

Article

On the Evaluation of Complex Networks Designs for an Energy-Efficient IP/WDM Core Network

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Abstract: As the Internet grows in capacity, the energy consumption of Information and Communication Technologies (ICT) are significantly increasing. Significant research efforts on energy conservation have been devoted to devise different technological solutions to address raised concerns surrounding the power consumption of networking equipment and its impact firstly on the emission of greenhouse gases and secondly on electricity bills. In this work, we investigate energy-efficient physical topologies for NSF IP over wavelength-division multiplexing (WDM) network for the purpose of minimizing energy consumption by redesigning its current physical connectivity. We implement different network topologies, such as implementing the small-world, scale-free (SFN), and random networks on the NSF network, then evaluate and compare its physical properties and network power consumption with the current NSF topology design using a mixed-integer linear programming model, all with the aim of minimizing the network total power consumption. The evaluation shall optimize and minimize the embodied energy consumption of network equipment in the IP and optical layers. Results have demonstrated that the implementation of the proposed energy-minimized topology designs can significantly improve the node's clustering coefficient, reduce network's diameter, and reduce energy consumption of the NSF IP over WDM network to 28% if compared with the current design implementation.



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Keywords: complex network; small-world networks; SFN; energy efficiency; WDM; optimization; MILP

1. Introduction

Over the past decade, the growth of internet traffic has significantly contributed to the increase in the amount of backbone network equipment required and the capacities of such equipment [1]. This growth has resulted in an increase in the running cost and energy consumption. Energy consumption rather than cost has been considered as a major concern as it has been found to be a contributor of greenhouse gases which have a great impact on the environment.

Recently, many research efforts have been devoted to greening the internet to reduce its carbon footprint and impact on the environment [2,3]. In [1], a MILP optimization model and energy efficient heuristics were developed to reduce power consumption for the IP over WDM networks. Results have shown that savings ranging from 25% to 45% can be achieved with the bypass Light path in comparison to the non-bypass. In [4], the authors developed a MILP model to optimize the physical topology of the National Science Foundation (NSF) network topology with the objective of reducing total network power consumption considering the different approaches, nodal degrees, and topologies. Authors in [4] also investigated the full mesh and star topologies and have shown significant savings in power that reach 95% and 92%, respectively. In [4], the authors have considered the use of renewable energy to reduce energy consumption and hence reduce the emissions of

greenhouse gases. The authors in [4] have also studied the adaptive link rates for different loads and its impact on the total power consumption. Results have demonstrated that with the use of renewable energy and adaptive rates, energy savings can reach 65%. In [5], the authors studied and investigated means of reducing the power consumption of IP over WDM networks with data centers. Authors have developed an MILP model to optimize the location of data centers and found that the routing approach, topology design, and number of data centers are the main factors that control the percentage of power savings that can be achieved while optimizing the locations of data centers. The authors in [5] demonstrated that savings in energy consumption can be up to 73% if data centers are located near the renewable energy sources and a replication scheme is considered.

In this study, for the achievement of more power savings on top of previously proposed approaches, we implement the MILP model developed in [1] to evaluate the NSF network with highly connected topology designs, such as the small-world, scale-free, and random complex networks to reduce energy consumption by efficiently utilizing communication links, router ports, and paths through means of grouping and consolidation.

The main contributions of our research are summarized as follows:

- We investigated network-related factors/properties including the clustering coefficient, network diameter, average path length, and their impact on overall network power consumption in IP over WDM networks.
- We improved the clustering coefficient and diameter of the NSFNet. The clustering coefficient indicates how good a node is connected to its neighbors' neighbors. A high clustering coefficient indicates that the network is composed of many strong ties. Our results demonstrated a 246% increase in the clustering coefficient when compared with the current NSF design.
- We improved the NSFNet path length. Our results, as shall be illustrated in a subsequent section, demonstrated that a reduction of 15% in the NSF network path length can be achieved with a small-world network design with $p = 1$.
- The contribution of backbone networks to the total network power consumption is increasing significantly with the growing popularity of bandwidth-intensive applications. This growth has resulted in an increase in the running cost and energy consumption. Energy consumption, rather than cost, has been considered as a major concern as it has been found to be a contributor of greenhouse gases which have a great impact on the environment. In this work, with the implemented topology designs on the NSFNet, we have achieved power savings of up to 27% more than the previously proposed topology.
- Implemented complex network designs, such as implementing the small-world, scale-free, and random networks on the NSFNet while maintaining the location of the nodes as well as the number of edges.
- We have optimized the implemented new NSFNet physical topology (small-world, scale-free, and random) using Tucker's MILP model under different traffic loads and time zones.
- We have analyzed the characteristics of the different topologies and shown that physical topology optimization can be viewed as a design process with the aim of minimizing the average network path.

The remainder of this paper is organized as follows: Section 2 presents the main properties of any network topology, with a focus on complex network properties such as the degree distribution, degree exponent, mean path length, and clustering coefficient.

In Section 3, for consistency and completeness, we revisit the IP over WDM network architecture and briefly describe the current NSF network topology. In Section 4, we demonstrate the complex network designs to be evaluated on the NSF node distribution. In Section 5, we describe the MILP model implemented to evaluate the total network power consumption of the NSF network when complex network connectivity is implemented. In Section 6, we provide the results and discussions. Finally, Section 7 provides the conclusions and future insights.

2. Complex Network Properties

In order to compare and evaluate the impact of different networks physical connectivity on the total power consumption, network properties and fundamental quantities such as the degree, degree distribution, degree exponent, mean path length, and clustering coefficient are worth studying. Table 1 lists and defines some of the main network properties used in the evaluation [6–9].

Table 1. Network property definitions.

Nodal Degree (k)	Nodal degree or degree of a node (k) presents the sum of links (neighboring nodes) directly connected to the node (i).
Degree Distribution $p(k)$	It is the probability distribution of a node, and it can be obtained by summing all nodes with different k links and dividing it by the total number of nodes in the whole topology.
Diameter	The diameter of a network is the length of the shortest path between the farthest-distanced nodes.
Path Length (L) and Mean Shortest Path Length $\langle L \rangle$	Path length (L) between any source (s) and destination (d) nodes in the network is the sum of all the traversed links between s and d, while the mean shortest path length $\langle L \rangle$ is the average of all shortest paths between all pairs of s and d nodes. $\langle L \rangle = \frac{1}{N(N-1)} \sum_{s \neq d} L_{sd}$ where L_{sd} is the length of the shortest path between nodes s and d and N is the total number of nodes in the network.
Clustering Coefficient C, Average Clustering Coefficient $\langle C \rangle$ and $C(k)$	The clustering coefficient in a graph is a measure of the network's tendency to create clusters together [6] and is represented by the number of triangles that traverses through node i. The clustering coefficient can be computed using [7]: $C_i = \frac{2T_i}{k_i(k_i - 1)} \quad (1)$ where T_i is the number of links connected with the (i) neighbors, k_i is the degree of node (i), and C_i is the number of triangles that pass through the node (i). The average clustering coefficient can be also computed by summing the C of all nodes and dividing by the number of nodes N for every i belonging to a G graph [6,7]. $\langle C \rangle = \frac{1}{N} \sum_{i=1}^N C_i \quad (2)$

3. Complex Network Designs

In this section, we review the complex networks, describe their properties, and justify recent interest by researchers for the consideration of such topologies in networks. The main models, covering random graphs, small-world network, and SFNs shall be described in this section.

Complex networks are found to be energy-efficient, robust, and fault-tolerant SFN physical topologies that display stability and a high degree of tolerance against physical impairments and link or node failures. In the occurrence of dynamic changes such as link failures or the removal of links from routing tables, these networks sustain and produce a new network that is still highly connected and able to deliver information and maintain delay with acceptable predefined performance measures. With the rich connectivity of the complex networks, the power consumption of the network can be reduced by grooming traffic on fewer links and putting underutilized links on sleep mode.

The main models of the complex networks, covering random graphs, small-world networks, and SFNs are briefly described in the following.

3.1. Random Networks

The purpose of random networks as first proposed by Erdos-Renyi (ER) in 1959 was to model networks with n nodes and generate a homogeneous graph $G(n, p)$ by randomly

selecting a pair of nodes with equal probability (p) and assign edges to connect them with the prespecified probability [9]. The generated random graph has $p[n(n-1)/2]$ randomly placed edges connecting a pair of nodes with independent probability (p). Random graphs have a low mean path length which is directly proportional to the network size [7].

3.2. SFNs

The scale-free networks (SFNs), modeled by Barabási and Albert, are described as inhomogeneous networks and characterized by a power-law degree distribution [8]. In SFNs, few nodes exist with a high number of links (hubs), and a high number of nodes with few links exist. The emergence of the SFN property is governed by growth and preferential attachment. When a new node is added into the network, the probability of the node's attachment to other nodes will be higher to those with a higher degree. As a result, hubs will have higher rates of connecting new nodes than other nodes; hence, a skewed degree of distribution with a heavy tail is produced (power-law behavior). Networks with power-law behavior are said to be SFNs.

In SFNs, more than 60% of nodes can be reached through heavily connected hubs, demonstrating a fruitful property of SFNs, in addition to the low diameter property of such models. The larger the network or the number of added nodes, the smaller the diameter and the shorter the path is between any two nodes [10].

3.3. Small-World Network

The small-world network was initially introduced by Watts and Strogatz to provide graphs that exhibit a high clustering coefficient with a small average shortest path length. A small-world network is a graph where most of its nodes are not adjacent to each other, however; the network has a low diameter, and most of its nodes can be reached by each other in a few hops. As the number of nodes in small-world networks increases, the diameter increases logarithmically, however; the number of links to interconnect nodes is kept to a minimum.

As illustrated in Figure 1, the model starts with a ring structure that consists of a specified number of edges (k) and nodes (n) that remain unchanged throughout the realization process. With a predefined probability (p), a few shortcuts are created to rewire and interconnect nodes with edges which are selected randomly. The number of generated shortcuts (S) are governed by the predefined probability and can be calculated using Equation (3).

$$S = \frac{(n)(k)(p)}{2} \quad (3)$$

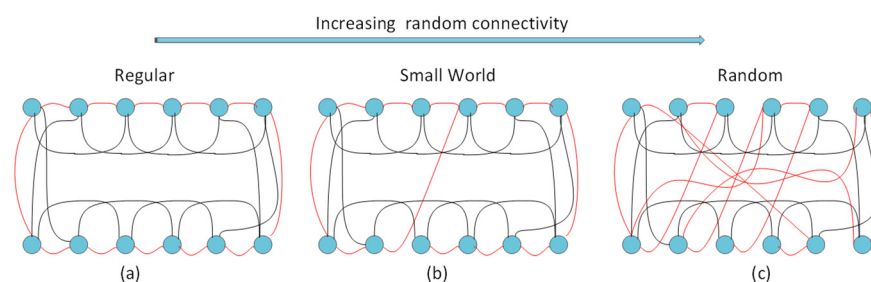


Figure 1. Small-world network realization for different probabilities without changing the number of nodes and edges; (a) $p = 0$, original graph and all edges are unchanged; (b) p is a number between $[0, 1]$; (c) $p = 1$, random network with all edges rewired [6].

The clustering coefficient and path length properties are highly affected by edge rewiring, which is governed by the predefined (p). For $p = 0$, the network is unchanged. However, as the probability increases to approach 1, all edges are rewired, and the clustering coefficient and average path length become the lowest that can be attained. Modifying the probability of edge rewiring for values between 0 and 1 (e.g., $p = 0.1$), a small-world

network will be generated with a high clustering coefficient, as with a regular graph, and a low diameter, as with a random graph.

4. Implementation of Small World, Random, and Scale-Free Networks on the NSF Network

In this section, we implement the small-world network, ER random network, and SFN on the NSF to produce different topologies using methods and codes presented in [11] to further study the impact of such networks on the average path diameter, average clustering coefficient, and the total network power consumption.

The NSF network as illustrated in Figure 2 consists of 14 nodes distributed in different states of the United States (US) with 21 bi-directional links. The network is referred to as the current NSF, and it has an average shortest path diameter of 2.175 and an average clustering coefficient of 0.0714.

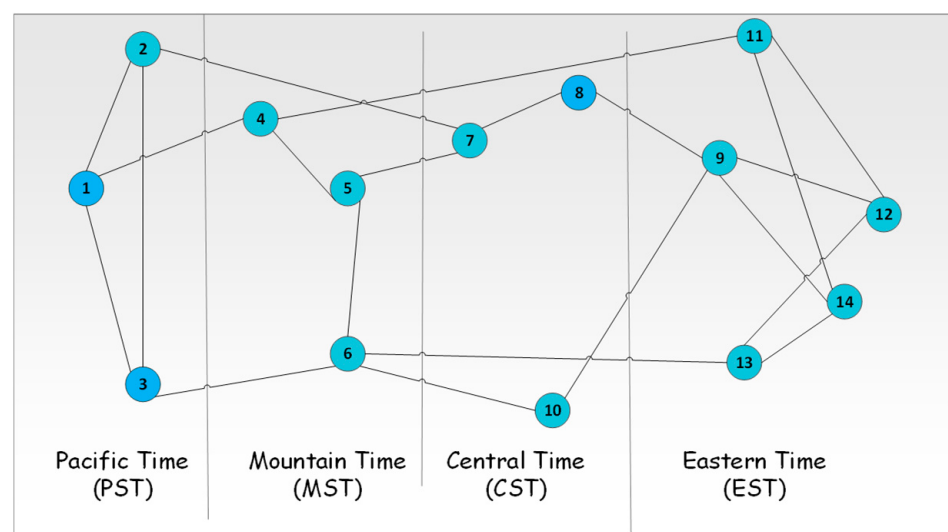


Figure 2. Base network topology: Current topology of the NSF network with time zones [4].

To create SFN graphs to interconnect the 14 nodes of the current NSF network illustrated in Figure 2, the algorithm described by Barabási and Albert in [11] is implemented. Multiple runs of the algorithm generate different graphs and yield different ways of connecting the NSF 14 nodes with 21 edges. Each modeled complex network graph was run more than 10 times, and the samples provided in this work are our best graphs in terms of power consumption conservation. However, the mathematical MILP model for each sample has given the same results (optimum), regardless of the number of times the model was run. Samples of such generated SFN topologies are illustrated in Figure 3. Vertices in red represent the nodes with dense connectivity (hubs).

To create small-world and random graphs to interconnect the 14 nodes of the current NSF network, the methods described by Watts and Strogatz in [11,12] are implemented. Figures 4 and 5 illustrate samples of generated small-world and random graphs that mimic the NSF's 14-node connectivity model.

The diameter of a network is the length of the shortest path between the farthest-distanced nodes. The cost metric is used to indicate which path is the shortest between all pairs of nodes. A cost measure of a graph can be the total distance, or the number of nodes traversed between every possible pair of source and destination nodes. Average path length is calculated by summing up all the shortest path lengths of all the source and destination pairs of nodes and dividing them by the total number of pairs.

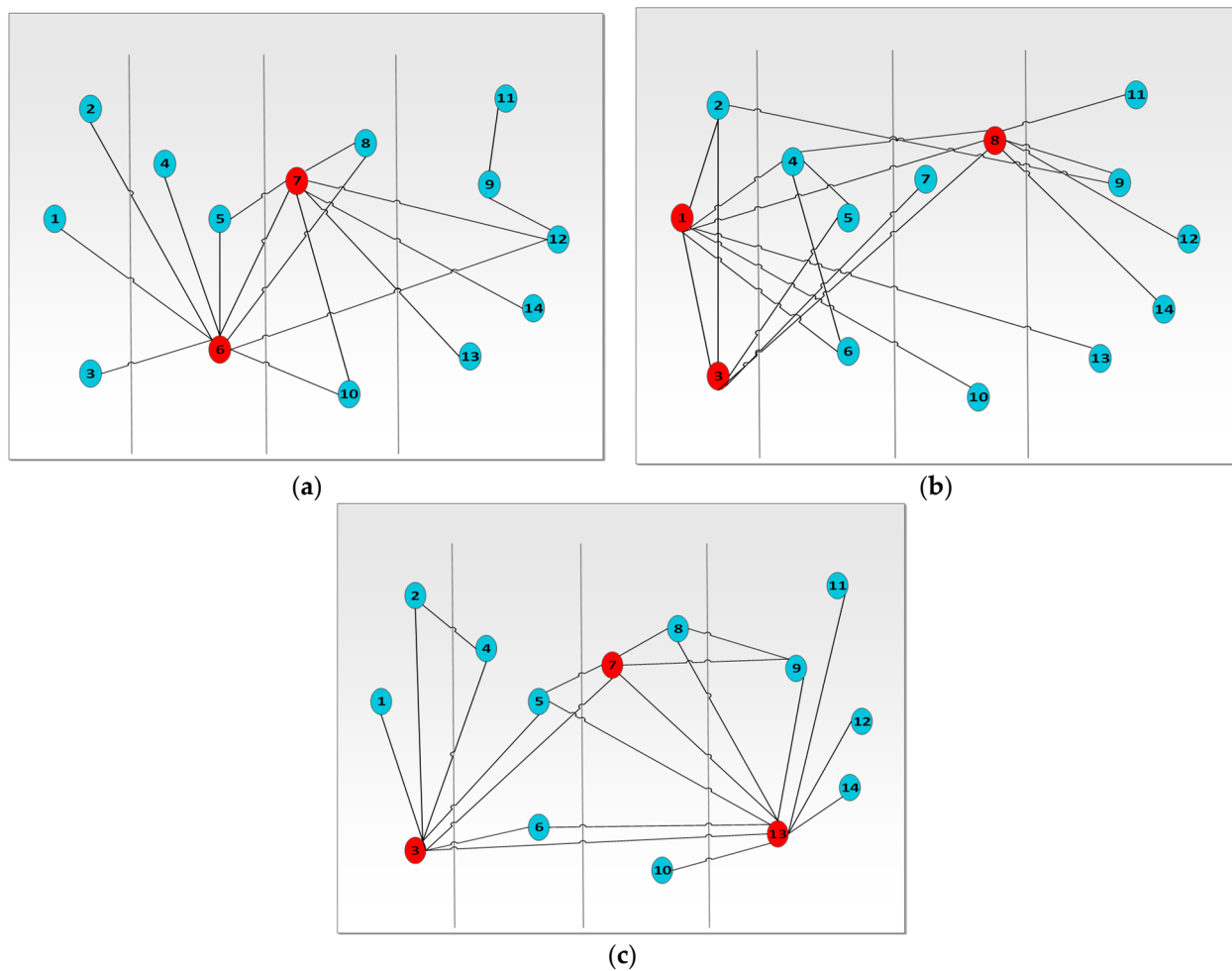


Figure 3. Samples of SFN graph's implementation on the NSF's 14 nodes with 21 edges; (a) SFN sample 1, (b) SFN network sample 2, (c) SFN network sample 3. (Note: nodes in red are heavily connected hob nodes).

From the results illustrated in Figure 6, the current NSF network shows a relatively longer average shortest path when compared with the small-world network topology implemented in the NSF. It is observed from the results illustrated in Figure 6 that as the rewiring probability is increased, more shortcuts between nodes are increased, and as a result the path length decreases. A small fraction change in the rewiring probability creates shortcuts which can connect widely separated nodes, and hence results in a significant reduction in the diameter of the whole network [6]. Results illustrated in Figure 6 demonstrate that a reduction of 15% in the NSF network path length can be achieved if a small-world network design with $p = 1$ (as in Figure 4d) is considered for interconnecting nodes in the NSF network.

Along with the shortest average path, small-world networks with $p = 1$ have a high node clustering coefficient. The clustering coefficient indicates how good a node is connected to its neighbors' neighbors. A high clustering coefficient indicates that the network comprises of many strong ties. Table 1 defines and demonstrates how the node's clustering coefficient can be calculated. If the node's clustering coefficient is 1, the neighbors of that node are fully connected, and when the neighbors are poorly connected, the value of the clustering coefficient will be near 0 [6]. Results illustrated in Figure 7 demonstrate a 246% increase in the clustering coefficient when compared with the current NSF design.

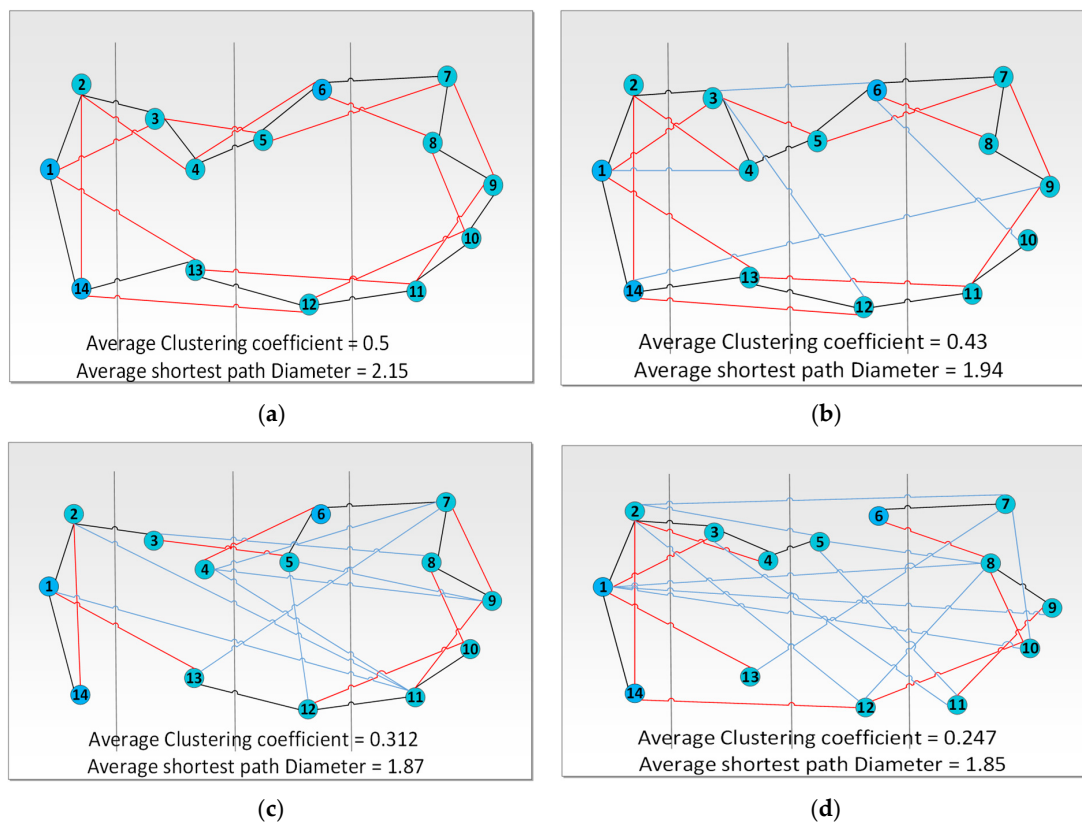


Figure 4. NSF small-world network with $k = 4$, (a) $p = 0$, (b) $p = 0.2$, (c) $p = 0.5$, and (d) $p = 1$.

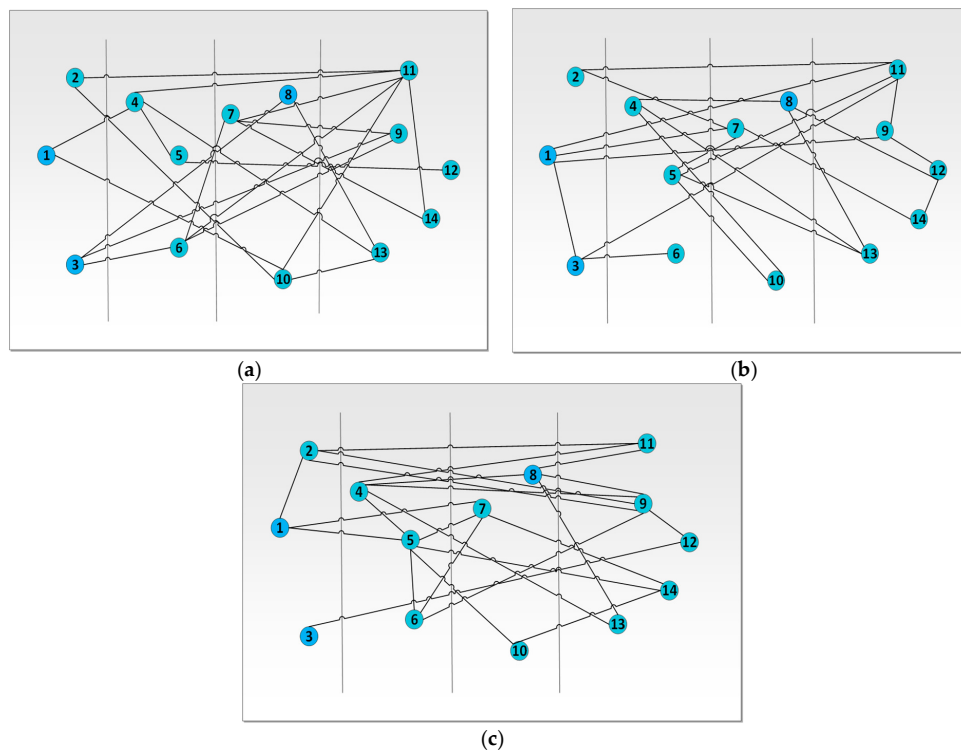


Figure 5. Samples of the NSF network random implementation with 14 nodes, 21 edges, and mean degree of 3. (a) Random network sample 1, (b) Random network sample 2, (c) Random network sample 3.

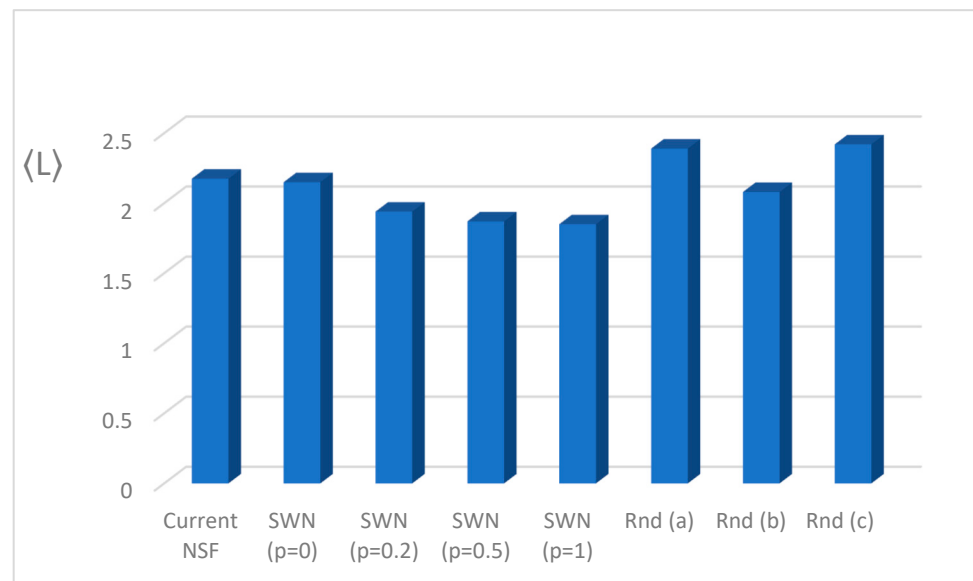


Figure 6. Average shortest path length $\langle L \rangle$.

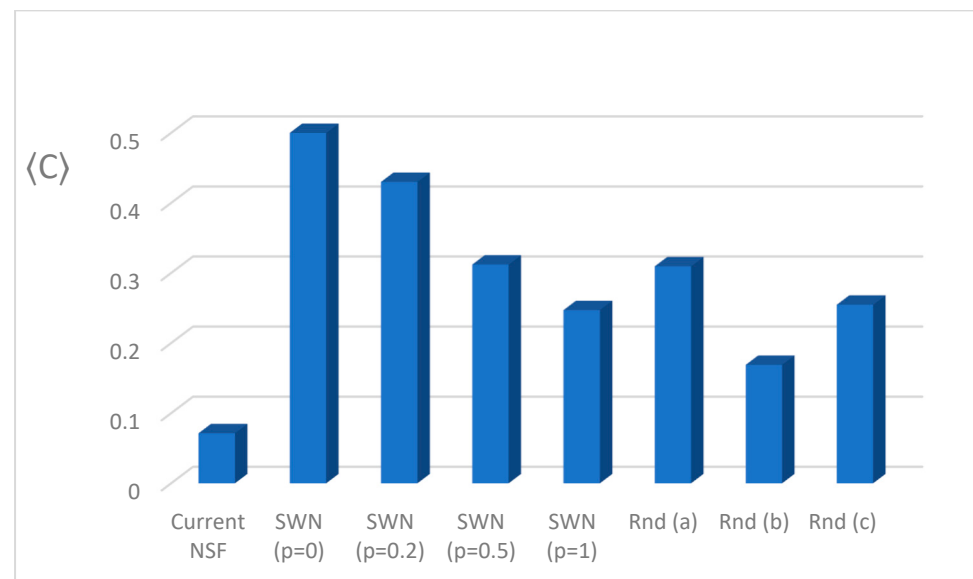


Figure 7. Average clustering coefficient $\langle C \rangle$.

To further study the impact of the implemented small-world, SFN, and random networks on the NSF network power consumption, in the following sections we briefly describe the IP over WDM networks, then present the MILP model implemented to evaluate the network power.

5. IP over WDM Core Network Architecture

The IP over WDM backbone network as described in [1,13] and illustrated in Figure 8 is composed of two layers: an IP layer and circuit-switched optical layer. The IP layer includes the IP routers, and the transparent optical layer consists of the optical switches (OXC), multiplexers, transponders, erbium-doped amplifiers (EDFAs), and regenerators. The two layers are interconnected through high speed short-reach optical interfaces to facilitate communication between low-end routers. A high-speed optical cable with multiple fibers is employed for interconnecting optical switches, with each fiber associated with two wavelengths for multiplexing and demultiplexing. The OXC is a preconfigured cross-connect system that is capable of inter nodes switching functionality. A pair of transponders

are also employed for converting an O–E–O (optical–electrical–optical) signal at the switch node during transmission. For long distance transmission, erbium-doped fiber amplifiers (EDFAs) are used to facilitate transmission for 80 km and provide 30-dB amplification gain to the signal [blackout resilient network]. Regenerators are an essential part of the IP over WDM network and are responsible for restoring the signal strength. A regenerator receives the optical signal, converts it to an electrical signal, removes unwanted parts, and converts it back to an optical signal for forward transmission. Finally, the electronic IP router connects the low-end routers with the OXC switches and is mainly responsible for traffic aggregation between the metro and core networks [13].

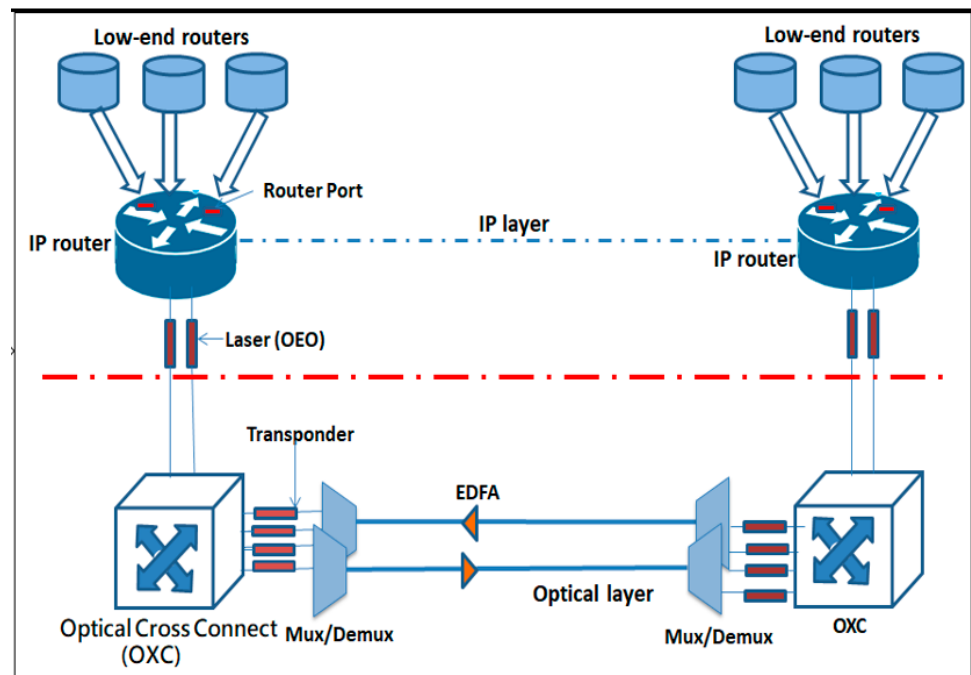


Figure 8. IP over WDM network architecture [13].

In the following section, we introduce the energy minimization MILP model to benchmark the IP over WDM network energy consumption between the developed small-world, SFN, and random NSF topologies' interconnections presented in Section 5 with the current NSF design.

6. MILP Model

In this section, we study the impact of the implementation of the small-world, random, and SFN physical topologies on the total network power consumption of IP over WDM NSF network. For completeness, we re-introduce the MILP optimization model developed in [Tucker and Dong] for a non-bypass IP over WDM network to evaluate and compare such proposed designs with the current physical topology of the NSF network. The model shall minimize the network power consumption by optimizing the network resources. Optimizing network resources through dynamic approaches by switching off underutilized resources at low traffic demands and grouping, grooming, and consolidating traffic efficiently on fewer resources. The focus in this work is on the core network of the IP over WDM; the access network and aggregation routers are not considered in the evaluation study.

Before introducing the model, we list the notations and parameters used in the model as follows (Tables 2 and 3).

Table 2. Notations and parameters [1].

N	Set of vertices (nodes)
$Nm_{\{i\}}$	Set of neighbors of node i
s and d	Denote source and destination pair
i and j	Denote end points of a virtual link in the IP layer
x and y	Denote end points of a physical link in the optical layer
P_{RP}	Denote power consumption of router ports
$P_{Transponder}$	Denote power consumption of a transponder
P_{OXC}	Denote power consumption of optical switch
P_{EDFA}	Denote power consumption of an EDFA
P_{Reg}	Denote power consumption of a regenerator
B	Denote capacity of a wavelength
φ_{xy}	Denote number of EDFAs on physical link (x, y) . φ_{xy} can be calculated as: $\varphi_{xy} = \left(\frac{\delta_{xy}}{d} - 1\right) + 2$, where d is the distance between two neighboring EDFAs and δ_{xy} is the distance between (x, y) nodes.
τ^{sd}	Size of traffic demand from node s to node d in b/s
η	Denotes number of wavelengths in each fiber

Table 3. Variables [1].

τ_{ij}^{sd}	The size of traffic flow from node s to node d that traverse the virtual link (i, j)
C_{ij}	The number of wavelength channels used in the virtual link (i, j)
γ_{xy}^{ij}	The number of wavelength channels used in the virtual link (i, j) that traverse physical link (x, y)
γ_{xy}	The number of wavelength channels that propagate physical link (x, y)
F_{xy}	Number of fiber strands in physical link (x, y)
β_i	Number of routers' i aggregation ports
NPC	Total network power consumption

The total network power consumption of the modeled network consists of:

1. Total power consumption of router ports

$$\sum_{x \in N} \sum_{y \in Nm} P_{RP} * \gamma_{xy} \quad (4)$$

2. The power consumption of transponders

$$\sum_{x \in N} \sum_{y \in Nm} P_{Transponder} * \gamma_{xy} \quad (5)$$

3. The power consumption of EDFAs

$$\sum_{x \in N} \sum_{y \in Nm} P_{EDFA} * F_{xy} * \varphi_{xy} \quad (6)$$

4. The power consumption of optical switches

$$\sum_{x \in N} P_{OXC} \quad (7)$$

5. Total power consumption of aggregation ports

$$\sum_{i \in N} P_{RP} * \beta_i \quad (8)$$

The total number of aggregation ports in each node:

$$\beta_i = \frac{1}{B} \sum_{d \in N} \tau^{id} \forall i \in N \quad (9)$$

6. Power consumption of regenerators:

$$\sum_{x \in N} \sum_{y \in N_m} P_{Reg} * RG_{xy} * \gamma_{xy} \quad (10)$$

The MILP model is defined as follows:

Objective: Minimize NPC

The total network power consumption (NPC) is given in (11):

$$\begin{aligned} NPC = & \sum_{x \in N} \sum_{y \in N_m} P_{RP} * \gamma_{xy} + \sum_{x \in N} \sum_{y \in N_m} P_{Transponder} * \gamma_{xy} + \\ & \sum_{x \in N} \sum_{y \in N_m} P_{EDFA} * F_{xy} * \varphi_{xy} + \sum_{x \in N} P_{OXC} \\ & + \sum_{x \in N} \sum_{y \in N_m} P_{Reg} * RG_{xy} * \gamma_{xy} + \sum_{i \in N} P_{RP} * \beta_i \end{aligned} \quad (11)$$

Subject to:

$$\sum_{j \in N, i \neq j} \tau_{ij}^{sd} - \sum_{j \in N, i \neq j} \tau_{ji}^{sd} = \begin{cases} \tau^{sd} & i = s \\ -\tau^{sd} & i = d \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

$$\begin{aligned} \sum_{s \in N} \sum_{d \in N, s \neq d} \tau_{ij}^{sd} & \leq C_{ij} \\ \forall j, i \in N : i & \neq j, \end{aligned} \quad (13)$$

$$\begin{aligned} \sum_{y \in N_m} \gamma_{xy}^{ij} - \sum_{y \in N_m} \gamma_{xy}^{ji} & = \begin{cases} C_{ij} & x = i \\ -C_{ij} & x = j \\ 0 & \text{otherwise} \end{cases} \\ \forall i, j, x \in N : i & \neq j, \end{aligned} \quad (14)$$

$$\begin{aligned} \sum_{i \in N} \sum_{j \in N} \gamma_{xy}^{ij} & \leq \sum_{i \in N} \sum_{j \in N} \gamma_{xy}^{ij} \leq * F_{xy} \\ \forall x \in N, y \in N_m, \end{aligned} \quad (15)$$

$$\begin{aligned} \sum_{i \in N} \sum_{j \in N} \gamma_{xy}^{ij} & \leq \gamma_{xy} \\ \forall x \in N, y \in N_m, \end{aligned} \quad (16)$$

The objective function given in (11) aims to minimize the total network power consumption in the IP and optical layers. The total network power is composed of the power consumed by router ports, transponders, EDFAs, optical switches, aggregation ports, and regenerators.

Constraint (12) is the flow conservation constraint which ensures that incoming traffic is equal to outgoing traffic for every node, except when the node is a source or a destination. Constraint (13) is the link capacity constraint, where it is ensured that traversing traffic through any virtual link does not exceed its capacity. Constraint (14) is the flow conservation constraints for the optical layer. Constraint (14) ensures that the number of traversing wavelengths in a link should equal to the total incoming wavelengths except at the source and destinations nodes. Constraint (15) ensures that the sum of all wavelengths traversing a link should not exceed its capacity. Constraint (16) ensures that wavelengths in a physical link do not exceed the total number of wavelengths in the physical link.

7. Results and Discussion

The base evaluated network model is the NSF network, as illustrated in Figure 2, and consists of 14 nodes located in different states of the United States (US) with 21 bi-directional links and with an average shortest path of 2.175. As depicted in Figure 2, the nodes of the NSF are in four time zones: Eastern Standard Time (EST), Central Standard Time (CST), Mountain Standard Time (MST), and Pacific Standard Time (PST). There is a one hour difference between every two adjacent time zones. During the day and night, different nodes experience different traffic loads. Figure 9 illustrates the traffic load in Gb/s between all node pairs for a period of 24 h. The traffic is generated using a gravity model based on the population of the city where the node is located [14]. The average traffic load between node pairs varies between 20 to 120 Gb/s, and the peak occurs at 22:00.

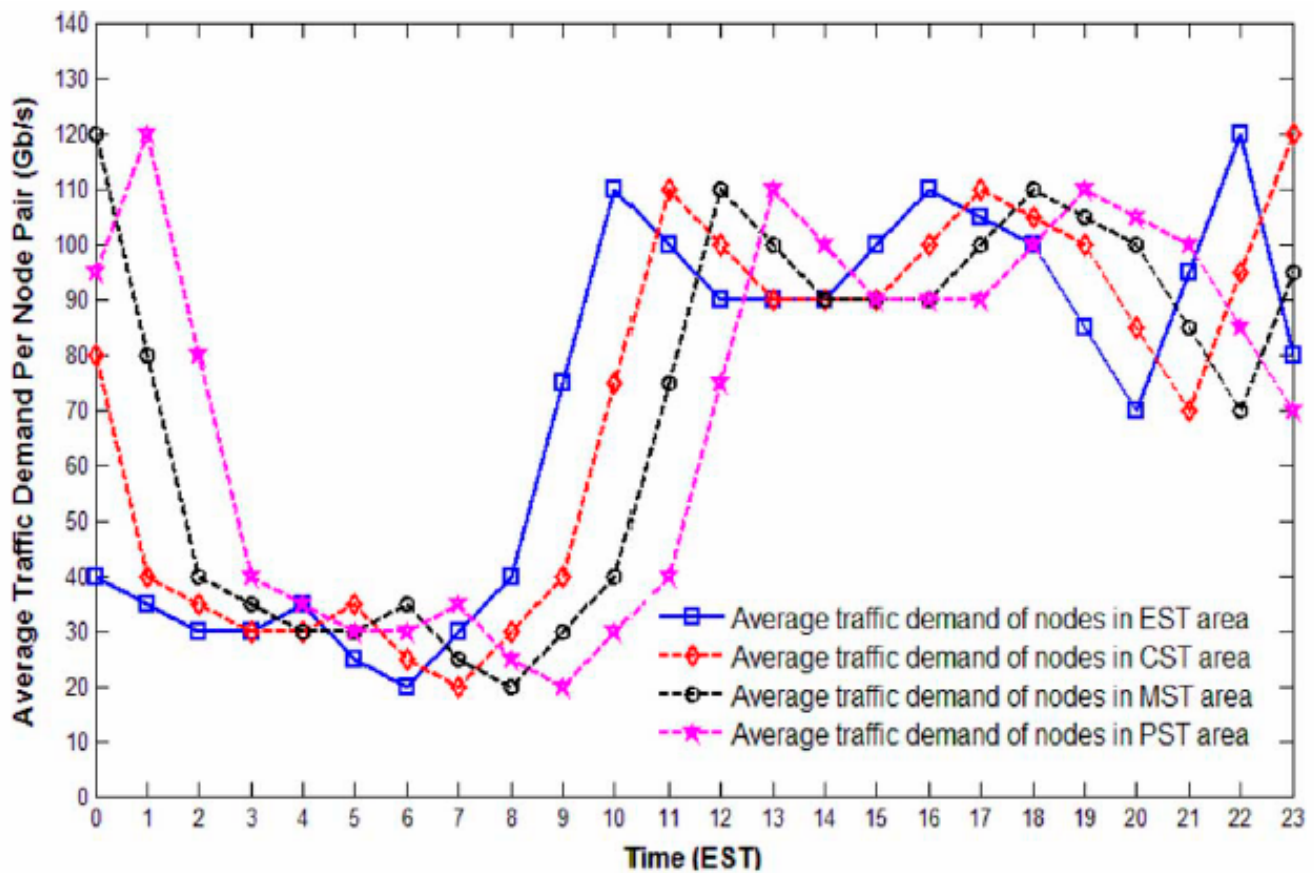


Figure 9. Average traffic load in the four time zones [4].

In this work, we follow assumptions made in [4] and assume that the traffic load between node pairs in the same time zone is random with a uniform distribution and no lower than 10 Gb/s [4].

Table 4 shows the parameters used in the MILP model, in terms of number of wavelengths, capacity of a wavelength, distance between two adjacent EDFAs, and the energy consumption of different components in the network such as the router's port, optical switch, multiplexer/demultiplexer, EDFA, regenerators, and transponders.

The MILP solver program used is AMPL/CPLEX on Lenovo with core i7 CPU, with a 2.8 GHz processor and 8 GB RAM [19]. CPLEX and AMPL make a powerful modelling tool for solving optimization problems, developed by IBM and Bell laboratories, respectively [19].

Table 4. Input parameters.

(d)	80 (km) [15]
(n)	16 [16]
(B)	40 (Gb/s) [17]
(P_{RP})	825 (W) [15]
$(P_{Transponder})$	167 (W) [15]
(P_{Reg})	334 (W) [15]
(P_{EDFA})	55 (W) [17]
(P_{OXC})	85 (W) [18]

Given the traffic between nodes in the NSFNET network as depicted in Figure 9, along with IP router ports power consumption in Table 4, it is clear that the power consumption of the IP routers is the major contributor to the total power consumption of the network. The power optimized topologies will be supported by the minimum number of IP router ports. Hence, after traffic being groomed on a minimum number of ports, unused router ports will be eliminated from the total network power calculations and considered as being in sleep mode.

Multiple random experiments (around 15 experiments) were conducted to get different sample graph networks for each of the scale-free, random, and small-world network designs. Sample networks provided in Figures 3–5 are our best obtained graphs in terms of power consumption conservation. However, the mathematical MILP model for each sample gave the same results (optimum) regardless of the number of times the model was run for each topology.

In this work, we show that a re-design of the topology interconnection can be undertaken to improve energy efficiency in IP over WDM core networks. As previously discussed in Section 4, the impact of the topology can greatly impact the average path length and clustering coefficient. In Section 4, we have demonstrated that a small change of rewiring probability creates shortcuts that can connect widely separated nodes, and consequently result in a significant reduction on the network diameter. In addition to network diameter, we have also shown that the design of the topology interconnection impacts the node's clustering coefficient, which is seen as a network property that indicates how weak or strong the ties between a node and its neighbors are. Reducing the diameter of a network while improving the clustering coefficient of the network's nodes can effectively reduce the network average path length and the number of nodes traversed during traffic forwarding. Consequently, the overall number of used links and network active components such as IP routers, EDFAs, regenerators, OXC, and transponders needed to support traffic demands are reduced.

The results demonstrate that to achieve the best results in energy conservation, targeting energy efficiency in the IP layer to minimize the total number of routers' line cards would be of great interest, as routers' ports are found to be the main contributors of power consumption in the IP over WDM networks (825 W) [15,20]. In this regard, considering the MILP optimization model described in Section 6, the network power consumption would be minimized by taking advantage of the introduced shortcuts using the redesigned topology interconnection and optimizing the network resources by means of grooming traffic demands on fewer links and putting underutilized router ports on sleep mode.

In this work, we have assessed the network power consumption of the redesign NSF topology for different average node's mean degrees ($k = 4$ and 6) to evaluate its impact on energy conservation of the implemented SWN described in Section 4.

As can be observed from Figure 10, with $k = 4$, energy savings achieved can reach 14.4% as the rewiring probability approaches to 1. The results illustrated in Figure 10 along with topology design for $k = 4$ in Figure 4, demonstrate that when $p = 0$, the effect on power consumption reduction is minimal; however, as the wiring probability in the

SWN increases, more shortcuts introduced. Shortcuts have an impact on decreasing the average path length (diameter) of the network, as widely distant nodes can be closer and reached with a fewer number of nodes traversed, and hence the result of a significant reduction in energy consumption as the number of network resources utilized (router ports, transponders, EDFAs, optical switches, and regenerators) to support traffic demands between nodes are lowered.

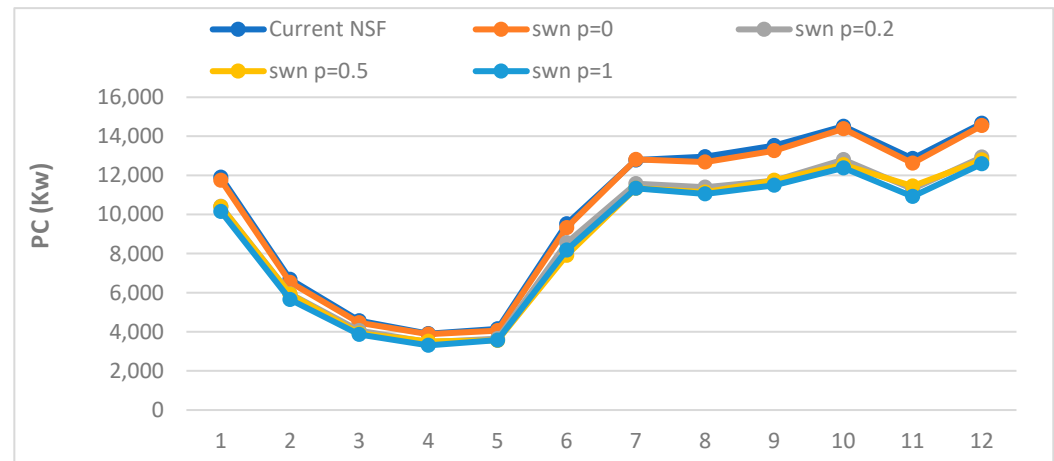


Figure 10. IP/WDM power consumption of SWN implementation on NSF network against current NSF topology design with $k = 4$.

Figure 11 illustrates the SWN with $k = 6$; it is observed that it is possible to further reduce power consumption to 28% if the average nodal degree is increased from 4 to 6. It is also notable that with the increase in k , the network diameter is decreased, and power consumption of the network can be reduced as traffic can be groomed on fewer links and underutilized resources can be put on sleep mode. Figure 12 presents the saving percentages that can be achieved for the different rewiring probability with $k = 4$ and 6, respectively.

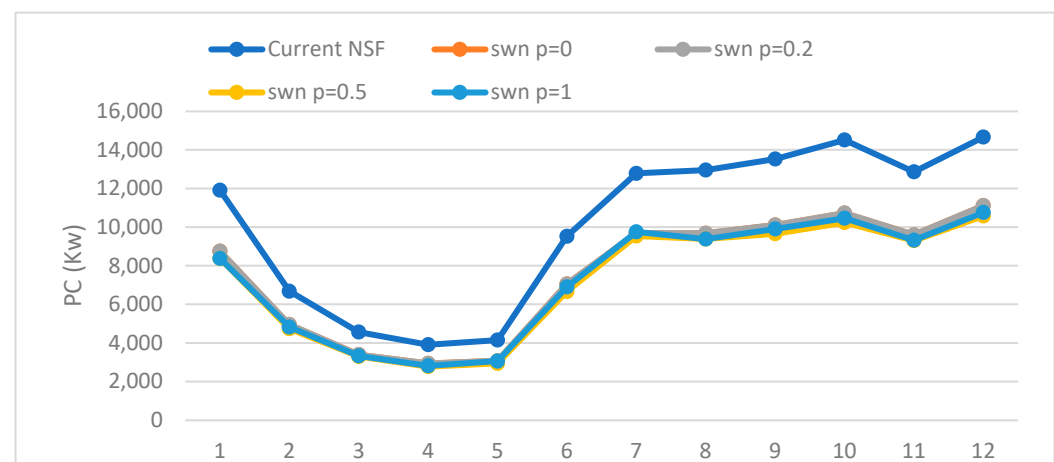


Figure 11. IP/WDM power consumption of SWN implementation on NSF network against current NSF topology design with $k = 6$.

SCF and random networks illustrated in Figures 3 and 5, respectively, evaluated using the MILP model described in Section 6 to assess the power consumption and compare with current and SWN NSF networks in order to find out if savings can be achieved. Results demonstrated in Figure 13 illustrate that the random design is not as efficient as the SWN

in energy savings. However, with the SCF savings can reach 13% when compared to the current NSF design.

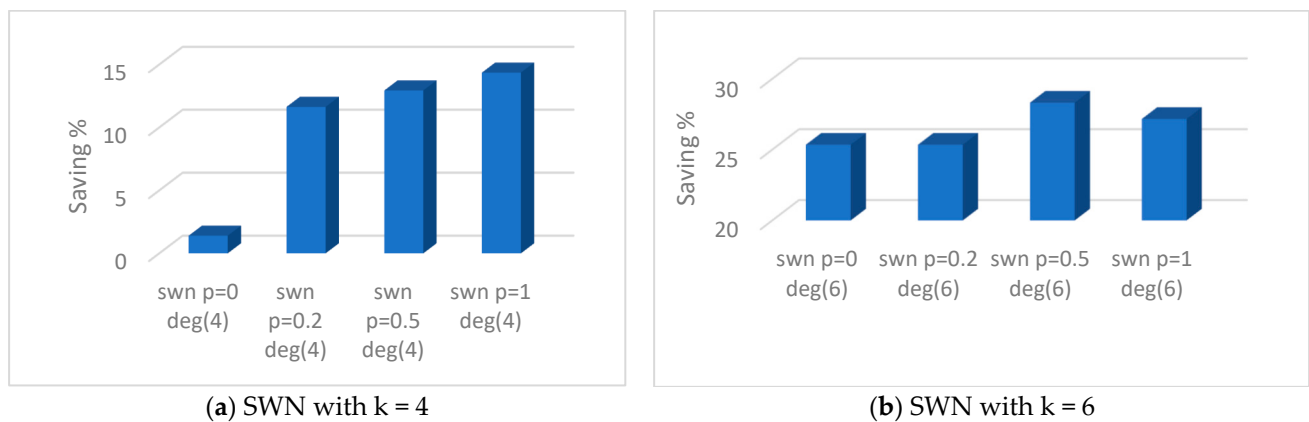


Figure 12. Savings percentage of energy consumption for different SWN configurations compared to current NSF.

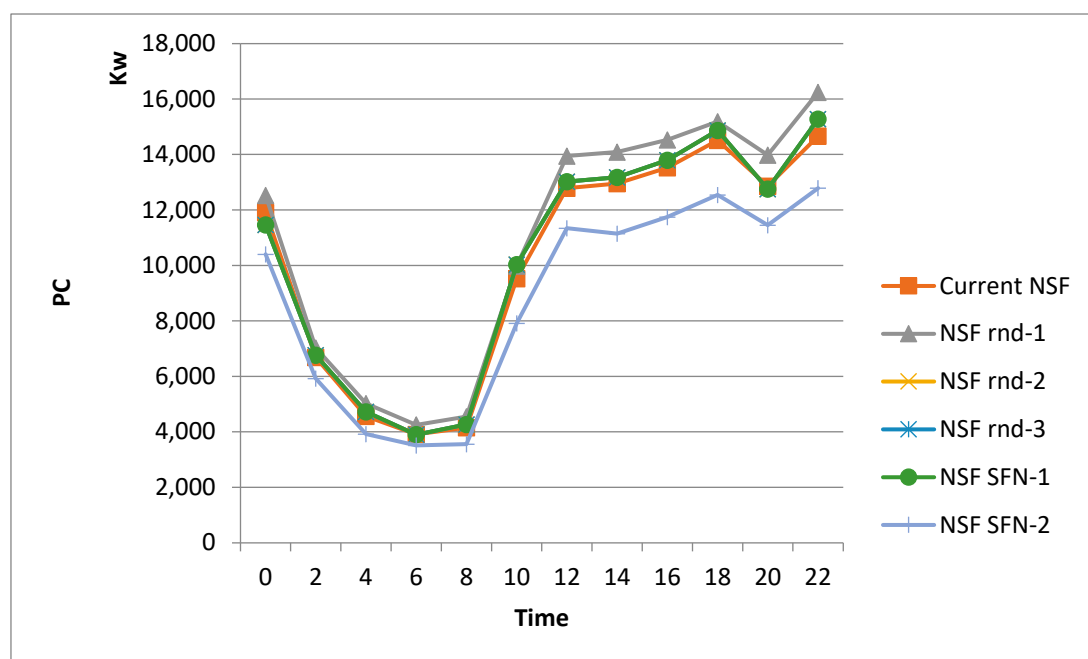


Figure 13. IP over WDM power consumption for SFN and random network compared with current NSF ($m = 21$).

The existence of hubs in the SFN reduces the network diameter and makes 60% of nodes reachable through them. This is due to the fact that the smaller the diameter, the shorter the average path length, the less the number of nodes traversed, the less links and devices used, and the less the power consumed.

Random graphs, as depicted in Figures 5 and 6, have a slightly higher average path length than the current SWN. Path length is directly proportional with the network diameter as the larger the network diameter, the longer the path is between any two nodes, which justifies the increase in the power consumption.

This study was based on modeling the NSF network which consists of 14 nodes to prove the possibility of minimizing energy consumption when applying the scale-free, random, and small-world networks to the NSF network is less complex to analyze in terms of the number of variables, especially when optimized using MILP. Larger networks with

a higher number of nodes and links appear to be an “NP complete problem”, with very high complexity. Solution to such problems with networks with high number of nodes and edges requires a design of heuristic algorithm which shall be considered for future work.

8. Conclusions

In this work, we show that in addition to the applied methods and approaches through means of a greedy algorithm and optimization models to ensure efficient resource utilization of a network to minimize its power consumption, network properties such as the clustering coefficient and average path length can play an important role in the further reduction of energy consumption in a network. In this work, we present the main properties and designs of the main complex network models, covering random, small-world, and scale-free networks, as well as the interplay between the topology design and the network’s power consumption in the IP/WDM core network. We performed a comprehensive comparison of properties and energy consumption between the small-world, SFN, and random topology designs against the current topology design of the NSF network (base network). A MILP model previously introduced by [1] was implemented for energy assessment of each of the developed topology designs. The results have shown that it is possible to further reduce the power consumption of the NSF network by 28% or 13% if the SWN or SCF network designs are considered. As a result, we find that changing the topology connectivity structure by implementing the scale-free, small-world, or random networks eventually changes the graph physical connectivity and therefore the nodal degree. An important note here is that the geographical location of the nodes, number of nodes, and total number of edges are not changed, and this supports the purpose of this research, which is that power consumption can be reduced if the topology is designed differently.

For future work, an energy-aware routing greedy algorithm shall be developed to mimic the behavior and verify the results obtained from the energy-minimized MILP model described in Section 6. Moreover, in future work, we will demonstrate that the proposed designs of small-world and scale-free networks with rich connectivity can be implemented to display a high degree of stability and tolerance against impairments and link or node failures.

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