Renewable Energy-Aware Grooming in IP-over-WDM Networks

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Abstract—The optical layer of a network is the energy-efficient technology to provision high bandwidths for data transport. Unfortunately occasional electronic processing, is unavoidable in current networks. This process is much more energy-consuming than the optical transport. Recent research has already yielded great improvements in terms of energy-efficiency. It is, however, observed that increased energy-efficiency typically leads to higher overall energy-consumption. Therefore it is imperative to reduce the environmental impact by additional means: maximizing the use of renewable energy. We present an approach to greenhouse gas (GHG) emission-reducing grooming by considering the heterogeneous distribution of fossil and renewable energy sources. We analyze various two step solutions for the route calculation and lightpath provisioning problem in IP-over-WDM mesh networks. We show that it is possible to reduce GHG emissions at a stable level of energy consumption and improved blocking performance compared to previous energy-efficient solutions.

Index Terms—optical WDM network; IP-over-WDM; grooming; GHG emission; green RWA; energy source awareness.

I. INTRODUCTION

By the year 2020, information and communication technology (ICT) will be responsible for greenhouse gas emissions (GHG) equivalent to 1.27 gigatons of carbon dioxide (1.27 GtCO₂e) [1]. Within the emissions related to ICT, telecommunication networks held a share of 22% in 2011.

Optical networks are inherently energy-efficient; electrical processing however is more energy-consuming. Electrical processing is necessary though, to reduce congestion and cost for transponders and optical fiber. Grooming is used to reduce the overhead of wavelength capacity compared to bandwidth requirements of many applications. Common current wavelength division multiplexing (WDM) technology offers 40Gbps up to 100Gbps of fixed bandwidth per wavelength. To use the capacity provided efficiently several low bandwidth streams are combined into larger streams. This process typically necessitates conversion from the electrical to the optical domain and back (OEO) to handle the data in an electronic switching matrix, for example an IP switch.

The subject of research in the networking community are energy-efficient protocols, technologies, and planning tools. The increase in energy-efficiency achieved in the last decade is spectacular [2]. Evidence suggests, however, that with an increase in energy-efficiency of a commodity, the demand for it increases to the extent where overall energy consumption actually rises [3]. Thus it is important to reduce GHG emissions by not only using energy-efficiently but also by using energy that is generated efficiently with respect to the emissions caused. The electricity grid is not adequately dimensioned to transport large amounts of power over great distances. Recent advances in research [4], [5], [6], [7], referred to as power source-aware approaches, consequently promote the use of locally available power generated from renewable (green) sources.

In this paper we present heuristics that move the OEO conversions and electrical processing towards green nodes in the network. Green nodes are powered by renewable energy sources. Thereby we move electrical processing from nodes that are powered by conventional/fossil power sources, black nodes.

We further reduce the negative impact on network performance at the same cost of previous energy-efficient approaches, which are strongly focused on data processing. The focus of this work in contrast is on data transport.

II. NETWORK, POWER AND EMISSIONS MODEL

In recent years the topic of energy consumption of information and communication technology has gained widespread attention. Essential topics include the accurate modeling and assessment of energy consumption values. In [8] the authors propose a comprehensive model for multi-layer network power consumption.

Several authors explore energy-efficient routing schemes, network planning, and selectively turning equipment on and off as strategies to reduce energy consumption. The authors of [9] present an approach to reduce the energy consumption in a grooming enabled network. They model the network equipment’s power consumption in detail, then use this information to find paths for requests that result in a minimum increase in overall energy consumption of the network.

Very recently, interest has risen in considering renewable energy sources in networking research. Solar power source aware routing with GMPLS is discussed in [7]. The authors of [6] present an approach that makes use of available information on dual power sources for a general RWA algorithm. A multi-layer approach is presented in [10]. For each network location, the authors model partial renewable-energy supply and also partial fossil-energy supply. The trade-off between increased emissions through transport and emission reduction through processing at green data centers is the topic of [11]. In [5] the authors study the combination of energy proportional routers with partial supply of green energy. We have previously presented power source-aware survivability algorithms in [4].

A. Network Model

We consider an IP-over-WDM multilayer network model [12]. The network consists of nodes \( n \in N \) and links \( l \in L \) forming a connected graph \( G \), the topology. A request \( r \) specifies a source and destination \( \{s, d\} \in N \), bandwidth requirement \( b_r \), and a holding time \( t_h \). Data is transported on links via wavelengths \( w \in W \), with a fixed capacity \( C_w \).
We assume bidirectional demands and homogeneous capabilities at all nodes. The physical implementation needs to be specified in order to make assumptions about the power consumption and is described in the next subsection.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{multilayer_node_model.png}
\caption{IP-over-WDM multilayer node model.}
\end{figure}

\textbf{a) Lightpath grooming:} Typically \( b_r \leq \) (or even \( \ll \)) \( C_w \) and we can combine possibly several \( r \) in a single wavelength. This capability is implemented at the IP layer of the node. Figure 1 illustrates the layers of the node. At the source the request arrives on the access layer \( (A_{IN}) \), continues through the IP layer and is possibly combined with other requests. The path continues through the optical-electrical conversion (OEO) layer \( (LP_A) \) and transmission layers to the optical switching layer where the lightpath leaves the node on one of the outgoing fibers \( (LP_{OUT}) \). Note that although we only show one symbolic pair of incoming and outgoing links, there are possibly many more pairs. The number of fiber pairs connected to a node is called the nodal degree \( \delta_n \). At the next node \( LP_{IN} \), several paths are possible:

- If the node is the destination node, the path will lead up through all layers \( LP_D \), IP-switch, to the data sink, connected to the access out port \( A_{OUT} \).
- If the node is not the destination of \( r \) but the terminal node for the specific lightpath, the request is passed to the IP layer where it is possibly again combined with other requests and forwarded on to another \( LP_{OUT} \).
- If the node is an intermediate node to the lightpath, it simply passes the optical switching fabric and leaves the node unmodified.

We assume bidirectional demands and homogeneous capabilities at all nodes. The physical implementation needs to be specified in order to make assumptions about the power consumption and is described in the next subection.

\section*{B. Power Consumption and Greenhouse Gas Emissions}

We adapt the power consumption model from [8]. The authors collected and thoroughly analyzed manufacturer data and compiled an up-to-date database of network equipment power consumption. In current literature many models for network power consumption are used, the above however is one of the most recent and allows convenient modeling of different multilayer configurations. We use this model in conjunction with the emerging GHG accounting standard [13].

The overall GHG emissions \( \Gamma \) in kg CO\textsubscript{2}e (GHG emissions in carbon dioxide equivalent) of the network during a duration \( T \) in hours are calculated as

\[
\Gamma = \int_0^T \left( \sum_{n} (p_n \times \epsilon_n) + \sum_{l} (p_l \times \epsilon_l) \right) dt
\]

where \( p_n = p(n,t) \) is the power consumption in kw of node \( n \) and \( \epsilon_n = \epsilon(n,t) \) the emission factor in kgCO\textsubscript{2}e/kWh. The values \( p_l = p(l,t) \) and \( \epsilon_l = \epsilon(l,t) \) describe power and emission factor of the link \( l \). Depending on the observation level the value might encompass a regional and grid specific energy-mix or can be used to model locations in a binary fashion as green (\( \epsilon \downarrow \)) or even black (\( \epsilon \uparrow \)). To calculate the power consumption \( p(n,t) \) of an entire node we need to sum up the power consumption of different layers: \( p_{IP} \) on the IP layer, \( p_{OEO} \) on the layer connecting IP and WDM layers, and \( p_{WDM} \) on the WDM layer. Unused layers are turned off and do not consume any energy.

\[
p_{IP} = (A_{IN} + A_{OUT} + (LP_D + LP_A) \times \rho_{TX}) \times \pi_{IP}
\]

\[
p_{OEO} = (LP_D + LP_A + 2LP_R) \times \pi_{OEO}
\]

\[
p_{WDM} = (LP_{IN} + LP_{OUT}) \times \pi_{TX}
\]

\begin{align*}
&+ (LP_D + LP_A + 2LP_R) \times \pi_{OXC} + \pi_0
\end{align*}

with \( A_{IN}, A_{OUT} \) functions of \( t \), describing the rate of incoming and outgoing traffic to and from the access side in Gbits. The time dependent symbols \( LP_D, LP_A, LP_{IN}, LP_{OUT} \) and \( LP_R \) stand for the number of added, dropped, incoming, outgoing and regenerated wavelengths respectively. Additionally to the node power we calculate the link power \( p(l,t) \).

\[
p(l,t) = \begin{cases} 
\frac{|d_l|}{d_{OLA}} \times \pi_{OLA} & \text{if } l \text{ is in use} \\
0 & \text{otherwise}
\end{cases}
\]

with \( d_l \) the length of the, \( d_{OLA} \) the reach of the optical line amplifier used (OLA) and \( \pi_{OLA} \) the implementation specific power consumption factor for OLAs. For the values assumed in the simulation the basic transmission rate of the transponders is \( \rho_{TX} = 10 \text{ Gbits} \) and the IP-layer efficiency \( \pi_{IP} = 10 \text{ W/Gbits} \). Implementation specific power consumption factors \( \pi_{OEO}, \pi_{TX}, \pi_{OXC}, \pi_0, \pi_{OLA} \) are 50, 85, 100, 150, 110 Watts respectively. Optical line amplifiers are needed every \( d_{OLA} = 80 \) km. The emission factor \( \epsilon_n = \begin{cases} 
1 & \forall n \in N_b \\
0.01 & \forall n \in N_g
\end{cases} \) kgCO\textsubscript{2}e/kWh. Where \( N_b \) and \( N_g \) designate subsets of \( N \) containing all black or all green nodes, respectively. A key value is \( \pi_0 \); even if a node is not used on any lightpath this is the minimum power consumption. Depending on the implementation of the underlying technology, unused nodes can be assumed to be turned off (only likely at very low traffic rates). Other authors include a factor for \textit{power usage effectiveness} (PUE) to their calculations. We skip this factor since it affects the emission-results proportionally to \( \epsilon \).

\section*{III. GROOMING HEURISTICS}

\textbf{A. Baseline Approach: Energy-Efficient Grooming}

Our approach is the first to consider emission-aware grooming. However, in terms of energy-consumption we will compare
An arriving request is routed on the shortest path along the virtual layer is added to enable the creation of lightpaths, those depending on the weighting, energy intensive grooming and established one. The essence of the first step is, however, that the cost for either power or emission as compared to a newly lightpaths will often be preferred, since they do not increase the request’s source to destination along existing lightpaths, shortest path algorithm to find the shortest feasible route from on one of these weights. For this purpose we use Dijkstra’s function of the request bandwidth or independent, depending (consumption) edges have a known weight which is either set to be the power layer connected to the IP layer. On this auxiliary graph, the a single node in Fig. 1) with the addition of a virtual lightpath the different layers of the node as explained in Section II-A. A virtual layer is added to enable the creation of lightpaths, those may directly connect nodes that are not physically connected. An arriving request is routed on the shortest path along the edges of the auxiliary graph, with the power consumption of the different levels as edge weights. If a request is using physical links, these links are deleted from the graph and replaced by the equivalent lightpath. A request can also, more energy-efficiently than establishing new paths, use remaining capacity on one or more existing lightpaths. We have adapted the approach to the more recent power consumption model explained in Section II-B and use it as an energy-efficient baseline for the newly proposed algorithms. Since the grooming problem is found to be APX-hard [14], we can not readily derive tight bounds for the problem.

B. Energy-Source-Aware Grooming Heuristics

We design the heuristics as a two stage process: route computation and lightpath provisioning. An auxiliary graph is established: Every physical node is expanded into a set of nodes representing the different layers a request has to pass through for different operations (grooming is done on the electrical layer as explained in Section II-A and illustrated for a single node in Fig. 1) with the addition of a virtual lightpath layer connected to the IP layer. On this auxiliary graph, the edges have a known weight which is either set to be the power consumption (P) or emissions (E). This edge-weight can be a function of the request bandwidth or independent, depending on the layer.

The first step of our heuristics, route calculation, is based on one of these weights. For this purpose we use Dijkstra’s shortest path algorithm to find the shortest feasible route from the request’s source to destination along existing lightpaths, available wavelengths on the physical layer that result in new lightpaths, or a combination of both. Note that existing lightpaths will often be preferred, since they do not increase the cost for either power or emission as compared to a newly established one. The essence of the first step is, however, that depending on the weighting, energy intensive grooming and wavelength conversion, can either be discouraged overall or concentrated towards green nodes.

The second step defines the creation of new lightpaths. Only if no route could be found entirely on one or more existing lightpaths is this step necessary; otherwise it is skipped. If any new lightpaths have to be set up that have a length ≥ 1 hop, we propose two methods: minimum lightpaths (Min), and proactive green (Pro). The former simply sets up lightpaths along the entire distance of a continuously available wavelength. Thus, the number of active transponders is kept to the minimum and with that, the power consumption. The latter approach inspects every node along the found path and proactively establishes lightpaths that terminate and re-emerge at every green node. Thus a larger number of lightpaths are created but between nodes where the excess energy-use causes fewer emissions. The motivation is to avoid being forced to terminate lightpaths for subsequent requests at black nodes because of a shortage in available wavelengths.

An example of the lightpath provisioning strategies is illustrated in Fig. 2(b). Assume a request from S to D has been assigned a route taking the power (P) approach. The route includes an existing lightpath from S to A and a continuous wavelength on physical links A-B, B-C and C-D (dashed lines). All nodes except node B are powered by black energy sources. We must therefore provision one or more lightpaths from node A to node D. The minimum approach (P-Min) will establish a single lightpath covering the entire distance, since a continuous wavelength was found (top). This lightpath bypasses nodes B and C all optically via the optical cross connects. The proactive approach (P-Pro) establishes two lightpaths, joined at the green node B (bottom). This increases the overall energy consumption because two more transponders are active for the lightpath and also electronic processing is required at node B. The overall emissions, however are only slightly affected because node B is powered by renewable energy sources.

We study all four combinations of the two approaches at each of the steps, illustrated in Fig. 2(a): Power minimized route with minimum number of lightpaths (P-Min) (which is the baseline approach implemented as described in [9]), emission minimized route with minimum number of lightpaths (E-Min), power minimized route with proactive green lightpaths (P-Pro) and emission minimized route with proactive green-lightpaths (E-Pro).
IV. SIMULATION RESULTS

A. Simulation Parameters

In this section, we discuss the results of simulations for the described network model with the proposed grooming policies. The simulation parameters are 8 wavelengths, with 10 Gbits capacity each, per link using the 14-node NSFnet topology shown in Fig. 3(a). We simulate 100,000 requests with Erlang(3) distributed bandwidth requirements with a mean of 4 Gbits as illustrated in Fig. 3(b). The bandwidth values are censored in such a way that values > 1 are set to 1, since we do not allow traffic bifurcation in our network model. The parameters for the bandwidth-generating function have been chosen such that the 95th percentile is close to one, meaning that the traffic consists of less than five percent of full wavelength requests. Full wavelength requests leave no spare capacity for grooming and are not the target of the approaches presented. The capacity of OEO and IP layer is dimensioned sufficiently large to handle maximum wavelength usage. Request arrival and holding times are exponentially distributed, resulting in a range from the low extreme of arrival rates to extremely high rates. The basic time unit is chosen to be 1 hour as in [13]. We simulate different availability levels of green energy in the network: 0%, 25%, 50% or 75% of the nodes are uniformly selected to be green. The greenness of 0% is useful to compare the approaches for their energy-efficiency. Uniform distribution of green nodes is assumed to test the robustness of our approaches. The emission-factor $\epsilon_l$ for links (used for emissions caused by links rather than nodes) is calculated as the average emission factor of its end-nodes. For the power consumption values see Section II-B. The same random distribution generators are used for all four approaches to enable fair comparison. Results shown are average values of 30 simulated scenarios, to reduce statistical error.

B. Emission Reduction—Energy-Consumption Increase

Reducing GHG emissions of network operations is our primary goal. This comes however at the cost of increased energy consumption.

1) GHG Emissions: The emissions caused during the entire simulated horizon are shown in Fig. 4(a). The values are normalized to successfully routed requests; see Section IV-C2 for blocking probabilities. The vertical axis indicated the emissions over the entire simulation horizon. The arrival rate is shown on the x-axis. It should be noted that for 10$^5$ requests and a basic time unit of 1 h the simulation horizon equals slightly more than a year at a rate of ten Erlang to less than two months at 120 Erlang. The lines represent the different approaches to emission-aware grooming.

For low arrival rates we can clearly distinguish two groups within the four approaches, characterized by the route selection step. The preference for emission reduced paths $E$-Min and $E$-Pro has a high impact since requests are not greatly overlapping spatially and temporally. Therefore the selection of a potentially longer route, i.e., using more resources, for an earlier request does not lead to a restriction in emission reduced-paths for requests arriving at a later time. The lightpath establishing strategy has little impact since at these low rates the probability of using them for a large number of requests (and thereby saving energy and emissions) is also low. As expected $E$-Pro and $P$-Pro result in slightly worse emissions since resources are allocated proactively but remain unused subsequently.

In the area of intermediate arrival rates where congestion starts and average blocking probability rises from 0% to about
10%, we find a change in the performance of the approaches.
As congestion starts to become a problem for the provisioning of requests the potential of proactively established lightpaths is used by algorithms P-Pro and especially E-Pro. Choosing the proactive lightpath allocation results in up to a ten percent improvement over the baseline. As the rates increase and the network becomes highly congested the trend reverses again to the initial situation, and the dominant factors are energy-efficient routes. The scarcity of available wavelengths at these arrival rates results in more and shorter lightpaths irrespective of provisioning method.

2) Traffic Dependent Energy Consumption: In Fig. 4(b) the total energy consumed is shown for the simulated time. Shown are values for 50% green nodes, the other distributions show proportional energy values with the exception of zero green nodes, where all approaches result in the same energy as they all converge to P-Min if all $\epsilon$ have the same value. Comparing Figures 4(a) and 4(b) we can see the trade-off for the lowered emissions: the performance of the approaches is inverted. The approaches E-Min and E-Pro are using longer routes, along green resources, that result in lower black but higher overall energy consumption. The excess (green) energy consumption is within the same dimension as the corresponding emission reductions (~10%). Assuming that green energy can either be produced by the network operators themselves or purchased at a lower price than fossil energy, this excess consumption will be compensated. Pending the introduction of carbon abatement schemes the reduction in fossil energy consumption becomes economically attractive, even with increased green energy consumption.

C. Network Performance

An increase in energy-efficiency and/or a decrease in emissions is unlikely to be achieved without any side effects and trade-offs in terms of network performance when compared to energy-unaware approaches. We study the proposed strategies with respect to blocking performance, i.e., the percentage of refused requests over the simulation horizon, and the average number of lightpaths traversed by successfully provisioned requests, which is also referred to as virtual hop-count.

1) Virtual Hop Count, Delay: With no green nodes, all emission factors $\epsilon$ being equal to one the emission values are identical to the power values and all approaches behave exactly identical.

The expected value of average hops $\bar{h}$ can be calculated from the network parameters [15]. The formula $\bar{h} = \sqrt{\frac{N-2}{3-1}}$ yields an average hop count of 2.45 for the NSFNet topology. The proximity of the observed values indicates that for higher arrival rates many requests are actually routed on the shortest paths from their source to their destination on lightpaths that connect immediately neighboring nodes. A nonlinearity can be observed at a 25% as shown in Fig. 4(c). The emission based path calculation results in a flat average hop count for almost the entire range of arrival rates. In Fig. 4(d) we observe that the average hop count increases considerably, especially for the approaches that performed best in terms of emissions. This is due to the intended application of the heuristics to networks with partial availability of green nodes. With the very large number of green nodes, these algorithms are likely to find a route on lightpaths that avoids black power sources entirely (except for black source or destination nodes) but is also likely to be considerably longer.

2) Request blocking probability: In Fig. 5 the probability of a request being blocked is shown for the different strategies over the range of simulated arrival rates. The results shown are for 50% green nodes, the other percentages yield proportional results. Comparing the approaches by route selection weight, we initially see a clear advantage for power awareness. This is due to the potentially longer paths the emission awareness can create to reach green nodes. We do however see that E-Pro has a performance comparable to the baseline P-Min for rates larger than 60 Erlang. We observe easily that P-Pro has the lowest blocking rates over the whole range, caused by the combination of greedy short (power efficient) route calculation and lightpath provisioning that allows for greater flexibility. Towards the highest simulated rates the network fills up considerably, and the performance of all strategies converge.

V. DISCUSSION, CONCLUSION, OUTLOOK

We have found that for different arrival rates different approaches yield the best results. At intermediate rates where requests sufficiently overlap, the proposed green aware P-Pro grooming method performs well. P-Pro results in significantly lower blocking probability and slightly lower emissions compared to the energy-efficient baseline, while having similar virtual hop count and energy-consumption. For extremely low arrival rates, where requests hardly overlap and extremely high arrival rates where blocking is $\gg 10\%$ green approaches struggle. In those cases, green nodes can be used by E-Min and E-Pro to reduce emissions, but only at the cost of increased energy consumption.

During simulation an observation was made that the results of individual scenarios vary considerably with the random placement of the green nodes within the topology. We will target our future work on quantifying the impact of the spatial green node distribution on the effectiveness of power source-aware network approaches. We will further explore the potential of the time dependent $\epsilon$ and the prediction of green energy availability, complementing time dependent, green-data center selection.
REFERENCES


