Energy-Aware Lightpath Routing Algorithm for Optical Transport Networks

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Abstract— **Current as well as future applications and services are characterized by bandwidth intensiveness and as such are directly driving the need for the deployment as well as operation of backbone networks that optimize on bandwidth provisioning. Since infrastructural hardware equipment requirements are trebling every two years because of continued surging bandwidth demands, the telecommunication industry is also a growing direct contributor to worldwide greenhouse gases (GHG) emissions as well as energy consumption. This is driving necessities to research on more energy efficient networking approaches. A novel optimized energy-aware lightpath routing (OEA-LR) algorithm is herein proposed. It primarily takes into account the effects of physical layer impairments (PLI) since their effects in high capacity translucent optical networks may not be ignored when formulating routing and wavelength assignment (RWA) algorithms. We assume an all-optical network hence connection requests from source to destination are entirely provisioned in the optical domain, thus optical-electrical-optical (OEO) conversions are not utilised. Both analytical and simulation results indicate that the proposed algorithm improves both energy efficiency operation as well as resource utilization of the network. We further conclude on a general observation of reciprocations between energy savings and blocking performance.**

***Keywords*— translucent network, optical fiber, physical layer impairments, energy efficiency, network performance metrics, RWA**

I. INTRODUCTION

The tremendous growth in the volume of telecommunication traffic has undoubtedly triggered an unprecedented information revolution. The emergence of high-speed and bandwidth-hungry applications and services such as high-definition television (HDTV) and online interactive media has forced the telecommunication industry to come up with ingenious and innovative ideas to match the challenges. With the coming of age of purposeful advances in DWDM technology, it is inherently practically possible to deploy ultra-high speed all-optical networks to meet the ever-increasing demand for modern telecommunication services. All-optical networks are capable of transmitting data signals entirely in the optical domain from source to destination, and thus eliminate the incorporation of the often bulky and high-energy consuming OEO converters at intermediate nodes. Predictably, all-optical networks consume appreciably low energy as compared to their opaque and translucent counterparts. This low energy consumption results in lower carbon footprint of these networks, and thus a significant reduction in the GHGs emission. In addition, transparent optical networks bring along other additional and favorable rewards such as high bit-rates and overall protocol transparency. Bearing in mind the benefits of transparent optical networks, it is vital to point out that there are significant setbacks that accompany these otherwise glamorous rewards. Since OEO conversions are eliminated at intermediate nodes in all-optical networks, the quality of the transmitted signal from source to destination may be severely degraded mainly due to the cumulative effect of physical-layer impairments induced by the passage through the optical fibers and associated network components. It is therefore essential to come up with routing schemes that effectively take into consideration the signal degrading effects of physical-layer impairments so as to safeguard the integrity and health of transmitted signals, and eventually lower blocking probabilities. Furthermore, innovative approaches need to be put in place so as to strike a delicate balance between reduced energy consumption in transparent networks and the quality of transmitted signals.

In practice, to establish an all-optical communication path between a source and destination node, the same dedicated wavelength has to be assigned throughout the transmission path. This all-optical connection is called a light path. Normally the lightpath is established prior to data exchange such that there would be no need for buffering the data at the intermediate nodes. Several lightpaths can utilize the same fiber link if only they use different wavelengths otherwise they will have to use separate fiber links. Overall, global energy consumption by the telecommunications sector is rapidly increasing [1], [2], [3]. This is creating an energy bottleneck which is increasingly becoming a limiting factor in the rolling out of further telecommunications network infrastructures. As such there are concerted and coordinated efforts globally to prioritize energy conservation and the scientific research community has been at the forefront of spearheading this noble cause [4]. It is evident from current data and statistics that traditional energy sources such as oil and coal are still widely preferred for energy generation. These energy sources are non-renewable and thus may eventually get used up in the near future. In addition, they pose serious global environmental and health challenges since they produce large quantities of the so-called greenhouse gases (GHG). GHGs are a major cause of global warming and their adverse effects include higher average global temperatures that lead to natural disasters like droughts and floods.

It is without doubt that the carbon footprint of the ICT sector has drastically increased over the past decade. This is mainly so due to the deployment of high-speed telecommunications networks to meet the ever-increasing demand for efficient and bandwidth hungry applications such as video streaming [5], [6], [7]. The advent of smart grids (SGs) has opened up the exploitation of vast renewable energy sources for the powering of high-speed telecommunication networks. SGs incorporate power generation from diverse sources such as wind and the sun and the benefits derived from such distributed generation include, improved energy system reliability, flexibility and efficiency. In the process the GHG emissions are significantly reduced due to the effective use of renewable energy sources such as solar and wind [8].

Taking into the cognizance the importance of reducing global warming, it is therefore logical and noble to design and develop energy-efficient next generation telecommunication networks. Since modern backbone telecommunication networks heavily rely on optical networks due to their superior speed and capacity, it becomes vital to study and come up with ingenious ideas to reduce energy consumption in these networks. Although a number of scholars have shown interest in pursuing studies in energy consumption of optical networks, research in promoting energy-efficient networking is fairly novel and in its infancy. The reduction of energy consumption in optical networks can be generally solved at component, transmission, network and application levels [7]. The deployment of all-optical components and related switching fabrics will evidently reduce energy consumption at the component and switching levels [9]. Introduction of low-loss and low-dispersion optical fibers and energy-efficient transponders has the potential to improve energy efficiency at transmission level. Energy-aware and efficient resource allocation strategies and green routing have been earmarked to be the front running techniques for the reduction of energy consumption at the networking level [10].

II. RELATED WORK ON ENERGY EFFICIENT NETWORKING

Due to the purposeful global campaigns aimed at mitigating factors that cause environmental pollution, the telecommunication sector joined the bandwagon in the quest to protect our environment by adopting initiatives that are geared towards energy-efficient telecommunications networks [11]. In addition, the current departure from the traditional technologies and strategies does not only result in the reduction of harmful gases released into the environment as stated earlier, but also lead to substantially low operational expenditures (OPEX) for network operators. A significant number of researchers have focused their attention in conducting research towards coming up with energy-efficient solutions for backbone networks as they consume most of the energy. Generally, the energy usage of any backbone network type can be significantly lowered by redesigning the physical links and the core nodes. Traditionally, the physical links rely on optical technologies, whereas the core nodes have essentially been based on electronic technology [8]. Since electronic devices are slower than their optical counterparts, there is a need to gradually replace them with their optical equivalents [12]. By redesigning the physical topology of the core networks via the optimization of available links, massive energy savings may also be realized [12]. Since the capital expenditure (CAPEX) of an optical core network is mainly determined by link deployment costs, it is therefore prudent and logical to interconnect core nodes through fewer number of links as is possible. However, it is crucial to strike a balance between the number of links and energy efficiency as some topologies may contain fewer links but end up consuming significantly large amounts of energy.

Another way of reducing energy consumption of core networks is to limit the use of network devices such as ports and fibers, by utilizing traffic grooming techniques [11], [14]. If several low-granularity traffic movements are aggregated into a few, high-granularity traffic flow, the number of wavelengths that traverse the core network will be drastically reduced and this leads to a reduction in demand of network resources. Wavelength grooming occurs when several sub-wavelength traffic is aggregated into a single wavelength, and waveband grooming arises when several wavelengths are aggregated into a single waveband. Since a large portion of modern backbone network traffic is for internet services, it implies that the connection requests arrive randomly, and their durations vary over different time periods. Several energy-reducing approaches have been proposed for such kinds of dynamic traffic, and some of the most effective dynamic grooming approaches include the Power-Efficient Grooming Algorithm (PEGA) and the Time-Aware Traffic Grooming (TATG) [15]. In PEGA, new lightpaths are only established in the event of capacity constraints on existing lightpaths, otherwise, the new requests are incorporated into lightpaths already in existence. The TATG approach uses appreciably less energy at low traffic loads but uses up more energy at high traffic loads. In a nutshell, traffic grooming is essential in modern backbone networks as it aids in reducing energy consumption by optimizing resource usage via minimization of network devices usage.

Network elements in core networks are configured to support peak-period traffic and thus during off-peak periods, significant amounts of energy are unwisely wasted since most devices will not be performing any functions [16]. Due to the increased sizes of current networks, and hence several energy consuming devices, it has become very critical and important to switch off some devices during low traffic periods, and this in turn calls for the adjustment of routing schemes to be fully optimized to become energy-efficient. A number of scholars have proposed and developed several schemes that are responsive to the energy demands of the networks, and these schemes can be subdivided into energy-aware routing and energy-aware network design. Energy-aware routing can be accomplished by exploiting the technique of multilayer traffic engineering (MLTE) whereby routing is optimized, and logical topology adaptation is enabled by the creation of a virtual mesh layer and the subsequent computation of the most energy-efficient route. This results in the rerouting and grooming of traffic and adaptation of the topology results in switching off devices that will not be in use.

A fairly novel approach to energy-aware routing involves the concept of *green routing* whereby network nodes are mindful of the source of their power [16]. In such schemes, routing can be optimized to utilize as much energy from renewable sources as is possible, thereby leading to lower GHG emissions that arise from powering communication networks. The remainder of the paper is organized as follows. The next section briefly overviews impairments in optical links as well as outlines a typical end-to-end lightpath energy consumption model. Section IV presents the proposed OEA-LR approach. Performance evaluation is carried out in section V, while section VI concludes the paper.

III. IMPAIRMENTS IN OPTICAL NETWORK LINKS

AWDM optical network architecture will consist of an electronic layer comprising components such as transponders (TR) as well as regenerators (REG). The TRs directly interface with peripheral network equipment such as IP routers whilst REGs are responsible for refreshing/reamplifying the optical signals. In addition, a further optical layer will add devices such an optical switching fabric, several Erbium doped fibre amplifiers (EDFAs,) and optical multiplexers/demultiplexers (DEMUXs) units at all start terminating points.

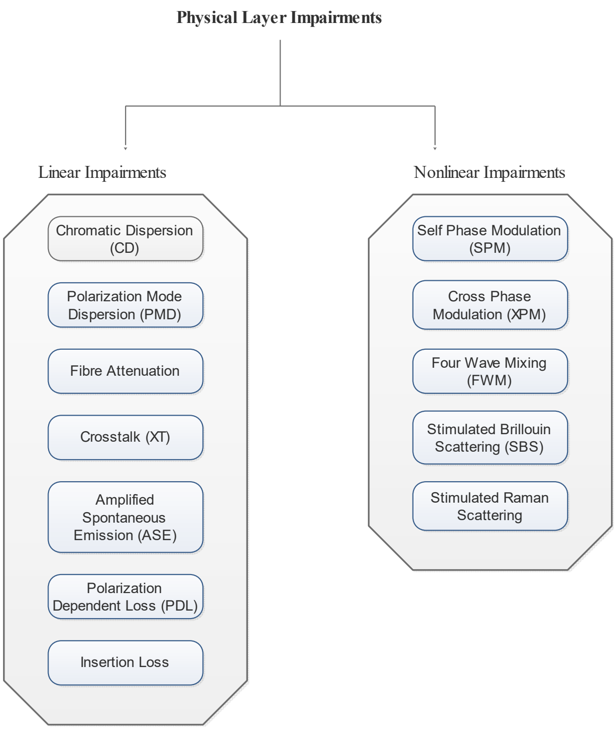

Figure 1: Summary Physical Layer Impairments in an Optical Network

In a given optical backbone network's operation, the objective is always to maximize the number of lightpaths that can be established simultaneously subject to the wavelength assignment constraint. The lightpath establishment is often dynamic as thus referred to as the dynamic routing and wavelength assignment (RWA) problem and this has to be carried out in an energy efficient manner. In this paper we focus on translucent optical networks and propose a scheme that takes account physical-layer impairment aware routing and wavelength assignment algorithms**.** The impairments include both linear and non-linear types. Linear impairments are independent of the signal power and affect each of the optical channels individually, whereas nonlinear impairments result in interference between channels in addition to affecting each optical channel individually. Both linear and non-linear impairments affect the integrity and quality of optical signals as they traverse the optical backbone network and these signal degrading factors are generally referred to as physical layer impairments (PLI). Due to the transparency of optical networks, noise and signal distortion that arise from PLI effects, accumulate along the lightpath and may lead to unacceptably low optical signal to noise ratio (OSNR) that will render the lightpath unusable. The most prevalent linear impairments that degrade optical signals in optical networks are, Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Fibre Attenuation, Polarization Dependant Losses (PDL), Crosstalk (XT), Filter Concatenation (FC), Amplified Spontaneous Emission (ASE) and Component Insertion Losses [17]. Pertinent non-linear impairments that adversely degrade optical signals are: self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated brillouin scattering (SBS), and stimulated Raman scattering (SRS) [18].

By taking into account, the PLIs, high quality of transmission characterized by lower lightpaths blocking probability can be achieved. Furthermore overall energy consumption by the networks is reduced. It is generally found out that the effects of impairments such as FC and SRS become prominent in high speed networks and may not be ignored in formulating RWA algorithms of these core networks .

An end-to-end lightpath connection normally comprise several concatenated transparent lightpaths.

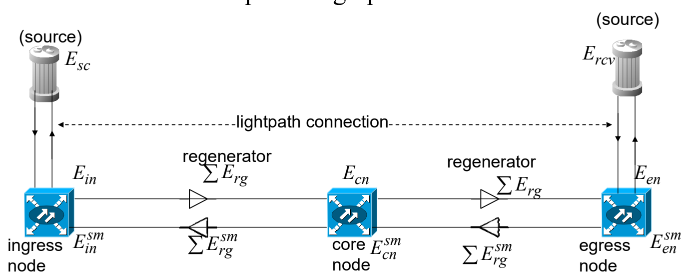

Figure 2: Energy consumption model

The regularly spaced repeaters throughout the optical backbone network refresh the lightpaths whenever it is desirable. In that way geographical coverage is extended, at a relatively lower cost since there is no need to place repeaters at every node as is the case with opaque optical backbone networks.
A typical energy consumption model representative of an end-to end OBS backbone network path is shown in Fig.2, in which:

- E_{sc} - is the energy consumption by a single source.
- E_{rcv} -is the energy consumption by a single receiver.
- E_{in} - EP_{in}^{sm} - typical energy consumption by the ingress node in active mode and SM respectively.
- E_{cn}, EP_{cn}^{sm} - typical energy consumption by a core node in active and SM modes respectively.
- E_{eg} , EP_{en}^{sm} - typical energy consumption by an egress node in active mode and SM respectively.
- E_{rg} , EP_{rg}^{sm} - typical energy consumption by a single regenerator in active mode and SM respectively.

The maximum energy consumed by the network when serving n lightpath connections concurrently is:

$$E_{net}^{\max} = n\left[E_{sc} + E_{rcv}\right] + E_{in} + E_{in}^{sm} + E_{cn} + PE_{cn}^{smp} + E_{eg} + E_{en}^{sm} \qquad (1)$$

whereas the minimum energy consumption is:

$$E_{net}^{\min} = 2 \times n \times E_{sc} + \left(E_{xc}^{sm} + \sum E_{rg}^{sm} + E_{rg}^{sm} \right) \times n \qquad (2)$$

IV. PROPOSED OEA-LR APPROACH

Primarily the goal of implementing energy-efficient strategies and algorithms is to lower the overall energy consumption of the networks. However is so doing the amassed energy gains must not compromise the integrity of the transmitted signals as well network performance.

We initially define a network element vector (NEV) that characterizes the state of a link in terms of its sustainable bit error rate (BER) and propagation delay (τ_l)

$$NEV_l = \left[BER_l, \tau_l\right]^T \qquad (3)$$

where, BER_l is the bit-error rate and τ_l is the propagation delay for link i respectively. The transpose is shown by T. The threshold expression for a given lightpath connection request is given by,

$$T^{(r)} = \left[BER_{thres}, \tau_{thres}\right] \qquad (4)$$

Thus, for a given lightpath connection request r, the NEV is given by,

$$NEV^{(r)} = \left[BER^{(r)}, \tau^{(r)}\right]^T = \left[\prod_{\forall l} \tau_l{}^{(r)}\right]^T \qquad (5)$$

We assume that a lightpath connection request can only be accepted provided the following constraints are observed,

$$BER^{(r)} < BER_{\max} \ \&\& \ \tau^{(r)} < \tau_{\max} \qquad (6)$$

The proposed algorithm assumes an *anycast* request that follows the Poisson distribution for the source and destination pairs (s, D_s). A bit-error rate (BER) of 10^{-12} and a zero (0) propagation delay are assigned to initialize the network element vector (NEV).

The destination set (D_s) is arranged according to the shortest widest-path (SWP). The shortest destination is selected from the set and a route is computed. The NEV for the route is computed if all intermediate nodes are available. If the BER and the propagation delay are above the set threshold, the request is dropped to guarantee an acceptable QoS. If one or more of the intermediate nodes belongs to a cluster that is in the OFF state, a new destination is selected. The selection is repeated with a modified destination set $(D_s' \backslash d_i')$ until a suitable destination is found. If any destination cannot be accessed, i.e. $(|D_s'| = 0)$, then the request is dropped. Algorithm I summaries the algoriyhm.

Algorithm I: PLI Aware Energy efficient lightpath connection provisioning algorithm

Input: $NEV_{initial} = [10^{-12}, 0], (s, D_s), T^{(r)}$
$SORT.SWP(D_s)$.
$D_s' = \{d_1', d_2', \dots, d_z'\}$.
$ROUTE = \{s, d_i'\}$.
$\boldsymbol{if}\ (n_k \forall k \in ROUTE = FREE) \& (|D_s'| \neq 0)\ \boldsymbol{then}$
  Calculate $NEV^{(r)} = \left[\prod_{\forall i} BER_i{}^{(r)}, \sum_{\forall i} \tau_i{}^{(r)}\right]^T$
  $\boldsymbol{if}\ NEV^{(r)} > T^{(r)}, \boldsymbol{then}$
    Request r is dropped
    exit
  else
    $ROUTE = \{s, \dots n_k, \dots, d_1'\}$.
    $\boldsymbol{if}(n_i \in C_{OFF}) \& (|D_s'| \neq 0)\ \boldsymbol{then}$
      $MOD\_REQUEST = (s, d_j'), i \neq j$
      $UPDATE(D_s') = D_s' \backslash d_i'$
    else
      $CONFIG\_LP \equiv (s, d_i')$
    : $CALCULATE\_ENERGY(s, d_i')$
    end if
  end if
else
  $UPDATE(D_s') = D_s' \backslash d_i'$
end if

The OEA-LR approach is premised on the assumption that the energy required to establish a connection request is equal to the summation of: the energy required for optical switching at intermediate nodes, the energy consumed by the transceivers, and the EDFAs energy consumption along each fibre link. The net energy consumption of the network is therefore equivalent to the sum of the energy used by all presently provisioned connection requests at any specific moment. Furthermore, the OEA-LR is anchored on the modification of the k - shortest-path algorithm presented in [3], [21].

Using the OEA-LR approach, up to k -shortest paths are calculated when a connection request is received, and the algorithm takes into cognizance the link-state in its search for a candidate lightpath route. Thus, fibre links that do not possess available wavelengths at any given instance are deleted from the logical topology on a temporary basis. During the computation of each candidate lightpath, each link (l) is assigned a cost (C_l) that is calculated as follows:

$$C_l = \begin{cases} \gamma * E_l & \text{, when fibre link is in use} \\ E_1 & \text{, when fibre link is not in use} \end{cases} \qquad (7)$$

Where, E_l is the total energy consumption required to operate all amplifiers on the fiber link l, and γ is a weighting factor whose values lie between 0 and 1, and it indicates the extent of energy savings in the OEA-LR. If the value of γ is equal to 0, the OEA-LR behaves like a pure energy saving approach, whereas for the values of γ equal to or close to 1, the OEA-LR appears to provision connection requests according to shorter routes. Since EDFAs are deployed after every 80 km, it may be assumed that their numbers are proportional to the length of the route under study. By varying the values of γ between 0 and 1, both energy usage and resource utilization are optimized. If a candidate path is found, the FFwO approach is utilized to search for an available wavelength along the path. If a free wavelength is not found among the k – paths, or there is no existence of a candidate path, blocking of the connection request occurs.

V. PEFORMANCE EVALUATION

The OEA-LR scheme is evaluated via simulations on the Pan-European and the NSFNET network topologies.

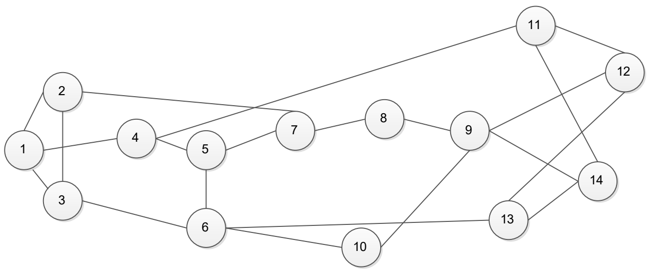

Figure 3: The NSFNET network topology

The considered Pan-European network comprises 11 nodes and 26 bidirectional fibre links, and the NSFNET topology comprises 14 nodes and 21 bidirectional fibre links. It is further assumed that each fibre link is capable of carrying a maximum of 16 wavelengths, and that there is no wavelength conversion in the network. Furthermore, the source-destination pairs of the connection requests are uniformly selected among the network nodes, and the connection request arrivals follow a Poisson distribution and the holding time per connection is distributed exponentially.

The following assumptions are made for the energy consumption of the network devices.

i. EDFAs, OXCs and transceivers can be instantly ordered to enter into sleep mode or switched-on depending on the traffic conditions. In addition, it is also assumed that no additional energy is expended during the transitions from sleep to switched-on mode, and vice-versa.

ii. Each EDFA consumes 12 W of power and the distance between consecutive EDFAs is $80 km$.

iii. Each transceiver uses 7 W of power at 10 Gbps.

iv. An OXC consumes 6.4 W of power.

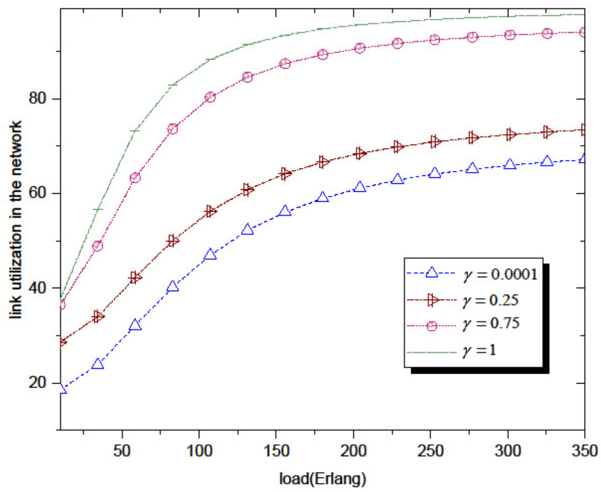

Figure 4: Relationship between link utilization and traffic load

Our results are obtained by further assuming that the weighting factor γ lies between 10^{-4} and 1, and a maximum of $k = 3$ candidate paths are calculated for each connection request. Fig 4 shows the relationship between link utilization and traffic load for the Pan-European network. The results show that when the OEA-LR approach bases its decisions only on minimizing the lengths of provisioned lightpaths, the fibre links usage drastically increases with increasing traffic load.

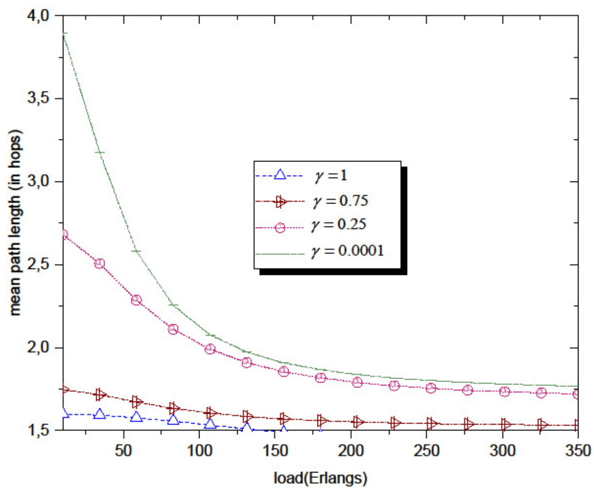

Figure 5: Relationship between saved energy and traffic load

This behavior is logically expected and acceptable since the routing strategy does not take into account the energy status of the network elements but is solely based on ensuring the provisioning of connection requests of shortest available path at values of γ close to or equal to 1. On the other hand, when γ is close to 0, the OEA-LR strategy attempts to minimize the energy consumption in the network by limiting the number of devices to be energized. As a result, the fibre link utilization grows almost in a linear fashion as the load increases. This implies that a significant number of fibre links will remain unused, hence the presence of fewer energy-consuming elements in the network. Consequently, under these conditions, a significant amount of energy will be saved in the network.

Fig 5 shows the variation of potential energy savings and network traffic load.

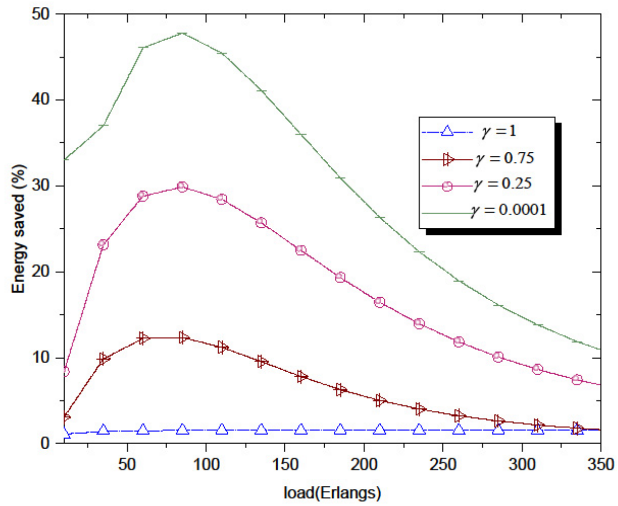

Figure 6: Relationship between mean path length (in hops) and traffic load

It can be observed that massive amounts of energy may be saved $(\approx 50\%)$ at sufficiently low values of $\gamma(\gamma = 0.0001)$. On the other hand, if γ is high (≥ 0.75), very little or no energy is saved in the network. Once again, this emphasizes the effectiveness of our proposed OEA-LR approach in realizing energy efficiency in optical networks.

Figures 6 and 7 present the relationship between average path length and traffic load for various values of γ for the NSFNET topology. In Fig 56 the number of hops are presented as a function the network load, whereas in Fig 6 , the physical distance values are given as a function of the network load. The results show that the use of the energy-aware routing strategy leads to higher average path lengths compared to the approach where energy awareness is not taken into account. These results confirm our expectation that, if path lengths are long, there is a likelihood that the network resources will be optimally utilized since traffic tend to traverse through already powered-on devices in the network. It can be clearly seen that the mean path length increase is capped at about 7% for γ values between 0.75 and 1, and thus a considerably acceptable increment in path length, bearing in mind the significant energy savings realized. However, there is need to trade-off the energy savings gains achieved through increased path lengths on one hand, and the transmitted signal quality on the other hand.

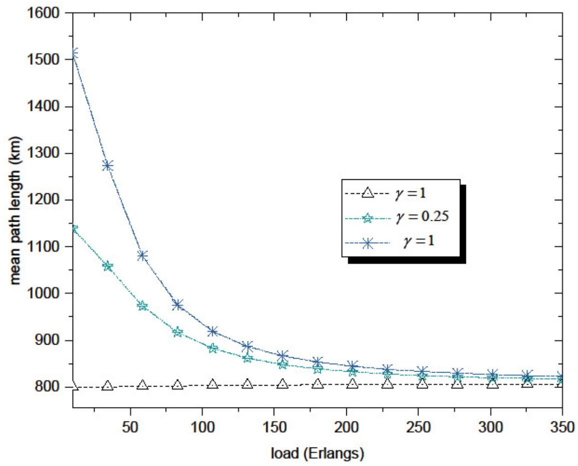

Figure 7: Relationship between mean path length (in km) and traffic load

We then go on to compare the performance of the proposed scheme with other similar approaches. These are:
k shortest path and first fit (FF) scheme presented in [19] which basically identifies and chooses the shortest path without taking energy consumption into consideration, and the lowest energy/power consumption (LPC) which always chooses a lightpath with the lowest power consumption [20]. In so doing our focus is on trying to balance between energy savings versus overall lightpath connection blocking performance. We slightly modified some of our simulation parameters by assuming that each lightpath connection bandwidth is fixed at 0.25Gbps and that the number of REGs on a given link d is $N_{reg} = d/80km$.

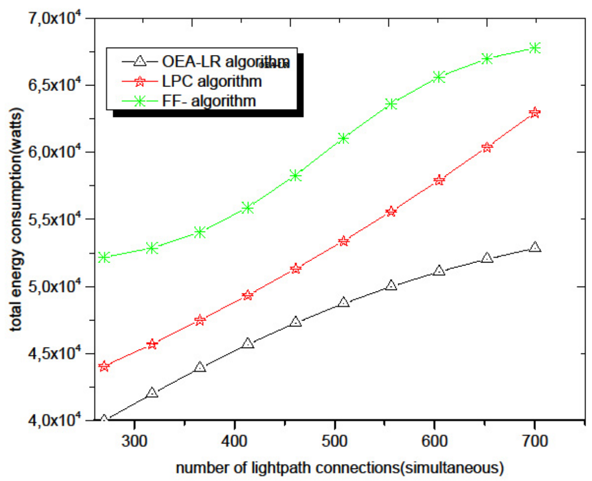

Figure : Energy consumption comparisons

Note that in all cases the total energy consumed is summed from the devices that have to be kept ON in order to enable establishment of end to end connection lightpath(s). Analytical results shown in Fig 7 indicate that the OEA-LR scheme provides relatively better performance for a given(fixed) blocking probability threshold.
With regards to the blocking probability, we further varied the parameter $\gamma = [0,1]$. Recalling that γ is indicative of energy

saving in each network, for the same further analysis showed that energy-efficient provisioning in networks and blocking performance almost reciprocate each other. i.e. when energy efficiency provisioning is enforced i.e. ($\gamma \to 0$), energy saving is high, but the blocking performance degrades drastically. However as γ slowly approaches 1, i.e. when. energy saving is minimized in the network, the blocking performance rapidly improves.

CONCLUSION

In this paper, a novel OEA-LR approach is proposed that simultaneously considers both energy minimization and resource utilization as a unitary cost function. The results from the simulations confirm the competitive edge of the approach in terms of both energy and network utilization efficiencies. However, it is noted that care must be taken so as to strike a healthy balance between energy savings, signal quality as well as blocking performance Overall it is established that energy-efficient provisioning in networks and blocking performance almost reciprocate each other. i.e. when energy efficiency measures are enforced blocking, performance degrades drastically and vice versa when, energy saving are totally relaxed, in the network, the blocking of lightpath connections becomes minimal. In future we will seek to improve on both energy savings and at the same time maintaining minimal blocking performance.

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