Energy-Efficient Lightpath Establishment in Backbone Optical Networks Based on Ant Colony Optimization

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***Abstract*—Energy-aware lightpath routing and establishment in optical backbone networks can reduce energy consumption while preserving performance levels. A heuristic method based on ant colony optimization (suitable for both network planning and operation) is proposed that reduces network's energy footprint by exploiting the basic principles of Swarm Intelligence for finding the most energy-efficient routes from source to the destination node per traffic request and at the same time, for reducing computational complexity to a polynomial level. The reduction of energy consumption is achieved in comparison to other related heuristics under representative backbone network topologies and their actual traffic demand. IP over WDM optical networks are considered for evaluating the performance along with the next generation elastic networks.**

***Index Terms*—Ant colony optimization, elastic networks, energy efficiency, IP over WDM, optical networks, traffic grooming.**

I. Introduction

THE size of the Internet is changing rapidly and its adoption has reached unexpected levels. Energy efficiency in optical computer networks becomes more important as their adoption rate keeps increasing. Optical communications should be efficient and at the same time, consume small amounts of energy. Internet will keep increasing in size [1], with the introduction of new multimedia, cloud, and other bandwidth-hungry services, leading to growth of up to 50 times within the next 10–15 years. Energy consumption of telecommunication networks has recently become a major concern, to the extent that it is conjectured that Internet growth may ultimately be constrained by energy consumption rather than bandwidth. Ensuring low energy consumption per transferred bit and controlling the energy density of large switching centers is regarded as a key economic, environmental, social and political issue [2].

Manuscript received April 5, 2016; revised July 16, 2016 and October 19, 2016; accepted October 25, 2016. Date of publication October 31, 2016; date of current version November 17, 2016. This work was supported in part by the NSRF (2007-2013) under Synergasia 2011/EPAN-II Program "Energy Efficient Optical Network Planning and Operation," and in part by the General Secretariat for Research and Technology, Ministry of Education, Religious Affairs, Culture and Sports under Contract 11SYN_6_1942.

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Digital Object Identifier 10.1109/JLT.2016.2623678

This research work relates to the concept of energy-aware lightpath establishment in optical backbone networks. This procedure initiates with a set of traffic requests that will be routed upon an optical backbone network. The way these requests are routed according to their occupied resources has explicit consequence to network's energy consumption. For that purpose, a method is proposed which is based on Ant Colony Optimization (ACO) and Traffic Grooming [3] practices that can perform energy-aware routing and lightpath establishment, aiming at consuming less amount of energy while preserving performance levels.

The main issue the current research confronts is the low lightpath reuse rate (directly correlated to the power consumption) of existing energy-efficient methods [4]–[6] for designing the virtual topology (set of lightpaths that fulfill logical connections between node-pairs), and the ability to effectively design the topology [7] with energy-efficiency as goal, either through off-line planning or during the on-line operation of a network. Power saving increases when the reuse rate gets higher, but this happens at the expense of the computational complexity. So, the Ant System (AS) is proposed as the means to reduce complexity to a polynomial form, since finding all paths that offer high available bandwidth and are energy-efficient is an NP-Hard problem [8]. This differs from the Shortest Path problem due to the fact that the available bandwidth of a route equals to the lowest available bandwidth of one of its consisting lightpaths. Also, the fact of carrying polynomial complexity makes the proposed method that is explained in Section III, suitable for execution upon large backbone topologies where exhaustive methods fail to deliver results in a feasible time frame. This work differs from other research efforts in this field since it achieves two main goals at the same time, i.e., higher power savings and the ability to create the virtual topology of large backbone networks in a feasible time frame, either on-line or off-line.

Network components that are considered for consuming high amount of energy are the router ports, transponders and line amplifiers [9]. Due to the very high energy consumption of router ports in comparison to the other two component types, most heuristic methods try to reduce their number by reusing existing lightpaths along the way of a new traffic request. That way, many low-bandwidth connection requests can be aggregated into single lightpaths and traverse the network topology, maximizing the utilization of its available resources, i.e., reducing the introduction of new router ports and other physical components along the node path. When the optical signal reaches a router port, Optical-Electrical-Optical (O-E-O) [10] conversion takes place, dissipating considerable amount of electrical power. So, the avoidance of new router ports along path nodes prioritizes too high in this research field. The lightpath bypass strategy is based on the capabilities that the optical physical layer offers. The optical signal that transfers data, starts from a node and is able to bypass intermediate nodes until it reaches its destination. The signal remains exclusively in the optical domain decreasing energy consumption.

Elastic/flexible optical networks [11] gain attraction lately due to the advantages they offer in their optical layer. The ability to adapt to actual traffic needs by utilizing variable-rate transponders and other network components confronts the problem of heterogeneity between traffic demands, leading to efficiency concerning bandwidth utilization. Instead of the traditional grooming in the electrical domain, they also offer grooming capabilities in the optical domain, avoiding that way costly O-E-O conversions. Multicore fibers also attract the attention of the research community lately due to the Space Division Multiplexing (SDM) they exploit, leading to capacity increase.

Both optical network types are considered in this work, i.e., IP over WDM and IP over elastic/flexible networks. The design of the platform defines the level of opacity/transparency in the network. The heuristic methods also have to take advantage of the underlying characteristics. For example, if a non-bypass heuristic is utilized, there will be signal conversions in every node the path consists of. In case of a direct bypass heuristic, all intermediate nodes along the path are bypassed, leaving the signal explicitly in the optical domain. If the platform is elastic, optical grooming is allowed along with electrical. If case of WDM, only electrical grooming is allowed.

II. Related Heuristics

The GreenSpark method [4] uses a typical *k*-shortest path algorithm to find the available paths from source nodes to the destination. These paths are evaluated according to their energy consumption and the most efficient one is utilized for fulfilling each request. The evaluation is based on the path's nodes, links and their load. Every node has variable and fixed power consumption. Also, the distance, the possible regeneration and the number of wavelength channels are taken into consideration. This method is utilized upon an IP over WDM network environment.

The A-ESR method [6] is based on ACO to deliver energy efficiency. It defines a new concept named traffic centrality and re-formulates the Integer Linear Programming (ILP) problem into a simpler one using the defined term. The re-formulated problem can be gradually solved by letting incoming flows be autonomously aggregated on specific links. The algorithm adjusts the energy consumption by tuning the node aggregation parameter b, which can reduce the energy consumption during nighttime hours (at the expense of tolerable network delay performance). Another trait of this algorithm is that it provides a high degree of self-organizing capabilities due to the advantages of the swarm intelligence that artificial ants exhibit. This method is utilized upon an IP over WDM network environment as the previous one.

Multihop Bypass [5] creates lightpaths consisting of multiple hops but it manages to save energy due to the lightpath reuse from previously established connection requests. The basic idea is that no new router port utilization will be required which consumes high energy, in contrast to the other two energy-consuming components (line amplifiers and transponders) that are considered. However, there is a slight penalty concerning light signal propagation delay due to the existence of multiple hops along path's node sequence, where an O-E-O conversion is required and performed. Also, there is elongation of some paths. This method is also utilized upon an IP over WDM network environment.

The MOLG method [12] that is designed for elastic optical networks divides its functionality into 5 grooming operations. Those include all-optical lightpath connections and conventional electrical grooming. Its achieves significant amount of power saving by utilizing sliceable transponders and it concludes that the energy saving does not change linearly while transponder sliceability increases.

III. The Proposed ACO-Split Bypass Heuristic

The proposed ACO-Split Bypass heuristic improves the performance which relates to the power consumption and execution time. In case a route consisting of pre-established lightpaths is found that is capable of carrying the initial request's bandwidth, it is used by creating a multihop lightpath using electrical grooming. If not, multiple paths are found by the ACO mechanism with low complexity that route smaller segments of the initial request's bitrate to the same destination. The maximum number of paths the ACO implementation searches for, is limited to a threshold of value 7. Higher values increase complexity and at the same time, don't contribute to significantly to power saving.

The first stream uses the path sorted according to the evaluation that takes place. If more streams needed, the second one uses the path with the next ranked value and the rest accordingly, until the threshold value is reached. In case there are not enough candidate routes for the whole bandwidth to be routed or the threshold is reached, a new Direct Bypass lightpath -the transfer of data from the source node to the destination remains in the optical domain bypassing the intermediate nodes- is established using a shortest path algorithm between the end nodes, carrying the initial requests' bandwidth. All these paths reach the destination and assembly of the data segments takes place in the electrical domain.

The AS implementation is initialized with the parameters of Table I that are extensively tuned in [8]. First, an initial amount of pheromone is deposited on all virtual topology's edges and equals to the pheromone quantity Q. In case these numbers increase, computation time suffers a linear increase and at the same time, improvement in results is insignificant. Parameters A and B are defined, so that the pheromone level of a neighboring node will be more significant in contrast to the heuristic information of reaching it. Convergence is accelerated that way.

TABLE I
ACO CONSTANTS

Evaporation rate	0.5
Iterations	10
Ants	30
'A' parameter	1
'B' parameter	5
Pheromone Quantity	100

Algorithm 1: Basic ACO outline.

```
set ACO parameters
initialize pheromone levels
while stopping criteria not met do
   for each ant ∈ ants do
      select source initial node
      repeat
         select next node based on decision policy
      until destination node is reached
   end for
   update pheromone levels
end while
```

Then, for every new request an attempt is made for creating a connection based on full reuse of previously established lightpaths. If there is success, energy consumption is minimized due to the absence of new router ports along the path. If not, a Direct Bypass lightpath is established along the shortest path, i.e., Dijkstra's algorithm, between the source and destination node pair. That way, the required transponders and amplifiers along the path are minimized and also there is chance for higher reuse rate of the next lightpath establishments.

Complexity is a key issue. Finding the routes by reusing lightpaths to fulfill a request becomes a difficult problem to solve for large network topologies with low average traffic requests (deeper search domain), wasting CPU and memory resources. Using heuristics based on Swarm Intelligence (such as the proposed one), complexity becomes polynomial [8], i.e., $O(N^3)$. The basic ACO outline (Algorithm 1) shows that complexity is not a hurdle for implementation and deployment. The outer loop represents the number of iterations. The inner depends on the number of ants. Every ant uses a recursive method that cannot be deeper than the number of topology nodes. So, the total algorithm's complexity is controlled with modern computational power.

Apart from the network Planning mode, ACO-Split Bypass is also suitable for Operation. Due to its polynomial complexity, the algorithm can be used to re-design the virtual topology for different parts of the daytime [13] when the network load changes considerably. For example, different virtual topologies are required for the morning, evening, midnight and weekends and can be designed with low use of computing resources before the beginning of each specific time period. Heuristic algorithms that solve NP-hard problems without tackling complexity issues, usually require weeks to execute, and that renders them unsuitable when frequent network load variations exist.

IV. THE ACO-SPLIT BYPASS IMPLEMENTATION

In this Section, the AS metaheuristic [8], [14] is extended by the current research to be able to find energy-efficient paths in a virtual network topology. ACO is utilized to achieve energy-efficient solutions and is presented next in detail. Although Multihop Bypass and the other related heuristics are more efficient than Direct Bypass according to simulation results presented by this research and [5], they leave space for further performance improvement. A new heuristic is required that is capable of taking advantage of adaptive and asymmetric bandwidth share through multiple streams (lightpaths), routed to the destination through different node sequences. The ACO metaheuristic [15] forms the basis for the proposed AS design and implementation, aiming at finding the paths with the highest efficiency (concerning power consumption) that fulfill each request. This leads to the avoidance of any type of brute force techniques that can carry exponential complexity, not suitable for deployment on mid-to-large scale topologies.

The basic idea of the AS is that virtual ants are exploited for finding paths with a specific property, e.g., less distance between physical nodes, in the same way nature guides real ants. A special chemical substance is being deposited upon their path which raises the probability for other ants to follow it during subsequent traversals. When this substance concentrates in high levels on a path, all other ants have high probability to follow it and at the same time, increment it even more. Evaporation takes place on paths that are less traversed. Usually, the path with the highest pheromone concentration (not always the case -that's why this is a heuristic method) is the shortest path [16] (or carries another important property), due to the less amount of pheromone that is able to evaporate because ants deposit to it more frequently. The AS emulates this nature's behavior with satisfying results. When the number of virtual ants and iterations are high enough, the right paths are usually found and this happens under polynomial complexity.

The core of the AS is the basic ACO outline of Algorithm 1. Initiating the procedure, basic parameters are set, i.e., the number of ants that participate and the number of iterations. These parameters are included in Table I. Next, the initial pheromone level is deposited upon all topology edges. The algorithm enters a loop for the predefined number of iterations and all ants are placed (one by one) on the path's source node in an effort to reach the destination node. The choice of the next node is being based on a policy by using a function that returns a corresponding probability number to every neighboring node. At the end of every iteration, pheromone evaporation takes place by a constant factor and the ants that successfully reached the destination node, update the remaining pheromone level by increasing it, upon their traversed path.

The AS implementation is utilized when a traffic request is ready to be fulfilled [17], [18], i.e., it is initialized with all currently established direct lightpaths fed to it, representing the directed graph edges with their currently used bandwidth as weight. The AS launches its basic outline implementation and

Algorithm 2: Pheromone update.

```
{Evaporation part}
for each edge ∈ edges do
   multiply pheromone amount by (1–rate)
   self-assign result
end for
{Increment part}
for each complete ant path do
   for each edge ∈ path do
      add amount of pheromone
   end for
end for
```

tries to find the best suitable path starting from request's source node to the destination. This path will be the most efficient (in terms of a heuristic's functionality that comes close to the optimal solution).

Pheromone levels upon edges vary according to the number of ants that traverse them. Edges contained within popular paths end up having high amounts of this virtual chemical substance in contrast to edges not close enough to candidate routes. When a full iteration is complete, ants that succeeded in finding the destination node deposit an amount of pheromone upon the edges they traversed but before that, evaporation by a constant factor takes place in all topology edges. The amount of increment is tightly correlated to the quality (path evaluation) of each solution. The procedure is described in Algorithm 2.

$$\tau_{ij}\left(t+1\right) = \rho \cdot \tau_{ij}\left(t\right) + \Delta\tau_{ij} \tag{1}$$

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{2}$$

$$\Delta\tau_{ij}^{k} = \begin{cases} \dfrac{Q}{L_k}, & \text{ant } k \text{ travels on edge } (i,j) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Pheromone $\tau_{ij}\left(t+1\right)$ denotes the amount after the update on edge *(i, j)* and $\tau_{ij}\left(t\right)$ the current level. The evaporation rate is $\rho \in [0,1]$. The amount to be added is $\Delta\tau_{ij}$ and depends on the amount every ant deposits, which also depends on the evaluation of its served solution. The predefined quantity of pheromone is Q and L_k is the tour length of ant k. The total number of ants is m. Small evaluation number means more quantity will be deposited, something that boosts good candidate solutions.

An ant chooses the next neighboring node for transition according to a probability array produced by formula 4. The summary of all neighboring probabilities equals to 1. The basic idea in this case is that higher amount of existing pheromone level along with high available bandwidth (interpreted as heuristic information), will raise chances for an ant to choose that neighbor and traverse to it.

$$p_{ij} = \begin{cases} \dfrac{\tau_{ij}^{\alpha} n_{ij}^{\beta}}{\sum_{h\in\Omega} \tau_{ih}^{\alpha} n_{ih}^{\beta}}, & \text{if } j \in \Omega \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

Algorithm 3: Ant recursion.

```
while found paths < threshold do
   if cycle detected then
      end ant traversal
   end if
   if destination node reached then
      store path
   end if
   get physical neighbors
   produce a transition probability to each one
   use probabilities to choose next neighbor
   if no available neighbor then
      end ant traversal
   end if
   self-call with next neighbor as current node
end while
```

Existing pheromone on edge *(i, j)* is represented by τ_{ij}. Heuristic information from node *i* to node *j* is fetched from η_{ij} and equals to $\frac{1}{bw_{ij}}$ where bw_{ij} is the used bandwidth of the lightpath that starts from *i* and ends to *j*. The set of an ant's available neighbors is Ω. It is implied that only neighboring nodes can be visited.

Under the proposed behavior, every ant uses a recursive method, starting from the initial node until it reaches the destination. Then the correct path is returned for evaluation at the end of every iteration as in Algorithm 3. For every neighboring node, the ant produces a transition probability and based on that it chooses the next node. It adds it to the current path and there is a self-call (recursion) until it reaches the destination.

The path evaluation is similar to the one of GreenSpark, but simplified. The node in the formulae is represented by *n*, the edge by *e* and the path by *p*. The used bandwidth of the lightpath is *x*. The device-specific static consumption of nodes is φ_n [19] and B_n is its aggregated bandwidth. The start of the edge is υ and the end ν. The power consumption of the interface on each node which is associated with a wavelength on a specific fiber, when operating at minimum speed without any loss or delay increase, is η.

$$E(x) = \sum_{n\in p} \Psi_n(x) + \sum_{e\in p} \Psi_e(x) \tag{5}$$

$$\Psi_n(x) = a_n(x)\theta_n(x) + (1 - a_n(x))\theta_n(x) \tag{6}$$

$$\theta_n(x) = 2\varphi_n - ln\left(\frac{e^{\varphi_n}}{B_n}(B_n - x) + \frac{x}{B_n}\right) \tag{7}$$

$$a_n(x) = \frac{B_n}{\max B_n} \tag{8}$$

$$\Psi_e(x) = \eta_e^{\upsilon}(x) + \eta_e^{\nu}(x) \tag{9}$$

V. Network Environment

Two backbone network topologies (Figs. 1 and 2) are used for testing the proposed and related heuristics' performance, i.e., the Deutsche Telekom (DT) 12-node network and the Telecom Italia (TI) 44-node reference core network. The execution time

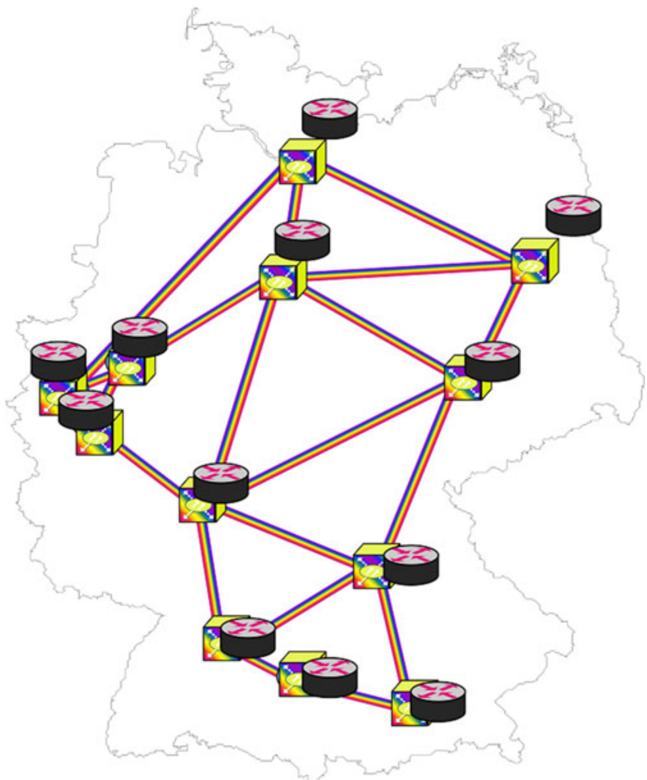

Fig. 1. Deutsche Telekom 12-node topology.

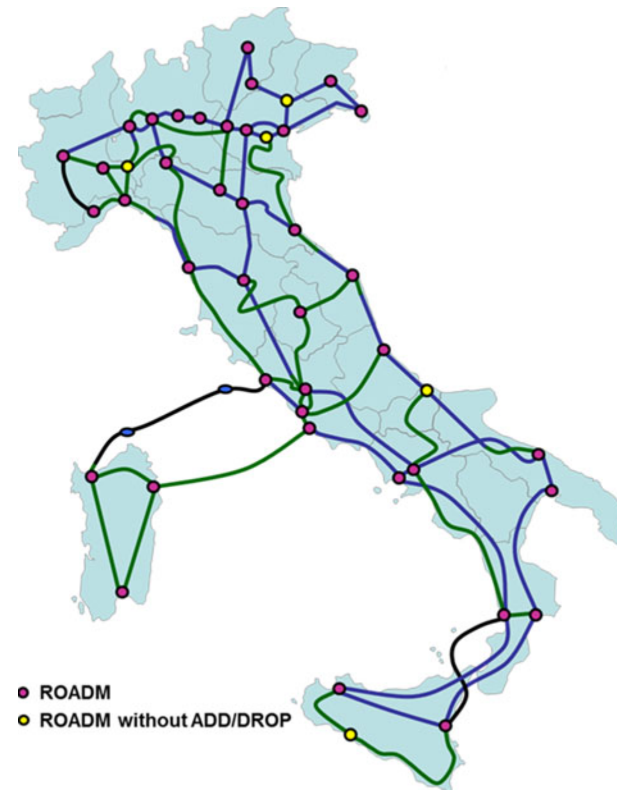

Fig. 2. Telecom Italia 44-node topology.

in the first topology for every configuration and utilized heuristic is typical on a modern CPU, due to the low number of network nodes that keep complexity in low level. The second topology can represent the backbone network of a typical large country, so energy minimization in this topology becomes a key factor. Brute force algorithms cannot be executed upon it because they become resource-hungry. It is important for every new heuristic to be able to execute upon both topologies in a predictable amount of time and resource usage.

The traffic matrices carry bandwidth requirements between node pairs (IP over WDM [20]) and are initialized in the beginning of simulation. Real traffic demand values were used and were provided by the two Telecom companies whose topologies the heuristics are executed upon. Concerning the DT topology, the corresponding traffic model relates to the IP packet load at the peak hour and represents the average traffic volume measured at every quarter of an hour, i.e., opaque to fast load fluctuations. The given traffic matrices refer to the years from 2011 to 2016, the last two of which were foreseen by the company. The volume is assumed to follow the long-standing annual growth rate of 35% flat for all traffic relations. The daily traffic profile shows the typical day-night shape and all traffic relations manifest very similar shapes. Besides these inherent dynamics, the traffic is considered as static. Concerning the TI topology, the traffic demand provided for the network originates from three sources: the optical connectivity required by the IP national backbone, an optical transport network that requires connectivity for the switches and a set of demands required directly at the optical layer by customers, recognized as Lambda Wholesale.

TABLE II
SIMULATION PARAMETERS

Wavelength max bandwidth	40 Gbps
Distance between two line amplifiers	80 km
Available wavelengths per fiber	16
Router port power consumption	1000 W
Transponder power consumption	73 W
Line amplifier power consumption	8 W

The first network installation which is called baseline, is foreseen for the year 2013 and is characterized by a total demand of 18 Tbps. Up to 13% of the traffic requires $1 + 1$ protection. As a result the total bandwidth (working plus protection) to be carried by the optical network is about 20 Tbps. The protection paths are routed independently from the corresponding main paths to the same destination, as different traffic requests.

Concerning the elastic network environment, the transponders utilize up to 10 slices, spectrum width of 25 GHz, a guard band of 2 frequency slots, each slice has rate of 40 Gbps and the modulation format is QPSK. The environment is similar to [12]. The ACO-Split method is adjusted to use the available transponder slices to route traffic. First, it tries to groom optically the connection by using available slices in source and destination nodes. If it fails, it uses the proposed ACO implementation to groom the traffic in the electrical domain. If still no success, new transponders are setup in both source and destination nodes that carry the request's traffic.

Concerning the utilized power model, as energy-consuming components (Table II) are considered the line amplifiers E_e, transponders E_t and router ports E_r, whose consumption values stem from Cisco white papers [9], the data sheets of CRS-1, ONS 15501 and Alcatel-Lucent WaveStar OLS 1.6T. Every physical link includes two (pre and post) amplifiers at its end points and one every 80 km in between. The maximum -per wavelength- bandwidth is 40 Gbps and every fiber can include up to 16 wavelengths. Every neighboring node pair can be interconnected with an unlimited number of fibers -the actual number of which is dependent on the heuristic being applied. The total energy consumption is computed with the formula 10 of [5] in Watt, i.e., the utilized power model of all evaluated heuristics. This formula consists of three parts, i.e., the router port, transponder and line amplifier power consumption. Router consumption is represented from the first part of the formula and it considers not only the consumption related to the number of ports but also the consumption stemming from the aggregation of data from the low-end routers at every topology node. For ensuring the fairness of the comparison to Direct Bypass when performing traffic grooming due to the larger switching capacity requirement, the term D_i (explained next) is utilized. The amount of traffic flows is considered along with the used rate of every flow in respect to the maximum allowed limit.

$$\begin{aligned} E_{\text{Total}} &= E_{r\text{Total}} + E_{t\text{Total}} + E_{e\text{Total}} \\ &= \sum_{i \in N} E_r (D_i + \sum_{j \in N} C_{ij}) + \sum_{m \in N} \sum_{n \in N_m} E_t w_{mn} \\ &\quad + \sum_{m \in N} \sum_{n \in N_m} E_e A_{mn} f_{mn} \end{aligned} \tag{10}$$

D_i is the number of ports that are used to aggregate data traffic from low end routers and equals to $\lceil (\sum_{d \in N} l^{id})/B \rceil$, l^{id} is the traffic demand between node pair (*i, d*) and *B* is the maximum wavelength bandwidth. C_{ij} is the number of wavelength channels (wavelengths that start from *i* and end to *j* with an uninterrupted physical single-hop light connection) upon the lightpath (*i, j*) and the summary denotes how many wavelength units are starting from node *i*and traverse to all other topology nodes. Next, w_{mn} is the number of used wavelengths on physical link (*m, n*). Finally, f_{mn} is the number of deployed fibers on the same physical link and A_{mn} is the number of amplifiers which equals to $\lceil \frac{L_{mn}}{S} - 1 \rceil + 2$. L_{mn} is the distance measured in kilometers and *S* is constant and equals to 80 km (the distance between two consecutive intermediate line amplifiers except the last one). The addition of 2 to this formula covers both amplifiers at the beginning and end of the physical link which perform pre and post light amplification. *N* is the number of topology's nodes.

VI. Results

Both topologies were extensively tested with various demand values with calculation of power consumption at the end of each network snapshot creation under specific load. Concerning the GreenSpark implementation for finding the shortest paths, the open source implementation [21] of the *k*-shortest path algorithm was used. An MILP formulation was solved with specialized software in [5]. Since the WDM network environment is identical, it can be used by the current research as well, for being aware of the upper bound of power consumption in presented figures. All parameters that define the simulation environment and were used in this study can be found in Tables I and II.

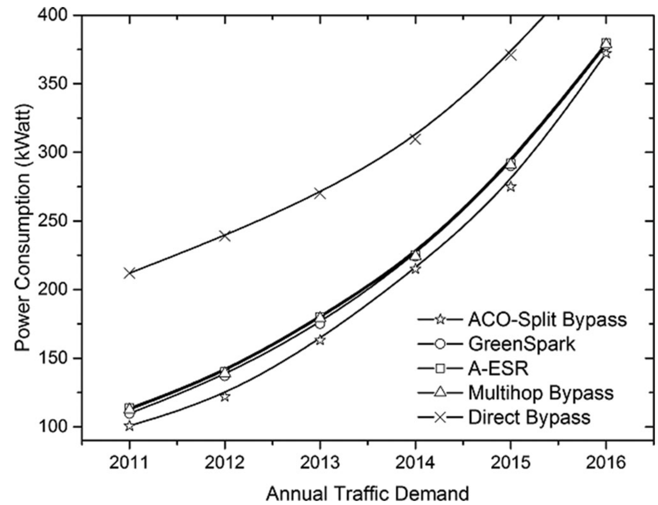

Fig. 3. Power consumption in DT topology [WDM].

For the elastic environment, ACO-Split and MOLG are executed under three different configurations, i.e., with Non-Sliceable Bandwidth Variable Transponder (NS-BVT), Partially Sliceable Bandwidth Variable Transponder (PS-BVT) and Fully Sliceable Bandwidth Variable Transponder (FS-BVT). In the first case, there is only one available slice per transponder, in the second case five, and in the last, ten.

Since each simulation run requires feasible physical computation time (except brute force attacks), the average output values of 100 runs of each configuration are shown to the resulting waveforms. The simulation was designed and implemented in C++14 with the aid of Boost Graph Library using the Clang/LLVM 3.8 compiler.

In Fig. 3, the power consumption of the ACO-Split Bypass method is lower in comparison to the other heuristics. When the values of the average traffic demand get higher, as is the case of the annual demand growth, the differences between heuristics tend to minimize. The upper bandwidth limit per lightpath is low when it is compared to the increasing average traffic demand which eventually surpasses 120 Gbps. So, there are less chances for a lightpath with spare bandwidth to be found for re-use.

In Fig. 4, the increase of the node-number (TI is a large backbone topology) does not negatively affect the performance of ACO-Split Bypass. It is important for a heuristic method to be able to deliver stable performance across a wide range of network configuration.

A simple topology consisting of 6 nodes can be used for simulating the ACO heuristic under brute force instead of using the ACO logic, for finding the most energy-efficient paths, although heavy use of computing resources takes place. This typical technique guarantees that optimal results can be obtained. The currently proposed ACO design and implementation comes

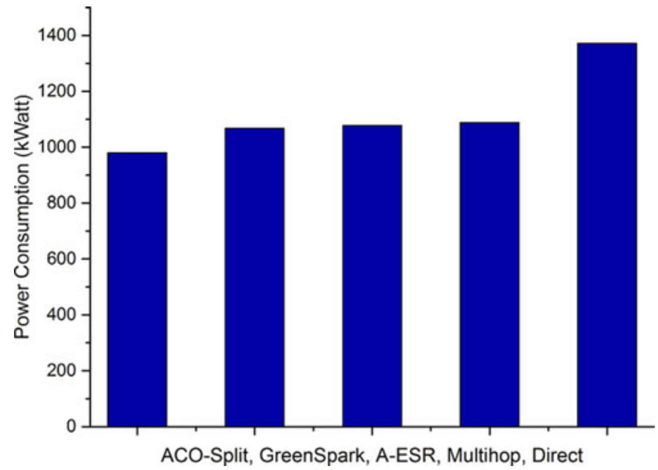

Fig. 4. Power consumption in TI topology [WDM].

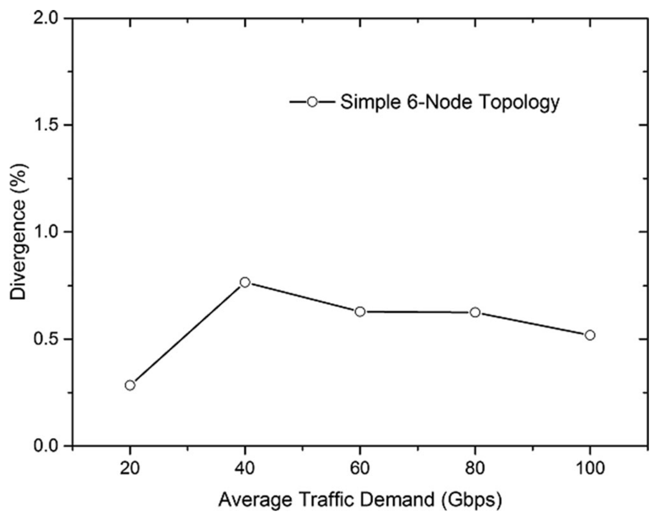

Fig. 5. Percentage of divergence [WDM].

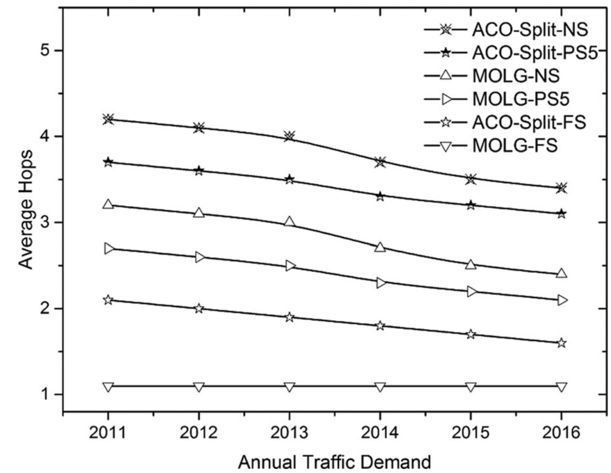

Fig. 6. Hop-count in DT topology [Elastic].

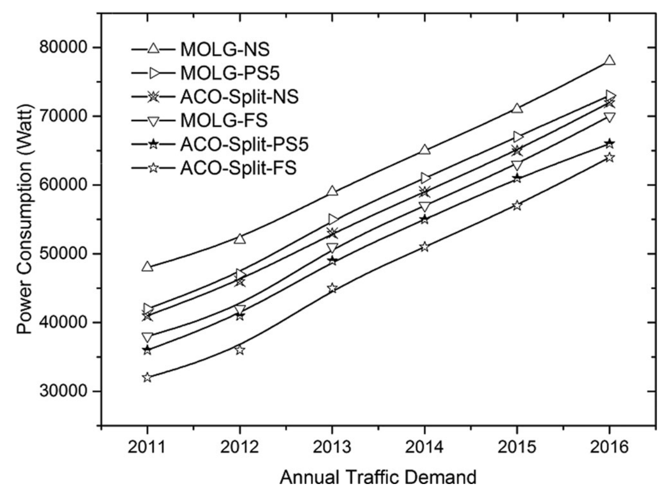

Fig. 7. Power consumption in DT topology [Elastic].

very close in terms of quality (convergence from brute force) in its results and at the same time, execution time is low due to its polynomial complexity as Fig. 5 shows. At average rate of 40 Gbps, there is a slight increase in the divergence since this is the limit of the bandwidth a lightpath can carry.

In Fig. 6, the average hop variation is depicted for the DT topology. There is almost linear performance for all evaluated ACO and MOLG methods which improves in absolute values as the average annual traffic demand increases. When demand gets higher, there are less chances for electrical grooming to succeed due to the less available bitrate the established lightpaths carry. Optical grooming or new transponders from source to destination, create all-optical lightpaths under one hop.

In Fig. 7, the ACO-Split is compared to MOLG which is specifically designed to save energy in the elastic environment. We conclude that as the number of slices increases, more energy is preserved. All-optical grooming takes places that exploits the available network components extensively. When more available slices exist, there are higher chances for optical grooming to succeed.

In Fig. 8, the CPU time that is needed to execute the connection establishment procedure is shown for 8000 random traffic requests uniformly distributed in the range [40, 2X-40], with the variable X equal to 200 Gbps. If the ACO methods were not based on an adaptive mechanism and were using brute force attack to find all suitable paths, the amount of needed resources (CPU and memory) would render their deployment practically infeasible in large topologies (unpredictable amount of execution time that can vary from days to months). To create the corresponding figure, an Intel i7 5th generation CPU is used on Debian 8.3×64. In the non-sliceable configurations of the environment, the execution time is less than the corresponding time in partially or fully sliceable configurations. This is the case due to less needed processing time for handling transponders that cannot be sliced.

In Fig. 9, the CPU time that is needed to execute the virtual topology construction is shown according to topology's node number. The ACO method exhibits linear increase in its execution time, while the MOLG method needs disproportionally more time. The latter method depends on the k-shortest

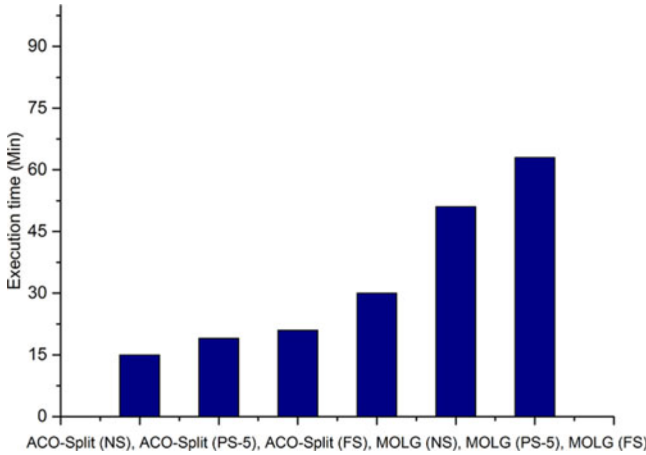

Fig. 8. CPU time in TI topology [Elastic].

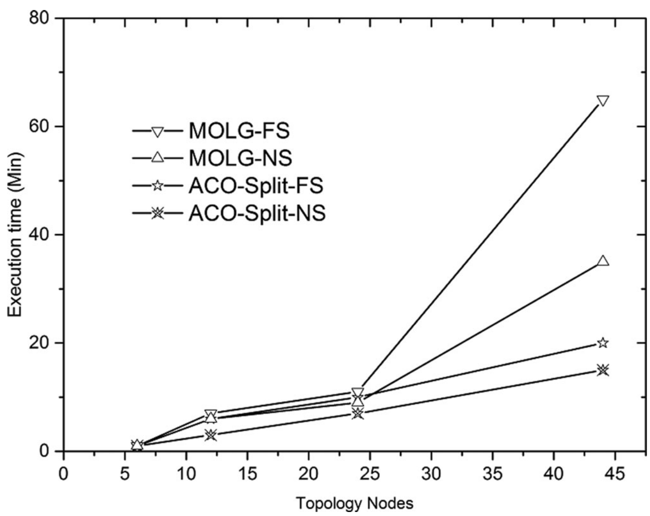

Fig. 9. The scaling of heuristics according to node increase [Elastic].

path algorithm to perform the electrical grooming part which is resource-heavy and renders the method unsuitable for large backbone topologies. The used topologies are a simple 6-node, 12-node DT, 24-node USNet and the 44-node TI. The synthetic traffic that was used is similar to the one of Fig. 8.

VII. Conclusion

Energy efficient methods for lightpath establishment in optical networks tend to become part of modern research, development and deployment with profound results concerning energy consumption. The ACO-Split Bypass heuristic that is proposed improves energy saving with minimal side-effect concerning the elongation of traversing paths. Two real topologies were used for extensive testing that consist a backbone network on national scale. Energy saving tends to vary according to the average demand for bandwidth between node pairs. Bandwidth requests up to 60 Gbps benefit the most from the ACO-Split embedding in computational logic, in contrast to higher traffic requests where differences in consumption are less profound but important.

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