Energy-aware Lightpath Routing in Optical Networks Based on Adaptive Heuristics

Constantine A. Kyriakopoulos, Georgios I. Papadimitriou, Petros Nicopolitidis, Emmanouel (Manos) Varvarigos

***Abstract*—Energy-aware lightpath routing and establishment in optical backbone networks can reduce energy consumption. A heuristic method suitable for network's Planning phase, based on Swarm Intelligence and Grooming practices is proposed that reduces the energy footprint by taking advantage of asymmetric bandwidth split across multiple streams routed to the same destination through different paths. The Ant System metaheuristic is being utilized for finding the most energy-efficient routes from source node to destination per traffic request. Performance improvement concerning energy dissipation was achieved against competing heuristics and is depicted via simulation results.**

***Index Terms*—energy efficiency, optical networks, ant colony optimization, aco, lightpath establishment, heuristics, 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. Extending this principle on a national scale, energy plants will have to produce less amounts of energy and optical networks will keep functioning with the expected performance levels. There will be profound positive side-effects to the environment. 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 Telecom 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 centres is regarded as a key economic, environmental, social and political issue [2].

This research work adheres 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 will be routed according to their occupied resources, has explicit consequence to network's energy consumption. So, a method is proposed which is based on Ant Colony Optimization (ACO) and Grooming practices that can perform energy-aware routing and lightpath establishment, aiming at dissipation of less amount of energy. Specifically, a snapshot of the network under full load is created, captured and analyzed, with the purpose of calculating its energy footprint. The way the procedure of lightpath establishment takes place and develops, based on a heuristic method, represents the core of this research. Elaborate creation of new and scrutinized reuse of old lightpaths in an optical backbone network, leads to energy efficiency. For example, if there are inefficiently created lightpaths (virtual links) that carry a lot of spare bandwidth, energy consumption will be higher due to the high number optical network's physical components that will be required for all traffic requests to be routed. Network components that are considered for consuming important amounts of energy are router ports, transponders and line amplifiers.

Three existing heuristic methods along with the proposed one (asymmetric ACO-Split Bypass), were simulated and evaluated upon three network topologies that cover a wide area of needs. The proposed heuristic manages to perform better according to the energy footprints of all participating methods. Simulation results confirm the efficiency of ACO-Split Bypass which is more profound when the bandwidth request of connections fluctuates on values that are practically feasible, on network topologies that can cover small and as well larger backbone networks. Evaluation includes power consumption, power saving against the simple Non-bypass method, ACO heuristic's performance against a typical brute force method, average hop-count of created lightpaths, bandwidth distribution on topologies' edges and the way requests' bandwidth is split into fragments.

The rest of this paper is organized as follows. Related research of this field is presented along with competing heuristics, in Section 2. The proposed ACO-based approach for finding existing paths with adequate spare bandwidth in Section 3. The proposed heuristic is analyzed in Section 4 and simulation results follow in Section 5.

II. RELATED RESEARCH

Extending the main principles of single-hop and multi-hop [3], [4] Grooming strategies [5], two heuristics were proposed [6]. The first one (Direct Bypass) directly establishes virtual (lightpath) links, whose capacity is sufficient to accommodate all traffic demand between each node pair. The second approach (Multihop Bypass) allows traffic demand between different node pairs to share capacity on common virtual links in order to improve capacity utilization. Although such an effort may elongate the traversing lengths (hop-count) of some traffic flows, turning out to waste network capacity, the overall improvement of network capacity utilization will be more than the waste due to longer IP traffic flows.

A standard Non-bypass method (reusing available path segments) can be used as the low anchor during the measurements throughout a simulation. Every node within the path of this

978-1-4799-5291-5/14/$31.00

typical heuristic is a point of energy consumption, i.e., O-E-O signal conversion is required and takes place. Dijkstra's shortest path algorithm can be applied for finding the route for every traffic request.

Direct Bypass is simple concerning its implementation yet powerful, achieving low energy consumption. A new direct lightpath is established per traffic request, bypassing intermediate nodes. Data remain in the optical domain throughout the shortest path connecting request's end nodes. This means that no O-E-O conversion is required or performed at intermediate nodes.

Multihop Bypass [6], the third method, was the one targeted for performance improvement from the proposed heuristic's (ACO-Split Bypass) perspective. Multihop Bypass creates lightpaths consisting of multiple hops but it manages to save energy due to lightpath reuse from previously established connection requests. So, in case the whole path of a new traffic request is covered by pre-existing lightpaths with adequate free capacity, all these will be reused to create the new groomed lightpath (First-Fit strategy). The basic idea is that no new router port utilization will be required which would consume high amounts of energy, in contrast to the other two energy-consuming components (line amplifiers and transponders) that are considered in this research. Also, there is elongation of some paths due to searching (utilizing brute force techniques) of the whole topology for finding pre-established lightpaths with spare bandwidth, not just within the shortest path connecting the two end nodes.

ACO along with its extensions has been applied successfully [7], [9] to Traveling Salesman Problem (TSP), converting complexity to a polynomial form. The purpose was to visit all cities sequentially with the minimum cost -represented by edge weights. The virtual mapping of lightpaths to physical connections for creating survivable topologies [10] can also be performed using ACO. It has also been applied to other hard combinatorial optimization problems such as quadratic assignment, vehicle routing, job-shop scheduling and graph coloring. Particle Swarm Optimization [11] also provides shortest path finding with low computational time.

The implementation of energy-efficient heuristics in optical backbone networks implies that the best paths with specific properties have to be obtained to be used. This is an NP-hard problem, so ACO serves the purpose of reducing complexity to polynomial scale. Ant System which is based on ACO principles (a set of main rules that describe the behavior of a class of heuristics) can be transformed [8] as well to solve the shortest path problem. Thus, restrictions have been applied, e.g., visiting only physically connected neighboring nodes and all ants starting their traversal from a specific source node to reach a specific destination node. It was demonstrated that the best paths can be easily obtained using low computational resources. The proposed heuristic uses ACO to curb complexity and become practically deployable.

The Traffic Grooming problem [3] was extensively studied and a mathematical formulation was presented [4], along with several typical heuristics. Two main heuristics were proposed with the first one being Maximizing Single-hop Traffic (MST) and the other Maximizing Resource Utilization (MRU). The former attempts to establish lightpaths between each source and destination node with the higher demand traffic values. The connection will be carried on a new established lightpath as much as possible. If there is enough spare bandwidth in the network, only single-hop lightpaths will be created. If not, the currently available spare capacity will be used. The latter heuristic defines a resource utilization parameter and tries to establish lightpaths between node pairs with the maximum resource utilization values. If it fails, the spare capacity will be used. The proposed ACO heuristic uses Grooming to achieve better resource utilization. Also, ACO is employed to handle [12] Grooming and RWA.

The IP over WDM network [13], [14] consists of two layers, the IP and the optical layer. In former, a core IP router is connected to an optical switch node via short-reach interfaces and aggregates data traffic from low-end access routers. The optical layer provides connectivity between IP routers. Optical switch nodes are interconnected with physical fibre links, each one of them may contain multiple fibres. Associated with each one of them, a pair of wavelength (de)multiplexers are deployed. The core optical switch box can be either an automatically controllable Optical Cross-Connect (OXC) or a dumb optical patch panel. The latter is employed in this research.

Next, the network environment this research also utilizes, is described in detail. The traffic matrix carries bandwidth requirements between each node pair (one request) and is initialized in the beginning of simulation. The formula of [6] is $X \in \{20, 40, ..., 100\}$ Gbps (the average value used for producing the waveforms) and the actual demand as a real number is produced by using a uniform distribution in range of [10, 2X-10] Gbps. Since the average traffic value can fluctuate considerably between simulations, the average output value of many executions should be recorded.

As energy-consuming components (Table I) are considered the line amplifiers E_e (8W per unit), transponders E_t (73W per unit) and router ports E_r (1000W per unit). Every physical link includes two (pre and post) amplifiers at its end points and one in every 80 km in between. The maximum -per wavelength-bandwidth is 40 Gbps and every fibre can include up to 16 of them. Every neighbouring node pair can be interconnected with an unlimited number of fibres -the actual number of them is dependent on the heuristic being applied. Total energy consumption can be computed with the following formula [6] in Watt.

$$E_{Total} = E_{rTotal} + E_{tTotal} + E_{eTotal} = \sum_{i \in N} E_r (D_i + \sum_{j \in N} C_{ij}) +$$

$$\sum_{m \in N} \sum_{n \in N_m} E_t w_{mn} + \sum_{m \in N} \sum_{n \in N_m} E_e A_{mn} f_{mn} \qquad (1)$$

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 destinate 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 fibres 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 kilometres 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.

III. ACO FOR FINDING PATHS WITH SPARE BANDWIDTH

Multihop Bypass is more efficient than Direct Bypass according to simulation results presented in [6], but leaves space for further performance improvement. As long as the node sequence of a new lightpath request is covered by pre-existing lightpaths with adequate spare bandwidth, this method is suitable for reducing energy consumption. If this is not the case, a new heuristic is required that is capable of taking advantage of adaptive and asymmetric bandwidth split through multiple streams, routed to the destination through different node sequences. The ACO metaheuristic forms the basis for the proposed Ant System (AS) design and implementation, aiming at finding the paths with the highest available bandwidth that will fulfill each request. This leads to the avoidance of any type of brute force technique that can carry exponential complexity, not suitable for practical deployment on middle to large scale topologies.

The basic idea of the Ant System is that virtual ants can be exploited for finding paths with a special property, e.g., less distance between end nodes, 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 a similar path. When the amount of this substance concentrates in high levels, all other ants follow the same path, and at the same time, increment it. Evaporation takes place on paths less traversed, on a higher rate. Usually, the path with the highest pheromone concentration (not always the case -that's why this is a heuristic method) is the shortest path (or carries another important property), due to less amount of pheromone that is able to evaporate because ants deposit to it more frequently, in contrast to longer distance paths. The Ant System emulates this behaviour with quality results. When the number of virtual ants and iterations are high enough, the right paths are usually found and this happens under polynomial complexity.

Under the current research, the basic criterion to apply ACO was not paths' distance but the available bandwidth they offer. That way, paths with the highest available bandwidth can be found and their spare bandwidth can be reused, for achieving better resource utilization that eventually will lead to energy efficiency.

The core of the Ant System is the basic ACO outline depicted in Algorithm 1. Initiating the procedure, basic parameters are set, i.e., number of ants that participate and the number of iterations. Next, the initial pheromone level upon all topology edges is being deposited. The algorithm enters a loop for a predefined number of iterations and all available ants are placed (one by one) on path's source node, starting their effort to reach the destination node. The choice of next node is being based on a policy by using a function that returns a probability decimal number for every neighbouring 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 pheromone level by increasing it, upon their traversed path.

Algorithm 1 Basic ACO outline

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

During every ant's traversal, there is a chance for a cycle to be formed. In that case, the ant stops its route formation without depositing pheromone on the next stage (not iteration). Also, if a disjoint node is found on its path (not connected to neighbours), the ant cancels its current traversal and doesn't deposit pheromone. When a full iteration is complete, ants that succeeded in finding the destination node will deposit an amount of pheromone upon the edges they traversed, but before that, evaporation by a constant factor will take place in all topology edges. The amount of increment is tightly correlated to the quality of each solution.

$$\tau_{ij}\left(t+1\right) = \rho \cdot \tau_{ij}\left(t\right) + \Delta\tau_{ij} \tag{2}$$

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{3}$$

$$\Delta\tau_{ij}^{k} = \begin{cases} \frac{Q}{L_k} & , ant\, k\, travels\, on\, edge\, (i,j) \\ 0 & , otherwise \end{cases} \tag{4}$$

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. 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 quality of its served solution. The predefined quantity of pheromone is Q and L_k is the tour length of ant k. Their total number is m. Shorter length means more quantity will be deposited, something that can boost good candidate solutions.

An ant chooses the next neighbouring node for transition according to a probability array produced by formula (5). The summary of all neighbouring probabilities equals to 1. The basic idea in this case is that higher amount of existing pheromone along with high available bandwidth (interpreted as heuristic information), will raise chances for an ant to choose that neighbour and traverse to.

$$p_{ij} = \begin{cases} \frac{\tau_{ij}^{\alpha} n_{ij}^{\beta}}{\sum_{h\in\Omega} \tau_{ih}^{\alpha} n_{ih}^{\beta}} & , if\ j \in \Omega \\ 0 & , otherwise \end{cases} \tag{5}$$

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 lightpath starting from i, ending to j. The set of an ant's available neighbours is Ω. The formula (6) was used for path evaluation. The used bandwidth of lightpath k is depicted by bw variable.

$$L = \frac{\prod_{k=1}^{N} bw_k}{\sum_{k=1}^{N} bw_k} \tag{6}$$

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. There are three escape conditions. (a) A cycle is formed. If an ant returns to an already visited node, the traversal is considered unsuccessful. A quick solution to this case would be to remove the cycle from current path and continue, but due to current configuration, the other ants will probably fetch an effective solution as experimental results have shown. So, there is no need to increase complexity. (b) Destination node is reached. The full path from source node to destination is returned. (c) The ant found a dead end (no available neighbors).

IV. PROPOSED ACO-SPLIT BYPASS HEURISTIC

The proposed ACO-Split Bypass heuristic (Figure 1) improves performance when trying to create a new lightpath, by asymmetrically splitting (using ACO principles) bandwidth along different paths, routed to the same destination. In case a route is found that is capable of carrying the initial request's bandwidth, it is used the same way Multihop Bypass would take advantage of. If not, asymmetric split based on ACO, takes place into several streams (until a threshold value is reached) which are being routed to the same destination using different node sequences with Multihop Bypass. The first stream uses the path sorted according to the highest available bandwidth that was found by applying ACO. The second stream uses the path with the next available one and the rest accordingly, until a threshold value that is dependent on current processing resources, is reached. Simulation results showed that a value higher than 7 will only increase complexity with no benefit to energy consumption. In case there are not enough candidate routes for the whole bandwidth to be routed or the threshold is reached, a simple new Direct Bypass lightpath is established using Dijkstra's shortest path between end nodes, carrying the initial requests' bandwidth.

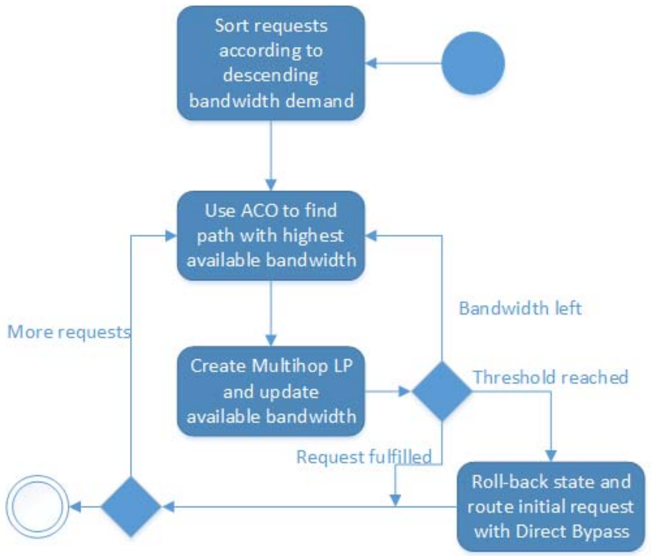

Figure 1. ACO-Split Bypass activity diagram

The Ant System implementation is being initialized with the following parameters that were tuned in [9] and can be found in Table I. First, an initial amount of pheromone is deposited on all graph edges (representing every topology) and equals to the pheromone quantity Q. Parameters *A* and *B* are set up in a way [9], so the pheromone level of a neighbouring node will be more significant in contrast to the heuristic information of reaching it.

Table I
ACO CONSTANTS

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

The ACO-Split method is a utilized algorithm in network's Planning phase that won't pre-process traffic requests before initiating lightpath establishment, except from an initial sorting that takes place in descending order, according to every request's bandwidth requirement. Then, for every new request, an attempt is being made for creating a lightpath 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 will be established through the shortest path between the source and destination node pair. The internals of this heuristic are depicted in the UML activity diagram of Figure 1.

Finding the routes by reusing lightpaths that carry adequate bandwidth to fulfill a request, is an NP-hard problem. Complexity becomes a hurdle to current research and Multihop Bypass suffers from it. It is performing for every new traffic request, a brute force attack to find a path consisting of lightpaths carrying enough spare bandwidth. This problem becomes difficult to be solved for large network topologies with low average traffic requests, wasting CPU and memory resources. Multihop Bypass has the advantage of shortening the search domain by choosing lightpaths for participating in it, that only carry enough bandwidth to fulfill the request, but it still suffers from low traffic requests.

On the other hand, using heuristics based on Swarm Intelligence (such as the proposed one), complexity becomes polynomial, i.e., O(N^3), so development and deployment become feasible for the majority of network topologies. 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 described by O(N^3).

Summing up, the main idea embedded in ACO-Split Bypass is the asymmetric division of initial bandwidth to smaller fragments (taking advantage of Swarm Intelligence for choosing the right paths) that will be routed independently using the pre-existing Multihop Bypass heuristic. When all these fragments reach the destination, assembly takes place in the electrical domain. That way, spare bandwidth of pre-existing lightpaths is being exploited in an advanced way, i.e., more demand for smaller bandwidth requests takes place (after splitting) that eventually leads to energy efficiency.

V. RESULTS

Three backbone network topologies (Figures 2, 3 and 4) were used for testing proposed heuristic's performance, i.e., a simple 6-node topology, NSFNet and the large USNet. It's significant for every new heuristic (such as the proposed one) to be able to be executed upon all three topologies in a predictable amount of time. These topologies were extensively tested with various values as average bandwidth demand, calculating power consumption at the end of each network snapshot creation under full load.

Figure 2. Simple 6-node test topology

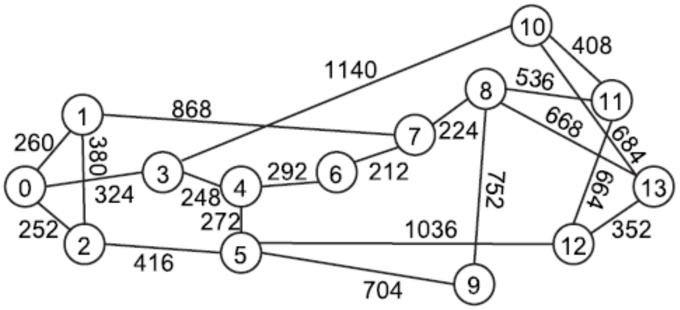

Figure 3. NSFNet test topology

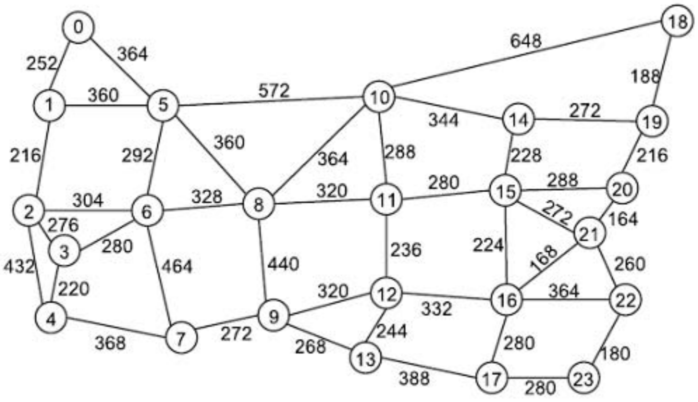

Figure 4. USNet test topology

The next step of experiments was to calculate the percentage of saved power from benchmarked heuristics, using the Non-bypass method as low anchor, i.e., power saving in comparison to this method. Next, there is comparison between applying brute force for finding the paths with adequate spare bandwidth against ACO. Brute force can only be executed upon the first two topologies due to its heavy use of computing resources. The average hop-count was also calculated for all topologies and heuristics, and finally, bandwidth distribution on tested graph topologies is depicted. All parameters that define the simulation environment and were used in this study can be found in Table II. Since each simulation run requires feasible physical computation time (except brute force attacks), the average output power value of 100 runs of each configuration are depicted to resulting waveforms.

Table II
SIMULATION PARAMETERS (CISCO WHITE PAPERS)

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

In Figure 5, power consumption in kW is depicted on vertical axis for ascending values of the average traffic demand

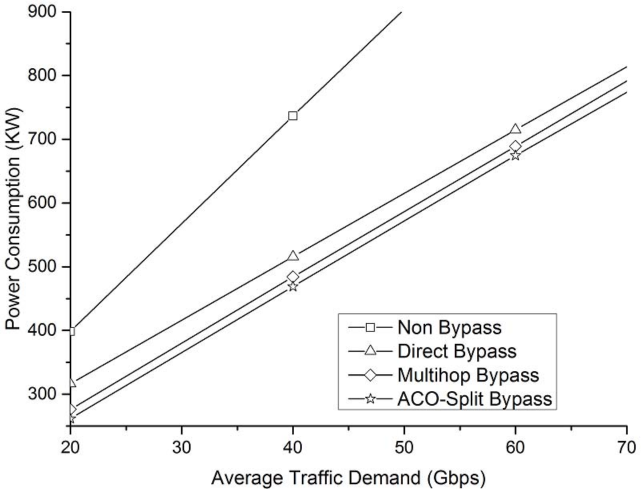

Figure 5. Power consumption in NSFNet topology

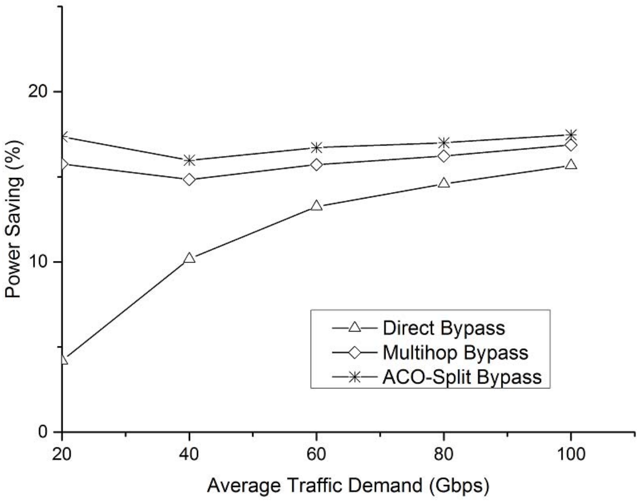

Figure 6. Power saving in 6-node topology

between node pairs (horizontal axis). This figure relates to NFSNet network topology. The most power-consuming heuristic is Non-bypass which is used as the low anchor in every test case. After a large margin, the other 3 heuristics prove their efficiency against it. According to their specific values of power consumption, Direct Bypass is less efficient, whilst ACO-Split Bypass outperforms all three of them. As second ranking heuristic, comes Multihop Bypass which takes the advantage from the third Direct Bypass due to its ability to reuse previously created lightpaths when carrying available bandwidth.

In Figures 6, 7 and 8, power saving of ACO-Split Bypass method outperforms those of competing heuristics. When the values of average traffic demand get higher, differences between heuristics tend to become minor. The upper bandwidth limit of lightpaths, i.e., 40 Gbps, is quite low when compared to the increasing average traffic demand which eventually reaches 100 Gbps. So, there are less chances for a lightpath with spare bandwidth to be found and be reused. So, energy efficiency is less prevalent for all participating heuristics within the high range. Energy efficiency is more important when there are low (in this scale) bandwidth requirements that define current consumer networks and needs.

In Figure 9, the CPU time that is needed to execute the lightpath establishment procedure is depicted in correlation to power saving percentage. The range of values that produce the average traffic demand belong to domain (1, 2 * average) in Gbps. If ACO-Split Bypass heuristic was not based on ACO and was using brute force attack to find all suitable paths, the amount of needed resources (CPU and memory) would render its deployment practically infeasible (NP-hard problem). For the creation of this figure, an Intel i7 2600K CPU was used along with Intel C++ Compiler v14, on MS Windows 8.1 x64.

Multihop Bypass is based on a brute force technique to find all lightpaths that can be reused for a destination node to be reached. So, a First-Fit strategy is required to curb complexity. This strategy leads to lightpaths consisting of higher number of hops -compared to ACO-Split Bypass when it uses only one stream to route traffic- which also creates deficiency by shortening the number of available direct lightpaths that can be reused by subsequent traffic requests.

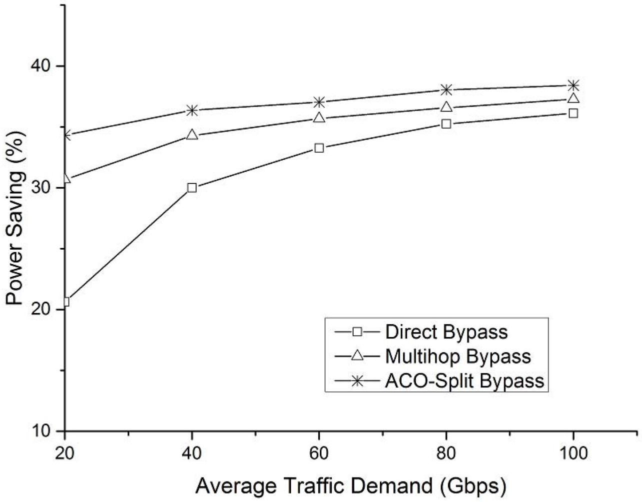

Figure 7. Power saving in NSFNet topology

On the other hand, ACO-Split has the advantage of running under polynomial complexity, thus it is able to find paths with less hops and at the same time, high available bandwidth. So, this comparison is depicted to the corresponding figures. Having less number of hops, leads to less O-E-O conversions and subsequently, total propagation time remains low.

The Figures 10, 11 and 12, show that Multihop Bypass outperforms ACO-Split in most cases, due to having the advantage of using only one stream to route traffic.

The first topology can also be run under brute force for finding paths with the highest available bandwidth, eventhough 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

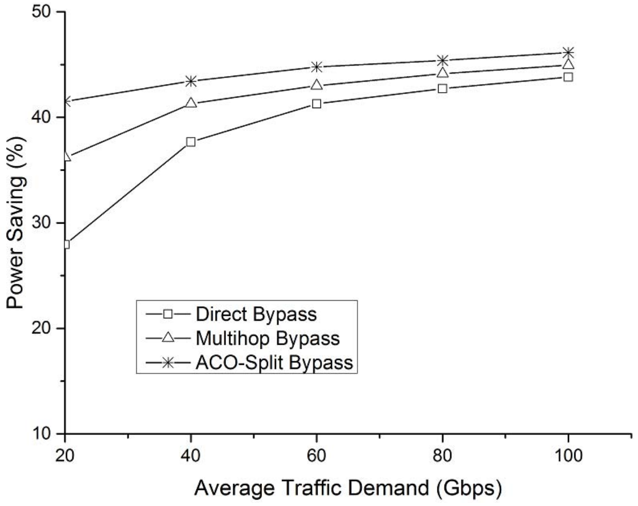

Figure 8. Power saving in USNet topology

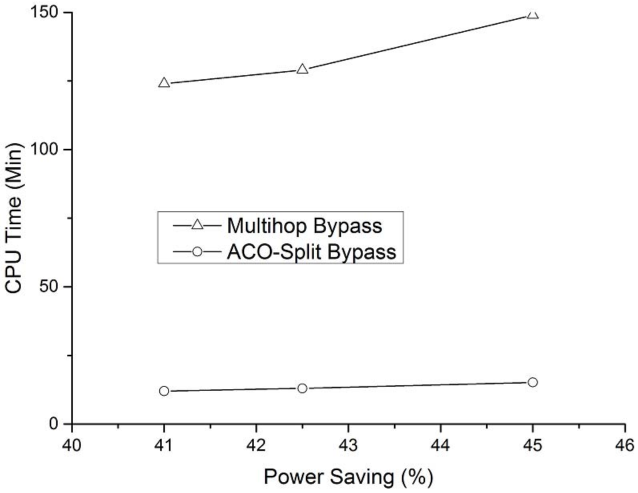

Figure 9. CPU time of heuristics in USNet

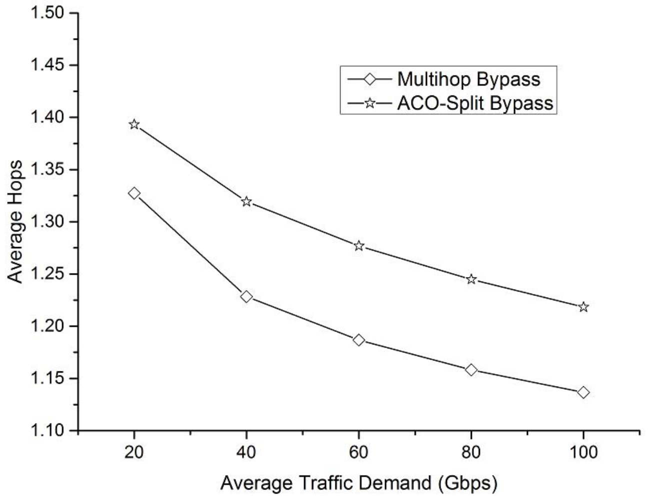

Figure 10. Average hop-count in 6-node topology

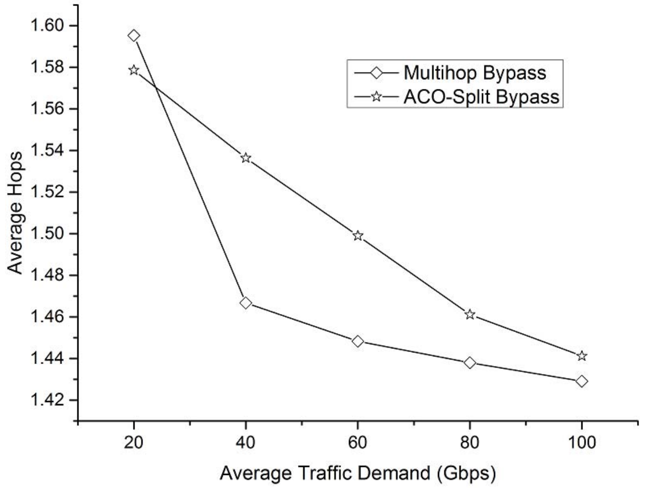

Figure 11. Average hop-count in NSFNet topology

very close in terms of quality in its results -verified by the corresponding waveform- and at the same time, execution time is extremely low due to its polynomial complexity. Included in computing resources that remain low, is also the main memory. Extensive tuning has been performed upon the proposed AS implementation, so the divergence from corresponding brute force results remains extremely low, as Figure 13 shows.

VI. 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. Traditional lightpath establishment procedures ignore the energy factor, though current research's results show that the performance penalty is minimal when energy efficient heuristics are embedded in computational logic and at the same time, power savings are high. The ACO-Split Bypass heuristic that was proposed improves energy saving according to simulation results with minimal side-effect concerning the elongation of traversing paths and merge time in electrical domain.

ACKNOWLEDGEMENTS

This work has been funded by the NSRF (2007-2013) Synergasia 2011/EPAN-II Program "Energy Efficient Optical Network Planning and Operation", General Secretariat for Research and Technology, Ministry of Education, Religious Affairs, Culture and Sports (contract no. 11SYN_6_1942).

REFERENCES

[1] White paper, “Cisco Visual Networking Index: Forecast and Methodology”, 2009-2014
[2] Green Touch, [www] greentouch [org]
[3] C. Xin, “Blocking analysis of dynamic Traffic Grooming in mesh WDM opticla networks”, IEEE Trans. Networking, vol. 15, no. 3, pp. 721–733, June 2002
[4] K. Zhu and B. Mukherjee, “Traffic grooming in an optical WDM mesh network”, IEEE J. Sel. Areas Commun., vol. 20, no. 1, pp. 122–3, 2002

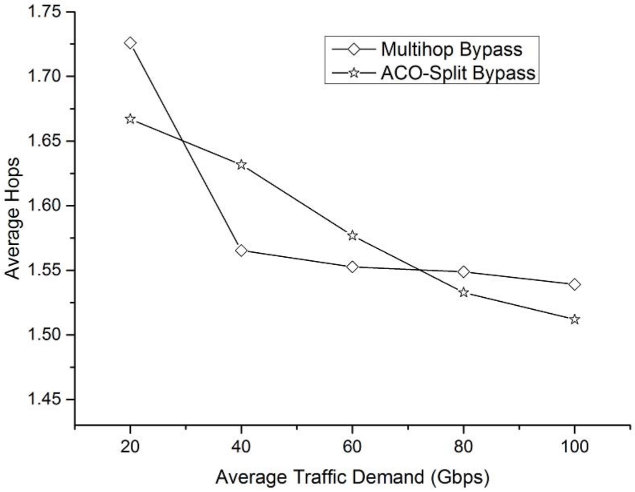

Figure 12. Average hop-count in USNet topology

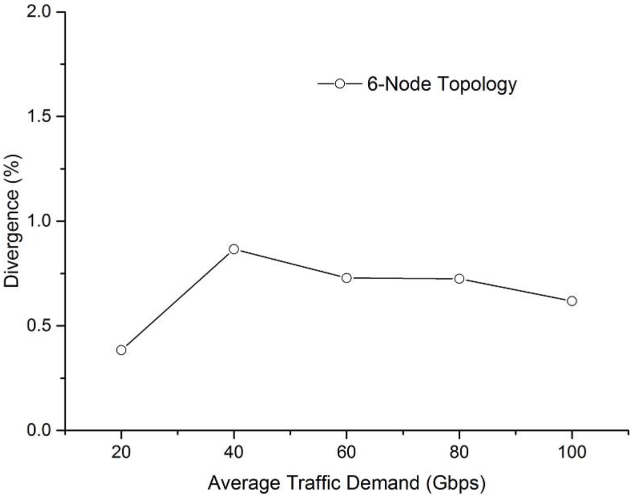

Figure 13. Percentage of divergence

[5] M. Masud Hasan, Farid Farahmand, Ankitkumar N. Patel, and Jason P. Jue, ”Traffic Grooming in Green Optical Networks”, Communications (ICC), 2010 IEEE International Conference
[6] Gangxiang Shen and Rodney S. Tucker, “Energy-Minimized Design for IP Over WDM Networks”, J. Opt. Commun. Netw. vol. 1, no. 1, 2009
[7] Marco Dorigo, Thomas Stutzle, “Ant Colony Optimization”, The MIT Press, Cambridge Massachusetts, London England
[8] M. Gaabowski, B. Musznicki, P. Nowak, P. Zwierzykowski, ”Shortest Path Problem Solving Based on Ant Colony Optimization Metaheuristic”, Image Processing & Communication, Volume 17, Issue 1-2, Dec 2012
[9] Bernd Bullnheimer, Richard F. Hartl, Christine Strau, “A New Rank Based Version of the Ant System - A Computational Study”, Working Paper No. 1, April 1997
[10] Elif Kaldırım, Fatma Corut Ergin, Sima Uyar, Aysegul Yayımlı, “Ant Colony Optimization for Survivable Virtual Topology Mapping in Optical WDM Networks”, September 14-16, 2009 METU Northern Cyprus Campus 344
[11] Neha Rathod, Rupali Bhartiya, “An efficient Particle Swarm Optimization technique for identification of shortest path in Distributed Network”, International Journal on Recent and Innovation Trends in Computing and Communication, Volume 2 Issue 7, 2014
[12] X. Wang, M. Brandt-Pearce, and S. Subramaniam, “Distributed Grooming, Routing, and Wavelength Assignment for Dynamic Optical Networks Using Ant Colony Optimization”, Journal of Optical Communications and Networking, Vol. 6, Issue 6, pp. 578-589 (2014)
[13] N. Ghani, S. Dixit, and T. S. Wang, “On IP-over-WDM integration”, IEEE Commun. Mag., vol. 38, no. 3, pp. 72–84, Mar. 2000
[14] Cisco whitepaper “Cost comparison between IP-over-DWDM and other core transport architectures”, 2007