Optimization for Optical Network Designs Based on Existing Power Grids

Areeyata SRIPETCH a), Student Member and Poompat SAENGUDOMLERT †, Nonmember

SUMMARY In a power grid used to distribute electricity, optical fibers can be inserted inside overhead ground wires to form an optical network infrastructure for data communications. Dense wavelength division multiplexing (DWDM)-based optical networks present a promising approach to achieve a scalable backbone network for power grids. This paper proposes a complete optimization procedure for optical network designs based on an existing power grid. We design a network as a subgraph of the power grid and divide the network topology into two layers: backbone and access networks. The design procedure includes physical topology design, routing and wavelength assignment (RWA) and optical amplifier placement. We formulate the problem of topology design into two steps: selecting the concentrator nodes and their node members, and finding the connections among concentrators subject to the two-connectivity constraint on the backbone topology. Selection and connection of concentrators are done using integer linear programming (ILP). For RWA and optical amplifier placement problem, we solve these two problems together since they are closely related. Since the ILP for solving these two problems becomes intractable with increasing network size, we propose a simulated annealing approach. We choose a neighborhood structure based on path-switching operations using k shortest paths for each source and destination pair. The optimal number of optical amplifiers is solved based on local search among these neighbors. We solve and present some numerical results for several randomly generated power grid topologies.

key words: physical topology design, routing and wavelength assignment, optical amplifier placement, integer linear programming, simulated annealing

1. Introduction

In recent years, several power utilities have been installing composite ground wires with optical fibers (OPGWs) in their high voltage lines to satisfy their own internal communication needs as well as to gain additional revenues by providing excess capacities to telecommunication service providers [1]. An OPGW is an optical fiber incorporated into a metallic ground wire at the manufacturing stage [2]. Once installed, the wire performs a dual role of communication medium and ground wire. Compared to optical fibers installed in other types of infrastructure networks, e.g. railroads and telephone lines, OPGWs are in well-protected environments, resulting in high reliability.

Since power grids typically cover more rural areas compared to other types of infrastructure networks, power utilities can play an important role in providing communication infrastructures to rural areas where electricity is available. A dense wavelength division multiplexing (DWDM) optical network using OPGWs is one promising approach to achieve a scalable backbone network that can help reduce the digital divide and create a truly universal information highway system for the society at large.

However, planning and designing of DWDM networks for power utilities is a demanding task. Designing of a network based on an existing power grid can be considered as one large optimization problem. However, for tractability, such network design problems are usually separated into subproblems at a cost of some suboptimality in the overall network cost. For the design of an optical network based on an existing power grids, the main relevant subproblems are:

1. Topology design based on existing infrastructure
2. Routing and wavelength assignment (RWA) for given traffic demands
3. Optical amplifier placements

Topology design of optical networks for power utilities requires the development of a network model that takes into account the limitation imposed by the existing topology of a power grid. In general, the objective of topology design is to select locations of switching nodes and their interconnections. The resultant design is known as the physical topology of the network.

For an optical network based on a power grid, we consider a network model based on the power grid topology with subset of substations as communication nodes, as shown in Fig. 1. A typical power grid topology contains a large number of substations. Only a subset of these are communication nodes. While most non-communication nodes can be neglected from the problem of topology design, those with node degrees at least 3, which we shall refer to as junction nodes, remain to preserve the topology information of the power grid, as illustrated in Fig. 1. In practice, junction nodes are not switching nodes. They cannot be used to switch traffic. More specifically, traffic that enters a junction node must leave on the same fiber.

RWA is considered an essential factor for an efficient design of a DWDM network. A wavelength-routed DWDM network can provide end-to-end optical communication channels through optical fibers and intermediate nodes with optical cross-connects [4]. An effective RWA scheme is required in order to obtain an efficient network.

Optical amplifiers are expensive devices; therefore, a high number of optical amplifiers can increase the overall network cost. Furthermore, the amplifier spontaneous emis-
Most work is based on a two-level hierarchical architecture. In [5], the authors propose a selection of concentrators or backbone nodes based on the number of nodes in the neighborhood around each node. Concentrators can also be selected based on the amount of traffic generated at each node as well as link and concentrator capacities [6], [7].

There have been relatively few work on physical topology design of optical networks in particular [8]–[11]. In [8], the authors present the design of physical topology that can be used to embed all possible logical ring topologies. In [9], the authors provide a heuristic for a large-scale optical network in a green-field scenario. These results are particularly relevant to metro area networks where the resultant topologies can be realized. In [10], [11], the problem of physical topology design is formulated as an optimization problem whose objective is to minimize the network cost based on some assumptions on transmission and switching costs. It is worth noting that all the work mentioned above do not pay attention to how we can utilize existing infrastructure networks in the physical topology design. For an optical network on top of a power grid, it is desirable to utilize an existing power grid topology. Such a consideration is one of the main contributions of this paper.

A large number of research studies have been conducted on the RWA problem [4], [12]–[16]. The RWA problem involves routing and wavelength assignment aspects. In the routing aspect, there are three basic types of routing approaches: fixed routing, fixed alternate routing, and adaptive routing [15]. In fixed routing, there is only one fixed route between a pair of source and destination nodes. In fixed-alternate routing, each node maintains a routing table that contains a list of fixed routes to each destination node. The actual route for a connection request can only be chosen from this set of routes. In adaptive routing, routing is based on the current wavelength availability on each link. Any feasible route from the source node to the destination node can be used as the actual route for a connection request. In this paper, we adopt the fixed-alternate routing approach in our network design. The routing result is used as the neighborhood structure in the simulated annealing algorithm.

There are several studies on amplifier placement solutions [17]–[19]. The authors in [17] propose two methods to minimize the number of amplifiers that do not require an amplifier in every node. One method describes the amplifier placement problem exactly and uses a nonlinear programming solver to obtain a solution. After pointing out the difficulty in solving the nonlinear problem, the authors propose another method which approximates some requirements in the problem and employs a linear programming solver to find the amplifier placement solution. It is worth noting that the solution in [17] is specialized for ring topologies. In [18], [19], the authors propose the method to solve the minimum amplifier placement problem for both equally powered and unequally powered wavelengths for tree topologies. Each optical amplifier has constraints on the maximum gain and the maximum output it can supply.

Simulated annealing is a local search algorithm capable of escaping from local (but not global) optima. Its ease of
implementation and convergence properties have made it a popular technique. There are several studies on simulated annealing [20]–[22]. The key feature of simulated annealing is that it provides a mean to escape local optima by allowing hill-climbing moves in hope of finding a global optimum [22].

3. Overall Design Strategy

The overall objective of this paper is to design a communication network based on an existing power grid using optimization procedure. The mathematical objective for optimization is to minimize the overall cost of constructing the network. While it is possible conceptually to cast the overall design problem as a single optimization problem, the complexity of such a problem would be enormous. Thus, we follow the conventional approach of breaking the problem into several subproblems. The design strategy includes solving the topology design problem, solving the RWA problem according to the physical topology solution, and solving the optical amplifier placement problem with respect to the RWA solution. The routing problem is solved by \( k \) shortest path. We consider opaque switching networks (optical switching with wavelength conversion), so wavelength assignment is straightforward. Note that the optical amplifier placement solution needs to satisfy the physical constraints, i.e., power level and OSNR constraints, to be feasible. For a given RWA solution, there may not exist an optical amplifier placement solution that satisfies the physical constraints, i.e., no feasible solution. If the optical amplifier placement problem is not feasible, the RWA problem is revisited and the routing is modified until it results in an optimal feasible solution. This iterative process is achieved using the simulated annealing algorithm. Figure 2 shows the block diagram of the optimization procedure.

4. Topology Design

In this section, we modify existing methods for topology design to take into account the topology limitation imposed by an existing power grid. For the design, we adopt a two-level hierarchical architecture consisting of a central backbone connecting multiple access networks, and formulate ILP problems that are used in topology design. In this design step, the goal is to find out how nodes should be connected so that each source-destination pair has working and backup paths whose lengths do not exceed some distance limit. The number of fibers used on each link will be determined later on when we solve the RWA problem, where traffic demands and the number of wavelengths in a fiber are taken into account. Over all, the topology design procedure is as follows.

1. Select a subset of nodes to be concentrators or backbone nodes by solving an ILP problem similar to the concentrator location problem.
2. For a reduction of computation, generate a simplified topology graph that includes only the concentrators and the junction nodes that need to exist for topology design.
3. Establish the connections among concentrators with the two-connected requirement using another ILP problem.

4.1 Selection of Concentrators

The selection of concentrators can be formulated as a modified concentrator location problem. The additional constraint that we introduce is the limit on the distance from a node to its concentrator. The measure of distance is based on the length of the shortest path on the power grid. Similar to the formulation in [6], there is no traffic parameter in the formulation. Typically, nodes with high populations tend to be the ones with high node degrees, which are often chosen to be concentrators. Hence, the traffic distribution is indirectly considered. Given the physical topology of a power grid, concentrator/switch capacity, and equipment cost, we formulate the problem of selecting concentrators as an ILP problem by minimizing the equipment cost as follows.

Given parameters:

\[ N = \text{number of nodes} \]
\[ C_{ij}^{\text{CNX}} = \text{fixed cost of connecting node } i \text{ to node } j \]
\[ C_j^{\text{CON}} = \text{cost of establishing a concentrator at node } j \]
\[ D_{ij} = \text{shortest distance from node } i \text{ to node } j \text{ based on the power grid} \]
\[ C_{\text{FIBER}} = \text{fiber cost per kilometer} \]
\[ K = \text{maximum number of nodes that can be connected to} \]

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**Fig. 2** Block diagram of the optimization procedure.
the same concentrator (concentrator capacity)

\[ D_{\text{max}} = \text{maximum distance between a node and its concentrator} \]

**Variables:**

\[ x_{ij} \in \{0, 1\} : \text{equal to 1 if and only if node } i \text{ is connected to} \]

\[ y_j \in \{0, 1\} : \text{equal to 1 if and only if node } j \text{ is selected as a concentrator} \]

**Objective:**

\[
\text{minimize } \sum_{i,j=1}^{N} (C_{ij}^{\text{CNX}} + C_{ij}^{\text{FIBER}} D_{ij} x_{ij}) + \sum_{j=1}^{N} C_j^{\text{CON}} y_j \quad (1)
\]

**Constraints:**

\[
\forall i \in \{1, \ldots, N\}, \sum_{j=1}^{N} x_{ij} = 1 \quad (2)
\]

\[
\forall j \in \{1, \ldots, N\}, \sum_{i=1}^{N} x_{ij} \leq Ky_j \quad (3)
\]

\[
\forall i, j \in \{1, \ldots, N\}, D_{ij} x_{ij} \leq D_{\text{max}} \quad (4)
\]

\[
\forall i, j \in \{1, \ldots, N\}, x_{ij}, y_j \in \{0, 1\} \quad (5)
\]

Constraint (2) requires that each node must be connected to exactly one concentrator. Constraint (3) assures us that the concentrator capacity will not be exceeded, and that no node will be connected to node \( j \) if \( j \) is not a concentrator, i.e., \( y_j = 0 \). Constraint (4) is the distance limitation between a node and its concentrator. Finally, the integer constraints are specified in (5).

### 4.2 Simplification of Topology Graph

After the selection of concentrators, the topology graph can be simplified in order to reduce the problem size in interconnecting concentrators. A simplified graph includes only concentrator and junction nodes. A junction node is a node that is not a concentrator and has node degree at least 3. Such a node needs to remain in the simplified graph for the topology design.

To generate the simplified graph, non-concentrator nodes with degree less than 3 are eliminated from the graph. If the eliminated node has degree 1, then the attached link is also eliminated. If the eliminated node has degree 2, then the two attached links are joined as one with the distance being the sum of the two link distances\(^1\). The eliminating process is iterated until all non-concentrator nodes have degree at least 3.

Figure 3 presents examples of node and link eliminations in an 8-node topology. In particular, 3 nodes and 3 links are eliminated. As we can see, the non-concentrator nodes with degree at least 3 remain; they are the junction nodes used in the next step.

### 4.3 Concentrator Connections

In determining how concentrators are connected to one another, we formulate another ILP problem with the objective of minimizing the interconnection cost. The main constraint in this problem is the two-connected requirement for survivability. This requirement is that the resultant network be either two-edge-connected or two-node-connected, which means that the removal of any single edge or node leaves the network connected. We can also extend the two-connected to \( k \)-connected requirement (with \( k > 2 \)) in cases that the network must survive up to \( k - 1 \) failures. In what follows, we shall consider two-node-connected requirement which implies two-link-connectedness since node-disjoint paths are also link-disjoint.

Our formulation is a modification of the formulation for \( k \)-connected requirement in [8]. Without any modification, the resultant topologies tend to be large rings which may be suitable for metro area networks considered in [8] but not suitable for backbone networks. Therefore, we include an additional constraint that limits the path distance to some maximum value. In practice, this constraint can help limit the failure recovery time. In some practical topologies, it is not possible to satisfy the two-connected requirement. For example, some concentrators may have node degree 1. In such cases, we need to ignore these concentrators by removing them from the topologies and proceed to connect the remaining concentrators. Given simplified topology graph with concentrators, junction nodes, and equipment cost, we formulate the problem of connecting concentrators as an ILP problem that minimizes the equipment cost as follows.

Given parameters:

\( N = \text{number of nodes} \)

\( E = \text{number of links} \)

\( S = \text{number of source-destination (s-d) pairs} \)

\(^1\)If we consider only node disjoint paths for survivability, then we can simplify the topology graph further using the following rule: if the newly created link is parallel to any existing link, then the link with a smaller distance is kept.
Variables:

\[ x_e \in \{0, 1\} : \text{equal to } 1 \text{ if and only if link } e \text{ is chosen to be in the backbone topology} \]

\[ f_{e,w}^s, f_{e,b}^s \in \{0, 1\} : \text{equal to } 1 \text{ if and only if the working flow is on link } e \text{ for s-d pair } s \]

Objective:

\[ \text{minimize } \sum_{e \in \{1, \ldots, E\}} C_e^{\text{LINK}} x_e \]  

Constraints:

\[ \forall s \in \{1, \ldots, S\}, j \in \{1, \ldots, N\}, \sum_{e \text{ into } j} f_{e,w}^s - \sum_{e \text{ out of } j} f_{e,w}^s \]

\[ \begin{cases} -1, & \text{if } j = \text{source of s-d pair } s \\ 1, & \text{if } j = \text{destination of s-d pair } s \\ 0, & \text{otherwise} \end{cases} \]  

\[ \forall s \in \{1, \ldots, S\}, j \in \{1, \ldots, N\}, \sum_{e \text{ into } j} f_{e,b}^s - \sum_{e \text{ out of } j} f_{e,b}^s \]

\[ \begin{cases} -1, & \text{if } j = \text{source of s-d pair } s \\ 1, & \text{if } j = \text{destination of s-d pair } s \\ 0, & \text{otherwise} \end{cases} \]  

\[ \forall s \in \{1, \ldots, S\}, \sum_{e \in \{1, \ldots, E\}} D_e f_{e,w}^s \leq D_{\text{max}} \]  

\[ \forall s \in \{1, \ldots, S\}, \sum_{e \in \{1, \ldots, E\}} D_e f_{e,b}^s \leq D_{\text{max}} \]  

\[ \forall s \in \{1, \ldots, S\}, e \in \{1, \ldots, E\}, f_{e,w}^s \leq x_e \]  

\[ \forall s \in \{1, \ldots, S\}, e \in \{1, \ldots, E\}, f_{e,b}^s \leq x_e \]  

\[ \forall s \in \{1, \ldots, S\}, j \neq \text{destination of s-d pair } s, \sum_{e \text{ into } j} f_{e,w}^s + \sum_{e \text{ out of } j} f_{e,b}^s \leq 1 \]  

\[ \forall s \in \{1, \ldots, S\}, j = \text{destination of s-d pair } s, e \text{ into } j, f_{e,w}^s + f_{e,b}^s \leq 1 \]  

\[ \forall s \in \{1, \ldots, S\}, e \in \{1, \ldots, E\}, x_e, f_{e,w}^s, f_{e,b}^s \in \{0, 1\} \]  

5. RWA and Optical Amplifier Placement

RWA and optical amplifier placement problem are solved together using simulated annealing.

5.1 k Shortest Path RWA

RWA is solved using the k shortest path algorithm with \( k = 3 \) [23]. The routing solution resulted from the topology design section is determined to ensure the two-connected property of the network. Since it may not be an optimal routing in terms of minimizing the network cost, we re-consider routing in this section. Since we consider opaque optical switching, wavelength assignment is straightforward. We shall use k shortest path routing for RWA and optical amplifier placement and allow the selection of non-shortest paths for load balancing. We have investigated the choice of \( k \) and we choose it to be 3 as explained in the later section on numerical results. Routes to be constructed include the first-shortest-path route, the second-shortest-path route, and the third-shortest-path route for each source-destination pair. All routes are limited to the maximum allowed distance. These routes form a set of paths to be used later by simulated annealing.

5.2 Optical Amplifier Placement

Optical amplifier placement based on the RWA solution must satisfy both power constraint and OSNR constraint. The locations of optical amplifiers will be based on the existing locations of the substations in the power grid. Total input powers of wavelengths for each amplifier location will be determined based on the given RWA. In this paper, we limit the number of wavelengths to 40 wavelengths per fiber and the maximum traffic of any s-d pair to 40 wavelengths. If any link has a load more than 40 wavelengths, the traffic will be distributed to different fibers based on the first-fit decreasing bin packing algorithm [24] with the constraint that each s-d pair has all its traffic on a single fiber, i.e., non-bifurcating flows.

Example: Suppose a link load is 80 wavelengths and there are 4 s-d pairs \( s_1, s_2, s_3, s_4 \) with traffic of 30, 10, 20 and 20 wavelengths respectively. We first sort s-d pairs based on the traffic, yielding \( s_1, s_3, s_4, s_2 \). We then start bin-packing by putting \( s_1 \) wavelengths on fiber 1. \( s_3 \) wavelengths are then investigated whether they can be put on fiber 1. Since it is not possible, we put them on the new fiber, i.e., fiber 2. Using the same process for \( s_4 \) wavelengths, we put them on fiber 2. Finally, \( s_2 \) wavelengths are put on fiber 1.

We adopt the power constraint model from [19] and OSNR constraint model from [25]. In order to determine the numbers and locations of optical amplifiers, we assume that optical amplifiers have the simple gain model shown in Fig. 4.

Since the actual amplifier gain can be obtained only after we have the routing solution, we need to use upper and lower bounds on the gains in order to obtain a feasible solution. We use the lower bounds in the power constraints to guarantee that the actual received powers at the
receivers are greater than the receiver sensitivity. For the OSNR constraints, the upper bounds are used to guarantee that the actual amplifier noise levels do not cause the OSNR at the receivers to fall below the required minimum value. The upper bound amplifier gain is obtained by multiplying the total number of wavelengths (link load) on the fiber with the receiver sensitivity \( P_{\text{sens}} \) and using the result as the input power level. The lower bound is obtained by subtracting the link loss from the maximum transmitted power level \( P_{\text{max}} \) and using the result as the input power level.

Example: Suppose we have a simple network with only one s-d pair 1-3, as shown in Fig. 5. Let \( P_{\text{sens}} = -30 \text{dBm} \), \( P_{\text{max}} = 0 \text{dBm} \), and fiber attenuation \( \alpha_{\text{FIBER}} = 0.25 \text{dB/km} \). Suppose the traffic for this path is 20 wavelengths. Then we can calculate the upper bound gain \( G_{eb}^{UB} \) and the lower bound gain \( G_{eb}^{LB} \) as follows.

\[
\begin{align*}
G_{eb}^{UB} &= G(1\mu W \times 20) = G(-17 \text{dBm}) = 17 \text{dB} \\
G_{eb}^{LB} &= G(1\mu W \times 20) = G(-17 \text{dBm}) = 17 \text{dB} \\
G_{eb}^{LB} &= G(0 - 0.25 \times 40) = G(-10 \text{dBm}) = 10 \text{dB} \\
G_{eb}^{LB} &= G(0 - 0.25 \times 30) = G(-7.5 \text{dBm}) = 7.5 \text{dB}
\end{align*}
\]

From these models, we formulate the optical amplifier placement problem as an ILP problem. Given network topology and RWA results, the objective is to minimize the total number of optical amplifiers in the network subject to the power and OSNR constraints. Note that dispersion constraints are taken care of by the maximum distance limitation of routes.

Given Parameters:

\( N \) = number of nodes in network
\( E \) = number of edges or links in network
\( \mathcal{E} \) = set of edges
\( \mathcal{P} \) = set of paths given from the routing solution
\( s(p) \) = source node on path \( p \)
\( L^p(n) \) = length of subpath from \( s(p) \) to node \( n \) on path \( p \)
\( E^p(n) \) = set of links on subpath from \( s(p) \) to node \( n \) on path \( p \)
\( G_{eb}^{UB} \) = upper bound of an amplifier gain at the amplifier on the terminating node on link \( e \)
\( G_{eb}^{LB} \) = lower bound of an amplifier gain at the amplifier on the terminating node on link \( e \)
\( P_{RX} \) = minimum received power at receiver/amplifier input port (dBm)
\( P_{TX} \) = transmitted power on each path (dBm)
\( \alpha_{\text{FIBER}} \) = attenuation of a fiber (dB/km)
\( n_{sp} \) = spontaneous emission factor
\( h \) = photon energy
\( \Delta \omega \) = bandwidth of optical fiber
\( \beta \) = \( 2n_{sp} \times h \times \Delta \omega \)
\( OS\text{N}_{RX} \) = required OSNR at a receiver

Variables:

\( z_e \in \{0, 1\} \): equal to 1 if and only if there is an amplifier on the terminating node on link \( e \).

Objective:

\[
\text{minimize } \sum_{e \in \mathcal{E}} z_e \tag{16}
\]

Constraints:

\[
\forall p \in \mathcal{P}, \forall n \in \mathcal{P}, n \neq s(p), \quad P_{RX} \geq \frac{P_{TX} - \alpha_{\text{FIBER}}L^p(n) + \sum_{e \in \mathcal{E}^p(n)} (G_{eb}^{LB} + z_e (G_{eb}^{UB} - 1))}{\beta} \tag{17}
\]

\[
\forall e \in \mathcal{E}, z_e \in \{0, 1\} \tag{19}
\]

Constraint (17) requires that the power constraint must be satisfied. Constraint (18) assures us that the OSNR constraint must be satisfied. Finally, the integer constraints are specified in (19).

6. Simulated Annealing Approach

Simulated annealing relies on local search among the neighbors of the current solution. We choose a neighborhood structure based on path-switching operation as follows. To obtain a neighbor of the current solution, we first randomly select an s-d pair. The path for this s-d pair is then randomly selected from the routing table generated from the \( k \) shortest path list. Thus, two routing solutions are considered neighbors if the paths are different by no more than for one s-d pair. The following notations will be used in the description of the simulated annealing algorithm.

- \( T_{\text{min}} \): termination temperature
- \( T_0 \): initial temperature, \( T_0 \geq 0 \)
- \( T_k \): temperature at \( k \)th step
• $\alpha$: cooling parameter, $\alpha < 1$
• $M_k$: repetition schedule
• $\omega$: current amplifier placement solution
• $\omega'$: new amplifier placement solution
• $f(\omega)$: cost of current amplifier placement solution
• $f(\omega')$: cost of new amplifier placement solution
• $\Delta f$: difference between cost of current and new amplifier placement solutions, $\Delta f = f(\omega') - f(\omega)$

The SA algorithm for RWA and optical amplifier placement that minimize the number of amplifiers is outlined as follows.

1. Initialization: Initialize the parameters.
2. Neighbor structure creation: For each s-d pairs, compute the routing table of three shortest paths by using $k$ shortest path algorithm.
3. Initial solution: Randomly select an RWA solution from the set of path as an initial RWA solution. Compute an optimal solution of optical amplifier placement based on initial RWA solution.
4. SA iteration:
   
   \[ k = 0 \]
   
   while $t_k \geq T_{\text{min}}$
   
   for $n = 1$ to $M_k$
   
   - Randomly choose a s-d pair and its routing.
   - Calculate a new solution $\omega'$ and its cost $f(\omega')$.
     (If the new RWA makes the amplifier placement infeasible, then set $f(\omega') = \infty$.)
   - Calculate the cost difference $\Delta f$.
   - If $\Delta f \leq 0$, then replace the existing solution with the new solution.
   - If $\Delta f > 0$, then replace the existing solution with the new solution with the probability $e^{-\Delta f / t_k}$.
   
   end (for)

   $k = k + 1$

   $t_k = \alpha t_{k-1}$

   end (while)

We use the minimum temperature as stopping criterion. If temperature is lower than $T_{\text{min}}$, then the algorithm terminates.

7. Numerical Results

To obtain numerical results, we randomly generate a 30-node network using MATLAB software [26]. To generate a network, we first select 30 random node locations according to the uniform distribution over a 100 km x 100 km area. Having obtained the node locations, node populations are randomly generated using uniform distribution to be in the interval of $[0, 1 \times 10^6]$. The degree of each node is then identified according to the node population as shown in Table 1. Finally, a link between each node pair exists with probability equal to $e^{-d}$, where $d$ is the distance between the two nodes. Note that a link with short distance is more likely to exist than a link with long distance. An example 30-node topology is shown in Fig. 6.

We solve the ILP problems for topology design using CPLEX software package [27]. The parameters used to obtain numerical solutions are based on [28] and summarized in Table 2 and Table 3. The resultant concentrator locations are shown in Fig. 7 together with the concentrator assignment for each non-concentrator node. Figure 8 shows the locations of concentrators, junction nodes, and remaining links in the simplified topology graph. For our example network, 7 non-concentrator nodes and 20 links are eliminated to obtain the simplified topology graph.

Figure 9 shows the concentrator connections without the limitation on the maximum path lengths. Figure 10 shows the same information but with the maximum path length limited to 250 km. Observe that more links are established in Fig. 10, i.e., 21 links compared to 14 links in Fig. 9 due to the maximum path length constraint.

After topology design was completed, we compute the
Fig. 7  Selection of concentrators and concentrator assignments for non-concentrator nodes. A concentrator is drawn as a big circle.

Fig. 8  Simplified topology graph. An eliminated node is drawn as a cross.

Fig. 9  Concentrator connections without the limitation on the maximum working or backup path length.

Fig. 10  Concentrator connections with the maximum path length limited to 250 km.

$k$ shortest path routings and save the results to be used for the neighborhood structure for the simulated annealing algorithm. Simulated annealing for RWA and optical amplifier placement is carried out using CPLEX software package. The parameters used to obtain numerical solutions based on [29] and the assumed traffic matrix is summarized in Table 4 and Table 5. One traffic unit represents one wavelength e.g. STM-16 at 2.5 Gb/s. The resultant optimal routings with the minimum number of optical amplifiers are (the number in parentheses specifies the fiber number if it is greater than 1):

\[
\begin{align*}
(1 \rightarrow 2) & : 4 \rightarrow 13 \rightarrow 15 \rightarrow 18 \rightarrow 27 \rightarrow 3, \\
(1 \rightarrow 5 \rightarrow 21 \rightarrow 29 \rightarrow 6, & \\
(1 \rightarrow 4 \rightarrow 18 \rightarrow 15, & \\
(1 \rightarrow 2) & : 5 \rightarrow 23 \rightarrow 20 \rightarrow 24 \rightarrow 22, \\
(3 \rightarrow 6 \rightarrow 10 \rightarrow 14 \rightarrow 6, & \\
(3 \rightarrow 27 \rightarrow 18 \rightarrow 15, & \\
(3 \rightarrow 28 \rightarrow 10 \rightarrow 14 \rightarrow 22, & \\
(6 \rightarrow 29 \rightarrow 21 \rightarrow 5 \rightarrow 2 \rightarrow 4 \rightarrow 13 \rightarrow 15, & \\
(6 \rightarrow 29 \rightarrow 21 \rightarrow 5 \rightarrow 23 \rightarrow 20, & \\
(6 \rightarrow 14 \rightarrow 22, & \\
(15 \rightarrow 13 \rightarrow 4 \rightarrow 2 \rightarrow 1 \rightarrow 2 \rightarrow 5 \rightarrow 23 \rightarrow 20, & \\
(15 \rightarrow 13 \rightarrow 4 \rightarrow 2 \rightarrow 1 \rightarrow 5 \rightarrow 21 \rightarrow 29 \rightarrow 6 \rightarrow 14 \rightarrow 22, & \\
(20 \rightarrow 24 \rightarrow 22, & \\
(13 \rightarrow 27 \rightarrow 18 \rightarrow 15 \rightarrow 13 \rightarrow 4 \rightarrow 2 \rightarrow 1, & \\
(6 \rightarrow 29 \rightarrow 21 \rightarrow 5 \rightarrow 2 \rightarrow 4 \rightarrow 13 \rightarrow 15, & \\
(6 \rightarrow 14 \rightarrow 6, & \\
(20 \rightarrow 23 \rightarrow 5 \rightarrow 2 \rightarrow 4 \rightarrow 13 \rightarrow 15, & \\
(22 \rightarrow 24 \rightarrow 20 \rightarrow 23 \rightarrow 5 \rightarrow 2 \rightarrow 4 \rightarrow 13 \rightarrow 15, & \\
(22 \rightarrow 24 \rightarrow 20). & 
\end{align*}
\]

Table 4 Parameters for numerical results for amplifier placement [28].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>$P_{\text{max}}$</td>
<td>0</td>
<td>dBm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$P_{\text{sen}}$</td>
<td>-30</td>
<td>dBm</td>
</tr>
<tr>
<td>Received power</td>
<td>$P_{\text{RX}}$</td>
<td>-28</td>
<td>dBm</td>
</tr>
<tr>
<td>Transmitted power</td>
<td>$P_{\text{TX}}$</td>
<td>0</td>
<td>dBm</td>
</tr>
<tr>
<td>Attenuation of fiber</td>
<td>$\alpha_{\text{FIBER}}$</td>
<td>0.25</td>
<td>dB/km</td>
</tr>
<tr>
<td>Spontaneous-emission factor</td>
<td>$n_{\text{sp}}$</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>Planck’s constant</td>
<td>$h$</td>
<td>$6.626 \times 10^{-34}$</td>
<td>J·s</td>
</tr>
<tr>
<td>Optical frequency</td>
<td>$v_0$</td>
<td>193</td>
<td>THz</td>
</tr>
<tr>
<td>Bandwidth of optical fiber</td>
<td>$\Delta v_0$</td>
<td>100</td>
<td>GHz</td>
</tr>
<tr>
<td>Required OSNR</td>
<td>$\text{OSNR}_{\text{RX}}$</td>
<td>20</td>
<td>dB</td>
</tr>
<tr>
<td>Cooling parameter</td>
<td>$\alpha$</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Repetition Schedule</td>
<td>$M_k$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Initial temperature</td>
<td>$t_0$</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

Simulated annealing yields the results shown in Table 6. Table 7 shows the link capacities used to support the given traffic matrix. We further investigate the performance of our algorithm by comparing the result from the SA algorithm with the result from shortest path routing. From Table 6, the optimal number of amplifier is 6. By solving the optical amplifier number for shortest path routing, we obtain the result of 8 amplifiers. Comparing the number of ampli-
fiers for the shortest path routing with the optimal number of amplifiers from the simulated annealing algorithm, as shown in Fig. 11 and Fig. 12, we see that we can achieve a better result than simply using shortest path routing.

In Fig. 11 and Fig. 12, links are bidirectional and the position of the amplifier indicates that the amplifier is placed on that node and that link. For example, in Fig. 11, the amplifier at node 10 indicates that the amplifier is placed at node 10 for link 28-10. By manual rechecking the solution using the actual amplifier gain obtained from the solution, we found that no amplifier location can be removed. Therefore, at least for the small example considered, our algorithm yields a reasonable result. Note that we use the actual physical topology, not the simplified graph, in the amplifier placement problem. In particular, node 28 has been put back in the topology since link 3-10 in the simplified graph composes of links 3-28 and 28-10.

We investigate the execution time for each step of the design process as shown in Table 8. Each entry is an average of 3 random scenarios. The entry “NA” in the table means that the CPLEX program cannot successfully solve for a solution. We choose $k$ for $k$ shortest path routing to be 3 because having $k = 3$ yields a reasonable number of choices for routing and we found that the results for $k > 3$ are in most cases the same as with $k = 3$, as shown in Table 9. In our examples, there is only one example that having $k = 4$ yields a better result than having $k = 3$.

<table>
<thead>
<tr>
<th>Node</th>
<th>1</th>
<th>3</th>
<th>6</th>
<th>15</th>
<th>20</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>5</td>
<td>16</td>
<td>20</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>12</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>12</td>
<td>4</td>
<td>0</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>16</td>
<td>4</td>
<td>12</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>22</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>16</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5 Traffic matrix.

<table>
<thead>
<tr>
<th>$T_{\min}$</th>
<th>0.9</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal number</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6 Numerical results from simulated annealing.

<table>
<thead>
<tr>
<th>$T_{\min}$</th>
<th>0.4</th>
<th>0.3</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal number</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 7 Link capacities (wavelengths) used.

<table>
<thead>
<tr>
<th>Link</th>
<th>Capacity</th>
<th>Link</th>
<th>Capacity</th>
<th>Link</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>41</td>
<td>5-23</td>
<td>38</td>
<td>15-18</td>
<td>37</td>
</tr>
<tr>
<td>4-1</td>
<td>41</td>
<td>23-5</td>
<td>38</td>
<td>18-15</td>
<td>37</td>
</tr>
<tr>
<td>1-5</td>
<td>70</td>
<td>6-14</td>
<td>40</td>
<td>18-27</td>
<td>17</td>
</tr>
<tr>
<td>5-1</td>
<td>70</td>
<td>14-6</td>
<td>40</td>
<td>27-18</td>
<td>17</td>
</tr>
<tr>
<td>3-27</td>
<td>17</td>
<td>6-29</td>
<td>40</td>
<td>20-23</td>
<td>38</td>
</tr>
<tr>
<td>27-3</td>
<td>17</td>
<td>29-6</td>
<td>40</td>
<td>23-20</td>
<td>38</td>
</tr>
<tr>
<td>3-28</td>
<td>36</td>
<td>10-14</td>
<td>36</td>
<td>20-24</td>
<td>32</td>
</tr>
<tr>
<td>28-3</td>
<td>36</td>
<td>14-10</td>
<td>36</td>
<td>24-20</td>
<td>32</td>
</tr>
<tr>
<td>4-13</td>
<td>37</td>
<td>10-28</td>
<td>36</td>
<td>21-29</td>
<td>40</td>
</tr>
<tr>
<td>13-4</td>
<td>37</td>
<td>28-10</td>
<td>36</td>
<td>29-21</td>
<td>40</td>
</tr>
<tr>
<td>4-18</td>
<td>20</td>
<td>13-15</td>
<td>37</td>
<td>22-24</td>
<td>32</td>
</tr>
<tr>
<td>18-4</td>
<td>20</td>
<td>15-13</td>
<td>37</td>
<td>24-22</td>
<td>32</td>
</tr>
<tr>
<td>5-21</td>
<td>40</td>
<td>14-22</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-5</td>
<td>40</td>
<td>22-14</td>
<td>68</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 Link capacities (wavelengths) used.

Fig. 11 Backbone topology for 30-node network (by SA algorithm). Locations of amplifiers are drawn in triangular shape.

Fig. 12 Backbone topology for 30-node network (by using shortest path routing). Locations of amplifiers are drawn in triangular shape.

Fig. 11

<table>
<thead>
<tr>
<th>Algorithm/Case</th>
<th>Concentrator Location</th>
<th>Concentrator Connection</th>
<th>Simulated Annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 – node</td>
<td>2</td>
<td>160</td>
<td>704</td>
</tr>
<tr>
<td>50 – node</td>
<td>4</td>
<td>4,681</td>
<td>1,056</td>
</tr>
<tr>
<td>100 – node</td>
<td>57</td>
<td>106,525</td>
<td>3,860</td>
</tr>
<tr>
<td>150 – node</td>
<td>360</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 8 Execution time for each algorithm (second).
Table 9 Running time and optimal solution for SA algorithm for 30-node networks with $k = 2, 3, 4$.

<table>
<thead>
<tr>
<th>Case</th>
<th>$k$</th>
<th>running time (sec)</th>
<th>optimal number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$k = 2$</td>
<td>560</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>704</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>712</td>
<td>6</td>
</tr>
<tr>
<td>Case 2</td>
<td>$k = 2$</td>
<td>320</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>400</td>
<td>2</td>
</tr>
<tr>
<td>Case 3</td>
<td>$k = 2$</td>
<td>560</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>702</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>720</td>
<td>6</td>
</tr>
<tr>
<td>Case 4</td>
<td>$k = 2$</td>
<td>128</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>113</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>152</td>
<td>0</td>
</tr>
<tr>
<td>Case 5</td>
<td>$k = 2$</td>
<td>638</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>684</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>1360</td>
<td>4</td>
</tr>
<tr>
<td>average running time</td>
<td>$k = 2$</td>
<td>441.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k = 3$</td>
<td>520.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$k = 4$</td>
<td>668.8</td>
<td></td>
</tr>
</tbody>
</table>

8. Conclusion

We presented a design approach for a DWDM network based on an existing power grid. We separate the design problem into two main steps. In the first step, we solved the physical topology design by solving ILP problems. In the second step, we combined the RWA problem and optical amplifier placement problem and solve these two problems together using simulated annealing.

Our design is different from previous work in the same area because of additional considerations in the existing power grid topology and the limitation on the maximum path length in topology design, yielding more efficient results for survivable networks compared to ring networks. In addition, we proposed to solve the RWA problem and the optical amplifier placement problem together. Previous work assumes either the RWA solution before solving the amplifier placement problem, or the amplifier locations before solving the RWA problem.

We solved the overall design problem and presented numerical results for an example randomly generated 30-node network. In addition to the resultant backbone topology, our numerical results indicate that using simulated annealing can achieve a better solution than using shortest path RWA followed by amplifier placement. We are currently investigating heuristics for randomly generated networks with large numbers of nodes and solving the combined RWA and optical amplifier placement problem with protection routing.

References


Areeyata Sripetch is a doctoral candidate in Telecommunications at the Asian Institute of Technology (AIT), Thailand. She received a B.S. degree in Electrical Engineering from Southern College of Technology, USA, in 1993, and an M.S. degree in Electrical Engineering from University of Colorado at Boulder, USA, in 1997. She also serves as a senior engineer at Electricity Generating Authority of Thailand (EGAT).

Poompat Saengudomlert received his B.S.E. degree in Electrical Engineering from Princeton University, USA, in 1996. He then obtained his M.S. and Ph.D. degrees, both in Electrical Engineering and Computer Science, from MIT, USA, in 1998 and 2002 respectively. Currently, he is an assistant professor at the Asian Institute of Technology, Thailand. His research interest includes communication theory, optical networks, and resource allocation problems.