated that the energy consumed by the Internet equipment is roughly 8% of the total energy (i.e., electricity) used in the US with the prediction that it can grow to 50% in a decade [2]. With ever increasing demand for bandwidth, computer networks require more devices, such as amplifiers, routers, storage devices, and communication links. These components tend to increase the energy costs of the Internet exponentially. Thus we see that the Internet is no longer constrained by it's capacity, but rather by its energy consumption [3].

The Internet expansion in reach and capacity can only be enabled by decreasing the energy consumption. Green Information Communication Technology (ICT) is focused on saving the networking industry $ 800 billion in annual energy costs by 2020 (Smart 2020) [4]. Many networking communities have already started research on saving energy in the Internet. This effort is sometimes referred to as "Greening the Internet" [6]. The energy saving approaches can include, a) putting the network interfaces and other routers to sleep and, b) at network level consider developing traffic shaping techniques, such that nodes can be put to sleep without significantly effecting the connectivity of the network.

The study of energy efficient strategies for optical networks is important, as they are the backbone networks for present day Internet. In this paper we propose a cluster based network architecture for optical backbone networks, in which the core nodes (wavelength routed nodes) adopt a sleep mode. In a sleep mode a wavelength routing node (WRN) does not take any new lightpaths, for which it acts an intermediate node. However WRN can still act as a source or destination node during their sleep mode. Due to the proposed sleep cycles, the connectivity of the network decreases and hence the probability of requests being lost increases. We propose an anycasting communication paradigm and show that it can, in order to achieve a trade off between the requests lost and energy efficiency. Anycasting is used in a number of scenarios where the request is to route data from a source to anyone of a possible set of destinations. Applications include data storage where anyone of several sites are acceptable as a destination (all sites synchronize with each other periodically) or processing, where any processing center in the set is acceptable.

This paper is organized as follows: In Section 2 we compute the energy consumed by the optical bit to traverse from one WRN to another. Section 3 proposes an energy efficient routing algorithm using anycasting. In Section 4 we compare energy consumption, and blocking probability for various routing algorithms. Finally in Section 5 we conclude the paper with possible future extensions.

2 Computation of Energy per bit

In this section we calculate the energy required to transmit an optical bit across an WRN. The WRN node architecture used in the computation of energy can be found in [5]. 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. Energy is defined as the product of power dissipated and time. There are two different types of energy associated with the optical networks, a) Energy associated with the transmission of one optical bit over fiber, b) Energy consumed by a router (WRN) for switching an optical signal. The average time to transmit an (optical) bit over a channel (fiber) is the inverse of the average bit rate (B). The energy associated with the transmission of a 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 dissipated. Thus (1) denotes the energy consumption for one optical bit for a distance of L km. Assuming that a path is composed of transmitter, a number of in-line EDFAs, a number of WRN and a receiver, then P_d is given by,

$$P_d = P_{in}^{(Tx)} + P_{in}^{(\text{EDFA})} + P_{in}^{(\text{WRN})} + P_{in}^{(Rx)}, \tag{2}$$

where $P_{in}^{(Tx)}$, $P_{in}^{(\text{EDFA})}$, $P_{in}^{(\text{WRN})}$, $P_{in}^{(Rx)}$ are the total powers consumed by (or the power from the grid), the transmitter, EDFA, WRN, and receiver respectively. 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 [7]. Thus we see that if an optical bit traverses H hops, with each hop consisting of k optical in-line amplifiers, then the total energy consumed due to WRN and EDFAs is

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

We calculate the energy per bit required to transmit an optical bit across the WRN based on the network architecture given in [5]. The energy per bit consumed for a given source-destination pair $\langle s,d \rangle$ is given by,

$$E_{bit}\langle s,d \rangle = \left(P_{in}^{(Tx)} + P_{in}^{(Rx)}\right) T_{bit} + \sum_{\forall i \in R} k_i E_{bit}^{(EDFA)} + (H+1)E_{bit}^{(WRN)}, \tag{4}$$

where R is the shortest-path route for $\langle s,d \rangle$.

3 Energy Efficient Architecture

We propose a cluster based architecture, in which the nodes of the optical backbone network are divided into disjoint sets. Each set consists of more than one node to form a single cluster. These clusters can be set to adopt a sleep mode initiated by the optical control plane (OCP). During the sleep mode of the cluster, the connectivity of the network decreases and hence there could be more request dropped. In order to decrease the request drops, we propose an *Anycasting* communication paradigm. Anycasting allows the flexibility of selecting a destination from a desired set of destinations. If a destination cannot be reached due to its intermediate node belonging to a cluster in an OFF state (i.e., sleep mode), then using anycasting, a next available destination can be chosen. An anycast request can be denoted by (s, D_s), where s is the source node and D_s $(m = |D_s|)$ are the probable destination candidates for the source node s.

In anycasting, the chosen destination can be at a longer distance, increasing the bit-error-rate (BER) and the propagation delay. Thus it is necessary to make the routing algorithm aware of the threshold conditions and decide on establishing a lightpath accordingly. We define a network element vector (NEV) which consists of information about the noise factor (relation between BER and noise factor is given in [5]) and propagation delay of the link (say i) as

$$NEV_i = [\eta_i, \tau_i]^T, \tag{5}$$

where η_i is the noise factor and τ_i the propagation delay for the link i respectively and T indicates the transpose. The threshold condition for a given request is denoted by $\top^{(r)} = [\eta_{max}, \tau_{max}]^T$. The overall (NEV) for a request r is given by,

$$NEV^{(r)} = [\eta^{(r)}, \tau^{(r)}]^T = \left[\prod_{\forall i} \eta_i^{(r)}, \sum_{\forall i} \tau_i^{(r)}\right]^T. \tag{6}$$

Since the noise factor and the delay are upper bounded by their respective thresholds, a lightpath can be established only when $\eta^{(r)} < \eta_{max}$ and $\tau^{(r)} < \tau_{max}$.

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Input: $NEV_{ini} = [1,0]^T$, $(s, D_s)$, $\top^{(r)}$
1:  $SORT.SP(D_s)$.
2:  $D'_s = \{d'_1, d'_2, \ldots, d'_m\}$.
3:  $ROUTE = (s, d'_i)$.
4:  if $(n_k \forall k \in ROUTE = FREE) \& (|D'_s| \neq 0)$ then
5:      Calculate $NEV^{(r)} = \left[\prod_{\forall i} \eta_i^{(r)}, \sum_{\forall i} \tau_i^{(r)}\right]^T$
6:      if $NEV^{(r)} > \top^{(r)}$, then
7:          Request $r$ is dropped /*Violation of service level agreement (SLA)*/
8:          exit.
9:      else
10:         $ROUTE = \{s, \ldots n_k, \ldots, d'_i\}$.
11:         if $(n_i \in C_{OFF}) \& (|D'_s| \neq 0)$ then
12:             $MOD\_REQUEST = (s, d'_j)$, $i \neq j$
13:             $UPDATE(D'_s) = D'_s \backslash d'_i$
14:         else
15:             $CONFIG\_LP \equiv (s, d'_i)$
16:             $CALCULATE\_ENERGY(s, d'_i)$
17:         end if
18:     end if
19: else
20:     $UPDATE(D'_s) = D'_s \backslash d'_i$
21: end if
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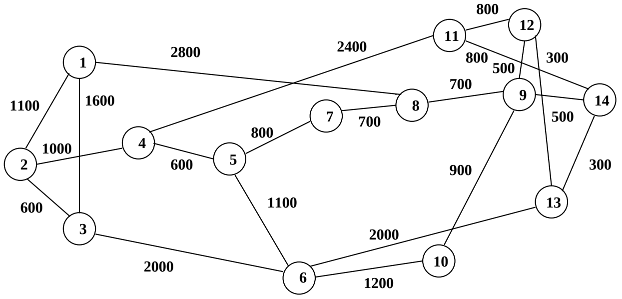
(a)



(b)

Figure 1: (a) Pseudo code for the proposed algorithm (b) National Science Foundation (NSF) Network

The pseudo code for the proposed energy efficient algorithm is given in Fig. 1a. The input to the algorithm is an anycast request where the source (s) and the destination set (D_s) are assigned from a uniformly distributed random variable. The network element vector (NEV) is initialized with noise-factor of unity and zero delay. Each anycast request is assigned threshold service parameters according to the service level agreement (SLA) of the application. The destination set D_s is sorted according to shortest path routing (Line:1). The nearest destination is selected from the set and a route is calculated (Line:3). If the links to all the intermediate nodes for d_i are available then the NEV for the route is calculated (Lines:4-5). If the QoS parameters violate the SLA then the request is dropped. If at least one of the intermediate node(s) belongs to a cluster which is in the OFF state, then a new destination is selected $(d_j, j \neq i)$ as given in Line:12. This algorithm is repeated with modified destination set $(D'_s \backslash d'_i)$. If any destination cannot be reached, i.e., $(|D'_s| = 0)$, then the request is considered as dropped or lost. A lightpath is only set up if none of the intermediate nodes belong to a cluster which are in the OFF state (Line:15).

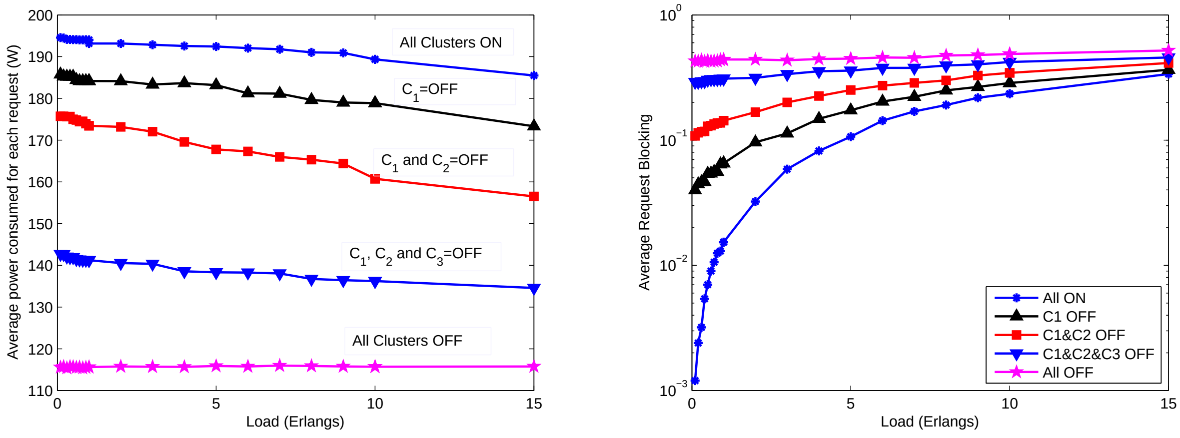
The Fig. 1b shows the topology of the NSF network used for the simulation study. The network is partitioned as the disjoint clusters. We define four clusters as $C_1 = \{1,2,3,4\}$, $C_2 = \{5,7,8\}$, $C_3 = \{8,9,10\}$, and $C_4 = \{11,12,14,13\}$. However selection and partitioning of the clusters is out of scope of the present work.

4 Simulation Results

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. 1b consists of bi-directional links, each carrying data at a rate of 10 Gbps. The weights on each link indicate the distance of optical fiber in kms. We assume that there is no wavelength conversion and regeneration capability in the network. Call arrivals follow a Poisson process with arrival rate λ. The length of the calls are exponentially distributed with an expected service time of $1/\mu$ seconds. The network load is defined as λ/μ. Links in Fig. 1b 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 $\top^{(\theta)} = [3.5, 15]^T$, i.e., the noise-factor and delay of the established session are upper bounded by 3.5 and 15 ms respectively. The noise factor 5.7 corresponds to BER of 10^{-12} [5].

Simulations are performed using discrete-event model, with 10^5 requests being considered for a given network load. The average energy consumed for each request is calculated as the ratio of the sum of the total energy to the number of requests. Thus the average power for each request is the product of the average energy consumed and bit rate. The average power consumed for each request with varying network load is shown in the Fig. 2a. This figure shows the power consumption for different choice of clusters in the sleep mode. When all the clusters are ON, in other words, there are no sleep modes, the energy consumption is high. In Fig. 2b we also show the request loss. A request loss can occur due to channel unavailability or because of the sleep mode. When all the cluster were ON, the average blocking probability is lower since the only loss that occurs is because of wavelength unavailability.

From Fig. 2a we observe that the power consumed for a given network load decreases when the clusters are put into sleep mode. However the decrease in energy is at the cost of increase in blocking probability (shown in Fig. 2b). When all the clusters are OFF (ideally the complete network is in sleep mode), the blocking probability is very high ($\approx$ 50%). This is because most of the calls have intermediate nodes that belong to the clusters in the OFF state. Only calls that are single hop exisit in the network. Hence the average energy consumption is constant as observed in Fig. 2a.



(a) (b)

Figure 2: (a) Average energy consumed for each request (b) Average request loss.

5 Conclusion

In this paper we have discussed energy cost in the Internet. We have also calculated the energy per bit consumed by the optical signal to traverse a wavelength routed network. Using an anycasting communication paradigm in a clustered node architecture in an optical network, we show a decrease in the energy consumption. Sleep cycles for the WRN are proposed. This work can be further extended to consider efficient traffic shaping techniques.

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