# Green optical backbone networks: virtual topology adaptation using a page rank-based rating system

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## SUMMARY

An energy-aware virtual topology rating system is proposed in this work, which can be utilized as a tool during the virtual topology reconfiguration procedure in an optical backbone network in order to reduce its energy consumption. It is well known that maintaining a static virtual topology in Internet Protocol (IP)-over-Wavelength Division Multiplexing (WDM) networks is not energy-efficient. To that end, virtual topology adaptation algorithms have been developed to adjust the virtual topology to the constantly fluctuating traffic load. While these algorithms achieve significant energy savings, further reduction on the total network energy consumption can be achieved through the proposed rating system. The proposed rating system is a modified version of the page rank algorithm, which ranks websites in the Internet based on their importance. The proposed rating system attributes ratings to lightpaths, which indicate the relative significance of a lightpath in the virtual topology in terms of energy consumption. The rating can be used during the routing procedure as an energy efficiency indicator, in order to increase the number of lightpaths that are deactivated from the reconfiguration mechanism and increase the utilization per lightpath. The proposed reconfiguration scheme (page rank-based virtual topology reconfiguration) achieves up to 12% additional energy savings in comparison to an existing virtual topology reconfiguration algorithm at the cost of slightly increased average hop distance. Copyright © 2015 John Wiley & Sons, Ltd.

## 1. INTRODUCTION

Global greenhouse gas emissions have risen 70% since 1970, and the Information and Communications Technology (ICT) sector contributes around 2.5% (computing, the Internet, and telecommunications), with this percentage expected to increase as the number of devices connecting to the Internet and the bandwidth demand per user are rising [1]. Moreover, ICT has shown a yearly growth 10% regarding the energy consumption of communication networks, which is much higher than the yearly worldwide energy consumption growth (3%) [2]. As a result, ICT companies are making efforts to render telecommunications more energy-efficient for both economical and environmental reasons.

IP-over-WDM optical backbone networks are a solid solution to support the constantly increasing bandwidth demand per user on the Internet. In optical backbone networks, a virtual topology is constructed over the physical topology, which is the set of established lightpaths that can route IP traffic flows from point to point. The results presented in [3] show that the maintenance of a static virtual topology during the network operation is not efficient on an energy consumption aspect. Contrary, an adaptive virtual topology scheme is more flexible as it can be adjusted on the current traffic load in order to reduce total energy consumption.

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In [3] and [4], a virtual topology reconfiguration algorithm is presented using a two-load thresholds mechanism to detect overloaded and underutilized lightpaths. The reconfiguration scheme keeps the virtual topology in load balance by deactivating low-loaded lightpaths and activating new lightpaths when traffic congestion is detected. By deactivating underutilized lightpaths and carrying their load through alternative lightpaths, the reconfiguration algorithm manages to save significant amounts of energy. Also, in these studies, the effect of the threshold parameter is studied. In [5], a routing strategy is proposed on top of the algorithm. The proposed routing strategy manages to save up additional energy by assigning weights to paths, attempting to keep the virtual topology in a load-balanced state.

In [6] and [7], another category of load-balancing approaches is presented that avoid traffic disruption and minimize the network delay. A genetic multi-objective algorithm is demonstrated in [8] aiming to minimize network congestion and energy consumption by using cognitive techniques. This work includes fault-tolerant virtual topology design with shared path protection. The algorithm in [9] also features a fault-tolerant topology presenting a virtual topology adaptation algorithm that takes into consideration back-up paths. In [10], a virtual topology reconfiguration algorithm that uses a traffic prediction mechanism is presented. A multi-objective design algorithm and a reconfiguration policy using cognitive techniques are suggested in [11]. An algorithm for distributed control of the virtual topology reconfiguration procedure is proposed in [12], focusing on minimizing congestion and responding fast to traffic pattern changes. A reconfiguration policy and a virtual topology design algorithm are presented in [13], aiming to minimize packet loss ratio and the operational expenditures. A virtual topology adaptation method that allows the network operators to dynamically lease the required amount of bandwidth is proposed in [14], in order to minimize the expenditures cost for maintaining the network operation. In [15], a heuristic algorithm based on the Lagrangian relaxation is employed, in order to achieve energy minimized routing and virtual topology design in polynomial time. A method of reconfiguring virtual topologies by exploiting traffic forecasting solutions and taking advantage of past history is presented in [16].

This paper is organized as follows: Section 2 briefly describes the virtual topology reconfiguration problem and the power model used to calculate the energy consumption of the network. In Section 3, the rating system is examined along with a network operation scenario. Section 4 presents results that demonstrate the increased energy savings of the proposed rating system. Finally, Section 5 concludes this work.

## 2. THRESHOLD-BASED VIRTUAL TOPOLOGY RECONFIGURATION

The issue of maintaining an adaptive virtual topology during the network operation has been extensively examined in many studies. It has been demonstrated that maintaining a static virtual topology is significantly more energy-consuming in comparison with an adaptive virtual topology. In this segment, a brief description of the reconfiguration problem and a review of the power consumption model that was applied in this work are provided. For further study of the virtual topology reconfiguration problem, consult [4].

### 2.1. Network topology

Each network node is modeled by two layers: an optical layer and a network one. Network nodes are connected with bidirectional fiber links creating a graph structure, which is the physical topology. In order to serve the IP traffic flows, directional lightpaths are established over the fiber links. Each lightpath occupies a wavelength across the fiber path and requires one optical transmitter on the initial node and one optical receiver on the ending node of the path. Wavelength availability and wavelength continuity constraints must be met during the network operation. Hence, the same wavelength cannot be used by two or more lightpaths on the same fiber link. In addition, in case of zero wavelength conversion functionality on the optical layer, the same wavelength must be occupied across the fiber path. In case of full wavelength conversion capability, the lightpath can occupy different wavelengths across the path, given that the intermediate nodes have the ability to converse those wavelengths. Upon the deactivation of a lightpath, the

corresponding optical transmitter and receiver must be deactivated, and the wavelengths used by the lightpath must be released. The virtual topology consists of the set of currently established lightpaths over the physical topology.

## 2.2. Problem description

Static virtual topologies become obsolete as the IP traffic flows between the network nodes alter through time. For that reason, virtual topology reconfiguration schemes have been developed, in an effort to adjust the virtual topology to the current traffic load and avoid traffic congestion or lightpath underutilization. Reconfiguration during the network operation aims to maintain an energy-efficient virtual topology capable of serving the existing network load without wasting network resources and power.

The initial virtual topology is constructed based upon the initial traffic load between the network nodes or the average observed traffic load during a period. Given an initial virtual topology, the load of each lightpath is monitored for a fixed time interval. As the load of IP traffic flows fluctuates through time, so does the load of lightpaths, which serve those IP traffic flows. At the end of each observation period, the average load of each lightpath is calculated and the reconfiguration mechanism is employed. The reconfiguration algorithm uses two thresholds to detect network congestion and lightpath underutilization. If the load of a lightpath is beyond a predefined upper threshold, a new lightpath is activated to support the increased traffic load and to avoid congestion. The new lightpath is usually established between the node pair whose load contributes the most in the load of the congested lightpath. If the load of a lightpath is below the low threshold, it is examined whether the IP flows, which are routed through it, can be rerouted through alternative lightpaths, and then it is deactivated, releasing network resources. Lightpath addition is prioritized over lightpath deletion, because it is more important to avoid traffic congestion or data loss than to reduce the overall energy consumption. Only one adjustment can be applied at the end of each observation period, so data transmissions are not disrupted from constant alterations on the virtual topology.

## 2.3. Power consumption model

In order to calculate and compare the total energy consumption of the network, the energy model proposed in [3] is used. The energy model divides total energy consumption between two layers: the optical layer, where an optical cross-connect is employed, and the network layer with the IP packet routers. Power consumption is calculated as

$$POW = \sum_{\forall (m,n) \in E} a_{mn} u_{mn} + \sum_{\forall i \in N} \varnothing_i n_i + \rho \sum_{\forall (i,j) \in D} \varepsilon^e \lambda_{ij} + (1-\rho) \sum_{\forall (i,j) \in D} \varepsilon^e l_{ij} + \sum_{\forall (m,n) \in E, m \neq s,d} \varepsilon^s p_{mn} \quad (1)$$

The first term of the equation calculates idle power consumption of the physical links, where $a_{mn}$ is the energy consumption of inline amplifiers on a fiber from node $m$ to $n$ and $E$ is the set of fibers in the network. $u_{mn}$ is equal to 1 if the fiber from node $m$ to $n$ is used by a lightpath, else it is equal to 0. The second term refers to the idle power consumption of nodes. $\varnothing_i$ is the electronic control power consumption at node $i \in N$. $n_i$ is equal to 1 if node $i$ is used by any lightpath, else 0. The third term calculates idle power consumption per lightpath, and the fourth term computes traffic-dependent power consumption per lightpath. $\lambda_{ij}$ is equal to 1 if there is a lightpath between nodes $i$ and $j$, else 0. $l_{ij}$ is the traffic load of a lightpath between nodes $i$ and $j$. $D$ is the set of lightpaths in the virtual topology. $\varepsilon^e$ is electronic processing consumption per IP port for 40 Gbps. The fifth term refers to power consumption of intermediate nodes, where the signal is only processed on the optical layer. $\varepsilon^s$ is energy consumption per wavelength, and $p_{mn}$ is the number of wavelengths on a fiber from node $m$ to $n$. The values of the parameters for Equation (1), which were also used in the simulation, are demonstrated in Table I.

Table I. Energy consumption parameters.

| Energy model parameters | | |
|---|---|---|
| Symbol | Description | Value |
| $a_{mn}$ | Energy consumption of inline amplifiers on a fiber link from $m$ to $n$ with distance $d_{mn}$ | $9\,\text{W}*[d_{mn}/80\,\text{km}+2]$ |
| $\varnothing_i$ | Electronic control power consumption | 150 W |
| $\varepsilon^e$ | Electronic processing power consumption per IP port (40 Gbps) | 667 W |
| $\varepsilon^s$ | Energy consumption per wavelength | 0.107 W |
| $\rho$ | — | 0.9 |

## 3. ENERGY-AWARE VIRTUAL TOPOLOGY RATING SYSTEM

This work proposes a rating system that can be used as a tool during the virtual topology adaptation. The proposed rating system evaluates the importance of a lightpath in the virtual topology relatively to other lightpaths. The rating of each lightpath can be utilized as an indicator to discern which lightpaths are more suitable for an energy-efficient virtual topology. The rating system is based on the principle that lightpaths that serve more traffic flows are more efficient in the virtual topology, while low-load lightpaths do not justify the maintenance energy cost and should be deactivated.

### 3.1. Page rank-based rating system

The rating system is based on the page rank algorithm presented in [17], which rates the importance of websites in the Internet relatively to each other. The websites are connected to each other through hyperlinks creating a graph. Likewise, the virtual topology is constructed as a graph, but the rating system is modified to fit the optical backbone network operation and the need to rate accordingly the lightpaths. Each IP data flow has an initial rating *1/n*, where *n* is the total number of IP data flows in the network. In the original page rank algorithm, websites transfer a part of their rating to the websites that they are connected with. Similarly, in the proposed rating system, each IP data flow can transfer rating to the lightpaths through which it is routed. In order to avoid attributing high rank to long multipaths, which may induce significant delay, the rating of each IP data flow is equally divided between each lightpath across the multipath. That means that a multipath of two hops will receive twice the rating for each lightpath across the path in comparison with a four-hops multipath for serving an IP data flow. Thus, the shortest path routes are highly rewarded, because they do not increase the delay. Finally, the aggregation of the rating of all lightpaths in the virtual topology rounds up at 1 in a similar manner to the page rank algorithm.

A virtual topology example is demonstrated in Figure 1. There are five lightpaths ({A, B}, {B, C}, {C, D}, {D, E}, and {E, A}) and six IP traffic flows routed over the virtual topology ([A, B], [A, C], [A, D], [B, C], [C, E], and [E, A]). Because the total number of flows is six, the rating a flow
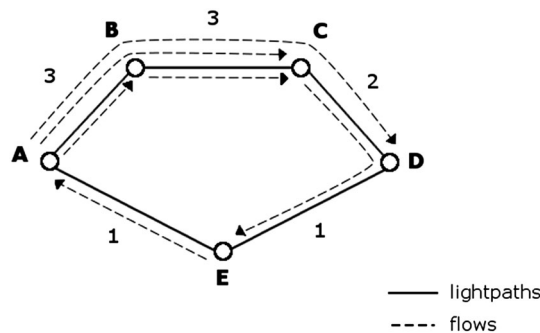


Figure 1. Example of virtual topology with five lightpaths and six routed IP traffic flows.

can attribute to a multipath is *1/6*. For example, flow [A, B] attributes *1/6=0.166* rating to the lightpath {A, B}, while flow [A, C] attributes *1/12=0.083* rating to lightpath {A, B} and *1/12=0.083* rating to lightpath {B, C}. The rank of each lightpath can be acquired by aggregating the ratings each lightpath has received from the IP traffic flows that are routed through it. In the example in Figure 1, the final rank of each lightpath is {A, B}$_{rank}$*=0.305*, {B, C}$_{rank}$*=0.305*, {C, D}$_{rank}$*=0.138*, {D, E}$_{rank}$*=0.083*, and {E, A}$_{rank}$*=0.166*. Lightpaths {A, B} and {B, C} are evaluated as the most important in the virtual topology, because they both serve three flows. However, the number of flows served by a lightpath is not the only factor that affects the rating. As it can be observed, lightpath {C, D} has a rank of *0.138* by serving a two-hops and a three-hops flow, while lightpath {E, A} has a rank of *0.166* by serving only a one-hop flow. Lightpath {E, A} has a greater rank than {C, D}, because routing the flows through shortest paths is considered more important for the performance of the network, because the transmission delay is not increased.

### 3.2. Implementation of the rating system

The proposed rating system can be incorporated in the virtual topology reconfiguration procedure. Given an initial virtual topology, each lightpath has an initial rank of *1/m*, where *m* is the number of established lightpaths in the virtual topology. At the end of each observation period, the reconfiguration algorithm is employed. Firstly, it is examined whether a lightpath has load above the upper load threshold. In case a lightpath is congested, a new lightpath is established to serve the excessive load. If none of the lightpaths were congested, it is examined if a lightpath has load below a low-load threshold. In case the traffic flows of the underutilized lightpath can be rerouted through alternative paths, then it is deactivated. If the virtual topology was alternated, then all IP traffic flows must be rerouted. The rating system is utilized at this step, in order to resolve any ties when there are two or more multipaths that can serve a traffic flow and have the same hop distance. The multipath with the highest rank is the most suitable, because it already serves efficiently more traffic flows than the other corresponding multipaths. As soon as the routing procedure is finished, a new rank is calculated for each lightpath based on the new virtual topology and routing. A step-by-step illustration of the reconfiguration algorithm is presented in Figure 2.

### 3.3. Network operation scenario

A network operation scenario is illustrated in Figure 3. A part of the virtual topology is presented with four lightpaths {A, B}, {B, C}, {A, D}, and {D, C}. It is assumed that the virtual topology has to route 20 traffic flows. In (a), the initial virtual topology is presented with the current rank of each lightpath. In (b), it is assumed that a lightpath outside this part of the topology is deactivated
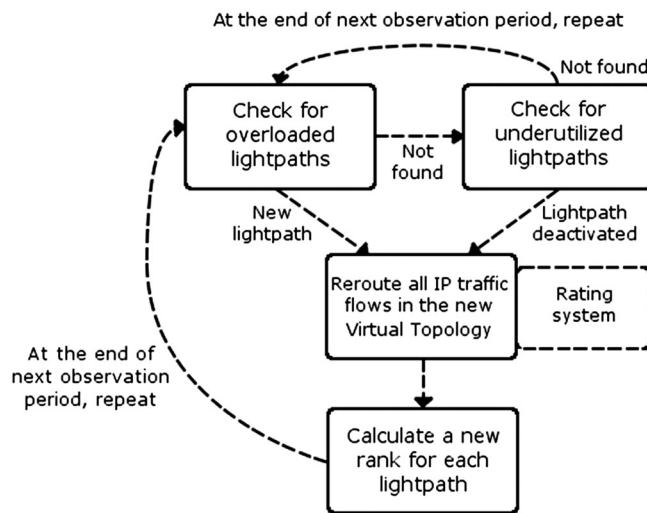


Figure 2. Virtual topology reconfiguration algorithm using the page rank-based rating system.
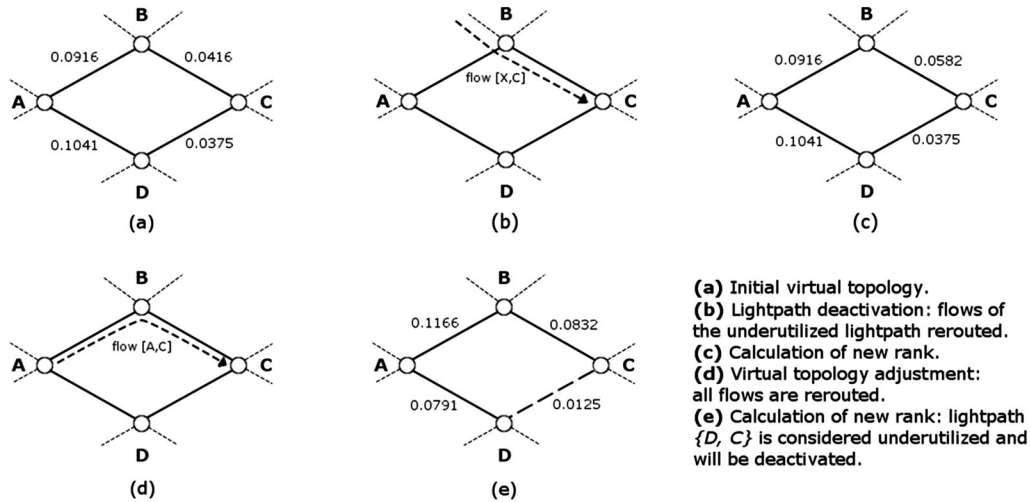
Figure 3. Network operation scenario of the reconfiguration scheme using the page rank-based rating system.

by the reconfiguration algorithm, thus the traffic flows of the underutilized lightpath must be rerouted. One of these traffic flows is [X, C] and is routed in a two-hops multipath through lightpath {B, C}. Because of the deactivation of a lightpath, all traffic flows are rerouted, and the new rank of each lightpath is calculated in (c). It can be observed that the rank of lightpath {B, C} is increased, changing the balance between multipaths {A-B-C} and {A-D-C}. Multipath {A-D-C} has an aggregated rank of *0.1416*, which was more than the old rank of {A-B-C} at *0.1332*. After the modification on (b) the new rank of {A-B-C} is *0.1498*. In (d), all traffic flows are rerouted after an adjustment and this time traffic flow [A, C] will be routed through {A-B-C}, because it has the same hop distance with {A-D-C}, but greater rank. This changes the balance in the virtual topology again, so after the calculation of the new rank at (e), lightpath {D, C} is considered underutilized by the reconfiguration mechanism and it is deactivated. This is an example of how the proposed rating system can trigger a snowball effect, deactivating several lightpaths and reducing total energy consumption further.

## 4. PERFORMANCE EVALUATION

### 4.1. Simulation environment

In order to evaluate the performance of the proposed rating system, an event-based simulator was built in Java. Simulations were conducted for 48 h, after a warm-up period of 2 days. Results were compared between a simple virtual topology reconfiguration scheme with two thresholds (simple virtual topology reconfiguration (VTR)), as presented in [3] and a virtual topology reconfiguration scheme using the proposed rating system (page rank-based virtual topology reconfiguration (PR-VTR)). The algorithms have been tested for three different sets of thresholds: {60–20}, {70–20}, and {80–20}. The observation period was set at 5 min. The network topology used in the simulation consists of 24 nodes connected with 42 bidirectional physical links. Each network node can employ simultaneously up to eight transmitters and eight receivers, while each physical link can support up to 16 different wavelengths. Lightpath capacity is assumed to be the same for all lightpaths at 40 Gbps. Also, it is assumed there is no wavelength conversion in intermediate nodes. The average distance between nodes is set at 400 km based on the network parameters demonstrated in [18]. Network traffic is modeled as in [3]. The parameters used in the simulation are demonstrated in Table II.

### 4.2. Power consumption results

In Figure 4, total power consumption during the network simulation is illustrated for the simple reconfiguration scheme and the page rank virtual topology reconfiguration for a standard set of

Table II. Simulation parameters.

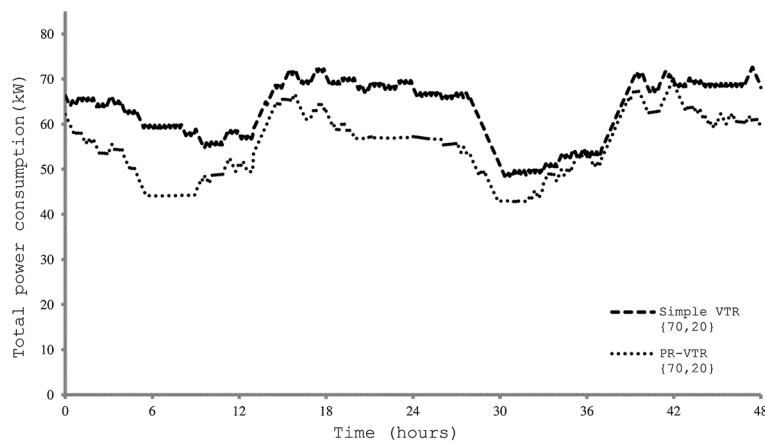| Simulation | |
|---|---|
| Warm-up period (days) | 2 |
| Simulation duration (days) | 2 |
| High threshold (%) | 60, 70, 80 |
| Low threshold (%) | 20 |
| Observation period (min) | 5 |
| Network topology | |
| Number of nodes | 24 |
| Number of fiber links | 42 |
| Transmitters per node | 8 |
| Receivers per node | 8 |
| Wavelengths per node | 16 |
| Wavelength conversion | None |
| Lightpath capacity (Gbps) | 40 |
| Average node distance (km) | 400 |



Figure 4. Total power consumption comparison between simple VTR and PR-VTR for thresholds {70, 20}. VTR, virtual topology reconfiguration; PR-VTR, page rank-based VTR.

thresholds (70, 20). It can be observed that PR-VTR has considerably lower power consumption in comparison with simple VTR throughout the whole simulation. This is because PR-VTR utilizes the proposed rating system, in order to make smart routing decisions. Specifically, the rating system suggests as routing options multipaths that already serve a large amount of flows efficiently, meaning that most of the flows are routed through the shortest paths. By concentrating more flows through lightpaths that already have high load, there is a chance that low-loaded lightpaths will get off-loaded, and the reconfiguration mechanism will deactivate those that have load below the low threshold at the end of the next observation period. So, PR-VTR manages to concentrate the traffic in fewer high-loaded lightpaths in comparison with simple VTR. Being able to serve the same amount of traffic with fewer lightpaths means that power consumption is reduced, because fewer lightpaths consume less energy through equipment as optical transceivers and IP ports.

In Figure 5, average total power consumption during the 2-day simulation period is demonstrated for three different sets of thresholds {60, 20}, {70, 20}, and {80, 20}. Consistent with other studies, like [2], higher upper threshold implies lower power consumption, because as the upper threshold increases, a greater fraction of the lightpath can be used to route traffic flows. Therefore, more traffic can be served with fewer lightpaths in comparison with lower upper thresholds. For both simple VTR and PR-VTR, as the high threshold decreases, total power consumption increases. The greatest difference between the two algorithms can be observed for thresholds {70, 20}, where PR-VTR achieves 12% energy savings with a total of 55 160 W power consumption on average
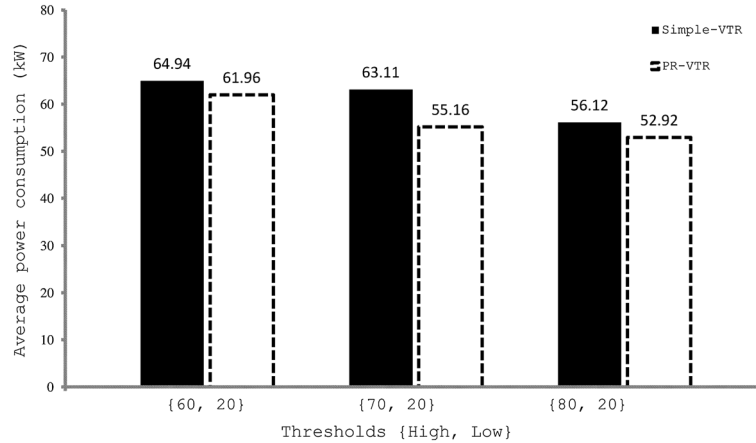
Figure 5. Average power consumption comparison between simple VTR and PR-VTR for different thresholds. VTR, virtual topology reconfiguration; PR-VTR, page rank-based VTR.

against the simple VTR, which has 63 110 W total power consumption on average. For thresholds {60, 20} and {80, 20}, PR-VTR achieves 5% energy savings.

## 4.3. Average weighted hop distance

In Figure 6, average hop distance weighted by the load of each IP traffic flow is illustrated for different sets of thresholds. Weighted hop distance was chosen because it is more representative as a parameter than simple hop distance, because the traffic flows do not have the same load. Average weighted hop distance increases as the upper threshold increases. This is considered normal, because virtual topologies with higher upper thresholds have fewer lightpaths. Fewer established lightpaths present reduced probability of having direct paths between two nodes in comparison with those of a larger virtual topology. It can be observed that PR-VTR has higher average weighted hop distance than simple VTR. PR-VTR manages to serve the same amount of load with fewer lightpaths in comparison to simple VTR, thus a trade-off is made between energy efficiency and hop distance. Based on the previous argument, PR-VTR features smaller virtual topologies and, for that reason, presents higher average weighted hop distance across all thresholds.

## 4.4. Utilization per lightpath

In Figure 7, average utilization per lightpath is shown for different sets of thresholds. Utilization per lightpath is a significant energy factor because it reveals how much capacity of the lightpaths is used
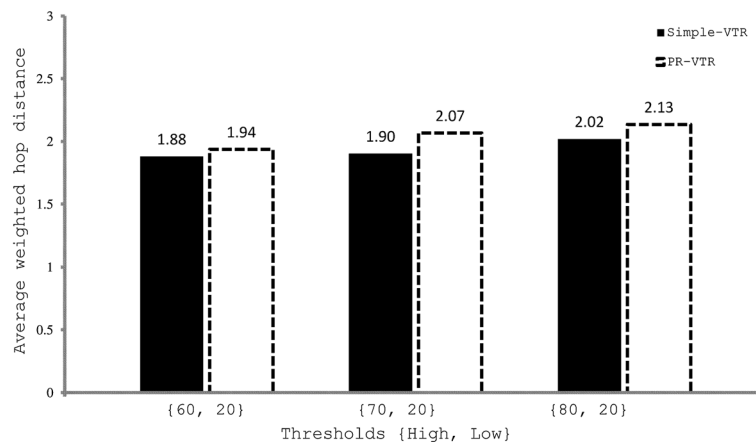


Figure 6. Average weighted hop distance comparison between simple VTR and PR-VTR for different thresholds. VTR, virtual topology reconfiguration; PR-VTR, page rank-based VTR.
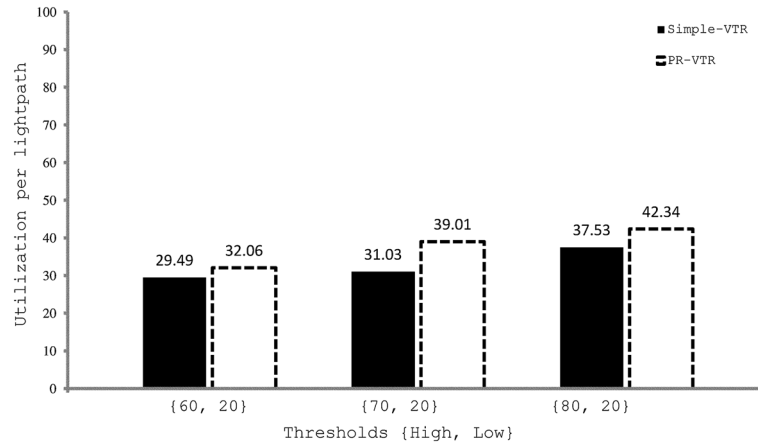
Figure 7. Average utilization per lightpath comparison between simple VTR and PR-VTR. VTR, virtual topology reconfiguration; PR-VTR, page rank-based VTR.

during the network simulation. It is vital to achieve high utilization, because utilizing a greater part of the lightpath capacity for routing IP traffic flows means that traffic load can be served with fewer lightpaths, and consequently, greater energy savings are achieved. PR-VTR has higher utilization per lightpath in comparison with simple VTR across all thresholds, because the rating system promotes the traffic flows through already high-loaded lightpaths in an effort to increase the utilization of the virtual topology and reduce the energy consumption.

## 5. CONCLUSION

A new scheme, PR-VTR, is proposed as an energy-aware solution for adjusting the virtual topology to the fluctuating traffic load during the network operation. This work proposes a rating system that attributes a rank on each lightpath, which can be used during the routing procedure, in order to identify the most suitable paths for an energy-aware virtual topology. The proposed rating system is a modified version of the page rank algorithm, which ranks websites in the Internet based on their importance. The virtual topology is constructed as a graph in a similar way to the Internet, where websites are connected to each other through hyperlinks. However, the proposed rating system is customized to fit the optical backbone network operation and the need to rate accordingly the lightpaths. PR-VTR has been compared with a simple reconfiguration algorithm using a two-thresholds reconfiguration mechanism and shortest path routing. PR-VTR increases the utilization per lightpath at the cost of slightly increased average weighted hop distance. In addition, PR-VTR achieves up to 12% energy savings in comparison with simple VTR for a standard set of thresholds {70, 20}, while it manages 5% energy savings in the other cases.

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