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Pareto Optimization of Optical Network in Electric Power Communication System Based on Genetic Algorithms

Yipeng Li, Chunming Huang

Intelligent Planning Research Center, Jiangxi Electric Power Research Institute,, Nanchang, China

ypligood@163.com

Abstract. As current electric power communication network planning can hardly consider multiple design objectives simultaneously, we proposed a general optimization model of multiple objectives optical network planning in electric power communication systems, based on Pareto optimization and genetic algorithms. The optical network in power system is modelled mathematically and the total cost functional is a combination of the overall network burden and the building cost weighted by a regularization parameter. After a series of optimization with different regularization, a Pareto frontier is generated to illustrate the trade-off between the two conflicting objectives, which provides a unified framework for planning and can navigate the operators' intelligent decision-making. Numerical results illustrate our conclusions.

Keywords: Pareto optimization; optical network; electric power

1. Introduction

In the last two decades, almost all industries in China have modernized themselves with the use of sensors, communications and computational ability, which results in enormous improvements in productivity, efficiency and even environmental performance. In electric power system, a smart grid is the use of sensors, communications, computational ability and control to enhance the overall functionality of the electric power delivery system. As the cornerstone of smart grid's development, electric power communication network has been continuously playing a growing role in the secure and economic operations of the power grid, which is one of the largest, or perhaps the largest scale system ever made. As the demand grows for higher network access speeds, technologies such as optical fiber have begun to overtake traditional copper wire for data in short haul networks as well as long haul networks[1][2]. In electric power system, the use of specific kinds of fibers like ADSS(All-dielectric Self-supporting Optical Cable), OPGW(Optical Fiber Composite Overhead Ground Wire), OPPC(Optical Phase Conductor), OPLC(Optical Fiber Composite Low-Volt age Cable) has significantly boosted the implementation of optical network in electric power communication system.

Communication network intelligent planning is a significantly important chapter in electric power industry's 12th five-year plan. However, most attention is paid on equipping the network nodes with the latest hardware, while the overall network planning seriously needs to be optimized.

In electric power optical network planning, the network nodes were usually decided, being either the dispatching centers or substations, then the nodes must be interconnected so that the expected bandwidth requirements can be satisfied, subject to various technical, political, social, economic and risk constraints[3]. Even ignoring other constraints and just focusing on constructing the optimized network by considering the economic cost is nontrivial. In this paper, we study the optical network planning problem by a Pareto optimization method which combines the network burden and the economic constraint to build the cost functional, and genetic algorithms are applied to generate the Pareto frontiers.

2. Methodology

2.1 Genetic algorithms

Genetic algorithms are stochastic search algorithms based on the mechanism of natural selection and natural genetics, and the usual form is described in [4]. Genetic algorithms start with an initial set of random solutions called population satisfying boundary or system constraints to the problem. Element in the population is called a chromosome, representing a solution to the problem at hand. Chromosome is a string of symbols usually, but not necessarily, a binary bit string. The chromosomes evolve through successive iterations called generations. Measures of fitness are defined and evaluated during each generation from the chromosomes. New chromosomes called offspring are formed by either merging two chromosomes from current generation using a crossover operator or modifying a chromosome using a mutation operator to create the next generation, c.f. Fig. 1. Each generation is formed by selection, according to the fitness values, some of the parents and offspring, and rejecting others so as to keep the population size constant. Genetic algorithms converge to the best chromosome after certain number of iterations, which hopefully represents the optimum or suboptimal solution.

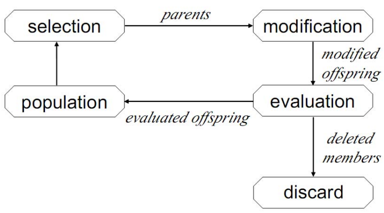

Figure 1 Genetic algorithm steps

Genetic algorithms combine elements of directed and stochastic search which can produce a remarkable balance between exploration and exploitation of the search space. A widely random and diverse population and crossover operator tends to perform wide-spread search for exploring all solution space. And the crossover operator provides exploration in the neighborhood of those high fitness solutions. Genetic algorithms perform multi-directional search by maintaining a population of potential solutions, which is hopeful to avoid trapping in local optima. Genetic algorithms use probabilistic transition rules to select someone to be reproduced and some to die so as to guide their search toward regions of the search space with likely improvement.

2.2 Pareto optimization

If there are more than one criterion which must be treated simultaneously in optimization problems, we have multiple objective optimization problems. Almost every real-world decision problem involves multiple and conflicting objectives which need to be tackled while respecting various constraints, leading to overwhelming problem complexity[5].

A multiple objective optimization problem can be formally represented as follows:

$$\begin{aligned} &\max\{z_1 = f_1(x), z_2 = f_2(x), \cdots, z_n = f_n(x)\} \\ &s.t. \quad g_i(x) \le 0, \quad i = 1, 2, \cdots, m \end{aligned} \tag{1}$$

Where x is a vector of decision variables, $f_i(x)$ are the objective functions, $g_i(x)$ are inequality constraint functions, which form the area of feasible solutions. The feasible area in decision space with the set S can be defined as:

$$S=\{x \mid g_i(x)\le 0,\quad i=1,2,\cdots,m\} \tag{2}$$

And the criterion space Z is defined as:

$$Z=\{z\in R^n \mid z_1=f_1(x),\cdots,z_n=f_n(x),x\in S\} \tag{3}$$

A solution may be best in one objective but worse in other objectives, therefore, there usually exists a set of solutions for the multiple objective case which cannot simply be compared with each other. Such kinds of solutions are called nondominated solutions or Pareto [6] optimal solutions, for which no improvement in any objective is possible without sacrificing at least one of the other objective functions. For a given nondominated point in the criterion space, its image point in the decision space is called efficient or noninferior, strict definition is:

Definition(Nondominated). For a given point $z^0\in Z$, it is nondominated if and only if there does not exist another point $z\in Z$ such that, for the maximization case,

$$z_k>z_k^0,\quad \exists k\in\{1,\cdots,n\},\quad z_l\ge z_l^0,\quad \forall l\ne k \tag{4}$$

where z^0 is a dominated point in the criterion space Z.

The Pareto frontier is the set of solutions that are Pareto efficient, and this is particularly useful in engineering by restricting attention to the set of solutions that are Pareto efficient rather than considering the full rage of every parameter. The convexity of the Pareto frontier is usually a desirable feature for regularized optimization problems.

The inherent characteristics of the genetic algorithm demonstrate why genetic search is possibly well suited to multiple objective optimization problems. The basic feature of the genetic algorithm is the multiple directional and global search by maintaining a population of potential solutions from generation to generation, and this population-to-population approach is useful to explore all Pareto solutions.

2.3 Problem formulation

In this paper we consider a greenfield scenario where the electric power communication operator has decided the locations of WDM network nodes, which are usually the electric power dispatching centers or substations of various voltages. Currently, simple point-to-point fiber links using just wavelength are deployed in most electric power communication networks in China in the form of SDH network, however, they are being expected to be upgraded to exploit the fiber optical capacity by attaching wavelength division multiplexing (WDM) equipment in the near future. The WDM equipments consist of tunable or fixed-wavelength transmitters/receivers and multiplexers that enable simultaneous communication in the same fiber using different wavelengths[7]. This helps satisfy the exponential increase in communication demand, and optical fibers can provide reliable communication over long distance with low delay.

Although delays are low in fibers, it is high in DXC(digital cross connect), because of the optical-electrical-optical conversion. As a result, the development of all optical network (AON) was spurred, in which each node is equipped with an OXC(optical cross connect) or an OADM(optical add drop multiplexer), and both can pass on the optical signals without OEO conversion[8].

We consider the case where some WDM network nodes were decided and they will be interconnected with links so that multiple objectives are balanced while continuous service is guaranteed. This multiple objective optimization problem can be formulated as:

$$\min\{z_1=f_1(\mathrm{x}),z_2=f_2(\mathrm{x}),\cdots,z_n=f_n(\mathrm{x})\},\quad s.t.\quad \mathrm{x}=[x_1\cdots x_p]^T,x_i\in\{0,1\},\quad i=1,2,\cdots,p \tag{5}$$

where $f_j(\mathrm{x}), j=1,2,\cdots,n$ are different cost functions to be minimized, and $x_i, i=1,2,\cdots,p$ are logic variables representing the state of the potential links between nodes. In electric power communication network, the cost functions can be defined by network burden, building cost, specific risk of operation, etc.

In electric power communication system, the network traffic is relatively static as compared to that in commercial telecommunication operators' network. Therefore, in this paper, the traffic is considered static and given as a set of K traffic demands. Each demand d_i can be defined by a set $\{N_{d_i}^s, N_{d_i}^d, V_{d_i}\}$, where $N_{d_i}^s$ and $N_{d_i}^d$ are the source and destination nodes, and V_{d_i} means the traffic volume. No hop limit or length limit is set on the paths which supplies a demand.

Here are the definitions of variables used in the paper: $D=\{d_1,\cdots,d_K\}$ is the set of traffic demands, $\{1,\cdots,N\}$ is the set of network nodes, $\{\{n,m\}\,|\,n,m\in\{1,\cdots,N\}\}$ is the set of potential links and $C_{\{n,m\}}^{link}$ is the building cost between nodes n and m, $A_{\{n,m\}}$ is the length of the fiber(duct) between nodes n and m, and the total cost function is defined as:

$$f(\mathrm{x})=f_1(\mathrm{x})+\lambda f_2(\mathrm{x}),\quad \lambda\geq 0,\ f_1(\mathrm{x})=\sum_{i=1}^{K},\sum_{\{n_1,n_2\}\in P_{d_i}(\mathrm{x})} V_{d_i}A_{\{n_1,n_2\}},\ f_2(\mathrm{x})=\sum_{\{n_1,n_2\}\in AL(\mathrm{x})} C_{\{n_1,n_2\}}^{link} \tag{6}$$

Where, $P_{d_i}(\mathrm{x})$ is the shortest path between nodes $N_{d_i}^s$ and $N_{d_i}^d$, $AL(\mathrm{x})$ is the set of connected links, given $x_i, i=1,2,\cdots,p$, and the optimal link configuration vector is defined as $\mathrm{x}^o(\lambda)$. In this paper the total cost functional is composed of two parts, the first is the overall network burden with specific traffic demand, and the second part is the building cost of all the connected links without considering the cost of node equipments. For simplicity, no protection paths are considered here and it's supposed that all traffic demands are satisfied by shortest paths.

For each $\lambda\geq 0$, the total cost functional is minimized by a genetic algorithm, and the pareto frontier is constructed from the optimization results with different λ.

3. Numerical Results

We apply our algorithm to an optical network planning problem in the northest JiangXi electric power communication system, where six locations (either local power dispatching centers or 500KV substations) are selected as network nodes. The traffic demand of the network is generated randomly in the simulation and identified in Fig. 2. Note that the node positions are different in Fig. 2-4 to better show the link connection, and this does not reflect the realistic geographic positions. For simplicity, the building cost for each potential link is proportional to the length of the link.

In the algorithm, $\lambda\geq 0$ serves as the regularization parameter, and we generate optimized link configurations by genetic algorithms for certain number of λ values to approximate Pareto frontiers displaying the network burden as functions of the building cost. To normalize the Pareto frontiers, the displayed values of network burden $Burd(\lambda)$ and building cost $Cost(\lambda)$ are defined as:

$$Burd(\lambda)=f_1(\mathrm{x}^o(\lambda))/f_1(\mathrm{x}^o(0)),\quad Cost(\lambda)=f_2(\mathrm{x}^o(\lambda))/f_2(\mathrm{x}^o(0)) \tag{7}$$

In Fig. 3, the optimization result of link configuration is plotted for the case $\lambda=0.1$, which illustrates the optimized solution to minimize the combination of network burden and building cost with weighted regularization parameter $\lambda=0.1$. Fig. 4 displays the case when larger regularization weigh parameter $\lambda=1.5$ is applied in the optimization, which results in a network with less links to reduce the building cost but certainly increase the network burden. To visualize the trade-off between the two conflicting objectives, Fig. 5 plots the Pareto frontier for the network burden function and the building cost function, and and we empirically observed that some gain in one objective results in the other's being worse off.

4. Conclusion

The electric power industry has arguably been the primary driver for China's growing economy in the last two decades. As the fast development of smart grid in power system, the intelligent planning of its communication network certainly requires great emphasis. This paper proposed a systemic method for optimal planning of optical network in electric power communication system by considering multiple conflicting objectives in realistic case.

The method generates the Pareto frontier by genetic algorithm optimizations, which provides a unified framework and clarifies the trade-off of multiple objectives in actual planning for network operators. Future research will focus on the cases with protection paths and other objectives such as traffic risk specifically in electric power system.

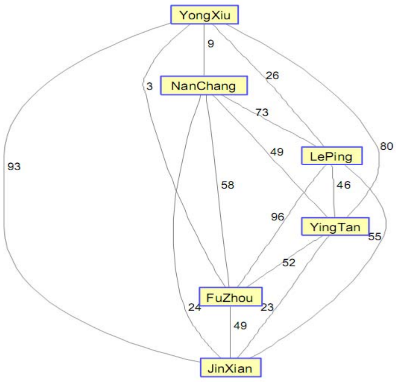

Figure 2. A network case in northeast JiangXi electric

power system

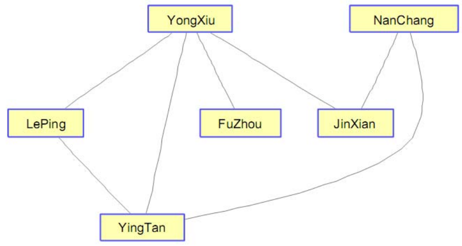

Figure 3. Optimal link configuration when $\lambda = 0.1$

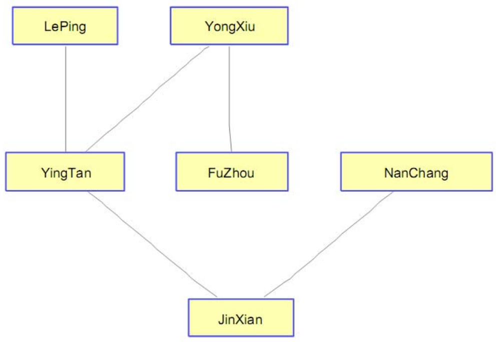

Figure 4 Optimal link configuration when $\lambda = 1.5$

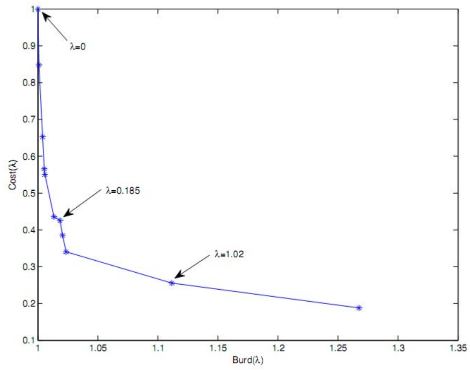

Figure 5 Pareto frontier for network burden and building cost

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