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Impact of data center placement on the power consumption of flexible-grid optical networks

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Abstract. The increasing trend of global IP traffic is mainly driven by high-definition video services and cloud computing and storage. Moreover, to maintain a high quality of service in content delivery networking, data are geographically replicated in data centers distributed within network topologies. Thus, data centers are an emerging scenario for research and development aimed at energy-efficient transmission and networking solutions. Previous research work has focused on intradata center energy efficiency while interdata center energy issues have not been extensively analyzed yet. We propose heuristics and meta-heuristics for optimal placement of data centers with minimum power consumption over a network topology relying on flex-grid spectral use. In order to minimize the network's power consumption, we have performed a detailed comparison of heuristic and meta-heuristic designs for different network scenarios based on real topologies. Moreover, our results show that meta-heuristic provides an optimum data center placement in a reasonable amount of time for a small- to medium-sized network. © *2020 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.59.1.016115]

Keywords: flexible-grid network; data center placement; network power optimization; IP over wavelength-division-multiplexing; lightpath topology; genetic algorithm.

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1 Introduction

The proliferation of data-intensive applications and services, such as high-definition interactive video services, has led to an overall increase in internet protocol (IP) traffic demand, globally.[1] Besides being capacity-hungry, high-definition interactive video services need a very low peer-to-peer latency, so content delivery networks are implemented by replicating data at various geographically distributed data centers (DCs). The most viable solution to connect these DCs is through optical transport networks. These networks currently rely on the transmission layer implementing the fixed-grid wavelength division multiplexing (WDM) based on 50-GHz spacing, as defined by the International Telecommunication Union (ITU). To implement the elastic paradigm in such a scenario down to the transmission layer, the technological update that operators are already deploying are flex-rate transceivers, which are commercially available down to a few Gbps granularity. These transceivers, given the symbol rate, adapt the actual data rate deployed on the allocated lightpath (LP) to the available quality-of-transmission in order to maximize capacity.[2–4] To this purpose, one of the most used techniques is the implementation of time-division hybrid modulation formats.[5]

The flex-rate/fixed-grid solution still introduces rigidity in network management, impeding the full exploitation of the optical transport layer.[6] So, flex-grid WDM spectral usage has been proposed and standardized by the ITU, and spectrally sliceable transponders represent a feasible solution for next-generation commercial products. This enables the abstraction of flex-rate/flexible-grid optical networks to be a predictable evolution for backbone networks, fully enabling the elastic paradigm maximizing the capacity usage of the transport layer.

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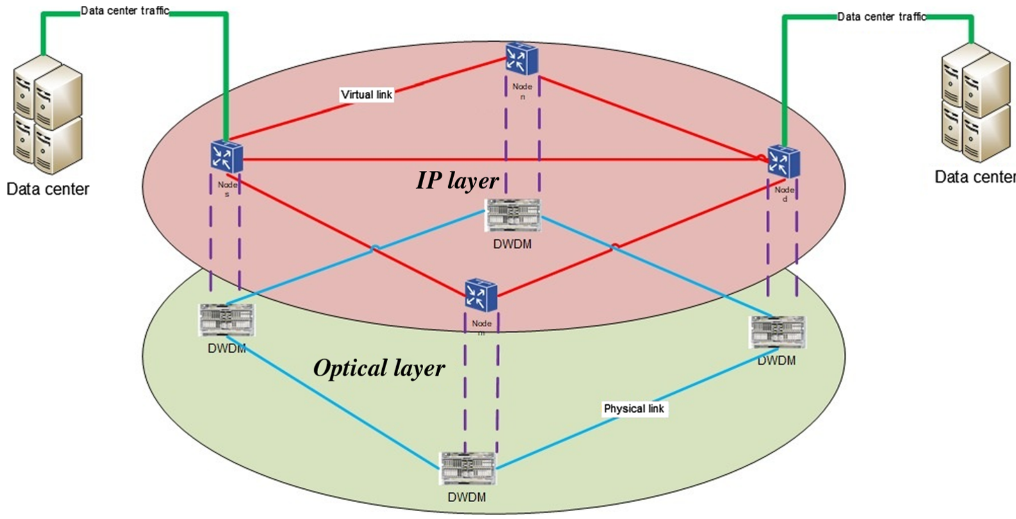

Fig. 1 IP over WDM network.

With the maximization of transport layer capacity, the power consumption of information and communication technology (ICT) devices has become a major issue. The current forecasting trends show that the global ICT footprint will grow from 0.5 out of 40 $GtCO_2$ of total emissions in 2007 to 1.4 out of 51.9 $GtCO_2$ of total emissions by 2020.[7] This increase of $GtCO_2$ emission by 2020 for the ICT industry is thus more than 50% from 2007. At the same time, IP router capabilities have been expanded from 100 Gbps to 10 Tbps, and accordingly, the energy usage grows from 1.7 to 50 kW.[8] In parallel to this, the escalation of data rigorous applications increases the demand for high-performance computing environment and DCs, which provide significant computing in a pay-as-you-go model. Large companies, such as Google, Amazon, etc., have their own DCs placed at geographically distributed locations to ensure excellence in the quality of service. Typically, DCs are interconnected through the IP over WDM infrastructures; contents and workload are shared among DCs, which affects the overall energy consumption of the network (inter-DC and intra-DC). The energy consumption of DCs is increasing rapidly due to high demands of IP traffic.

A DC is a centralized infrastructure of information technology equipment deployed on nodes of IP over a WDM network. The presence of a DC on a particular node creates a hot spot scenario for a particular node because huge amounts of traffic move through this node. This can significantly increase IP over WDM power as the number of ports and slots of different modules varies with the amount of traffic.

In order to decrease the core backbone network power consumption, it is highly recommended to decrease the inter-DC power consumption in parallel to the intra-DC. The main advantage of the proposed work is that we consider the DC placement problem focusing on power consumption for an inter-DC scenario considering both DC-to-DC traffic and DC-to-user traffic. Most of the existing research works based on inter-DC power consumption have focused on different techniques, such as selectively turning off network modules, energy-aware network architecture, energy-aware IP packet forwarding, and green routing. There are only a few research articles that have covered the DC placement problem focusing on power consumption. The previously studied DC placement problem in IP over a WDM network focused mainly on disaster tolerance,[9,10] energy-efficient DC placement on the basis of proximity to renewable sources,[11] network cost minimization,[12] efficient bandwidth utilization,[13] demand-based content distribution,[10] and also minimizing network latency and congestion. In Refs. 9 and 10, the authors focused on failure protection during disaster conditions. In Ref. 9, the authors focused on network cost minimization, while in Ref. 10, the authors focused on content availability and priority-based delivery. In Ref. 13, the authors addressed the DC placement problem in term of efficient utilization of bandwidth resources.

In Ref. 14, the authors considered different dedicated path protection schemes for the DC placement problem over the elastic optical network. Limited contributions exist on the DC

Table 1 Summary of related works.

Sr. no.	Investigator	Findings of the study
1	9	(i) DC placement problem focused on failure protection during disaster conditions in IP over WDM network
		(ii) Cost minimization of IP over WDM network
2	11	(i) DC placement problem in IP over WDM network on the basis of proximity to renewable sources
		(ii) Minimization of network cost
3	12	(i) DC placement problem in IP over WDM network on the basis of network cost minimization
4	10	(i) DC placement on the basis of demand-based content distribution and priority-based delivery
		(ii) Minimizing network latency and congestion
		(iii) Failure protection during disaster conditions in IP over WDM network
5	13	(i) DC placement focused mainly on efficient utilization of bandwidth resources in IP over WDM network
6	14	(i) DC placement problem on the basis of different dedicated path protection schemes in IP over WDM network
7	15	(i) DC placement problem in IP over WDM network to minimize the power consumption using linear programming

placement problem in terms of energy-aware IP over WDM. In Ref. 11, the authors focused on DC placement in terms of proximity to renewable energy sources, as well as minimization of network cost. In Ref. 15, the authors provide linear programming for optimized DC placement in an IP over a WDM network to minimize the nonrenewable power consumption. A detailed summary of the related work is given in Table 1.

In comparison to the work done in Refs. 11 and 15, this work provides a metaheuristic and heuristic model for the optimized DC placement in an IP over a WDM network. Use of a metaheuristic for such a type of problem is justified as it provides an excellent trade-off between time complexity and optimality of the obtained solution. In this paper, first, a simplified analytical power model considering the IP layer power and optical layer power is proposed. The proposed power model depends upon two major network parameters, i.e., traffic demand and hop distance. Second, the placement of the DC localities is optimized in order to minimize the total IP over WDM power consumption. A heuristic and metaheuristic model with this particular objective is also proposed along with a detailed comparison of heuristic and metaheuristic against different network scenarios, real and random network topologies. Finally, we discussed how the proposed metaheuristic can provide an optimum DC location not only in terms of minimizing total IP over WDM power consumption, but also in simulation time and complexity for a small to medium-sized network.

The rest of the paper is organized as follows. In Sec. 2, the system model is discussed. The proposed network design is explained in Sec. 3. In Sec. 4, the various network architectures and results are provided. Finally, Sec. 5 details our conclusion and possible directions for future work.

2 System Model

In this section, we describe the overall system model that has been considered in this research work.

Table 2 Details of the available modulation formats.[16]

Modulation level	BPSK	QPSK	8QAM	16QAM	32QAM	64QAM
Transmission rate (Gb/s)	12.5	25	37.5	50	62.5	75
Optical reach (km)	4000	2000	1000	500	250	125

2.1 *Network Model*

We consider the IP over a flexible-grid optical network (Fig. 1). The physical topology (PT) of the network is represented by a directed graph, where the edges are the physical links that connect the network nodes. Every node in the considered network is equipped with a flex-grid optical cross connect (OXC). In addition, each node is capable of serving as a DC candidate location.[15] In this network, each source node s to destination node d is separated through a physical link having a length L_{sd} in km. All physical links are assumed to be symmetrical, so that $L_{sd} = L_{ds}$. Table 2 highlights the available modulation levels m_i, data rates, and the corresponding optical reach.[16]

A three-tier DC is assumed, which consists of core, aggregation, and access layers[17] (Fig. 2). The access layer is the lower level layer connected with the computing nodes. The access layers are further connected with the next higher layer, i.e., aggregation layer. The aggregation layer is used to provide cross rack communication. With the addition of the aggregation layer, a large number of computing nodes can be supported. The topmost is the core layer, which connects the aggregation layer with the external connectivity.[18] Further, the racks are used to group the computing nodes. The typical rack holds more than 30 computing nodes connected with a top of the rack (ToR) switch. The ToR layer switches are the access layer and multiples of them are connected with the middle-level router to ensure redundant communication links. The topmost layer is equipped with high specification routers to process packets at a much faster rate than switches at other layers. The core layer router is connected to all of the routers in the middle layer.[19] The ToR is responsible for handling a local rack's traffic; whereas, the traffic across the racks is handled through an aggregate router. However, the traffic between racks connected with the different aggregate router is handled through the core router.[20]

In DCs, traffic is categorized into two types: DC-to-user traffic and DC-to-DC traffic. In DC-to-user traffic, the flow of traffic is from DCs to the end users. This traffic accounts for two-thirds of the total cloud traffic.[21] In DC-to-DC traffic, the flow of traffic between two DCs, such as virtual machine migration and content distribution, accounts for one-third of the total cloud traffic.[21] Both types of traffic are considered in this DC placement heuristics, in contrast to an earlier work that only focused on DC-to-user traffic.[22]

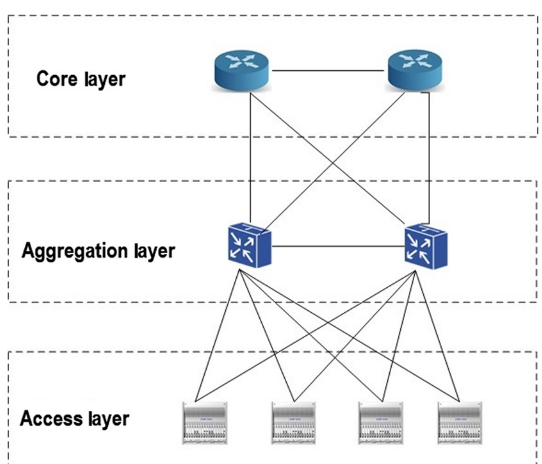

Fig. 2 Three-tier DC.

The traffic from each source node to the destination is transmitted using LPs, an end-to-end optical channel that starts at the source and terminates at the destination while traversing through multiple physical links. Each LP is created by the flexible transponder. The flexible transponder generates LPs at the different modulation levels described in Table 2. A flexible transponder having maximum capacity C_{max} equal to 400 Gb/s is considered in this work. In order to support a 400-Gb/s transponder, we assume 10 client cards each of capacity 40 Gb/s.[23]

In the given network, switching between two consecutive LPs is performed by the router. Similarly, the LPs passing through the intermediate nodes are optically bypassed through flexible-grid OXCs. The flexible-grid overcomes the mismatch limitation of a fixed grid network and offers more efficient spectrum utilization by enabling much finer frequency granularity slots of 12.5 GHz,[16] resulting in a total of 320 slots per link for the C band with a total capacity of 4 THz. For correct switching of the LPs through OXC, a single guard band (one slot) is inserted between back-to-back LPs. A particular modulation level and consequently the number of spectrum slots are thus associated with every LP. This set of LPs completes the LP topology design (LTD) of a network.

2.2 *Power Model*

Each node in the IP over a flexible-grid optical network is equipped with an IP router and OXC. The IP router selected is a Cisco CRS-3 series router, which comprises a line card shelf (LCS),[24] line cards (LCs), and fabric card shelf.[25] CRS-3 LCS has 16 slots and each slot holds a single LC. The LCs are responsible for the traffic flow between the nodes of the backbone network. In the context of the optical network, each LC can generate and terminate an LP and send data directly to the optical layer. Multiple LCS can be joined in a multiple chassis configuration to help in load balancing. The IP layer power usage is equal to the total power consumption of all IP router modules as expressed in Eq. (1). To model the power consumption of IP layer, the power usage of individual router modules is thus calculated instead of evaluating the power usage from a generic W/Gbps expression:

$$\mathbf{P}_{\mathrm{IP}} = \mathbf{P}_{\mathrm{LCS}} + \mathbf{P}_{\mathrm{LCs}} + \mathbf{P}_{\mathrm{FCS}}. \tag{1}$$

In the optical layer, we consider major power elements, such as OXCs (80 channel capacity), transponders (400 Gb/s), and optical line amplifiers (OLAs), having a span length of 80 km. The number of OLAs varies according to the length of the physical link. We represent the power consumption of OXCs, transponders, and OLAs by $\mathbf{P}_{\mathrm{OXC}}$, $\mathbf{P}_{\mathrm{TRANSPONDER}}$, and $\mathbf{P}_{\mathrm{OLA}}$, respectively. The total power consumption for any LP is thus the combined power consumption of all IP routers and the power consumption in the optical domain, which can be modeled as

$$\mathbf{P}_{\mathrm{TOTAL}} = \Sigma_{i=1}^{N}(\mathbf{P}_{\mathrm{IP}} + \mathbf{P}_{\mathrm{OXC}})_i + \Sigma_{j=1}^{M}(\mathbf{P}_{\mathrm{OLA}})_j + \Sigma_{k=1}^{O}(\mathbf{P}_{\mathrm{TRANSPONDER}})_k, \tag{2}$$

where N represents the total number of nodes in the network, O represents the total number of transponders in the network, and M denotes the total number of OLAs installed in the complete LP. We follow the power dissipation statistics of IP routers, OXCs, transponders, and OLAs derived from Refs. 26, 27.

3 Network Design

In this section, we detail different heuristics in order to minimize power consumption for IP over WDM networks, for supporting distributed DCs. We assume the following parameters: K is the set of DCs deployed in the network; O_{sd} is the optical reach between source s and destination node d. An optimization variable Q_{on} is introduced, which represents network power consumption in Watts.

Algorithm 1 Exhaustive data center placement heuristic.

```
Begin from a network graph with n number nodes and K DCs
for all nodes n do
  C_n = all_combination(K, n);
end for
for all max_num_DC do
  DC_location =Place_Dc(Dc_arr);
end for
for all nodes n do
  for all max_num_DC do
     O_sd = min_optical_dist(DC_location,n);
     if distance feasibility && traffic demand true then
       establish_direct_LP(DC_location, n);
     else
       establish_concurrent_LP(DC_location, n);
     end if
     Q_on = calculate_IP_over_WDM_Power;
   end for
 end for
```

3.1 *Exhaustive DC Placement*

An exhaustive DC placement (E-DC-P) algorithm selects every possible combination C_n for DC placement. After selecting each C_n, E-DC-P calculates the IP over WDM power Q_{on} based upon the optical distance and modulation level and finally selects the optimum value. This heuristic gives the optimum value as it considers each and every combination of DC placement inside the network. This method is suitable for small networks having low values of C_n. For large networks having large C_n values, the computational complexity increases, resulting in an increase in the time frame required for finding an optimal solution. The main steps of E-DC-P are briefly explained in the pseudocode of Algorithm 1.

3.2 *Random DC Placement*

Random DC placement (R-DC-P) randomly selects any combination C_n of DC placement inside the network. After placing DCs, R-DC-P calculates the average IP over WDM power against each and every C_n based upon the optical distance and modulation level. This heuristic produces an output that is below the suboptimum value in comparison to E-DC-P due to R-DC-P inside the network. The main steps of R-DC-P are briefly explained in the pseudocode of Algorithm 2.

3.3 *Traffic-Based DC Placement Heuristic*

Traffic-based DC placement heuristic (TB-DC-PH) places DCs on the nodes having high traffic demands. After placing DCs on high traffic nodes, TB-DC-PH associates the non-DC nodes to the nearest DC based upon the optical reach. After association of nodes to the DCs, TB-DC-PH

Algorithm 2 Random data center placement heuristic.

```
Begin from a network graph with n number nodes and K DCs
for all nodes n do
    C_n =random_combination(K, n);
end for
for all max_num_DC do
    DC_location = Place_Dc(Dc_arr);
end for
for all nodes n do
    for all max_num_DC do
        O_sd = min_optical_dist(DC_location, n);
        if distance feasibility && traffic demand true then
            establish_direct_LP(DC_location, n);
        else
            establish_concurrent_LP(DC_location, n);
        end if
        Q_on = calculate_IP_over_WDM_Power;
    end for
end for
```

generates the LPs according to the traffic demands of DC-to-node and DC-to-DC traffic. Finally, the power of IP over WDM is calculated by TB-DC-PH. This heuristic gives the suboptimum value, which is somewhere between R-DC-P and E-DC-P. The main steps of TB-DC-PH are briefly explained in the pseudocode of Algorithm 3.

3.4 *Genetic Algorithm for DC Placement*

The E-DC-P is suitable for a small network size ($< \sim 20$ nodes). E-DC-P takes a long time to discover an optimum solution for large network topologies. In comparison, the TB-DC-PH is scalable, but it rarely provides the optimal solution. The genetic algorithm for DC placement (GA-DC-P) is presented as a scalable solution that can provide the optimal solution to the DC placement problem in a rational time frame.

The GA-DC-P is a metaheuristic developed on the doctrine of natural evolution. This iterative metaheuristic performs a deep search (new generation process) through a huge pool of feasible solutions for a particular objective function (fitness function) optimization. There are four basic rudimentary features of a genetic algorithm. The first one is the individual/chromosome, which is any feasible solution to the problem that is to be addressed. The second one is the fitness function representing the objective function of the optimization problem. The third one is the population, which is the total number of chromosomes in the particular generation. The final one is the offspring, which is actually originated by the mutation of the previous population. For better understanding, let us consider an example having a set of five genes in a population of individuals, where each gene can hold one of the binary values 0 or 1. The fitness value is exploited by the number of 1 s present in the chromosome/individual. If there are five 1 s, then the chromosome has the maximum fitness. If there are no 1 s, then it has the minimum fitness. This simple example tries to maximize the fitness function to provide a population consisting of

Algorithm 3 TB-DC-PH.

```
start from a PT graph with n number nodes
for all nodes n do
  trx =max_traffic_node (traffic matrix);
end for
for all max_num_DC do
  DC_location =max_trx_node_Place_DC(trx);
end for
for all nodes n do
  for all max_num_DC do
    O_sd = min_optical_dist(DC,node);
    if distance feasibility && traffic demand true then
      establish_direct_LP(DC,node);
    else
      establish_concurrent_LP(DC,node);
    end if
    Q_on = calculate_IP_over_WDM_Power;
  end for
end for
```

the fittest individual, i.e., individuals with five 1 s. Moreover, in this example, after mutation, the least fit individual is replaced from the new fittest offspring.

In the context of this work, a chromosome is a feasible solution of any DC placement combination in the network, i.e., a set in which each member represents a possible combination of DC location, number of LPs generated, and the optical fibers deployed between each node pair. Similarly, the fitness function(solution) in GA-DC-P is the IP-over-WDM network power consumption. The population is the total number of combinations of DC placement in a single run. The offspring are the new combinations obtained from shuffling (mutation) of the previous combinations (parents).[25]

The main steps of the GA-DC-P are briefly explained in Algorithm 4. The important parameters for GA-DC-P include network designing parameters NetPar, datacenter parameters DcPar, power consumption parameters PrPar, and also the parameters for algorithm development AlgPar. More specifically, NetPar includes the PT, the node to node traffic request (TR_n), the PT graph G_n, the maximum capability of an LC C_{LC}, and the wavelengths used per optical fiber W. The DcPar includes DC-DC traffic request ($\mathrm{TR}_{\mathrm{dc}}$) and set of DC placement combinations C_n. Moreover, PrPar comprises the power consumption of the LC α, the power consumption β for router of category c for every $c \in C$. Finally, AlgPar includes total generations count Δ, the population individuals Φ, and the offspring individuals count Ψ, where $\Phi > \Psi$. The end product of GA-DC-P is network building (Netbuld), i.e., the LTD and the number of optical fibers Z_p deployed on any link $p \in P$. The LTD characterizes the LPs that have to be created and the category of the routers that has to be deployed. Furthermore, Netbuld also includes routing of LPs over the physical links.

First of all, GA-DC-P initializes a random pool of chromosomes Θ. These generated chromosomes constitute the first population, which is actually the various combinations of DC placement inside the network (code-line 1). Fitness function is applied on the generated chromosomes

Algorithm 4 Genetic algorithm for DC placement.

Require: NetPar, DcPar, PrPar, AlgPar

Ensure: Netbuld

```
1:  population =first_population(NetPar,DcPar,Φ);
2:  g = 0;
3:  fitter = fitness_function(population, PrPar);
4:  while g ≤ Δ do
5:    offspring =create_offspring (population, Ψ, NetPar, DcPar);
6:    if feasibility is true then
7:      population = new_population (population, offspring, Φ);
8:      fitter = fitness_function (population, PrPar);
9:      if new fitter ≥ fitter then
10:       g + +;
11:     else
12:       g = 0;
13:       fitter = new fitter;
14:     end if
15:   else
16:     discard individual;
17:   end if
18: end while
19: Netbuld = chose_design(population);
```

(code-line 3), which starts the evolution phase. In every new generation, the offspring Ψ of the present population is bred (code-line 5). Offspring are the new combinations of DC placement originating from the previous combinations of DC placement. Each new offspring is obtained by mutating the parent chromosome that belongs to the former population. Mutation is actually the shuffling of the combination of parent chromosomes. Before adding the new chromosome to the offspring of the present population, its feasibility is checked (code-line 6). If the individual fails the feasibility check, it is discarded (code-line 16), otherwise it becomes the offspring of the present population. The next population is ready at the termination phase of mutation (code-line 7). The new generation is the combination of the Ψ chromosomes of the newly generated offspring and the fittest (Φ-Ψ) individuals of the previous population. After this, the fitness of the chromosomes of the newly generated population is measured (code-line 8). Finally, the fitness cost is differentiated with the lowest value and eventually stored (code-lines 9 to 14). The iteration procedure is concluded for Δ generations (code-line 4) when GA-DC-P has reached its steady equilibrium state, with the objective of minimizing fitness function.

4 Results

In this section, we present the performance evaluation results of the various heuristics proposed. We used a custom network simulator written in C++ in which network topology is built on the basis of graph theory. The network topology is mainly characterized by edge and vertex. In the

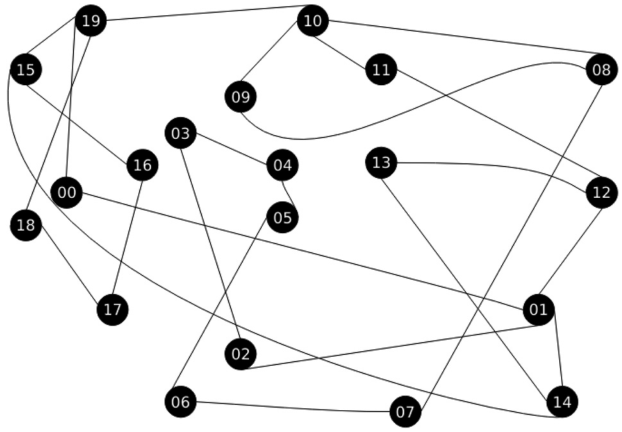

Fig. 3 Random network topology.

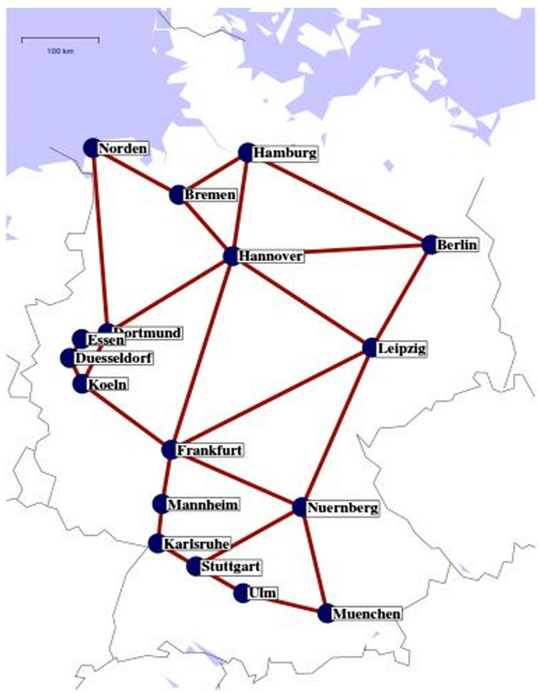

Fig. 4 German network topology.

context of PT building, a vertex represents a node of a network while an edge represents a fiber connecting the two nodes. In addition to this, a detailed power model for the IP-layer and optical-layer is implemented in the simulator. Moreover, the simulator supports three-tier DC architecture. We employ three different network scenarios in our simulations. The first network scenario is random network topology generated by considering 20 nodes (Fig. 3), the second topology is the 17-node German network (Fig. 4),[25] and the third one is the 37-node PAN-EU network (Fig. 5).[28] The number of available DCs (K) is varied between 15% and 45% of the total network nodes. Basic details of all these network scenarios are shown in Table 3.

For the random network case study, we consider an aggregate traffic of 24TB DCs-to-users (DC-USER) and 12TB of interDCs (DC-DC).[13] The DC-USER traffic is uniformly distributed among the nodes, and DC-DC traffic is uniformly distributed among the installed DCs. The number of available DCs (K) is varied between values of three and five. An average link length of 250 km is considered. Figure 6 shows the power consumption results for the random topology when we varied the number of DCs installed. The X axis of the graph represents the proposed DC placement heuristics while the Y axis represents the IP-over-WDM power consumption against

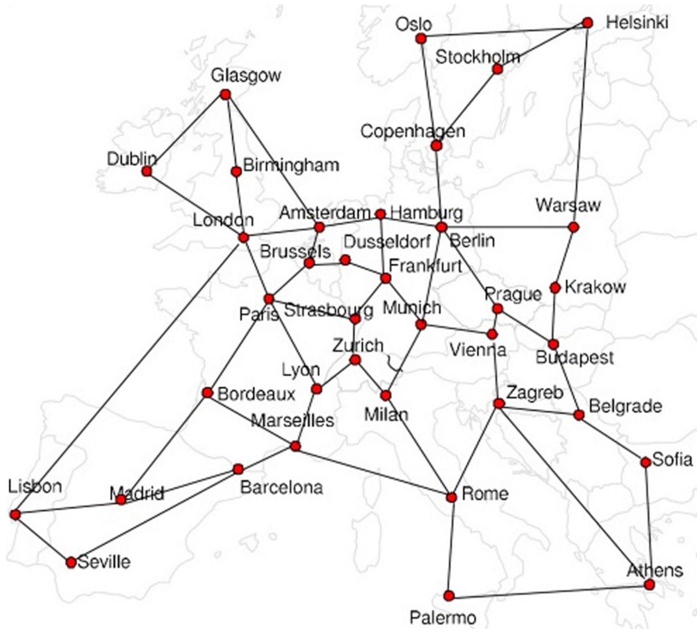

Fig. 5 PAN-EU network topology.

Table 3 Pan-Eu, German, and random topologies.

Parameter	Pan-Eu			German			Random		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Fiber distance (km)	648	218	1977	144	29	263	250	12	465
Node degree	3.08	2	5	3.05	2	6	3	2	4

every heuristic for each value of K. The graph shows that for each heuristic of DC placement, the power consumption decreases with the increase in the value of K. This is because with more DCs in the given network, the optical distance between users and DCs, and interDCs, decreases, permitting the use of high-order modulation formats. The enabling of high-order modulation formats leads to a decrease in the respective number of LPs per fiber, which ultimately decreases IP-over-WDM power consumption of the network.

Also note that E-DC-P presents the base line for all our comparisons, since a better solution than this exhaustive search is not possible. It is shown that the GA-DC-P heuristic performs similarly to the E-DC-P, while taking much less time than the E-DC-P (Table 4). The other two heuristics, TB-DC-PH and R-DC-P, consumed much more power, as they failed to discover the optimal solution. This is also evident in Fig. 7, which shows the percentage power consumption variations for a particular value of K against each DC placement heuristic. GA-DC-P performs

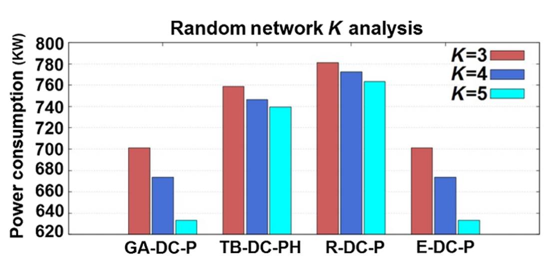

Fig. 6 Random network: power consumption analysis.

Table 4 Simulation time analysis.

Data center (K)	$K = 4$			$K = 5$		
Node (N)	$N = 10$	$N = 15$	$N = 20$	$N = 10$	$N = 15$	$N = 20$
GA-DC-P simulation time (min)	19.4	25.6	31.2	20.7	26.9	32.5
E-DC-P simulation time (min)	68.59	90.51	147.1	137.2	181.01	274.4

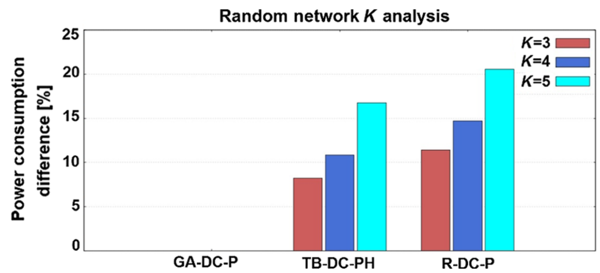

Fig. 7 Random network: power consumption difference (%) analysis.

extremely well with 0% difference for all values of K. TB-DC-PH performs well on low values of K (10% difference for $K = 3$), but it gives a high-percentage difference with increase in K. A similar trend is followed by R-DC-P, with an even greater percentage difference (20% for $K = 5$).

In Fig. 8, the network power consumption is analyzed in terms of varying traffic. In this analysis, the number of DCs is kept constant ($K = 5$) while traffic per node is varied among 1000G, 2000G, 3000G, and 4000G. The aggregated traffic for analysis is 20TB, 40TB, 60TB, and 80TB. The trend of the graph shows that the increase in the network traffic increases network power consumption due to resultant increase in number of LPs. The graph shows that with the percentage rise in power with increasing traffic, the performance of GA-DC-P is almost equal to E-DC-P, while in contrast, with TB-DC-PH and R-DC-P the percentage rise is quite more than E-DC-P. We also investigate the suggested router analysis for this random network. These routers have been suggested based on the optimal solution proposed by each heuristic algorithm. Once the optimal DC placement is finalized by each algorithm, an appropriate router is selected for each node that can satisfy the overall traffic requirements. Figure 9 shows the breakdown of routers considering the four investigated heuristics. Interestingly, both E-DC-P and GA-DC-P suggested more low capacity and low power routers (mostly SH-IP-1280) in contrast to TB-DC-PH and R-DC-P, which mostly suggested more high power and capacity routers (SH-IP-1920).

Figure 10 shows the link length analysis performed on a random network scenario. In this case, the value of K is fixed ($K = 5$). The considered average link lengths are 250, 500, 750, 1000, and 2000 km. As the trend of the graph shows, the increase in the link length raises the network power consumption due to generation of concurrent LPs. Moreover, the graph also shows that with the percentage rise in the power consumption with increasing link length, the

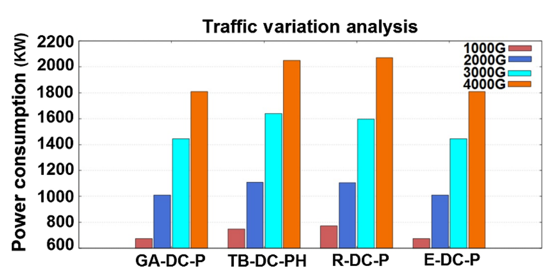

Fig. 8 Random network: traffic variation analysis.

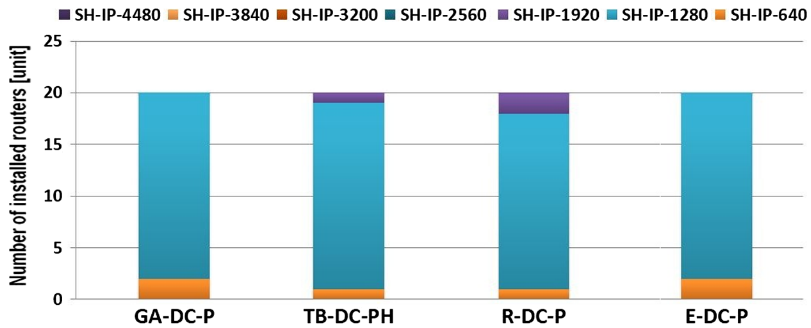

Fig. 9 Random network: installed routers analysis.

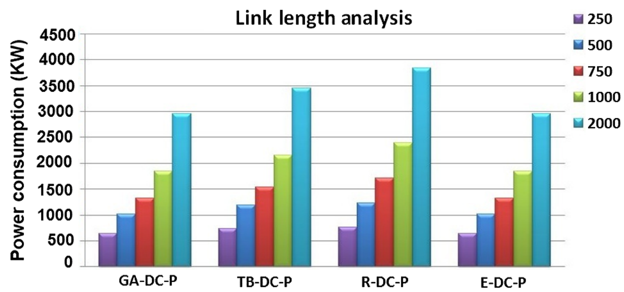

Fig. 10 Random network: link length analysis.

GA-DC-P performs almost equal to E-DC-P in contrast to TB-DC-PH and R-DC-P where the percentage increase is far more than E-DC-P.

Next we consider the German network case study for which we use 32TB (DC-USER) and 16TB (DC-DC) traffic.[13] The value of K is varied between five and eight. The power consumption for a given value of K against each DC placement heuristic is shown in Fig. 11. The abscissa of the graph shows DC-placement heuristics, while the ordinate represents IP-over-WDM power consumption against a particular heuristic for each value of K. The graph shows that for a particular heuristic of DC placement, the power consumption decreases with the increase of K value. This is because with more DCs in the network, optical distance decreases, which enables the use of high-order modulation formats. Enabling the high-modulation formats decreases the number of LPs per fibe,r which eventually decreases IP-over-WDM power of a network. Figure 11 also shows that the performance of GA-DC-P is almost similar to E-DC-P with low complexity and reasonable execution time (Δ varies from 30 to 50), depending upon the size of network and obtaining the global minimal point. Furthermore, TB-DC-PH performs in reasonably short time, but it does not give the ultimate optimum DC placement. R-DC-P also executed in a reasonably short time similar to TB-DC-PH, but it performs worst among all of the DC placement heuristics. Figure 12 shows the percentage difference of each DC placement heuristic with reference to E-DC-P, the most optimum DC placement heuristic. GA-DC-P performs

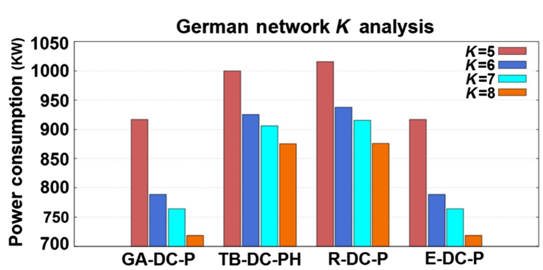

Fig. 11 German network: power analysis.

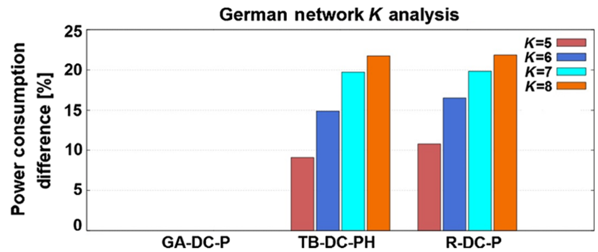

Fig. 12 German network: power consumption difference (%) analysis.

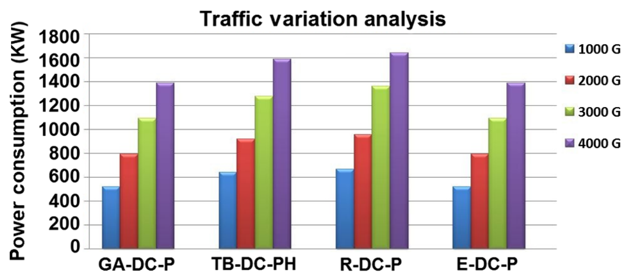

Fig. 13 German network: traffic variation analysis.

extremely well (0% difference) for all values of K. TB-DC-PH and R-DC-P both result in high-percentage differences with an increase in K.

Figure 13 shows the network power consumption analysis in terms of varying traffic. In this analysis, the number of DCs is kept constant ($K = 4$) while traffic per node is varied. The considered traffic per node is 1000G, 2000G, 3000G, and 4000G. The aggregated traffic for analysis is 17TB, 34TB, 51TB, and 68TB. Increase in the network traffic demands raises the network power consumption due to the increase in number of LPs. The graph also shows that with the percentage rise in the power consumption with increase in traffic, the performance of GA-DC-P is almost equal to E-DC-P, while in contrast to TB-DC-PH and R-DC-P the percentage rise is quite more than E-DC-P. We also investigated the router breakdown for the German network. Figure 14 shows the breakdown of routers considering E-DC-P, TB-DC-PH, R-DC-P, and GA-DC-P. Similar to the random topology, E-DC-P and GA-DC-P suggest the use of more low capacity and low power routers as compared to TB-DC-PH and R-DC-P.

We next performed simulations on a larger network topology, the PAN-EU network. In this case, 66TB (DC-USER) and 33TB (DC-DC) traffic is considered.[13] The value of K is varied between 5 and 10. The power consumption for given values of K against each DC placement heuristic is also shown in Fig. 15. The graph follows the same pattern as followed in the German network, i.e., for each heuristic of DC placement, the power decreases with the increasing value of K. This is because with more DCs in the network, the optical distance decreases, which enables the use of high-order modulation formats.

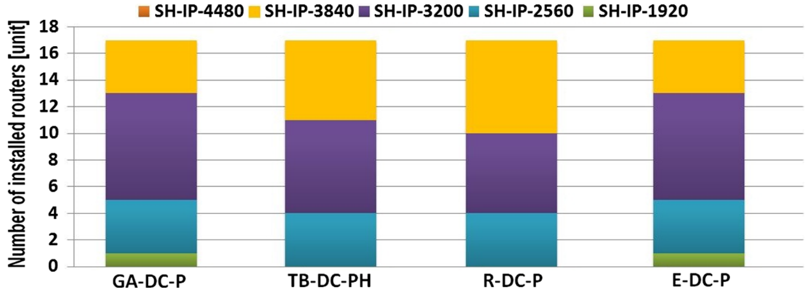

Fig. 14 German network: installed routers analysis.

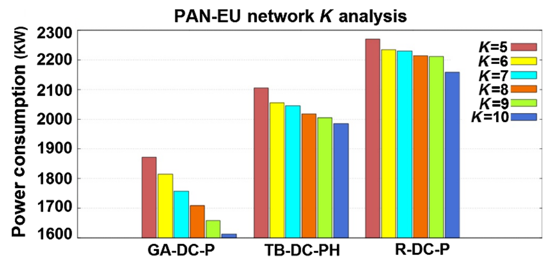

Fig. 15 PAN-EU network DC placement power analysis.

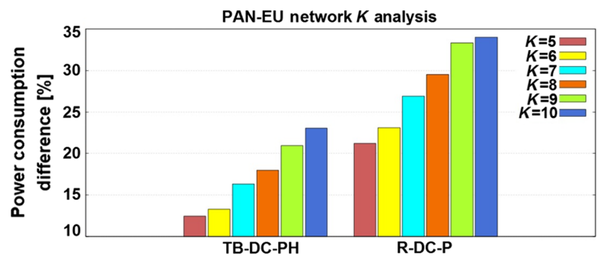

Fig. 16 PAN-EU network DC placement power consumption difference (%) analysis.

Unlike the German network, E-DC-P cannot be executed on a larger network such as the PAN-EU network. The reason is E-DC-P is computationally complex and requires extensive simulation time (Table 4). The graph details the GA-DC-P, TB-DC-PH, and R-DC-P IP-over-WDM power consumption trends along with the varying K values. GA-DC-P provided the optimum location of DC placement in terms of minimizing the power consumption of IP-over-WDM network. Figure 16 shows the percentage difference analysis of each DC placement heuristic for the PAN-EU network with reference to GA-DC-P. Furthermore, Fig. 16 also shows that TB-DC-PH and R-DC-P give high-percentage differences with respect to GA-DC-P with an increase in K.

In Fig. 17, the network power consumption is analyzed in terms of varying traffic. In this analysis, the number of DCs is kept constant ($K = 8$) while the traffic per node is varied. The considered traffic per node is 1000G, 2000G, 3000G, 4000G, and 5000G, while the aggregated traffic for analysis is 37TB, 74TB, 111TB, and 148TB, respectively. The trend of the graph shows that an increase in the network size raises network power consumption due to the higher number of LPs. The graph also shows that the percentage increase in power consumption with increasing traffic for TB-DC-PH and R-DC-P is far higher than for GA-DC-P.

We also investigated the router breakdown for the PAN-EU network. Figure 18 shows the breakdown of routers considering TB-DC-PH, R-DC-P, and GA-DC-P. Interestingly, in GA-DC-P, a higher number of low capacity and low power routers are installed as compared to TB-DC-PH and R-DC-P.

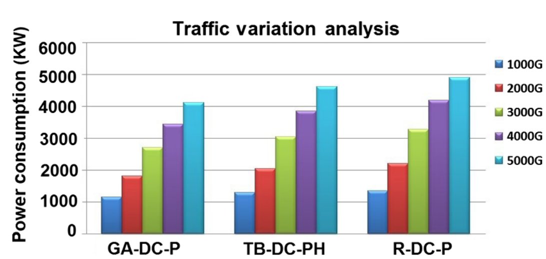

Fig. 17 PAN-EU network traffic variation analysis.

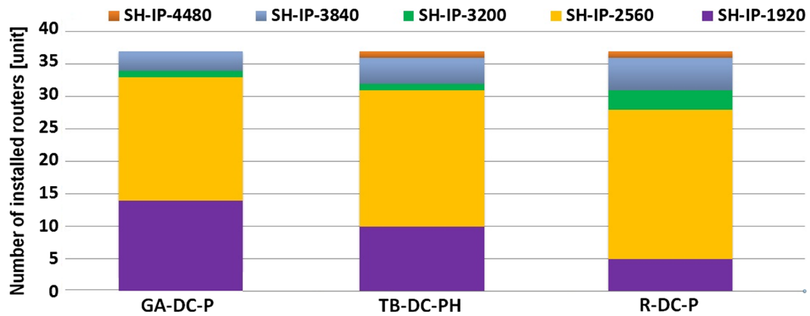

Fig. 18 PAN-EU network installed routers analysis.

5 Conclusions

In this paper, several heuristics have been proposed for optimizing DC placement in a flexible-grid optical network with the objective of minimizing the total power consumption of IP-over-WDM. Four different DC placement heuristics, namely E-DC-P, TB-DC-PH, R-DC-P, and GA-DC-P, have been proposed. A detailed comparison of the proposed heuristics has also been made on 20 node Random, 17 node German, and 37 node PAN-EU networks. Results show that the proposed GA-DC-P performs similarly to E-DC-P for the German network but, unlike E-DC-P, it can provide optimum DC placement for the PAN-EU network in a reasonable amount of time. Moreover, GA-DC-PC provides up to 22% improvement over TB-DC-PH for both network scenarios. For future research work, we plan to focus on the DC placement problem incorporating the availability of renewable energy resources, whereby the assignment could be made on the basis of weights, making potential DC sites with green power more attractive for inclusion in the topology.

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