Achieving Energy Efficiency Using Traffic Grooming in WDM Networks

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Contents

1 Abstract 3

2 Introduction 4
  2.1 Introduction ................................................. 4
  2.2 Terminology .................................................. 6
  2.3 Need for Green Optical Networks ............................. 9
  2.4 Outline of the Survey ........................................ 9

3 Energy Efficiency using Traffic Grooming 9
  3.1 Why Traffic Grooming ........................................ 9
  3.2 Algorithms ................................................... 10
    3.2.1 RWA and Traffic Grooming ............................... 10
    3.2.2 Power Aware Provisioning (PAP) ....................... 10
    3.2.3 LUB and RSB ............................................. 11
    3.2.4 TATG .................................................... 12
  3.3 Methodologies/Approaches .................................. 14
    3.3.1 Power Consumption Analysis ............................. 14
    3.3.2 IP-BG ................................................... 15
    3.3.3 ILP .................................................... 16
    3.3.4 Auxiliary Graph ........................................ 19

4 Test Beds 20

5 Discussion of Papers (Annotations) 22
  5.1 Power Efficient Traffic Grooming in Optical WDM Networks .... 22
  5.2 Traffic Grooming: A Changing Role in Green Optical Networks ... 23
  5.3 Traffic Grooming in Green Optical Networks .................. 25
  5.4 Green Provisioning for Optical WDM Networks ................ 26
  5.5 Greening the Optical Backbone Network: a Traffic Engineering Approach ......................................................... 27
  5.6 Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks ......................................................... 28
  5.7 Designing Power Efficient WDM Ring Networks .................. 29
  5.8 Effect of Sparse Grooming on Power Consumption of Optical Networks ......................................................... 30
  5.9 Power-Aware Routing and Wavelength Assignment in optical networks ......................................................... 31
  5.10 Energy Minimized Design For IP Over WDM Networks .......... 31
  5.11 On the Energy Efficiency of IP-over-WDM Networks .......... 32
5.12 Energy Efficiency in Telecommunications Networks: Link-by-Link vs. End-to-End Grooming ........................................ 33
5.13 Energy Saving and Cost Reduction in Multi-granularity Green Optical Networks .................................................. 34
5.14 Green Multicast Grooming Based on Optical Bypass Technology ................................................................. 38
5.15 Energy-Awareness in Dynamic Traffic Grooming ................................................................. 41
5.16 Traffic Grooming Algorithms for Power Efficiency in IP over WDM Networks ................................................ 42
5.17 Reducing NGN energy consumption with IP/SDH/WDM ................................................................. 44
5.18 Energy Efficiency in Telecom Optical Networks ................................................................. 45
5.19 Power Reduction Techniques in Multilayer Traffic Engineering ................................................................. 48

6 Conclusion .................................................................................. 51
1. ABSTRACT

Energy conservation has been given a very significant place in society in recent years Zhang et al. [2010]. Due to concerns such as global warming and depletion of natural resources, governments around the world have started introducing various bills that would allow them to cut their carbon footprints. These concerns extend to the energy utilization of various commodities that we use in our daily life, one of them being the Internet. To accomplish a good service to the end users ISPs have been working really hard, due to the current economic situation as well as the aforementioned energy issues. ISPs are looking towards routing possibilities that can help them achieve both. The area of energy conservation in a backbone network is quite broad, and thus in this survey the area has been narrowed down. The main reason for wastage of energy is the over-provisioning of backbone networks Chabarek et al. [2008]. If resources are active to their full capacity 24/7 irrespective of the variation in traffic requirement, this will result in higher OPEX (Operational Expenditure) and increased wastage of energy Chabarek et al. [2008]. Hence, the need for such awareness is necessary so that more and more research concentrates in putting to a rest. This survey explores the various approaches made to conserve energy in the optical domain using traffic grooming problem.
2. INTRODUCTION

2.1 Introduction

Great concerns are been raised over environmental protection and energy crisis Zhang et al. [2010]. ICT (Information and Communication Technology) is one of the major players of today's modern society and is alleged to consume 8% of the total power consumption of the world Zhang et al. [2010]. Optical networks form the backbone (core) of the network infrastructure of many countries, and for some countries like United States, it is penetrating the Access and the Metro networks Zhang et al. [2010]. Looking at the urgency of the matter in hand, many authors have delved in the area of energy conservation in optical networks to propose various solutions like putting passive components to sleep, using traffic grooming to save energy, using traffic grooming approach along with some packet forwarding approaches, etc. Hou et al. [2011] provide the readers with an important realization about the environmental concern that extensive use of network equipment is raising, by putting forward their argument on the fact that the optical bypass can save up to 25-45% compared to network without optical bypass. Due to the vastness in the field of energy conservation in optical networks, this survey concentrates its analysis on various traffic grooming approaches introduced so far.

After deciding the topic for the survey, various synonyms for the keywords in the topic where used to search in “Google Scholar”. For example “Energy Efficiency” can have some similar words like “Power Aware”, “Energy Aware”, etc. This approach helped to identify only relevant papers. “Advanced Scholar Search”, also helped in concentrating only in the articles published in the computer science field. The University of Windsor Leddy library’s web portal to various digital libraries such as IEEE Xplore, ACM, springerlink, etc. further helped in accumulating relevant papers. Using some search operators like; “author: authorName” (search the papers published by the author), helped in searching specific papers that where relevant to the topic. Combinations of various synonymic search terms were used to distinguish between the search results. The paper accumulated from the above mentioned sources, were the first round of the paper collection. The next and more refined search for the papers were made possible by reading through collected papers and recognizing relevant research work that the authors of the papers referred. This was also achieved by help of the website citeceer which provided services like Citation statistics, Reference linking etc. The whole process resulted in 40 papers among which 20 were designated as “most important papers”.

Papers that were published in conference proceeding, included, Ajaykumar and Ghosh [2008], Baliga et al. [2008], Cerutti et al. [2009], Chabarek et al. [2008], Cianfrani et al. [2010], Dharamaveera et al. [2010], Gupta and Singh [2003], Hasan et al. [2010], Hasan et al. [2010], Hou et al. [2010], Huang et al. [2010], Idzikowski et al. [2010], Keslassy et al. [2003], Li et al. [1996], Pattavina et al. [2003], Puype et al. [2009], Van Heddeghem et al. [2010], Wu et al. [2009], Xia et al. [2010], Yetginer and Rouskas [2009], Zhang et al. [2010] and Zhu et al. [2002].

The papers that were published in journals, included, Zhang et al. [2000], Aleksic [2009a], Aleksic [2009b], Areg Alimian [2008], Bregni et al. [2011], Gunaratne et al. [2008], Hamad and Kamal [2010], Hou et al. [2011], Shen and Tucker [2009], Tucker [2011], Tucker [2006], Wang et al. 2011, Xia et al. [2011], Zhang et al. [2010] and

ACM Journal Name, Vol. V, No. N, Month 20YY.
Papers in 2000 were Zang et al. [2000], in 2001 were Konda and Chow [2001], in 2002 were Zhu and Mukherjee [2002] and Zhu et al. [2002], in 2003 Pattavina et al. [2003], Gupta and Singh [2003] and Keslassy et al. [2003], in 2006 were Tucker [2006] and Mukherjee [2006], in 2008 were Chabarek et al. [2008], Baliga et al. [2008], Ajaykumar and Ghosh [2008], Baliga et al. [2009], Areg Alimian [2008], Chiaraviglio et al. [2008], Gunaratne et al. [2008] and [Bandyopadhyay 2008], in 2009 were Yetginer and Rouskas [2009], Song [2009], Aleksic [2009], K. Ley and Nguyen [2009], Ceuppens [2009], Huang et al. [2009], Wu et al. [2009], Aleksic [2009], Puype et al. [2009], Kame [2009], Shen and Tucker [2009], Cerutti et al. [2009] and Baliga et al. [2009], in 2010 were Wang et al. [2011], Cerutti et al. [2010], Hou et al. [2011], Feng et al. [2010], Dharmaveera et al. [2010], Zhang et al. [2010], Hou et al. [2010], Zhang et al. [2010], Hamad and Kamal [2010], Hasan et al. [2010], Xia et al. [2010], Cianfrani et al. [2010], Hasan et al. [2010], Van Heddeghem et al. [2010] and Idzikowski et al. [2010] and finally the papers published in 2011 were Tucker [2011], Bregni et al. [2011], Hou et al. [2011] and Wang et al. [2011].

Analysis of an area of research first starts with basic understanding of the broad area of which the research is a subset, hence this survey presents the reader with basic introduction to optics and various terms that seemed to be vital in understanding this survey. It is critical to answer the question where one is headed with the survey in hand, hence the this section promptly lets the reader identify what to expect from the survey. The readers may like to go ahead and critically read the core analysis of the survey which is followed by the “Discussion of Papers”, giving a fair idea of work done so far in the area of interest.

The paper Zhang et al. [2010] present a comprehensive survey on energy conservation in optical networks, hence making this paper an important one in assisting the construction of this survey. The paper Zhang et al. [2010] has been the first “milestone” of all the 20 important papers as it had references to 10 papers that were considered “most important” ones. [Xia et. al. 2010; 2011], were the papers that can be grouped together as the former paper acted as the base paper for the work done in the paper published in 2011. [Hasan et. al. 2009] and [Hasan et. al. 2010] are the sister papers where the former paper is responsible in presenting the ILP formulation and the later gives a full explanation of an auxiliary graph approach which is used in grooming heuristic algorithm presented [Hasan et. al. 2010].
2.2 Terminology

Traffic Engineering. As mentioned in the paper Xia et al. [2010] traffic engineering is to assign the network traffic to the available bandwidth, which finally allows the routers to the route the network traffic.

Grooming Graph. Because of a dynamic energy and time-aware traffic grooming some authors e.g. Zhang et al. [2010] have used Grooming Graph which is divided into $W+1$ planes, where $W$ is the number of wavelengths the network can support plus the ‘1’ is for an extra plane representing the VTP (Virtual Topology Plane). With three different kinds of edges; Lightpath Edges (edges between nodes in VTP if there is an edge in corresponding physical network), Wavelength Edges (if in physical topology there is a fiber between two nodes that carry a free wavelength $\lambda$, then there will be a wavelength edge between the two nodes) and Transceiver Edges (edges between corresponding nodes of WP and VTP if their exists a unused transceiver). Authors of Hou et al. [2011], also have an identical approach but they have named the graph as Integrated Graph (IG) which includes a Virtual Layer (VL) (analogous to VTP) and multiple Wavelength Layers (WLs, which is analogous to WTP).

Traffic Grooming. Bandwidth is efficiently utilized when considering this technology.

OXCs (Optical Cross Connects). OXCs can be implemented in either in the electronic domain or the optical domain. In the electronic domain the optical signal is de-multiplexed by the de-multiplexer and converted to an electronic signal, then the electronic signals are switched using the electronic backbone routers [Bandyopadhyay 2008]. Ultimately when the electronic signal needs to be transmitted back to the optical domain, lasers are used to convert it back to some relevant light signals and then multiplexed to the optical domain. This technique is very energy inefficient and adds a speed constraint to a network [Bandyopadhyay 2008]. On the other hand it allows better quality monitoring of the electronic signal. The second technique is known as transparent OXC as the optical signal is not converted into an electronic signal. This removes the constraint of being slow but the quality management of optical signal monitoring adds new challenges [Bandyopadhyay 2008].
OCS (Optical Circuit Switched) Networks. OCS is an all-optical network. An OCS network generally has a backbone network consisting of OXCs (all-optical) which are responsible for switching the lightpaths and perform RWA Dharamaveera et al. [2010]. The access routers on other hand collect the destined information from the backbone to deliver the content to the customer. Fig will give a better understanding.

![OCS Network model with the top and bottom routers representing Access routers and the middle part represents the OXCs](image)

Gravity Model. A Gravity model is used to generate traffic in some network models, as used in Dharamaveera et al. [2010], the authors use the following formula to calculate traffic between two population center (population representing the number of users and centers represents the nodes).

\[
t_{i,j} = \frac{kP_i P_j}{d_{i,j}^{1.5}}
\] (1)

Where \( P_i \) and \( P_j \) are the population in nodes. \( d_{i,j} \) represents distance between \( i \) and \( j \).

Optical Bypass Technology. In the paper by Hou et al. [2011], the authors describe precisely the technology with the emphasis on how it can contribute in saving significant amount of energy. The paper presents the reader with the following figure:
In the above figure, the low-end routers are the customer facing routers responsible to collect all the traffic from various sources. The IP core router then aggregates the traffic and passes it on to OXCs. Consider traffic at OXC-1 has the destination OXC-3. Now a network without optical bypass, would need 2 lightpaths (lightpath 2 and lightpath 3), needs to be created and there will occur OEO conversion at OXC-2 even though there is no relevant local data that would interest the OXC-2 and its IP core router. If the optical bypass technology is considered then only one lightpath needs to be generated with no OEO conversion at any intermediate nodes, hence, saving energy.

Optical Carrier Transmission Rates. Optical Carrier Transmission also abbreviated as \( OC-n \), where \( n \) gives the notion of amount of bandwidth. With a base rate of \( OC-1 = 51.84 \text{Mbps} \), \( OC-n \) is \( n \times 51.84 \text{Mbps} \).

Sub-wavelength traffic grooming. Similar to traffic grooming, sub-wavelength grooming is (de)multiplexing and switching sub-wavelength traffic into larger wavelength streams Feng et al. [2010]. The advantages of this method are also similar to traffic grooming Feng et al. [2010]. This approach enables a large number of low utilization streams to be merged into fewer high utilization streams to be merged into fewer high utilization streams, saving interface ports and wavelengths Feng et al. [2010].

SDH/SONET. Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) are the two standardized multiplexing protocols that set the rules for flow of “multiple digital bit streams” over optical fiber by means of lasers or highly coherent light from light-emitting diodes (LEDs) [REF]. [subir] points out that SDH and SONET are virtually the same, with major difference in terms of market penetration between the two – SDH being the most used one.
2.3 Need for Green Optical Networks

Hasan et al. [2010] put the point forward by quoting the basic fundamentals of physics that states that since photons have “zero rest mass”, “weak photon-to-photon interaction” and are $10^6$ times larger than electrons, they tend to have a greater footprint and power consumption in a network where the optical transmission is only the case, in other words in all-optical networks. Since the Internet consumes 4% of the electricity produced, among which the routers and other network equipments consume 14.8% of the total Internet energy consumption which is likely to go up by 21.8% by 2020 Xia et al. [2011]. Bregni et al. [2011] bring out few more facts about energy consumption in ICT (Information and Communication Technology), where the energy consumption is quoted as 7-8%. Bregni et al. [2011] also predict that the bandwidth requirement will go up by 50-times, in the next 10 years. Since an optical network is generally created to exist for a long period of time, the amount of energy wasted can result in increased operational cost and contribute to green house gas emissions Dharamaveera et al. [2010].

2.4 Outline of the Survey

So far, the survey has introduced the terms that will be used frequently and argued why there is a need for an optical network with a power or energy conservation employed in it. Section 3 starts with an argument on the significance of traffic grooming in energy conservation in optical WDM networks. The next subsection further supports the argument by introducing some of the algorithms that have been proven to conserve energy by exploiting the benefits of traffic grooming. The survey further delves into various models that helped researchers to develop power efficient network design. Section 4 gives an overview of some interesting test beds that the researchers used to carry out their practical experiments. Finally the survey shares some of the important papers introduced in this field so far.

3. ENERGY EFFICIENCY USING TRAFFIC GROOMING

3.1 Why Traffic Grooming

Traffic grooming in general used to reduce the number of OEO conversions Zhang et al. [2010]. This is achieved by assigning traffic with common destination into one entity. The irony is when traffic grooming when employed requires electrical multiplexing and OEO conversion, but it is used because it reduces the overall OEO conversion. But since OEO is a power consuming process lots of research has been focused on energy efficient traffic grooming Zhang et al. [2010].

As brought up by the paper Hou et al. [2010], employment of traffic grooming for saving power is motivated by the fact that on multiplexing several IP level requests into the high-capacity lightpath can lead to power conservation as the number of low-end router ports used to transmit those requests individually and the times of O/E and E/O conversions are mitigated. In Hasan et al. [2010], the authors put forward the comprehensive vision of IEEE 802.3az Task Force as to “enable new system level energy management techniques that will save energy beyond the network interface”, to catch the attention of the interested readers towards the potential amount of attention given to the problem of energy conservation in networking world.
A critical analysis done in Xia et al. [2010], shows that there are some traffic engineering approaches that can be proved to perform and yield better results than traffic grooming approach, when applied to the problem of energy conservation issue in optical WDM networks. Sometimes traffic grooming can be cost ineffective, and hence some papers such as Dharamaveera et al. [2010] and Cerutti et al. [2010] suggest to incorporate traffic grooming at specific points of the network.

3.2 Algorithms

3.2.1 RWA and Traffic Grooming. In the paper by Wu et al. [2009], the authors divided the whole problem of RWA with traffic grooming into two parts - Routing and Fiber & Wavelength Assignment. The routing was approached using three heuristics. The main purpose of going to this extent was to compare all the three approaches by mix-matching them with the solutions for Fiber & Wavelength assignment.

1. LCP – also recognized as Least Cost Path as introduced in Zang et al. [2000], computes a shortest path for each request.

2. MUP – augmented as Most-Used Path, can be categorized as an algorithm with memory Wu et al. [2009]. This algorithm essentially keeps track of the most used shortest paths and tries to use them as often as possible.

3. OLMUP – better known as Ordered Lightpath Most Used Path, is in the same category as of MUP, with some extra features Wu et al. [2009]. The algorithm works by considering lightpath to be routed as the one that lessens the “incremental cost”, for each iteration. The cost over here can be considered as power or energy. After the LS (Lightpath Selection) Phase, Routing Update Phase (RU phase), which essentially is MUP itself.

This puts the paper into the position where the authors, give a single approach for Fiber & Wavelength assignment. The approach is known as “First Fit” which was introduced in Zang et al. [2000], where the wavelength is selected according to the availability. New wavelength is selected only when the capacity of the current wavelength is full – hence employing the traffic grooming approach.

3.2.2 Power Aware Provisioning (PAP). Power aware provisioning uses an optical bypass, traffic grooming and hybrid strategies, to route traffic on auxiliary graph where the weights on the auxiliary graph are considered to be the power usage Xia et al. [2010;2011]. The auxiliary graph (explained in detail in subsection 3.3.4), here, considers various components of the network that the Xia et al. [2010;2011] contemplate as a contributing factor to the energy consumption and connect them with edges only if they are interacting with one another Xia et al. [2010;2011]. PAP takes the auxiliary graph into consideration after generating the sequence of connection and runs Dijkstra’s algorithm to find shortest path, with weight been the amount of power used by a particular components while performing a certain operation Xia et al. [2010;2011]. The final result obtain from this algorithm is the shortest paths among the components, denoting the minimum amount of energy consumed Xia et al. [2010;2011].

The following figure is the segment of the algorithm for better understanding -
3.2.3 **LUB and RSB.** With the aid of auxiliary graph, authors of the paper by Wu et al. [2009] exploited the advantages of modular network nodes to groom the traffic and achieve energy efficiency. The auxiliary graph along with request allocation heuristics gave a strategy for energy conservation. Authors provided two approaches to request allocation, namely, RSB and LUB. Both algorithms have common purpose of sorting the source-destination pair so that the next few steps of the traffic grooming algorithm can allocate the request and achieve the optimum energy conservation.

1. **RSB** – In this approach Wu et al. [2009] propose sort the source-destination pairs by total demands between the pair.
2. **LUB** – authors Wu et al. [2009] in this approach sort a pair of source and destination according to the utilization of link which is given by the following formula:

\[
Link Utilization = \frac{Total Demand}{Shortest Physical Distance} \tag{2}
\]

The algorithm is described in the diagram.

---

**Algorithm 1 Power-Aware Provisioning**

<table>
<thead>
<tr>
<th>Input:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Connection request set C;</td>
</tr>
<tr>
<td>2) Topology G(V, E);</td>
</tr>
<tr>
<td>3) Number of wavelength per link K;</td>
</tr>
<tr>
<td>4) Power consumption for each operation.</td>
</tr>
</tbody>
</table>

| Output: Total Operational Power P for connection set C. |

1. \( P=0; \)
2. Generate a sequence for the connections;
3. Construct the initial auxiliary graph \( G_A(V_A, E_A) \);
4. Perform link weight assignment on \( G_A \);
5. For each connection \( c \)
6. Run Dijkstra’s algorithm on \( G_A \) between \( s \) and \( d \);
7. If a path can be found with path weight \( P_c \);
8. Decrease the requested bandwidth on the links of existing lightpaths in the virtual topology layer;
9. Decrease one-wavelength bandwidth on physical links in the physical layer;
10. If new lightpaths are set up
11. Add links in the virtual topology layer of \( G_A \);
12. \( P = P + P_c \);
13. Else
14. Block this connection;
15. Return \( P \);

---

**Fig. 3.** [Xia et al. 2011 page 443] Power Aware Provisioning Algorithm
Input: The physical topology and set of requests.
Output: Virtual topology with traffic grooming.
Steps:

1) Sort node pairs in descending order based on total demand (for RSB) or link utilization (for LUB). Assume $L$ represents the sorted list of node pairs.

2) Choose the first node pair, $(s, d)$ from $L$. For each individual request, $r$ from $s$ to $d$, in sorted order of demand, perform the following steps in the AG.
   a) Delete all lightpath links whose available capacities are lower than the demand, $r$.
   b) Find the shortest path, $p$, from the output vertex of the access layer of $s$ to the input vertex of the access layer of $d$. If no such path exists, request $r$ is blocked and removed from $L$. Otherwise, allocate $r$ along $p$. Zero or more lightpath links may be created in this process.
   c) Re-establish the lightpath links deleted in Step a.

3) Delete $(s, d)$ from $L$. If $L$ is not empty, go to Step 2.

Fig. 4. [Wu et al. 2009 page 3] Algorithm for traffic grooming on AG using LUB/RSB sorting approach

3.2.4 TATG. TATG adopts the similar concept to Zhu et al. [2002], with a difference of weight assignment to the edges. The weight assignment adopted by Zhang et al. [2010], is calculated using the following equations.

\[
W_{\text{lightpath}} = \begin{cases} 
  p \times b_r \times h, & h \leq H_l \\
  p \times b_r \times h + P_0(h - H_l), & h > H_l 
\end{cases} 
\]  

(3)

\[
W_{\text{transceiver}} = \frac{(P_0 + p \times b_r)}{2} 
\]  

(4)

\[
W_{\text{wavelength}} = \delta 
\]  

(5)

Here

1) $H_l$ is the holding time of corresponding lightpath which is computed by $\text{latestTearDownTime} - \text{currentTime}$ of the request that is traveling the lightpath.
2) $b_r$ is the bandwidth requested.
3) $P_0$ is the fixed power consumption when the network components which constitute the lightpath are turned on.
4) $p$ is the coefficient of power consumption per additional unit of traffic.
5) $h$ represents the holding time for the request.
6) $\delta$ is a very small number.
Authors Zhang et al. [2010] ran a shortest path algorithm on the network, where the weights assigned to the edges by weight assignment scheme are evoked energy consumption by each edge. In equation (3) the type of energy consumption of a lightpath is determined by the $h \leq H_t$ (traffic dependent) and $h > H_t$ (traffic independent). For the condition $h > H_t$, the lightpath will be kept alive for extra $h - H_t$ duration of time. In (4), a lightpath is created only if corresponding transceiver edge is chosen on the auxiliary graph.

Table I: Important papers with the type of algorithm(s) employed

<table>
<thead>
<tr>
<th>Title</th>
<th>Algorithm</th>
<th>Problem Explored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Efficient Traffic Grooming in Optical WDM Networks Yetginer and Rouskas [2009]</td>
<td>MILP</td>
<td>studied the advantages of power efficient traffic grooming strategy by introducing a new MILP</td>
</tr>
<tr>
<td>Traffic Grooming in Green Optical Networks Energy Awareness in Dynamic Traffic Grooming Hasan et al. 2010; Hasan et al. 2010</td>
<td>ILP &amp; Heuristic</td>
<td>studied the advantages of power efficient traffic grooming strategy</td>
</tr>
<tr>
<td>Power Reduction Techniques in Multilayer Traffic Engineering Puype et al. [2009]</td>
<td>ILP &amp; Heuristic</td>
<td>Using auxiliary graph and traffic grooming, a new approach to energy conservation was proposed.</td>
</tr>
<tr>
<td>Traffic Grooming: A Changing Role in Green Optical Networks Huang et al. [2009]</td>
<td>MILP &amp; Heuristics</td>
<td>extended the traffic grooming problem by adding new constraint of power conservation</td>
</tr>
<tr>
<td>Power Aware Routing and Wavelength Assignment in Optical Networks Wu et al. [2009]</td>
<td>MILP &amp; Heuristics</td>
<td>Explore the energy conservation problem in WDM network by employing adding a constraint of minimizing energy consumption while forming an ILP for RWA problem in a WDM network</td>
</tr>
</tbody>
</table>
3.3 Methodologies/Approaches

3.3.1 Power Consumption Analysis. It’s been observed that many papers present an analysis of power consumption. Yetginer and Rouskas [2009] initiated the power consumption analysis, and provided a very generic mathematical formula that gave the power consumption at component level

\[ P_c = P_0^c + p_c^t(t) \]  \hspace{1cm} (6)

Also in Huang et al. [2009] this concept is extended further and divided in more granular component giving us the detailed picture of energy consumption in optical WDM networks. Xia et al. [2010;2011] have come up with the formula \([P = P_O + P_T \times t]\) that specifically pertains to operational power consumption of the optical network component. In the formula authors represent \(P\) as the power consumed, \(P_O\) as the overhead (fixed), \(P_T\) is the traffic dependent power and finally \(t\) carries a binary value that determines is there exits some traffic or not, therefore \(t \in [0,1]\). They finally retreat to a similar concept shown in Huang et al. [2009] by coming up with the following formula.

\[ P_{Total} = 3P_{ES} + 3P_{EO} + 2P_{OS} + 2P_{TX} + 2P_{AM} + 2P_{RX} + 2P_{OE} \]  \hspace{1cm} (7)

The above equation (3) presented by Xia et al. [2010;2011]represents the granularity of the energy saving problem when traffic grooming is used between two nodes. Authors presented a brief example of traffic been groomed from node A (say) to node B(say) to reach the destination node C(say). \(P_{ES}\) denotes the power consumed during the electronic switching of the optical signal, \(P_{EO}\)represents the power consumption for electronic to optical signal, \(P_{OS}\) is the power consumed when the signal is optically switched. After the signal is been optically switched,
the transponder is responsible to transmit it to the destination/fiber link which consumes $P_{TX}$. The power consumed by the amplifier to amplify the weak signals is presented by $P_{AM}$. The power consumed in receiving the signal is represented by $P_{RX}$. Finally, the $P_{O/E}$ denotes the power consumed when optical signal is converted to electronic signal. The number in pre-pending each symbol is the number of times each operation is performed.

The equation (2) is also adopted by Hou et al. [2010], to evaluate the energy consumed by a lightpath. The equation was expanded by considering various possibilities of energy consumption, e.g. energy consumed by transceiver, power consumption by the router port that connects the OXC, energy consumed by the amplifier, power consumption by transmitting and aggregating ports, etc.

3.3.2 IP-BG. IP-BG stands for “IP with Bypass and Grooming” Bregni et al. [2011]. This method introduces new paradigm to already introduced model of IP-NB (IP with No Bypass) and IP-B (IP with Bypass) Bregni et al. [2011]. This method can be considered equivalent to the concept of sparse grooming introduced in Dharamaveera et al. [2010]. In both papers the authors have talked about grooming when necessary. Since traffic grooming can get expensive in terms of cost as well as power consumption if used at its extremities Dharamaveera et al. [2010]. IP-BG can be solved using ILP Zhu and Mukherjee [2002], by Double Layer (physical + logical) flow formulation. It is considered to me intermediary to IP-NB and IP-B, where the grooming is taken care by IP-NB and IP-B takes care of the optical switching Bregni et al. [2011]. The following figure (Fig.) gives the general idea on how the power is consumed in each case.

<table>
<thead>
<tr>
<th></th>
<th>IP-NB</th>
<th>IP-B</th>
<th>IP-BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILP model</td>
<td>Single layer Multicommodity-Flow-based</td>
<td>Single layer RWA Formulation</td>
<td>Double Layer Flow Formulation</td>
</tr>
<tr>
<td>Switching</td>
<td>Electronic (E)</td>
<td>Optical (O)</td>
<td>Mixed (E &amp; O)</td>
</tr>
<tr>
<td>Grooming</td>
<td>Performed</td>
<td>Not performed</td>
<td>Performed</td>
</tr>
<tr>
<td>Objective</td>
<td>minimize $P_{tot} = P_t + P_c$</td>
<td>minimize $P_{tot} = P_t + P_c$</td>
<td>minimize $P_{tot} = P_t + P_c$</td>
</tr>
<tr>
<td>Constraints</td>
<td>Flow Conservation and Capacity constraint</td>
<td>Flow Conservation, Capacity constraint and</td>
<td>Flow Conservation, Capacity constraint and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda$-continuity constraint</td>
<td>$\lambda$-continuity constraint</td>
</tr>
</tbody>
</table>

Fig. 5. [Bregni et al. 2011 page 481] ILP models of the three architecture along with their power consumption.

In the figure the mathematical symbols represents the power consumption by a network component or an operation, e.g. $P_t$ is the power consumption while transmitting the optical signal, where as $P_a$ and $P_r$ represent the power consumption during the optical switching and optical to electronic conversion respectively Bregni et al. [2011]. The mixing of optical bypass with traffic grooming when ran through an auxiliary graph results in power aware provisioning Xia et al. [2011], where the power is considered to be the minimizing factor. On assigning the arcs of an
auxiliary graph a weight (that would represent amount of power consumed, during optical bypass and traffic grooming) Xia et al. [2011], were able to find the shortest route which meant to have the least weight in total and hence consumes the least power.

<table>
<thead>
<tr>
<th>Title</th>
<th>Problem Explored</th>
<th>Year</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy-Minimized Design for IP over WDM Networks</td>
<td>Work done was the first one to consider and compare bypass and non-bypass performance in terms of energy conservation</td>
<td>2009</td>
<td>Shen and Tucker [2009]</td>
</tr>
<tr>
<td>Traffic Grooming Algorithms for Power Efficiency in IP over WDM Networks</td>
<td>Two heuristics — bypass (single-hop) and non-bypass, presented and compared. Saved energy by traffic grooming with optical bypass</td>
<td>2010</td>
<td>Hou et al. [2010]</td>
</tr>
<tr>
<td>Energy efficiency in telecommunications networks: Link-by-link vs. end-to-end grooming</td>
<td>Considered various traffic including a bypass traffic, to compare the type of traffic grooming</td>
<td>2010</td>
<td>Van Heddeghem et al. [2010]</td>
</tr>
<tr>
<td>Green Multicast grooming based on optical bypass</td>
<td>MGG (Multicast Green Grooming ) along with optical bypassing of the trafficMGG (Multicast Green Grooming ) along with optical bypassing of the traffic</td>
<td>2011</td>
<td>Hou et al. [2011]</td>
</tr>
</tbody>
</table>

Table II. List of work that employed 'Bypass Approach'

3.3.3 ILP. It is a well-known fact that ILP is one of the most employed options available for problem solving in operational research [Kamath 2011]. Some of the core components (problems) of operational research include network flow problem and multi-commodity flow, which can be analogous to some of the problems that the researchers face in optical networks, e.g. Routing and Wavelength Assignment [Kamath 2011]. That said, few of the works included in this survey have also employed ILP as their approach to solve the problem of energy conservation using traffic grooming with the succor of ILP Yetginer and Rouskas [2009] and Zhang et al. [2010]. Yetginer and Rouskas [2009] had three separate objective functions with the same constraints. This was done to achieve optimum solution for to the grooming problem Yetginer and Rouskas [2009]. The first objective function was aimed to minimize the number of lightpaths between a source and destination pair.

\[
L_{\text{min}} = \min \sum_{(i,j) \in Z} b_{ij} \tag{8}
\]
The second ILP achieved minimum number of electronically switched traffic, which ensured minimum number of OEO conversion and hence less energy/power utilization.

\[
T_{\text{min}} = \min \sum_{(i,j) \in Z} \sum_{(s,d) \in Z} t_{ij}^{sd} - \sum_{(s,d) \in Z} t_{sd}^{sd}
\]  

(9)

The third objective function concentrated on minimum power consumption.

\[
P_{\text{min}} = \min P_0 \sum_{(i,j) \in Z} b_{ij} + p \sum_{(i,j) \in Z} \sum_{(s,d) \in Z} t_{ij}^{sd}
\]  

(10)

According to Zhang et al. [2010] the objective of the ILP was to abate the overall power consumption which consisted of a traffic independent part and a traffic dependent part

\[
\sum_{T_a \in T} \left\{ P_0 \sum_{i,j} V_{ij}^{w,T_a} + p \sum_{i,j} \sum_{r \in R} b_r \times \lambda_{ij}^{r,T_a} \right\} \times |T_a|
\]  

(11)

Following table gives a brief view of the papers that have employed ILP as one of the approach to traffic grooming along with energy conservation problem.
<table>
<thead>
<tr>
<th>Title</th>
<th>Problem Explored</th>
<th>Year</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-Aware Routing and Wavelength Assignment in Optical Networks</td>
<td>The PA-RWA problem can be defined using an integer linear programming (ILP) formulation</td>
<td>2009</td>
<td>Wu et al. [2009]</td>
</tr>
<tr>
<td>Energy-Minimized Design for IP Over WDM Networks</td>
<td>an energy-minimized model was introduced that had the sole objective of minimizing total energy consumption associated with various network components that included IP routers, amplifiers, and WDM transponders.</td>
<td>2009</td>
<td>Zhang et al. [2010]</td>
</tr>
<tr>
<td>Power Efficient Traffic Grooming in Optical WDM Networks</td>
<td>Three separate objective functions provided with the general motive of performing power efficient traffic grooming</td>
<td>2009</td>
<td>Yetginer and Roukas [2009]</td>
</tr>
<tr>
<td>Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks</td>
<td>Objective function included two parts – traffic independent and dependent. One of the constraints considered the virtual topology.</td>
<td>2010</td>
<td>Zhang et al. [2010]</td>
</tr>
</tbody>
</table>

Table III. List of work that employed 'ILP'
3.3.4 Auxiliary Graph. Without reiterating the definition and the use of auxiliary graph, this section gives a tabular representation of the work that incorporated auxiliary graph in the research work.

<table>
<thead>
<tr>
<th>Title</th>
<th>Problem Explored</th>
<th>Year</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Efficient Time-Aware Traffic Grooming Routing Networks</td>
<td>Introduced a new category of Auxiliary Graph that consisted of VTP and WP, which further assisted in traffic grooming.</td>
<td>2010</td>
<td>Zhang et al. [2010]</td>
</tr>
<tr>
<td>Energy awareness in Dynamic Traffic Grooming</td>
<td>Auxiliary Graph representing the physical architecture of a node.</td>
<td>2010</td>
<td>Hasan et al. [2010]</td>
</tr>
<tr>
<td>Green Multicast Grooming Based on Optical Bypass Technology</td>
<td>Multicast auxiliary graph.</td>
<td>2011</td>
<td>Hou et al. [2011]</td>
</tr>
</tbody>
</table>

Table IV. List of work that employed 'Auxiliary Graph'
4. TEST BEDS

Every research work has a purpose which is best displayed in the form of results and comparison [Caprette 1997]. The main purpose of is to present and illustrate ones findings. To arrive at a conclusion, “a rigorous, transparent, and replicable” [Caprette 1997] testing of scientific theories are required. Test beds provide a platform for such experimentation.

It was observed that most of the research work tend to use two famous test beds available - USNET and NSFNET. The table below provides the list of work that used USNET, NSFNET or 6-Node Network. The deviation came when different authors of varying papers considered the bandwidth capabilities or randomness of a traffic request etc.

Table V: List of work with the 'Test Bed' Used

<table>
<thead>
<tr>
<th>Title</th>
<th>Test Bed</th>
<th>Problem Explored</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Grooming: A Changing Role in Green Optical Networks</td>
<td>14 Nodes NSF. Request and capacity where randomly changed</td>
<td>Authors extended the traffic grooming problem by adding new constraint of power conservation</td>
</tr>
</tbody>
</table>
| Energy-Minimized Design for IP Over WDM    | (1) Number of nodes: 6  
(2) Number of links: 8 (n6s8),  
(3) NSFNET: 15-node 21-link network  
(3) USNET :24-node 43-link  
Traffic Demand:  
$X\{20,40,...,120\}$ Gbps Physical Distance between two amplifiers: 80km. Average power consumption per IP router port: 1000 W  
Power consumption per transponder: 73 W  
Power consumption per EDF A: 8W | The research concentrates on the minimizing the energy consumption issue by presenting a MILPs and Heuristics for network which carry IP over WDM. The approaches thrive on concepts like virtual topology and traffic grooming design. |
| Power-Aware Routing and Wavelength Assignment in Optical Networks | No clear mention of a specific test bed was made. | Concept of Power Aware RWA (PA-RWA) was introduced. |
| Power Efficient Traffic Grooming in Optical WDM Networks | Since only ILP is investigated, authors considered 6 node network, with no. of links = 16, wavelength support = 3, with capacity of 48. | studied the advantages of power efficient traffic grooming strategy |
| Energy awareness in Dynamic Traffic Grooming | NSF networks: 14-node, 21-link network AND 24-node, 43-link network Bandwidth = OC-192, Demands = OC-3,12, 48 or 192 | Using auxiliary graph and traffic grooming, a new approach to energy conservation was proposed. |
| Traffic Grooming Algorithms for Power Efficiency in IP over WDM Networks | USNET: 24-node and 43-bidirectional Links Distance between in-line amps =80 (kilometers) and Et (Energy consumed by transceiver) =73 (W), Ed (Energy consumed by amp)=8 (W), Eoep = EAP = ETP =1000 (W) Zhang et al. [2010] Bandwidth = OC-192, STS-1, OC-3, OC-12 or OC-48 Wavelengths per fiber = 4 and 6. | two heuristic algorithms proposed - Power-aware Grooming with Single-hop based on Wavelength Integrated Auxiliary Graph (PGSWIAG) and Power-aware Grooming with Multi-hop based on Wavelength Integrated Auxiliary Graph (PGMWIAG). Auxiliary Graph was employed for grooming. |
| Designing Power-Efficient WDM Ring Networks | Same as above | the authors discuss techniques that can be employed to introduce energy saving capabilities in WDM networks |
| Green Multicast Grooming Based on Optical Bypass Technology | USNET, # of wavelengths/link = 2, Bandwidth = OC-48, Demands = OC-1 | Multicast auxiliary graph, using optical bypass |
5. DISCUSSION OF PAPERS (ANNOTATIONS)

5.1 Power Efficient Traffic Grooming in Optical WDM Networks

Problem Addressed. In the paper Yetginer and Rouskas [2009] the authors had studied the advantages of power efficient traffic grooming strategy.

Previous Work. In Gupta and Singh [2003] authors propose putting the network components to sleep using two approaches to conserve energy; one of them been uncoordinated sleeping mode, where the network components make their own sleeping decisions, on the contrary, in coordinated sleeping mode the sleeping decisions are conjoinly made.

In Chabarek et al. [2008] the authors extend an idea of coordinated sleeping of network component, by adapting the concept in power-aware routing algorithm, where the route adjustment can be made on “relatively coarse time scales” Yetginer and Rouskas [2009].

In Gunaratne et al. [2008], the author propose a technique called Adaptive Link Rate (ALR) to conserve energy in Ethernet Networks.

In Huang et al. [2009] the authors have come up with two ILP formulations, that supports energy conservation using Traffic grooming technique. The authors of the above mentioned paper also provide a heuristic for one of the two ILP formulation.

Shortcomings. No shortcomings are listed by the authors.

The New Idea. By highlighting the current approaches to traffic grooming authors prove the point that traffic grooming is an ideal tool for energy conservation. The two approaches are – minimization of number of lightpaths and minimization of electronically routed traffic. Since the problem of traffic grooming is NP-Complete, the authors present their problem for a small sized network only. The authors point out that the maximum energy consumption is observed in the equipment used in the network. The authors further classify the energy consumption of a network component into two categories; traffic independent power consumption and traffic dependent power consumption.

The Algorithm. Based on above classification, authors come out with an equation that is the summation of all the power consumption. Eventually the equation will become the base for the ILP formulation that the authors design. Authors pick two ILP formulation from Konda and Chow [2001] that minimizes the number of lightpaths – with the objective of minimizing the number of active ports. The second ILP formulation is responsible to minimize the amount of traffic that is electronically switched. Finally, the authors come up with an objective function that minimizes the total power consumption.

Experiment And Analysis. The authors analyze the power-consumption in all three of the ILPs presented in the paper. The authors had considered a very small network that consisted of 6 nodes with 16 links. They considered 3 wavelength channels for each link. Each wavelength had the capacity of 48. The authors also considered the fixed power consumption of each lightpath as 0.25 and the maximum power consumption by a lightpath as 1. After successful simulation the authors were able to compare all ILPs based on number of lightpaths used, amount
of electronically routed traffic (by each traffic grooming method) and finally the authors compared the extra amount of power that the first two ILP consume when compared to the third one (invented by the authors).

**Results.** The final result that the authors claim to achieve is that the proposed ILP consumes much less energy (power) compared to the current approaches of traffic grooming. Finally, they summarize their result by highlighting that only considering the minimization of lightpaths or minimization of amount of electronically switched traffic is not enough for realizing energy conservation in optical WDM network, and therefore a power-aware traffic grooming strategy is required.

### 5.2 Traffic Grooming: A Changing Role in Green Optical Networks

**Problem Addressed.** An interface based formulation is presented for traffic grooming problem, with a primary focus to reduce the energy ingestion of an optical network.

**Previous Work.** While discussing other research works that have raised concern and given some solution for the energy conservation issue in optical networks, authors mention the paper [Keslassy et al. 2003; Tucker 2006], with the comment that the paper is first of its kind to introduce the concept of putting network devices to intelligently to sleep. Authors refer to Gupta and Singh [2003], to prove the point that bypassing an optical signal not destined for a node, is the most efficient approach in context of energy conservation.

**Shortcomings.** From the papers [Keslassy et al. 2003; Tucker 2006] the authors express the issue of how little work has been done on the processing of the optical traffic at packet level in terms of power consumption.

The authors also point out that lately the energy conservation issues has been mostly been dealt in wireless domain, as the equipments in this domain generally work on battery.

**The New Idea.** The authors approached the problem by formulating two types of ILPs, one of them been flow based which used the ECR metric, and calculated the power consumption for optical bypassing, circuit switching and packet processing. The second ILP was based on Interface based, where the authors calculated the power consumption at a network node level. They decomposed the power consumption at a network node into a static and a dynamic part where the power consumption at the dynamic part always varied.

**The Algorithm.** The authors proposed three types of Heuristic Algorithm to tackle the NP complexity of the ILPs. The three algorithms were Path based, Linked Based Heuristics and Flow Deviation. All these concentrate on putting ports or network devices to sleep after the traffic grooming has been performed.

**Experiments and Results.** The authors considered a NFS network to prove their ILPs and Heuristics. The authors claim that in their experiment when the number of nodes where increased significantly, the path based heuristic completely stops showing any result but uses the least number of interfaces when compared to link based and flow deviation heuristics. When the flow deviation approach is used with the link based heuristic, the number of nodes used by the heuristic decreases by
Fig. 6. [Huang et. al. 2009 page 6] Average number of interfaces switched on as a function of traffic load at connectivity 0.4.

12%. The figures Fig 1. and Fig 2. give a better visual explanation.

Fig. 7. [Huang et. al. 2009 page 6] Average number of interfaces switched on as a function of traffic load at connectivity 0.8

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5.3 Traffic Grooming in Green Optical Networks

*Problem Addressed.* In the paper Hasan et al. [2010] authors have come up with an algorithm that reduces the number of active components by looking into the physical modular structure of the node.

*Previous Work and.* Authors refer to Gupta and Singh [2003] to point out the attempt made to save power in wire-line network but the concentration been till now only given to Ethernet. Referring to a CISCO manual [CISCO 2009] on CRS-I equipped with Cisco Integrated Services, allows inactive modules to go to sleep.

*Shortcomings.* The only shortcoming that the author mention that the current works are have till now only concentrated on Ethernet technology, but not on optical, which the author thinks is more prominent.

*The New Idea.* The authors have employ auxiliary graph to represent the relationship between the wavelength, lightpath and physical components like multiplexers de-multiplexer. Then they go further and divide the auxiliary graph into layers based on functionality of each relationship.

*The Algorithm.* After establishing their auxiliary graph based on the relationships, authors proposed two kinds of request allocation protocol Request Size Based and Link Utilization Based, these two algorithms had the responsibility to perform the traffic grooming.

*Experiments and Results.* The experimental results; the authors claim are based on the two algorithms proposed by them. Since energy conservation is the issue they also claim to consider assigning the cost to the nodes based on the few known facts of the Cisco routers they considered for the experiments. The authors claim that the algorithms work better, i.e. show more energy awareness, when the traffic is low. The “traditional approach” of the RSB and LUB algorithm, where there is no energy awareness involved, seems to conserve a lot less energy than the algorithms proposed by the authors. The table in the figure shows the results that authors claim to have achieved. The table clearly shows that when no algorithm is used (100% active) the networks (14 nodes and 24 nodes) the energy consumption is at its peek when compared to the networks where the algorithms are deployed. Overall, RSB with energy awareness gives better energy conservation.

<table>
<thead>
<tr>
<th>Networks</th>
<th>Schemes</th>
<th>Energy Usage (KWh)</th>
<th>Cost (thousand US $)</th>
<th>Saving (thousand US $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 nodes</td>
<td>100% active</td>
<td>4262870</td>
<td>469</td>
<td>0</td>
</tr>
<tr>
<td>14 nodes</td>
<td>RSB-traditional</td>
<td>4007335</td>
<td>441</td>
<td>28</td>
</tr>
<tr>
<td>14 nodes</td>
<td>RSB-energy aware</td>
<td>2922315</td>
<td>321</td>
<td>148</td>
</tr>
<tr>
<td>24 nodes</td>
<td>100% active</td>
<td>11421351</td>
<td>1256</td>
<td>0</td>
</tr>
<tr>
<td>24 nodes</td>
<td>RSB-traditional</td>
<td>6672702</td>
<td>734</td>
<td>522</td>
</tr>
<tr>
<td>24 nodes</td>
<td>RSB-energy aware</td>
<td>4762803</td>
<td>524</td>
<td>732</td>
</tr>
</tbody>
</table>

Fig. 8. [Hasan et. al. 2010 page 4] Annual power conservation.
5.4 Green Provisioning for Optical WDM Networks

Problem Addressed. In the paper Xia et al. [2011] authors have discussed various approaches to energy aware optical networks using auxiliary graphs - one of them been traffic grooming. Authors also extend their work by proposing an power aware scheme and compare them with traffic grooming and direct-lightpath approach.

Previous Work. Authors refer to Gupta and Singh [2003] to grab the attention of the readers towards the various approaches that can be incorporated in greening the Internet. Authors have listed three papers that are closely related to their work and showed the comparison in a tabular format as shown in Table 1.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Category</th>
<th>Topology</th>
<th>Approach</th>
<th>Overhead</th>
<th>Traffic Grooming</th>
<th>Power Model</th>
<th>Network Layer</th>
<th>Traffic Model</th>
<th>Objective Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huang et al.</td>
<td>Network Planning</td>
<td>Mesh &amp; Ring</td>
<td>R.P &amp; Heuristic</td>
<td>N/A</td>
<td>Enabled</td>
<td>Operation Level</td>
<td>Virtual</td>
<td>Static</td>
<td>Number of interface pairs</td>
</tr>
<tr>
<td>Coretti et al.</td>
<td>Traffic Engineering</td>
<td>Ring</td>
<td>R.P</td>
<td>N/A</td>
<td>Enabled</td>
<td>Component Level</td>
<td>N/A</td>
<td>Static</td>
<td>N/A</td>
</tr>
<tr>
<td>Our work</td>
<td>Traffic Engineering</td>
<td>Mesh &amp; Ring</td>
<td>Heuristic</td>
<td>Considered</td>
<td>Enabled</td>
<td>Operation Level</td>
<td>Physical &amp; Virtual</td>
<td>Static</td>
<td>Dynamic</td>
</tr>
</tbody>
</table>

Table 1. [Xia et al. 2011 page 440] Comparison among the works that focus on energy consumption of Optical WDM Networks

Shortcomings. No shortcomings are listed by the authors.

The New Idea. Authors argue the importance of their research interest by delivering the fact that power consumption (specifically operational power consumption) attains its peak when there is sudden increase in the traffic. They further explain the dependence of operational power consumption on the provisioning strategy (e.g. traffic-grooming, direct bypass, etc.).

The Algorithm. In their problem definition the authors have stated their objective as to minimize the overall operational power consumption while provisioning the connection. Authors claim to achieve their objective by coming up with a auxiliary graph that represents a both physical optical network topology and the underlying logical topology. Authors then apply power aware provisioning algorithm on the AG. In the power aware routing (using either Traffic Grooming or Optical Bypass) author had first assigned the weights to each node of the AG and then perform Dijkstra’s Algorithm on it.

Experiments and Results. In their power consumption analysis, authors had considered overhead as one of the power consuming factor, for which they come up with the ratio as follows -

\[ R_O = \frac{P_O}{P_T} \] (12)

where \( R_O \) is the “Ratio of Overhead” and \( P_O \) and \( P_M \) are the “two operation-dependent” parameters.
Authors compare three algorithms - traffic grooming, direct lightpath, traffic grooming with power and classify the comparisons in the following categories, while changing the overhead ratio -

1. Power Versus Network Load: Here the authors come up with a chart (Fig. 4) where the network load is varied against power consumption to see the behavior of the three algorithm in different traffic load. The overhead ratio is kept constant at 0.2. The proposed algorithm seems to work the best among others.

2. Power Versus Ratio of Overhead Ratio: Here the authors have analyzed the behavior of the algorithms (Fig. 5) in varying overhead ratio. Here also it has been observed by the authors, that since the power aware algorithm, combo of the two algorithms, it always consumes the least power.

3. Full-Wavelength Versus Sub-Wavelength Traffic: Even in variable traffic pattern with constant overhead of 0.2 the power aware algorithm works the best (Fig. 6).

4. Power Versus Network Load with limited Network Capacity:

5.5 Greening the Optical Backbone Network: a Traffic Engineering Approach

Problem Addressed. In the paper Xia et al. [2010], authors present a traffic engineering approach to energy conservation in optical backbone networks. Just like in Xia et al. [2011] authors try to reduce the operational power of the network with a difference that this time they are trying to reduce the power consumption at optical backbone level. According to the authors the main objective of their research is to provision a service in an optical backbone network while taking care of the operational power consumption.

Previous Work. Authors refer to Shen and Tucker [2009] to point out the contribution made so far in the field of energy aware traffic engineering.

Shortcomings. The two shortcomings that the authors mention about the paper are; the traffic model considered in Shen and Tucker [2009] is only static, which very unrealistic, and overhead is not considered, which according to the authors, considered to be the major contributing factor in the operational power conservation.

The New Idea. The idea in this paper is very much similar to Shen and Tucker [2009] with the only difference that the authors of this paper have analyzed the power consumption at much more granularity.

The Analysis and Algorithm. Authors give a brief and transparent explanation of the theory on which their power consumption analysis was based on. The authors considered 3 nodes A, B and C, where the traffic is suppose to travel from A to C. Since authors considered an improvement over the traffic grooming problem, they explain and analyze the power consumption that occur in traffic grooming and come up with a mathematical equation where power consumptions at all the DXCs of the nodes + OEO transmission at all nodes + Electronically Switched (ES) traffic at all nodes + Optically Switched traffic at all nodes. Authors further considered the power consumption by amplifiers and receivers at the WDM terminals. Considering
the above analysis, the authors constructed an auxiliary graph and came up with a power aware algorithm that incorporated traffic grooming.

**Experiments and Results.** Authors used 24-node US mesh network with 43 fiber links. Each of the links contained 100 wavelengths with capacity of OC-192, with wavelength availability divided in OC-1s. They distributed the demands uniformly into OC-1, 2, 3, etc. Authors used the same overhead ratio as in Shen and Tucker [2009]. The results that authors came up with show that the power aware traffic grooming algorithm saves a comparable amount of energy against a traditional traffic grooming algorithm.

5.6 Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks

**Problem Addressed.** In this paper Zhang et al. [2010], the authors analyze the static and dynamic traffic grooming problem with added constraints of time awareness and energy minimization.

**Previous Work.** The authors list out few papers that relate to the authors’ work, some of them also signify the work done so far in the field of energy conservation using traffic grooming. The paper Shen and Tucker [2009] presents us with MILP and heuristics for energy-efficient static traffic grooming. Huang et al. [2009] Proposes two models – flow based and interface based. Yetginer and Rouskas [2009] Presents ILP formulation based on interface based model. Hasan et al. [2010] and Hasan et al. [2010] also analysis the problem of energy minimization in optical networks where the traffic grooming is employed.

**Shortcomings.** The authors point out the fact that the previous works missed one of the factors that effect energy efficiency of traffic grooming. The factor being time, the authors consider it as a contributing as energy consumption is the product of both power and time. Hence, not ruminating the aforementioned fact - according to authors - may lead to just reduction of power consumption, not energy.

**The New Idea.** The idea in this paper is very much similar to Shen and Tucker [2009] with the only difference that the authors of this paper have analyzed the power consumption at much more granularity. Authors proposed static and dynamic traffic grooming with time awareness and energy conservation. They formulate an ILP for the static traffics where the tear-down time of a connection is known beforehand. The dynamic traffic is dealt with a layered Grooming Graph.

**The Analysis and Algorithm.** The authors presented an energy consumption model which was based on Interface based formulation. Authors claimed that the model irrelevant of it been interface based; can be applicable to any other energy conservation model. The modification in case of static traffic would be to change the objective function accordingly and in case of dynamic traffic, the change would occur in the Grooming Graph.

Since the request is known beforehand in case of the static traffic, the authors considered the incoming request as a set of time, source, destination and bandwidth demanded. Based on the traffic request set, authors came up with an ILP which had the objective to minimize the total energy consumed. The energy consumption included a traffic independent and dependent part.
For dynamic energy and time aware traffic grooming authors used Grooming Graph that assisted the authors to efficiently assigned weights to the traffic request based on the strategy and then groom traffic so as to achieve the minimum power consumption. The proposed algorithm is TATG (Time-Aware Traffic Grooming). Finally, authors adopted two separate policies to compare the energy efficiency – MinLP (which tries to minimize the number of new lightpaths to be established to fulfill an incoming request) and Min-hops (that tries to minimize the number of lightpaths that a connection traverses).

**Experiment and Results.** Authors compared their proposed algorithm in terms of energy consumption and blocking probability. The figures clearly show that in case of high traffic load the proposed algorithm (TATG) does not perform well compared to other two algorithms. The authors try to establish the point that time awareness is an important factor to achieve energy efficiency and different strategies should be adopted accordingly. Authors also conclude that “Minimizing power consumption may not necessarily save energy”.

5.7 Designing Power Efficient WDM Ring Networks

**Problem Addressed.** In the paper Cerutti et al. [2010], the authors discuss techniques that can be employed to introduce energy saving capabilities in WDM networks. Authors argue their point by introducing traffic grooming capabilities in WDM metro rings and then comparing their design with CAPEX-optimized designs.

**Previous Work.** Since this paper is one of its kinds, no relevant references were made by the authors.

**Shortcomings.** No shortcomings are listed by the authors.

**The New Idea.** In the paper the Cerutti et al. [2010], authors considered three different network architectures which had different levels of optical transparencies and grooming capabilities. The three different architectures are namely – FG (First Generation): every node is electronically processes traffic, i.e. no grooming is involved. SH (Single Hop) nodes have electronic bypass capabilities, and only the traffic with the destination of node is processed electronically, otherwise other traffic are forwarded as optically bypassed data, MH (Multi-Hop): here the traffic is groomed at selected nodes and hence the OEO occurs in few of the nodes.

**The Analysis and Algorithm.** The authors came up with a “power budget” model, where they considered power efficiencies of various components of an optical WDM network. Authors discussed the power consumption at OEO interfaces, optical layer (which is proportional to the number of OADM ports) and electronic layer (which is proportional to number of DXC ports). The next thing to consider was the different network architectures, which is already discussed above.

**Experiments and Results.** The experiments were carried out by the authors where with a goal to compare the various WDM network architectures, which were designed to achieve optimum CAPEX or OPEX minimization. In Fig[#] authors clearly show that, for MH, the power consumption is least when minimization of number of OEO interfaces is considered as against minimization of number of...
wavelength, hence showing that the traffic grooming if considered as an option to minimize the energy will prove to be optimum. Authors came up with a general conclusion that minimizing CAPEX can lead to minimization of OPEX (which was the case for FG and SH).

5.8 Effect of Sparse Grooming on Power Consumption of Optical Networks

Problem Addressed. In this paper Dharamaveera et al. [2010], authors have presented a new methodology that allows the WDM network to employ a less switched traffic model by placing routers strategically which in turns conserves energy.

Previous Work. The authors referred to few work done in the area of sparse traffic grooming, but the papers never considered the energy consumption as a constraint.

Shortcomings. The papers referred by the authors never considered the energy consumption as a constraint.

The New Idea. Authors presented a new approach to strategically place the backbone routers and perform sparse grooming of the network traffic to reduce the energy consumption in the optical WDM network. They further extended the research study by comparing the power consumption of an OCS (Optical Circuit Switched) network with and without backbone network.

The Analysis and Algorithm. The network model represents an all-optical OCS (Fig. 1). Gravity Model was used to generate traffic. For RWA, authors claim that, any the methodology can adapt any type of scheme. Traffic grooming done at IP-level, added an ability to reduce the number of lightpaths established between source and destination access nodes. The energy conservation in the network was carried out by strategically placing the routers in the network if the following criterion was met:

ACM Journal Name, Vol. V, No. N, Month 20YY.
where $P_C$ is the power consumed by the core routers, and $P_L$ represents the power consumed by the reduced number of lightpaths due to sparse grooming.

Experiments and Results. Authors successfully showed that by placing backbone routers at lower population density areas considerably decreases the energy consumption.

5.9 Power-Aware Routing and Wavelength Assignment in optical networks

Problem Addressed. Wu et al. [2009] explore the energy conservation problem in WDM network by employing adding a constraint of minimizing energy consumption while forming an ILP for RWA problem in a WDM network. They further add a traffic grooming constraint of minimizing the number fiber used (re-using the fibers). The authors call their problem of approach – Power Aware RWA (PA-RWA).

Previous Work. No relevant paper mentioned.

Shortcomings. No shortcomings were listed by the authors.

The New Idea. Authors introduced the concept of power conservation while solving the RWA problem. They added an extra constraint of traffic grooming hence making sure that fibers are reused.

The Analysis and Algorithm. Authors approach the RWA, by using an antique technique, i.e. by splitting the problem into two sub-problems. The first sub-problem solved the issue of routing and the second one solved the problem of assigning wavelengths and fiber. For the first sub-problem authors compared three different approaches – Least-Cost Path (for each request a shortest path is computed), Most Used Path (every time a path is computed, its cost is updated for the next routing computation), Ordered Lightpath Most-Used Path (first a lightpath is selected such that the selection reduces the incremental cost and on the chosen path MU is applied). For the second problem of wavelength assignment traffic grooming is employed.

Experiments and Results. The authors used many scenarios and network model to test the validity of their algorithm. The two network models used were bidirectional ring architecture and random lightpath physical topology. The authors claim that bidirectional ring topology proved to be most efficient in terms of conserving energy when used along with LCP and traffic grooming.

5.10 Energy Minimized Design For IP Over WDM Networks

Problem Addressed. The research concentrates on the minimizing the energy consumption issue by presenting a MILPs and Heuristics for network which carry IP over WDM. The approaches thrive on concepts like virtual topology and traffic grooming design.

Previous Work. The heuristics are extended from single-hop and multi-hop grooming strategies in the traditional traffic grooming, as presented in Zhu and Mukherjee [2002] to employ the energy efficiency.
Shortcomings. No shortcomings were listed by the authors.

The New Idea. The authors developed an MILP model that concentrated on minimizing the overall energy consumption, of an IP over WDM network, by minimizing the total number of components used in the network. The components that authors considered to be the most power consuming were the IP routers, optical amplifiers (EDFAs), and transponders. The also pointed out that if the energy is minimized then it takes care of the cost too.

The Analysis and Algorithm. Authors introduced ILP and two heuristics. The ILP had the an objective function of minimizing the energy for the given network graph that represented the physical topology. It had three constraints that would ensure the objective function is met -

(1) All the incoming requests are served.
(2) Limit the maximum number of wavelength used (per fiber).
(3) Limit the number of IP router ports used.

The heuristics were Single hop and multi-hop traffic grooming with added functionality of energy conservation.

Experiments and Results. The authors used many scenarios and network model to test the validity of their algorithm. The two network models used were bidirectional ring architecture and random lightpath physical topology. The authors claim that bidirectional ring topology proved to be most efficient in terms of conserving energy when used along with LCP and traffic grooming.

5.11 On the Energy Efficiency of IP-over-WDM Networks

Problem Addressed. The authors of the paper Van Heddeghem et al. [2010] brought forward the comparison between link-to-link traffic grooming and optical end-to-end traffic grooming

Previous Work. The authors derive the idea of comparison between the aforementioned traffic grooming architectures, from the paper Aleksic [2009b], which shows the discrepancies.

Shortcomings. No shortcomings were listed by the authors.

The New Idea. The authors developed an MILP model that concentrated on minimizing the overall energy consumption, of an IP over WDM network, by minimizing the total number of components used in the network. The components that authors considered to be the most power consuming were the IP routers, optical amplifiers (EDFAs), and transponders. The also pointed out that if the energy is minimized then it takes care of the cost too.

The Analysis and Algorithm. Authors introduced ILP and two heuristics. The ILP had the an objective function of minimizing the energy for the given network graph that represented the physical topology. It had three constraints that would ensure the objective function is met -

(1) All the incoming requests are served.
(2) Limit the maximum number of wavelength used (per fiber).

(3) Limit the number of IP router ports used.

The heuristics were Single hop and multi-hop traffic grooming with added functionality of energy conservation.

*Experiments and Results.* The authors used many scenarios and network model to test the validity of their algorithm. The two network models used were bidirectional ring architecture and random lightpath physical topology. The authors claim that bidirectional ring topology proved to be most efficient in terms of conserving energy when used along with LCP and traffic grooming.

5.12 Energy Efficiency in Telecommunications Networks: Link-by-Link vs. End-to-End Grooming

*Problem Addressed.* The authors of the paper Van Heddeghem et al. [2010] brought forward the comparisons between link-to-link traffic grooming and optical end-to-end traffic grooming.

*Previous Work.* The authors derive the idea of comparison between the aforementioned traffic grooming architectures, from the paper Aleksic [2009a], which shows the discrepancies between circuit switching (similar to end-to-end traffic grooming) and packet switching (similar to link-by-link traffic grooming). Baliga et al. [2009] showed the per-customer power consumption in WDM links, access, metro and core network.

*Shortcomings.* No shortcomings were listed by the authors.

*The New Idea.* Authors used a pan-European core network to monitor realistic traffic demands for two types of aforementioned traffic grooming algorithms and compare the efficiency of the algorithms in terms of energy consumption.

*The Analysis and Algorithm.* Link-by-link traffic grooming: since all the traffic demands on a link are considered to be one, authors proposed to implement the grooming using TDM, where the O-E-O needs to performed when converting all the optical demands to electronic signals to perform the grooming at electronic domain. To determine type of equipment best suited to achieve the least energy consumption – authors consider each node to be equipped with only one high end core router.

End-to-end traffic grooming: Authors found out that all the traffic between two nodes are considered to be one in this type of traffic grooming, authors proposed 3 types of traffic for which they determined the equipment that will likely result in less consumption of energy. The types of traffic were: Add/Drop Traffic, Bypass Traffic and Regenerated Traffic. The following figure gives the big picture of how each type of traffic behaves:
Fig. 10. [Van Heddeghem et al. 2010 page 3] Example traffic in a node, consisting of link traffic $T_{\text{link}}$, bypass traffic $T_{\text{bypass}}$, regenerated traffic $T_{\text{regen}}$, and add/drop traffic $T_{\text{add/drop}}$.

**Experiments and Results.** The authors claim to have reached the conclusion that End-to-end grooming support the energy conservation in better manner than the link-by-link traffic grooming. To reach the conclusion, authors considered few core routers’ power consumption like the T-series routers. Then they proceeded into calculation of the Node Power consumption, for link-by-link Grooming. In case of End-to-end grooming the authors had to consider both – power consumption at Core Routers and power consumption at Regeneration Equipment. WDM Link Power consumption was calculated with the assist of the following formulae:

$$P_{\text{link}} = P_{a}.N_A = P_{a}.N_{\text{fibers}} \cdot \left( \left\lfloor \frac{L_{\text{link}}}{80 \text{ km}} \right\rfloor + 2 \right)$$

(14)

Where power consumption $P_{\text{link}}$, is calculated for a link with length $L_{\text{link}}$ on which resided $N_A$ number of amplifiers. Authors claimed that $P_{\text{link}}$ is a function of $L_{\text{link}}$ and $N_{\text{fibers}}$, which denotes the number of fibers per link.

Finally, the result obtained over 5 years of monitoring traffic groomed using both type of traffic grooming approaches individually, to reach the afore-mentioned conclusion.

5.13 Energy Saving and Cost Reduction in Multi-granularity Green Optical Networks

**Problem Addressed.** Using traffic grooming and optical bypass (leading to less number of OEO conversions) authors of the paper Wang et al. [2011] try to solve the Energy Consumption issue in optical networks.

ACM Journal Name, Vol. V, No. N, Month 20YY.
Previous Work. Authors point to the papers [Shen and Tucker 2009; Yetginer and Rouskas 2009; Huang et al. 2009; Hasan et al. 2010; Van Heddeghem et al. 2010; Hou et al. 2010] to reflect the new algorithms proposed to effectively reduce the energy consumption in an optical network, by combining all traffic with low bandwidth demand to into few bigger bandwidths (lightpaths) using traffic grooming and use bypassing of the traffic that may result in less utilization of equipment and hence cut down the power consumption at the same time cut some cost.

Wang et al. [2011]Authors give more specific explanation of the work done in Shen and Tucker [2009] to bring forward claims made in Shen and Tucker [2009]. In Shen and Tucker [2009], mention that the two problems of saving the energy and reducing cost are similar in nature. A similar approach is considered in Yetginer and Rouskas [2009], where the authors came up with an ILP which has the objective to cut the energy consumption by reducing the number of OEO ports for a digital cross connect switch (DxCs).

In Huang et al. [2009], heuristics are introduced to solve the energy consumption problem using two approaches - flow based (traffic dependent) and interface based (traffic independent). The interface based approach is implemented using three methodologies - path based, shortest path routing and link based algorithm. Work in Hasan et al. [2010] contributes a graph based heuristic with an objective to increase the number of idle state components. Authors refer to Van Heddeghem et al. [2010] to point out the importance of the appraisal made between link-to-link grooming and end-to-end grooming.

Authors of Hou et al. [2010] give two types of traffic grooming along with optical bypass, which are, single hop optical traffic grooming and multi hop hybrid traffic grooming.

Shortcomings. The only general short coming in the above papers that authors point out is that the papers don’t consider the optical network at a granular level, which involves detailed inclusion of components of an optical network. Referring to [Shen and Tucker 2009; Yetginer and Rouskas 2009], authors highlight the fact that the papers were not successful in bringing forth operational heuristic algorithms despite knowing the fact that MILPs and ILPs, cannot solve the problem for big networks.

In the works [Huang et al. 2009; Hasan et al. 2010; Van Heddeghem et al. 2010] authors point out that the problem of energy conservation is tackled by categorizing the problem into two classes – traffic dependent and traffic independent, authors suggest that the two classes should be jointly considered in future.

For the work done in Hou et al. [2010], the authors point out the fact that energy conservation in modules, chassis and line card ports in core router are not considered.

The New Idea. Authors had used combination of various problems to solve the cost and energy conservation problem. The various problems considered in Multi-Granular grooming were - regular grooming approach on VTAG and waveband switching. The combination of the two problems and consideration of energy consumption of various network components allowed authors to come up with a new approach which they termed as Multi-Granular Traffic grooming using optical by-
The Analysis and Algorithm. Authors considered the energy consumption at aggregating port in the core router, OEO port at DXC, switch port at MG-OXC, for the calculating the energy consumption for a traffic dependent scenario. For traffic independent scenario, the energy consumption was calculated at core router interfaces, transceiver and fiber link. Authors presented a Virtual Topology Auxiliary Graph (VTAG), to calculate the energy consumption at virtual topology level. Authors implemented the multi-granular grooming mechanism in coalition with traffic grooming and waveband switching. The multi-granular grooming was achieved by dividing the VTAG into two auxiliary sub-graphs – the wavelength sub-graph was used to groom all the low-rate traffic to a lightpath on this sub-graph, the lightpaths were further groomed on the wavelength auxiliary sub-graph.

Experiments and Results. Authors claim to have reached a conclusion that single hop traffic grooming strategy consume more energy than the multi hop traffic grooming, which they further proved by the following graph –

![Graph Comparison](image)

Fig. 11. [Wang et al. 2011 page 682] Comparison of energy efficiency between multi-hop hybrid grooming and single-hop grooming with network load increasing.

After simulating the results for waveband switching, authors came to a conclusion regarding energy consumption and cost of operation. The comparison was done based on the types of grouping available in waveband switching. In case of Average Port Cost (APC), same sub-path grouping proved to cost less than end-to-end grouping. Adversely, in case of Average Energy Consumption, same sub-path...
consumed more energy than end-to-end. The graphs below proves the above claims made by the authors.

![Graph showing APC comparison](image1)

Fig. 12. [Wang et al. 2011 page 683] Comparison of APC between end-to-end grouping and same sub-path grouping with waveband granularity increasing

![Graph showing ACE comparison](image2)

Fig. 13. [Wang et al. 2011 page 684] Comparison of ACE between end-to-end grouping and same sub-path grouping with waveband granularity increasing

Authors claim that their multi-granular grooming approach, allowed them to achieve the optimum solution for cost reduction problem. They compared the results with traditional integrated and single hop multi grooming.
5.14  Green Multicast Grooming Based on Optical Bypass Technology

Problem Addressed. Using multicast grooming and with help of auxiliary graph, authors of Hou et al. [2011] formulate a unique approach to energy conservation in optical networks known as Multicast Green Grooming (MGG).

Previous Work. Authors refer to the work showed in Hasan et al. [2010] and Yetginer and Rouskas [2009], to bring forward the initiative taken in by them. In Shen and Tucker [2009], the authors effectively implement MILP and analyzed how expedient optical bypass is, in terms of energy conservation when a large amount of IP-Level traffic needs to be handled. Authors indicate the comparison made between to link-by-link grooming and end-to-end grooming to come with the result that the later can end up saving 50% more energy than the former. Authors got the idea of including network constraints like number of Add Drop Multiplexer (ADM), number of OEO and number of wavelengths, for a formulation of energy conservation system, which is divided in to 3 layers, optical layer, circuit layer and packet layer, from Huang et al. [2009]. In Hamad and Kamal [2010], the authors present the scheme to save power by solving the multicast routing problem, by dividing the problem into two parts.

Shortcomings. The only shortcoming that in Hou et al. [2011] put forward is the fact that in Hamad and Kamal [2010] the problem of multicast routing is solved without using traffic grooming, hence the energy conservation is seen more in the approach employed by the authors as compared to traditional one presented in Hamad and Kamal [2010].

The New Idea. The authors claimed that their work is the first one to address the problem of energy conservation through multicast grooming. The authors introduced the concept of multicast grooming by enforcing four policies that would make sure that the network that incorporates the proposed MGG, uses the available resources efficiently at the same time making sure that least amount of energy is consumed. Integrated graph (IG) was used to implement the heuristic.

The Analysis and Algorithm. The IG was divided in to 3 layers, where the nodes in physical layer and wavelength layer were connected among themselves by wavelength link and the nodes in virtual layer were connected through lightpath link. All layers are inter-connected through virtual links. The algorithm consisted of initialization of IG according to the physical link. When a traffic demand appears at a node the route is calculated according to the four policies that would ensure the effective utilization of the resources and then record the info into the IG. After performing the operation of filtering and path determination, the resources are allocated to the multicast demand.

Experiments and Results. The authors consider the 24 nodes and 34 links USNET network as their test bed, with each link having 2 wavelengths and bandwidth of OC-48, with the assumption that each node is equipped with Grooming and Multicast Capable OXC. The four policies described by the authors were used to categorize the Multicast Grooming in four categories, where MGG used all four policies, MG.1 uses policies (1 + 3 + 4), MG.2 uses (1 + 4) and finally MG.3 used (1 + 3). The authors claimed that the MG.3 had the highest blocking probability,
to prove their point they present with the following graph.

Fig. 14. [Hou et al. 2011 page 116] Blocking probability in different network loads.

Authors considered different network components and strategies to observe different effects of loads on each categories of multicast grooming. The network components considered are transceiver, amplifier and core routers; and the strategies were testing the energy consumption with and without bypass. Authors claim to observe that core routers tend to consume the maximum energy among the network components. In the field with optical bypass, MG.3 tends to work the best, in terms of energy conservation. Following are the graphs to prove the above statements.
Fig. 15. [Hou et al. 2011 page 116] (a) Average energy consumption of transceiver in different network loads, (b) Average energy consumption of amplifier in different network loads, (c) Average energy consumption in different network loads.
5.15 Energy-Awareness in Dynamic Traffic Grooming

**Problem Addressed.** The key impact of this paper Hasan et al. [2010] is that the authors introduce energy-awareness in dynamic traffic grooming and indicate that modular nodes offer considerable energy-savings in network procedures.

**Previous Work.** This paper quotes the comprehensive vision of IEEE 802.3az Task Force [IEEE] as to “enable new system level energy management techniques that will save energy beyond the network interface”, to catch the attention of the interested readers towards the potential amount of attention given to the problem of energy conservation in networking world. Authors also raise some praise for the modular structure of novel nodes by referring Chabarek et al. [2008]. To bring out the significance and the common use of traffic grooming in WDM networks, when it consists of sub-wavelength granularity (which it generally does), authors refer to the paper Mukherjee [2006].

**Shortcomings.** Authors’ only complaint is the work that they were able to find so far didn’t come up with any heuristic, as the ILPs are NP-hard.

**The New Idea.** Authors considered modular network equipment (router, transponder in other words nodes), to exploit few advantages of the modular architecture of the nodes, like better power management, better fault tolerance and facility for air-cooling. Since the paper considered the energy consumption issue in optical domain, the authors specifically mused on modular architecture in the photonic ADM. Authors reduced the OPEX by mitigating the power consumption for dynamic request. Power conservation was achieved by the grooming the incoming traffic on auxiliary graph that mapped the modular architecture the node.

**The Analysis and Algorithm.** With the aim of reducing the power consumption for dynamic traffic requests, authors formed a heuristic to groom the traffic with existing lightpaths, with the help of auxiliary graph. The graph represented the physical network architecture. The architecture been modular contained virtual paths between multiplexers, chassis, port etc. The energy consumption of each part of the equipment was considered as the cost for the edges (virtual links) which helped to find the shortest part. The result was compared with traditional grooming where energy consumption was not considered as cost factor for routing the traffic.

**Experiments and Results.** The comparison was made with the traditional approach to traffic grooming where no energy conservation was taken into account. Following graph gives a representation for the result obtained by the authors.
5.16 Traffic Grooming Algorithms for Power Efficiency in IP over WDM Networks

Problem Addressed. The work Hou et al. [2010] present two power-aware algorithms using Single hop and multi hop approaches, with the help of an auxiliary graph. Finally, they compare the performance of the two algorithms to pick the best one.

Previous Work. Authors refer to Shen and Tucker [2009] and Yetginer and Rouskas [2009], stating the work done towards power/energy conservation in optical networks using the traffic grooming technology.

Shortcomings. The authors bring out the shortcomings of the paper by spotting out the fact that in work done so far, researchers have considered MILPs/ILPs and heuristics for small networks, which are only able to handle offline (predefined) traffic requests. Authors argue that generally the requests are dynamic in nature and hence solving the problem of power awareness/conservation in optical networks using traffic grooming technology based on offline traffic requests is just like a "drop in a bucket".

The New Idea. Authors presented a new approach to solve the problem of power-aware traffic grooming by considering dynamic IP over WDM networks. They proposed two heuristic algorithms called Power-aware grooming with Single-hop based on Wavelength Integrated Auxiliary Graph (PGSWIAG) and Power-aware grooming with Multi-hop based on Wavelength Integrated Auxiliary Graph (PGMWIAG) to develop the power efficacy.

The Analysis and Algorithm. The author started with network model that included the analysis of the components that contributed the most in terms of energy consumption. The next phase of the authors’ research included a mathematical equation that was put together with help of analysis done in the first phase of the paper. The mathematical equation essentially calculated the energy consumption by a lightpath.

\[ PC = PC_0 + PC(t) \] (15)

ACM Journal Name, Vol. V, No. N, Month 20YY.
The equation (15), constituted of two parts - traffic dependent and a traffic dependent part respectively.

The calculation of power consumption was followed by formulation of another equation that presented the amount of energy saved by the employment of traffic grooming.

\[ SP = SP_{tps} + SP_{oer} \]  \hspace{1cm} (16)

The equation (16), \( SP \) represented the saved power, \( SP_{tps} \) was power saved at transporting ports after traffic grooming had been applied and the last term \( SP_{oer} \) represented the power saved in due to the reduced OEO on employment of optical bypass.

After the above formulation the next article that followed was the derivation of grooming and routing algorithms, which included two approaches – single-hop and multi-hop, implemented on auxiliary graph.

*Experiments and Results.* For the purpose of testing the theory, the authors considered few parameters that would reflect the effectiveness of the algorithms discussed so far. Performances of Average Power Consumption (APC), Average Saved Power (ASP) and Power Ratio (PR) for PGSWIAG and PGMWIAG on various situations were considered. PR was the ratio of the total power consumption over the total saved power, hence smaller PR induce power efficiency in grooming. Authors claim that their results depicted a smaller APC for PGMWIAG than that of PGSWIAG. The above statement is supported by the following charts.

Authors also claim to have observed that extra power that was consumed by the transceivers can be saved in PGMWIAG. The also claim that the power consumption of amplifiers in PGMWIAG is similar with that in PGSWIAG. The simulation carried out by the authors also show that, ASP of PGMWIAG appears to be significantly smaller than that of PGSWIAG. The authors proved the above claim by presenting the readers with the following chart.
5.17 Reducing NGN energy consumption with IP/SDH/WDM

Problem Addressed. In this paper Feng et al. [2010], the authors tackle the problem of increasing energy efficiency in the current visions for Next Generation Networks.

Previous Work. Authors refer to the papers Baliga et al. [2009] and Shen and Tucker [2009] to point out the fact that a major work has been done to signify the energy conservation capabilities in optical layer (SDH and WDM), when traffic grooming is used.

Shortcomings. Authors point out that the researchers have not yet considered the effects of using SDH as auxiliary tool for grooming in addition to the grooming capabilities of IP router.

The New Idea. In the paper, authors explore the current visions for next generation Networks (NGN). The authors argue that the removal of the legacy SDH transport layer will result in lower energy efficiency the authors provide analysis by comparing three different network architectures: IP/WDM, IP/SDH/WDM and SDH/WDM.

The Analysis and Algorithm. After presenting equation for payload utilization, authors presented three network architectures namely,

1. IP/WDM – where the grooming was performed at IP level only.
2. IP/SDH/WDM – where the grooming was performed at both IP as well as SDH level.
3. SDH/WDM – where the grooming was performed at SDH level only.

Experiments and Results. The experiments were performed to see the payload carrying capacity of each type of network architecture, in unison with the energy conservation capacity of each. Authors claim to have achieved a significant gain in energy saving in case of SDH/WDM network architecture, but with least payload utilization. In case of IP/SDH/WDM, the payload utilization was 53% (same as IP/WDM) but it consumed half as much power as IP/WDM.
5.18 Energy Efficiency in Telecom Optical Networks

*Problem Addressed.* The paper presents a survey of various work done in the field of optical network to reduce energy consumption and improve the OPEX. The paper also discusses various opportunities that some research works have already identified and few other that are been proposed in aforementioned area of interest.

*Previous Work.* Authors refer to Ajaykumar and Ghosh [2008], to set the tone of significance for the traffic grooming technology in designing a cost effective optical WDM network.

*Shortcomings.* No shortcomings were listed.

*The New Idea.* Authors presented a lock, stock and barrel of approaches available for energy conservation in their survey. Among the heap of research work aimed towards the energy conservation authors isolated the importance of traffic grooming. The whole paper was divided into five levels of energy conservation - component, transmission, network, and application. The main idea behind this paper was to study the energy efficiency of optical networking technologies and focus the region of discussion around energy consumption data and energy conservations approaches in three network domains - Core, Metro and Access.

*The Analysis and Algorithm.* In this survey paper the authors have summarized the various energy saving approaches that are currently been incorporated in various optical research areas. In the paper the authors divided the energy consumption in optical network into five levels; namely –

1. **Component level:** where all optical processing occurred. Referring to Tucker [2006] and Tucker [2011] authors were able to come to a conclusion that, the components like optical buffers, switching fabrics, and wavelength converters are been developed that can reduce the energy consumption to a significant level.

2. **Transmission level:** referring to Tucker [2011] the authors came to a standpoint from where they could tell that research work on energy efficient transmission is in progress.

3. **Network Level:** referring to Song [2009] the authors mention the investigation that was carried out in resource allocation, green routing, long-reach optical access networks; to bring in energy efficiency in network level. The authors mention their main objective of the survey is to focus on “the energy-saving approaches at the network level” Zhang et al. [2010]. The authors then further divide the network level into three more domains: core, metro and access. The authors further clarify their intention by mentioning that the survey will mainly focus and discuss the various approaches in all the three domains. Authors’ analysis on each domain is discussed briefly as follows:

   a. **Core:** After providing a brief introduction to this domain, authors summarized the energy consumption of network components of the core network and claimed that the optical switching is more energy efficient than electronic switching. The authors dwell further into the energy-conservation in core network by classifying the various approaches of energy consumption in core network into four categories.
i. “Selectively Turning Off Network Elements” Zhang et al. [2010]: According to authors there are three approaches to this solution:

A. Switching of the idle nodes Chiara viglio et al. [2008].
B. Switching off the idle links Chiara viglio et al. [2008].
C. Switching off the idle line cards Idzikowski et al. [2010] and Zhang et al. [2010].

ii. “Energy-Efficient Network Design” Zhang et al. [2010]: Considering Shen and Tucker [2009] and Ceuppens [2009], as examples, the authors claim that energy efficiency can also be achieved by introducing energy efficient architectures during the network design phase.

iii. “Energy-Efficient IP Packet Forwarding” Zhang et al. [2010]: Referring to Chabarek et al. [2008], authors conclude that energy aware packet forwarding can be used to lower the energy consumption at IP Layer. Considering the proposal in Li et al. [1996], authors added another approach to energy efficient IP packet forwarding by pipeline forwarding. The last approach which contributes further to energy saving in context of IP packet forwarding; that the authors discuss is the optical implementation of the time-driven paradigm from Pattavina et al. [2003].

iv. “Green Routing” Zhang et al. [2010]: Referring to Chabarek et al. [2008], the authors highlight the energy-aware routing scheme which tends to consider the line card/chassis reconfiguration. Giving further insight, by the support of the above paper, authors compare the non-energy-aware routing with energy-aware routing to ultimately conclude that the latter is more energy efficient. The authors forge ahead on the same note by referring to another paper (Cianfrani et al. [2010]), which studies how OSPF can be adapted in green routing.

v. Traffic Grooming: Though author has considered traffic grooming as the integral part of “Green Routing” Zhang et al. [2010], this annotation considers the traffic grooming approach to the issue of energy-conservation in optical network separately. Referring to ILP formulations in Yetginer and Roussas [2009], the authors discuss the significant energy saving that can be achieved with energy-efficient traffic grooming. Authors have also referred to Huang et al., which gives a MILP and heuristic approach to RWA to minimize the energy consumption by minimizing the number of interfaces of lightpath. The author further discusses the investigations presented in Xia et al. [2010] and Xia et al. [2011], about grooming traffic in optical backbone networks. Authors discuss two more approaches in energy efficient traffic grooming, where one of them (Puype et al. [2009]) presents an energy efficient traffic grooming approach at the lightpath layer, and the other paper Hasan et al. [2010] present the energy-aware dynamic traffic grooming problem. Finally the authors summarize all the approaches to green routing in terms of algorithms, energy cost, necessity of change in network architecture (retrofit), degree of energy savings, and many other categories.

ACM Journal Name, Vol. V, No. N, Month 20YY.
(b) Metro Networks: the authors listed some of the network elements along with their energy consumptions. Based on the analysis provided in Cerutti et al. [2009], the author came up with a conclusion that MH (Multi-Hop) networks are way better than all-optical SH (Single-Hop) networks in terms of energy efficiency, due to the fact that the MH networks are more flexible to perform multiplexing in an energy efficient way.

(c) Access Networks: The authors considered the access network as “last mile” of a telecom network that connects the end user to Central Office (CO), hence the author states that they have highest share of energy consumption. The authors have listed some of the network elements involved in access network in table 4 alongside their energy consumption. Based on the data and discussion provided in Baliga et al. [2008], the authors conclude that PON and point-to-point optical networks are the most energy efficient access network alternatives. The survey further provides with some detailed discussion and comparisons of types of networks incorporated in access networks, e.g. PON (further classified into GPON and EPON), xDSL, WOBAN and Long-Reach PON (LR-PON) in terms of energy consumption and research made so for making the listed networks more energy efficient. Authors also discuss the possibility for maintaining the QoS in parallel with energy efficiency.

(4) Data Center: Authors have also quoted the importance of data centers in terms of mammoth amount of data (traffic) these have to manage to support various kinds of telecom applications. As the optical technologies tend to form an important part of the data centers’ infrastructure and the amount of energy consumption that the data center contribute made authors concentrate their discussion on energy-efficiency of these data centers. The authors classified the role of optical network in data centers’ infrastructure in two types of connection levels:

(a) Inter-connection level: where the data is productively routed through re-configurable optical networks. Authors list few of the technologies that introduce the flexibility in the network – GMPLS (Generalized Multi-Protocol Label Switching) and ASON (Automatically Switched Optical Network). Referring to the work done in K. Ley and Nguyen [2009], authors highlight the importance of load distribution in order to conserve energy.

(b) Intra-connection level: this level accentuates connections between boards, chips and memories of the data servers. Authors claim that the optical technology can play an important role in solving the various problem in intra-connections like system synchronization, accurate clock distribution etc. Authors quote some work done in Kant [2009] towards power control of high speed network intra-connection.

Authors also discuss some other miscellaneous approaches like location of data centers near the sites where renewable source of energy are available, single power control to multiple data centers and power benchmarking framework for network devices.

(5) Application level: The authors further add to their main objective by stat-
ing that the survey contents will also have the review of some energy-saving approaches in the application and data centers. The authors support their intention of doing so by giving the following reason:
(a) Both domains contribute a significant amount of energy consumption in the field of telecom networks.
(b) Furthermore both domains include optical networking.
Following are the different approaches the authors have discussed in the survey which can be incorporated to ensure energy efficiency in application domain:
(a) Modification of Internet protocol (e.g. TCP/IP) so that they can adapt to energy efficient design.
(b) There was a lot of talk going on to make the idle machine sleep, when they are not in use. To implement the theory, software need to be designed to enable sleep mode in the hardware components of the network.
(c) The hardware on other hand must be able to understand the control signal coming from the software, and hence need to be configured to get the desired behavior.

Experiments and Results. Authors finally claim that coming out with a survey on energy-efficient optical networks is appropriately timed and fruitful to the researchers that are currently working on various aspects of energy-efficiency in optical networks. They further claim that the survey may eventually help researchers to come with new ideas as the survey contains a comprehensive classification with comments on the efforts and approaches in the topic of discussion.

5.19 Power Reduction Techniques in Multilayer Traffic Engineering

Problem Addressed. This paper presents two novel approaches to energy conservation in the optical network using MLTE and traffic grooming.

Previous Work. Puype et al. [2009] refer to Gupta and Singh [2003], to point out the importance of energy awareness in multilayer networks. Puype et al. [2009] also refer to Chabarek et al. [2008], to bring attention towards the fact that, apart from the internal design of the level-3 node, the energy consumption generally depends on two major factor - amount of traffic and size of the packet.

Shortcomings. No shortcomings are discussed by the authors.

The New Idea. Puype et al. [2009] presented and compared two power reduction techniques using the MLTE and grooming strategies. One of them tries to scale down the equipment power requirements and the other introducing inmoderate changes to equipment architecture, which will let the equipment intelligently reduce the idle energy consumption.

The Analysis and Algorithm. Authors first explained MLTE as an engineering technique that used IP layer cost function to perform IP flow routing and construct the logical topology. The routing used shortest path algorithm to route the traffic over virtual IP layer mesh, with the cost/weights on each link corresponding to load on that link. The above method helps in grooming the traffic over virtual full mesh. The weight assignment is decided according to a LLT (Low-Load Threshold). A link was assigned higher weight when the load was below LLT. The theory mentioned
above was derived from one of the older research that authors had worked on. When different values of LLT was used to observe the variation in power consumption, it was observed that at higher levels of LLT, lower power consumptions were observed.

**Experiments and Results.** The paper Puype et al. [2009] considered two techniques of MLTE to combat the energy conservation issue in discussion and then compare them to get the notion of how much reduction in power dissipation is achieved. The first approach was to apply the new CMOS technology and reduce the power consumption in the node itself. The second approach related to improving the whole architecture of the equipment, e.g. scaling back clock rates, power down some parts etc Puype et al. [2009]. The following diagram gave the visual representation of what authors had achieved.

![Diagram showing power scaling and idle power reduction](image)

Fig. 19. [Puype et al. page 3] Power scaling and idle power reduction

The paper Puype et al. [2009] also presented the comparision between Full Mesh, MLTE with 20% LLT and MLTE with optimized LLT. It was observed by the authors that the optimized MLTE consumed the least amount of energy. The figure below gives the proof.
Fig. 20. [Puype et al. page 3] Case study base scenario

No power reduction

<table>
<thead>
<tr>
<th></th>
<th>Power req. (normalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>90</td>
</tr>
<tr>
<td>MLTE</td>
<td>50</td>
</tr>
<tr>
<td>MLTE opt.</td>
<td>40</td>
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</tbody>
</table>
6. CONCLUSION

Optical networks have been studied for many years, and have successfully been able to affect our lives directly or indirectly. Continued use of Internet in our daily lives show the fact that without ISPs being connected through high speed optical cables across continents, we may be stranded with few and unreliable resources to access the Internet. Recently, the need for better power management and designing cost effective network architecture have led to much research in the area of energy conservation in optical networks. Due to the vast availability of solutions to the issue in hand Zhang et al. [2010], this survey concentrates on the approach of traffic grooming. The majority of the papers discussed can be put into categories of: Auxiliary Graph approach - Zhang et al. [2010], Hasan et al. [2010], Hou et al. [2011] and Wang et al. [2011], Bypass Approach - Shen and Tucker [2009], Hou et al. [2010], Van Heddeghem et al. [2010] and Hou et al. [2011], Time-Aware Approach Zhang et al. [2010], Partial Grooming Approach - Dharamaveera et al. [2010] and others. The major achievement was contributed by Zhang et al. [2010], which essentially presented a novel survey on the general broad topic of energy conservation in optical WDM networks hence creating a tacit notion that the survey also included few of the “most important” papers included in this survey. By a thorough analysis it can be concluded that traffic grooming has its merits and demerits, which is making researchers around the world solve the energy conservation problem in harmony with this approach. Some work e.g. Dharamaveera et al. [2010], have critically opposed the very idea of using the full power of traffic grooming to achieve power awareness in WDM networks, on the other hand some suggest that traffic grooming can be used effectively, when combined bypass or time awareness.

A survey will be incomplete without a proper investigation of future work. As a conclusion to this survey, a full analysis of the future works is presented. To make full use of the NGN in future networking, Feng et al. [2010] suggest taking present energy consumption into account, and making the NGN adopt accordingly in the future Feng et al. [2010]. Yetginer and Rouskas [2009] mention a heuristic algorithm that may be able to handle a larger network as an extension to the work done. Van Heddeghem et al. [2010] suggest getting the discernible understanding of the concept, real life data should be taken into consideration. Theoretically Van Heddeghem et al. [2010] the approach presented can be improved if network recovery strategy is also employed. Further study of the two grooming strategies introduced in the paper can be tested for their dependence and convergence of power consumption Van Heddeghem et al. [2010]. Examining the research with real world traffic gives a better understanding of how the theory propose will behave if needed to be incorporated into industry, hence Huang et al. [2009] suggest a future extension to include the electronic domain into the modular architecture presented and to take dynamic traffic into consideration. To implement multicast routing in optical networks; light tree needs to be created using light splitter, which may cause the signal to attenuate and hence Wang et al. [2011] suggest that reducing the use of light splitters can lead to better quality of signal and better utilization of power.
REFERENCES

IEEE Potentially energy efficient Ethernet task force.


ACM Journal Name, Vol. V, No. N, Month 20YY.


