Power-aware Algorithms for Energy-efficient Elastic Optical Backbone and Metro Networks

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Abstract: Research in Optical Networking has recently focused on Elastic Optical Network architectures, that support elastic band connections to increase spectrum availability, support high transmission rates and reduce network costs. Elastic optical networks offer flexibility in the way capacity is assigned to connections and are considered the most prevalent solution for the next generation metro/backbone networks. Reduction in energy consumption is an important issue in such networks. In this work, a new power aware algorithm is introduced, which selectively switches off network links under low utilization scenarios supporting energy efficiency. A new power-aware scheme is proposed, which reduces the total energy consumption, while maintaining a low blocking probability under dynamic traffic. Extensive simulation results are presented, which indicate that the proposed heuristic algorithm achieves a power saving of up to 9%, compared to a simple energy unaware dynamic RSA algorithm.

1 INTRODUCTION

The demand for bandwidth is annually growing exponentially, driven by an increasing number of global internet users. In addition, future needs will also be driven by emerging capacity-demanding applications, including autonomous vehicles, the internet of things, high bandwidth enhanced video and virtual reality. According to Cisco, global IP traffic stood at 122 Exabytes in 2017 and it is estimated that these numbers will triple by 2022 (Cisco, 2019).

Historically, WDM optical networks technologies have used a fixed grid plan to accommodate the requested traffic demand. Wavelengths of line rate 2.5, 10, 40, and 100 Gb/s have all been suited with 50-GHz spacing in backbone networks and 100-GHz spacing in metro-core networks (Simmons, 2014). However, it is likely that bit rates greater than 100 Gb/s will not fit into this scheme (Gerstel et al., 2012). Elastic optical networks (EON), as a novel concept of WDM networks, are considered the most suitable architecture for backbone and next generation metropolitan networks as they are characterized by high spectral efficiency and adaptability (Jinno, 2017). EONs, based on orthogonal frequency-division multiplexing (OFDM) (Dao et al., 2018) support lightpaths with different bitrates, exploit the flexible grid technology where the spectrum is split into 25, 12.5 GHz or less slots compared to coarser splitting of 50 GHz or 100 GHz of traditional WDM networks. Hence, the slots are combined to create channels, which are not overlapping due to OFDM's orthogonality capacity, of the desired size using bandwidth what is strictly necessary for the transmission spectrum (Soumplis, 2017).

The energy consumed by ICT (Information and Communication Technology) equipment, which is rapidly expanding (Belkhir and Elmeligi, 2018), (Beletsioti et al., 2016), causes a significant economic and environmental problem. According to European Framework Initiative for Energy and Environmental

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Efficiency in the ICT Sector, ICTs account for 8-10% of the European electricity consumption and up to 4% of its carbon emissions. Furthermore, the network infrastructure is becoming a large portion of the energy footprint in ICT. In (Pickavet et al., 2008) M. Pickavet et al., mention that for network equipment, the energy consumption growth rates are typically about 12% per year. Thus, the concept of energy efficient or green networking has been emerged as a research topic.

A multitude of published papers have considered energy efficiency in the design of IP Over WDM optical networks (Shen and Tucker, 2009), (Chabarek et al., 2008), (Melidis et al., 2019). An important approach towards energy saving in IP over optical networks is the selective switching off of inactive network components when the traffic load is low, i.e. during night hours (off-peak hours), while maintaining the vital functions of the network, accommodating the residual capacity. In (Chiaraviglio et al., 2009b), energy efficient solutions ranging from Mixed Integer Linear Programming (MILP) to heuristics are proposed. More precisely, these schemes disable different network elements when the load is reduced, while ensuring a set of important constraints such as full connectivity and maximum utilization of a link. The same authors in (Chiaraviglio et al., 2009a) evaluate the actual power consumption savings considering a real IP backbone network and a real traffic profile.

Besides the selective disconnection and low power mode of networks elements, a considerable part of studies are focused on virtual topology reconfiguration algorithms. The authors in (Gençata and Mukherjee, 2003) and (Yayimli and Cavdar, 2012) propose a method of configuring the virtual topology in WDM networks which constantly presents alternating traffic over time. Two thresholds corresponding to the load of the optical paths are introduced: one to detect overloaded and one to detect underutilized lightpaths.

Additionally, various power-efficient algorithms considering the design of IP over EON (Zhu et al., 2019) can be found in the literature. A fairly common, yet effective method of energy saving is the extensive application of optical bypass, reducing thus the number of high energy-consuming optical-electrical-optical (O-E-O) conversions, as the signal can be transported, amplified and switched directly in the optical domain. In (Zhang et al., 2015), energy efficient traffic grooming in IP-over-elastic optical networks taking into account sliceable optical transponders is studied. MILP models among their corresponding heuristics are implemented, for each of three different types of bandwidth variable transponders, and investigated in terms of energy efficiency. Based on traffic and optical grooming methods, Selene heuristic (Kyriakopoulos et al., 2018a) is an online algorithm which exploits the innovative Signal Overlap technique for power savings in EONs. The work in (Vizcaíno et al., 2012) is dedicated to the study of energy efficiency in optical transport networks, comparing the performance of an innovative flexible network grid based on Orthogonal Frequency Division Multiplexing (OFDM) with that of Wavelength Division Multiplexing (WDM) with a Single Line Rate (SLR) and a Mixed Line Rate (MLR) operation. Energy-aware heuristic algorithms are proposed for resource allocation both in static (offline) and dynamic (online) scenarios with time-varying demands for the Elastic-bandwidth OFDM-based network and WDM networks (with SLR and MLR). Lopez et al. in (Vizcaino et al., 2012), provides an in depth energy efficient comparison between conventional path protection schemes for fixed-grid (WDM) and flexible-grid (EON) networks.

In this paper, an algorithm, namely SOLA (Switch Off Links Algorithm), that disables EON network links during the operation phase in low-use scenarios based on a threshold value is proposed. The proposed technique is based on prior knowledge in techniques which switch off and/or put in low power mode network equipment in fixed grid networks. However, the impact of the contiguity constraint has not been extensively researched in cases of shutting down network components, which is the main contribution of this work. Extensive simulation results indicate that the presented algorithm accomplishes energy efficiency and maintains tolerant bandwidth blocking probability.

The rest of the paper is organized as follows. Section 2 introduces the Elastic Optical Network model, power model and constraints. Section 3 presents the proposed algorithm. Section 4 gives the network environment, and Section 5 concludes this paper.

2 NETWORK MODEL

2.1 IP-over-EON Architecture

In this paper, a mesh based metropolitan or a backbone network which uses an IP-over-EON architecture as shown in Fig.1, is considered. A typical EON architecture consists of optical fiber links and optical switches. Each optical switching node is connected to the IP router ports through bandwidth variable transponders (BVTs) (Yi and Ramamurthy, 2016).

At the starting point of the data transmission path, the transponder, converts the electrical flows com-

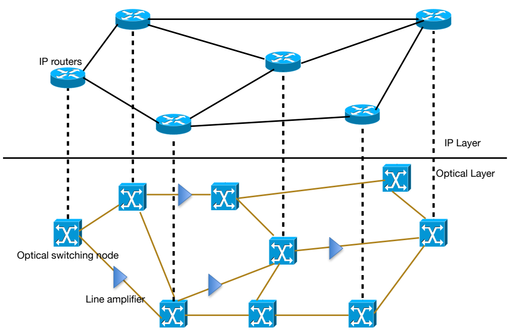


Figure 1: IP-Over-EON Architecture.

ing from the IP source router to the optical domain (E/O conversion), and then the traffic entering the optical layer is routed over the optical network in all-optical connections (lightpaths). The traffic travels along the lightpath in the optical layer, arrives at the optical layer destination node and finally reaches the end point at the IP layer. At the destination of a lightpath, the signal is converted back to electrical at the transponder (O/E conversion). Data is then forwarded and handled by the corresponding IP router. In order for the optical signal to travel over long distances, line amplifiers are deployed along the fiber in every 80 km.

2.2 Power Consumption Model

The main components that may affect the energy consumption of an elastic optical network are the IP router ports, bandwidth variable transponders (BVTs) and line amplifiers. Details are given below.

IP Router Ports: A 400 Gb/s IP router port is connected to a bandwidth variable transponder and consumes 560 Watt (Vizcaino et al., 2012), (Zhang et al., 2015), (Biswas and Adhya, 2019) as shown in (1).

$$PC_{IP} = 560(Watt) \tag{1}$$

Bandwidth Variable Transponder: According to (Zhang et al., 2015) and (Kyriakopoulos et al., 2018b) the power consumption of a BVT can be expressed as in (2), in which TR represents the transmission rate of the optical transponder. An additional 20% of power consumption is considered as an overhead contribution for each transponder.

$$PC_{BVT} = 1.683 \times TR(Gb/s) + 91.333(Watt) \tag{2}$$

Line Amplifier: Erbium Doped Fiber Amplifiers are considered as line amplifiers in this study. The power of the EDFA is represented in Equation (3), in which X is the spectrum width for amplifying.

$$PC_{EDFA} = 0.0075 \times X(GHz) \tag{3}$$

2.3 Elastic Optical Network Constraints

When designing an IP over EON, one should select the route, and spectral resources for a connection request arriving to the network. This is known as the problem of Routing and Spectrum Assignment (RSA) (Martínez and Pinto-Roa, 2017), (Fan et al., 2015). The EON implementation imposes to the RSA problem three constraints: (1) *the wavelength continuity constraint*, that is the allocation of a connection, must follow the same wavelength on each link along the route, (2) *the spectrum contiguity constraint*, that is the allocation of a connection must be on contiguous FS on each link along the route, and (3) *the spectral conflict constraint*, that is a connection allocated to a certain spectral resource, cannot overlap with the spectral resources of other connections.

3 SOLA DESCRIPTION

The main idea of the proposed algorithm is the design of an energy efficient scheme which reduces the total energy consumption during network's operation, by selectively switching off networks links in low-use scenarios while keeping the blocking probability in low percentages under dynamic traffic. In the operation phase of the network, new and variable rate connection requests arrive dynamically and have to be served upon their arrival, one by one. SOLA algorithm consists of two separate periods. The first period involves the observation period of the algorithm, during which some calculations are made regarding the utilization of the links, while the second period refers to the estimation of total power consumption.

Algorithm 1 shows the pseudocode of the proposed algorithm SOLA. During the observation period, the algorithms starts routing the traffic demands which arrive dynamically in the network. SOLA calculates the shortest paths between the node pairs, using the k-shortest path method, and routes the demands according to the First Fit algorithm. During this period, the existing links on the physical topology are monitored for a fixed number of arrivals.

By the end of the observation phase, link utilization percentages for each link in the physical topology have been calculated. Afterwards, links of the physical topology are sorted in descending order according to these previously calculated values. Low threshold value (LT) is estimated using Equation (4) and (5), and the number of links to be switched off from the physical topology can been determined. In detail, Eq. (4), is an empirical formula and refers to the utilization factor of the link. For a given network

Algorithm 1: SOLA.

Input : $G(N,L)$: Physical Topology
N: Set of nodes in the network
L: Set of links in the network

Observation Period

Calculate k-shortest paths
Route demands FirstFit
Record link utilization statistics
Record blocked connection requests (with respect to bandwidth)

Decision Making

According to recorded statistics **do**:
Order links according to utilization
Calculate UF
Calculate LT
Estimate BBP
Calculate energy consumption using eq. 1, eq. 2 and eq. 3

foreach *link* $\in L$ **do**
  if *link utilization <= low threshold (LT)* **then**
    remove link from network topology
  else
    continue

Operation Period

Input : $G'(N,L')$: New Physical Topology
N: Set of nodes in the network
L': Set of links in the network

Calculate k-shortest paths
Route demands FirstFit
Estimate BBP
Calculate energy consumption using eq. 1, eq. 2 and eq. 3

load, topologies consisting of large number of links are expected to experience lower utilization per link in contrast to smaller ones. Therefore, it is expected that the utilization factor (UF) is inversely proportional to the number of active links (n) found on the physical topology. The UF formula presented in Eq. (4) is, consequently, structured to reflect the aforementioned observation. Eq. (5) declares the Low Threshold value. Every link that has a utilization value less that LT should be switched off. In the final step of this period, the power consumption as well as the bandwidth blocking probability (BBP) of the initial physical topology are estimated, and the specific links are switched off. The number of links that has to be deactivated is used as an input parameter to the second phase of the algorithm. The extreme case that all links that traverse a network node were deactivated simultaneously is not assumed in this study, as the network node is isolated and the network becomes connectionless.

Next the algorithm enters the operation phase. During this period, SOLA, takes place on a new network topology, having excluded the deactivated links. K-shortest paths are recalculated for the new network topology and new demands are routed using First Fit once again. Finally, the energy consumption of the network equipment on the new network topology and the BBP are estimated.

$$UF = e^5/n \tag{4}$$

$$LT = 10 \times UF \tag{5}$$

4 PERFORMANCE EVALUATION

4.1 Study Cases

In order to evaluate the performance of the proposed algorithm, a set of simulation experiments were conducted. To estimate the overall power consumption of different design solutions, two network topologies were considered. Fig.2 and Fig.3 show a mesh based network (Antoniades et al., 2004), which consists of 29 nodes and 41 links, for each of which two directions will be considered and a backbone transport network, NFSNET (Shen and Tucker, 2009) of 14 nodes and 21 links, respectively.

4.2 Simulation Assumptions and Parameters

An elastic optical network simulator has been implemented, using Python 3.7 on Spyder (The Scientific Python Development Environment). The complete set of parameters used in this study are listed below.

1. The number of frequency slots (FS) on a link equals to 160. This is a typical value which is used in many previous works.
2. Each FS is assumed to have a spectral width of 25 GHz.
3. Connection requests follow a Poisson process with an average connection's inter arrival time

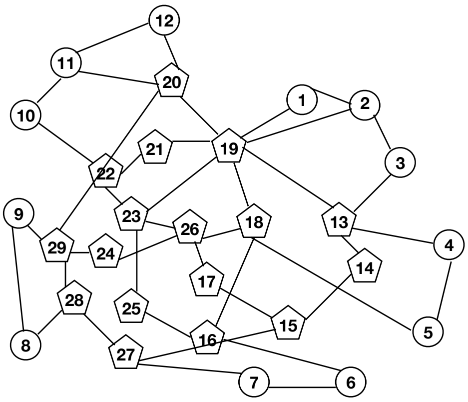


Figure 2: Mesh based Metropolitan network.

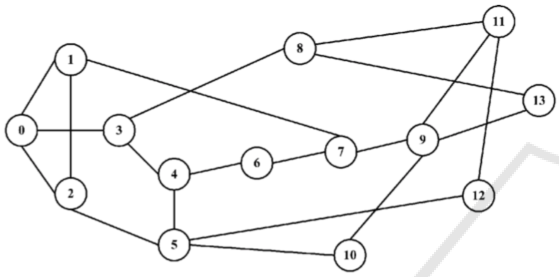


Figure 3: Transport backbone network, NSFnet.

($\overline{IAT}$) equals to 1 (λ), while their holding time follows a negative exponential distribution with mean value (μ). The latter is tuned to achieve the desired traffic load (Comellas and Junyent, 2015).

4. The number of FSs per connection corresponds to the uniform distribution. Each new coming connection can take any value from 1 to 9 with a uniformly distributed probability (Comellas and Junyent, 2015).
5. The source and destination nodes of a request are randomly and independently selected from the network topology.
6. K-shortest path, with k=3, and widely known First Fit scheme, are used for solving the RSA problem.
7. One line amplifier and eight BVT per physical connection are considered in this study.
8. The offered load is determined by λ / μ (Erlang).
9. One FS as a guard-band associated with each of the connections is considered.
10. The modulation format used in every connection is assumed to be the same during the whole simulation and the connection requires the same amount of bandwidth as its bit rate (Fan et al., 2015).

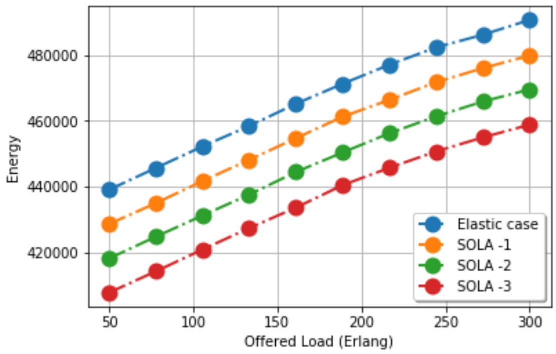
4.3 Numerical Results

The performance metrics such as energy consumption, bandwidth blocking probability (BBP), energy savings and average hop distance have been evaluated in metropolitan and backbone networks.

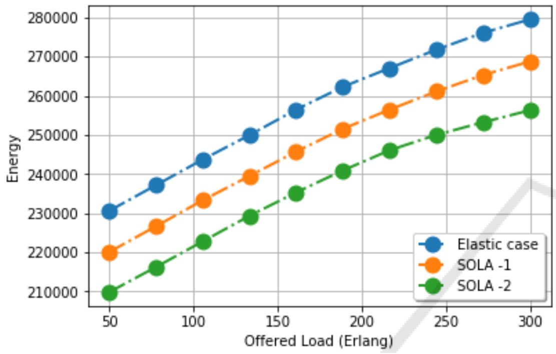
A simple non-energy aware routing and spectrum assignment approach, namely Elastic, has been implemented. This algorithm which provides non power awareness, just routes the incoming requests using the first fit strategy without deactivating any network resources, exploiting the advantages of EONs. According to equations (4) and (5), three (SOLA -3) and two (SOLA -2) links should be activated, when SOLA is applied in both Metropolitan and NSFnet backbone networks respectively. Nevertheless, for the sake of completeness, energy consumption (Fig. 4), BBP (Fig. 5), energy savings (Fig. 6) and average hop distance (Fig. 7), are depicted even when fewer links are deactivated for each network topology, i.e. SOLA-1 and SOLA-2 for metropolitan network and SOLA-1 for the backbone network.

Figure 4 illustrates the total energy consumption versus the offered load (Erlang) between SOLA and Elastic case algorithm. In detail, Fig. 4a relates to energy consumption in Metropolitan network, while Fig. 4b refers to energy consumption in NSFnet backbone network. The energy consumption of each compared method rises in a common way as the offered load increases. It is worth noticing that in both network topologies SOLA always outperforms the reference Elastic case algorithm. Corresponding results obtained in terms of power savings are summarized in Fig. 6. These results are translated into profit by up to 7% and 9% for Metropolitan and backbone NSFnet networks respectively.

From the algorithm description, it is evident that a small part of network's resources is sacrificed in order to achieve lower power consumption values. Notwithstanding, extensive simulation results have proven that this sacrifice is minimal in terms of energy savings attained. To support this, bandwidth blocking probability (BBP), in linear and logarithmic (inline plots in the Figure) scale, versus the increasing offered load is depicted in Fig. 5. BBP of both algorithms increases when the traffic load increase. As it could be seen, BBP remains the same as long as the offered load is light for both SOLA and Elastic case algorithm. Although, as expected in higher offered load values the Elastic case algorithm results in lower BBP, as the lightpaths have more chances to be accommodated in a network with a greater number of links. However, the proposed algorithm manages to save important amounts of energy without signifi-

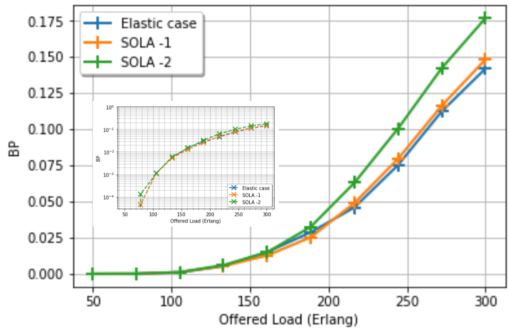


(a) Energy consumption (Watt) in Metropolitan network.

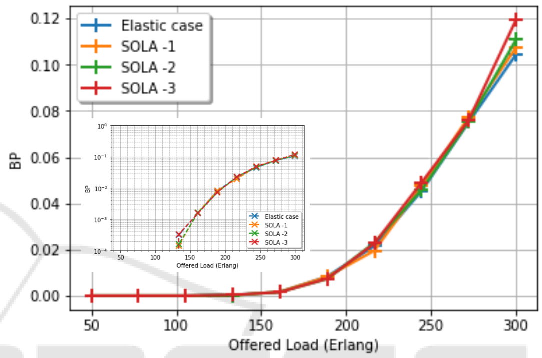


(b) Energy consumption (Watt) in Backbone network (NSFnet).

Figure 4: Energy consumption under different network topologies.



(a) Bandwidth blocking probability in Metropolitan network.



(b) Bandwidth blocking probability in Backbone network (NSFnet).

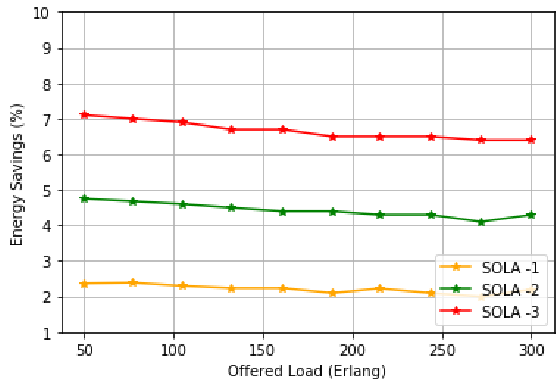
Figure 5: Bandwidth blocking probability under different network topologies.

cantly increasing the BBP, which fluctuates from just 1 to 2.5 %.

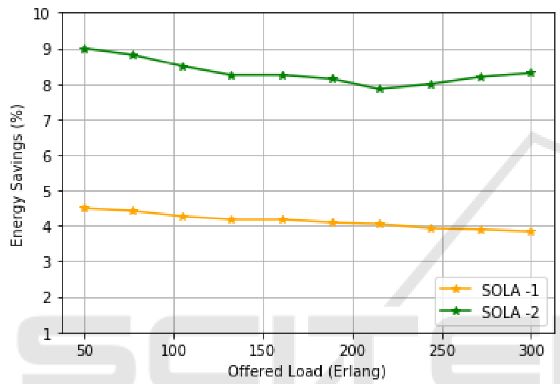
The estimates for the average hop distances as come from the Elastic case algorithm and the proposed SOLA are given in Figure 7. More precisely, this figure describes how many hops a lightpath traverses on average to reach its destination. In both subfigures 7a and 7b, the Elastic case algorithm shows a minor advance (this minor advance could be translated to only 1-2.7% profit), as there is no deactivation of any link and the possibilities of finding shorter paths, in comparison to SOLA, are increased. This small increment in terms of average hop distance is a small but necessary price that the algorithm must pay to achieve significant energy savings, while keeping the overall performance in high levels. In addition, this minor drawback is quiet common and is observed in many previous energy efficient related papers ((Beletsioti et al., 2018), (Kyriakopoulos et al., 2018b)).

5 CONCLUSION

In this paper a new power aware algorithm, namely SOLA, has been implemented for Elastic Optical Networks. The main objective of the proposed algorithm is the reduction of energy consumption during the network operation, by selectively deactivating network links under low utilization scenarios, while it manages to keep the bandwidth blocking probability in low percentages. To attain a more realistic approach towards energy savings in EONs, optical grooming is intended to be introduced as a primary future work goal. Furthermore, decision making strategies with respect ro adaptivity issues during network operation will also be reconsidered. The proposed scheme can be the base of a new generation of energy efficient algorithms for elastic optical networks.

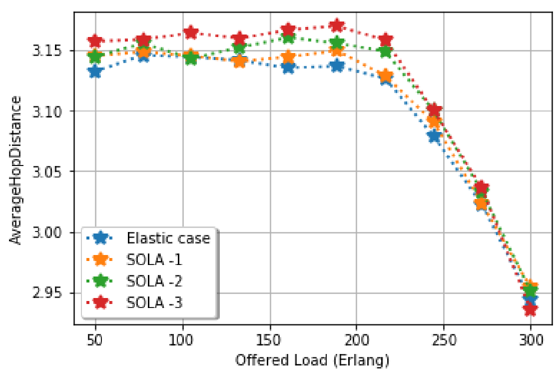


(a) Percentage of energy savings (%) in Metropolitan network.

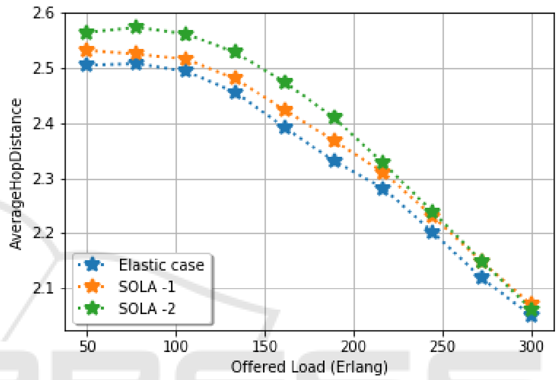


(b) Percentage of energy savings (%) in Backbone network (NSFnet).

Figure 6: Percentage of energy savings (%) under different network topologies.



(a) Average Hop Distance in Metropolitan network.



(b) Average Hop Distance in Backbone network (NSFnet).

Figure 7: Average Hop Distance under different network topologies.

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