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Generating desirable network topologies using multiagent system[☆]

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ABSTRACT

Designing network topologies requires simultaneous consideration of multiple criteria, such as network cost and reliability. So, the author applied the analytic hierarchy process, a way to make a rational decision considering multiple criteria, to network topology evaluation. However, the time required to construct the candidate topology set greatly increases as the network scale grows. Therefore, the author proposed to generate candidate topologies within a practical time frame for large-scale networks by limiting the positions for putting links to a small set of candidates. However, the diversity of the obtained candidate set is limited because the links are always put at certain link positions and are never put at a majority of the other link positions in all the candidate topologies generated. Therefore, this paper proposes to use of a multiagent system, in which each agent autonomously behaves to maximize each criterion, for generating a candidate topology set with high diversity within a practical time frame for large-scale networks.

1. Introduction

For network carriers and ISPs operating and managing physical network resources, one important problem is how to design a network topology. Recently, network virtualization technique in which network resources can be flexibly reserved for each network service has been widely investigated [27]. Using this technique, ISPs can flexibly design their network infrastructure for each service, so developing optimal design method of network topologies becomes more important for ISPs. For a backbone network topology, we should carefully consider both the connectivity between any pair of edge nodes and the redundancy for maintaining the connectivity in case of node or link failure. To improve the redundancy, increasing the routes between each edge node pair by providing more intermediate nodes and links is desirable. However, the increase in nodes and links will also increase equipment and operating costs. For users, avoiding congestion at intermediate nodes and having a shorter path length to reduce the packet network delay is desirable. If we decrease the number of nodes and links to reduce the network cost, the flexibility of path design is degraded, so suppressing the path length becomes difficult. Therefore, when designing a network topology, we need to consider multiple incompatible criteria with different units, such as cost, reliability, and path length.

There are many works designing network topologies. One proposed a physical topology design minimizing the total physical link count under the condition that connectivity between all pairs of nodes is maintained in the case of a single physical link failure [24]. Ramaswami and Sivarajan [19] and Krishnaswamy [17] proposed a logical topology design minimizing the maximum link load in a wavelength-routed optical network. A design method minimizing the average hop count of wavelength paths was proposed in [1], and another method maximizing overall throughput in a wavelength-routed optical network was proposed in [30]. Chattopadhyay et al. [6] and Gersht and Weihmayer [7] presented heuristic approaches using a branch-and-bound method or a greedy method to solve the cost minimization problem with a constraint on the delay between nodes. Steiglitz et al. [23] presented a heuristic method using a local search that solves the cost minimization problem with the constraint that all node pairs have more than a specified number of disjoint routes. Wille et al. [29] depicted heuristic approaches using a tabu search and generic algorithm for solving the same problem with the constraint that the connectivity between any pair of nodes is maintained for any single-node failure. However, all these works consider only a single criterion as the optimization target.

As an approach that considers multiple criteria, the concept of the Pareto frontier is well known [26], and one study applied this concept to logical topology design [10]. Assume that there are M criteria, $V_1, \ldots, V_M$, and let $V_{m,x}$ denote the mth criterion of

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candidate x. We can say that candidate x is better than candidate y in the Pareto sense only if $V_{m,x} \le V_{m,y}$ for any m and there exists criterion m that satisfies $V_{m,x} < V_{m,y}$. (Assume that smaller values are desirable in all criteria.) All candidates that are surpassed by no other candidates are the optimum solution set, i.e., the Pareto frontier. However, a large number of candidates are regarded as the Pareto frontier, so it is difficult to effectively limit the optimum candidates and select one network topology to use.

The analytic hierarchy process (AHP) is a way to make a rational decision considering multiple criteria [9,20]. Using AHP, we can reflect the relative importance of each criterion in the evaluation result. AHP considers all the related factors in a hierarchical structure and quantifies qualitative factors, such as the importance of each criterion, using paired comparison. Therefore, we have applied AHP to network topology evaluation to consider multiple criteria simultaneously [11]. When evaluating network topologies using AHP, we need to construct a set of topology candidates prior to evaluation. However, the time required to construct a candidate set increases in the order of $2^{N \times N}$ as the number of nodes N increases; therefore, it is difficult to construct a set of topology candidates within a practical time frame for large-scale networks.

In general, enumerating all candidates satisfying certain conditions without replications is known as an enumeration problem [8]. In such a problem, it is important to reduce the required calculation time while satisfying both completeness, i.e., enumerating all candidates satisfying the condition without any omissions, and uniqueness, i.e., enumerating candidates without duplications. There are mainly two approaches for enumeration algorithms: a binary partition and a reverse search [25]. We applied the binary partition method to the construction of candidate topologies [12]. However, it is difficult to construct candidate topologies within a practical time frame for large-scale networks with about 10 or more nodes when using the binary partition method [13].

To generate candidate topologies within a practical time frame for large-scale networks, we should take another approach, i.e., generating only some candidate topologies instead of generating all the candidate topologies satisfying the conditions. In this approach, generating desirable and diverse candidate topologies is important to suppress the influence on the AHP result. Based on this approach, we proposed generating candidate topologies by limiting the candidate positions for locating links in a small set [13].

To satisfy the connectivity requirement between nodes, this method first constructs a topology in which some links are added to the minimum spanning tree. Next, this method selects candidate positions where we can put links. Although we can dramatically reduce the time required to construct the candidate topology set by using this method, the diversity of the generated topologies is low. This is because that links are always put at the positions constructing the initial topology, whereas links are never put at a large part of positions in all the generated candidates. Therefore, the results of applying AHP to the generated candidate set are expected to be largely different from those obtained by applying AHP to all the candidate topologies that can be constructed.

A multiagent system (MAS) is used for investigating the environment in which multiple agents behave autonomously, such as the ecosystems of animals and social systems [22,28]. MAS is mainly used to analyze the environment resulting from the autonomous behavior of multiple agents or to investigate the control method for generating a desirable environment for the whole system. Systems such as ecosystems and social systems that can be investigated by MAS often show high robustness against changes of environment or failures, and this robustness seems to be derived from the diversity of the systems as a result of dynamic interaction among the agents [28]. Therefore, if we regard the evaluation criteria of AHP as agents and simulate MAS in which each agent autonomously adds or removes links at any candidate position to optimize its evaluation criterion, we can expect to construct candidate topologies with high diversity, which are evaluated highly by AHP.

This paper proposes to construct a candidate topology set by using MAS and investigates its effectiveness by numerical evaluation.[1] In Section 2, we summarize the evaluation method using AHP for network topologies. In Section 3, we briefly describe the construction method for candidate topologies that limits the candidate positions for putting links, proposed in [13]. We describe the proposed construction method for candidate topologies using MAS in Section 4 and show the numerical results in Section 5. Finally, we conclude the paper in Section 6.

2. Topology evaluation using AHP

2.1. Overview of AHP

In a decision-making problem, there are normally three kinds of elements, i.e., *problem P*, *evaluation criteria V*, and *alternative plan G*. As shown in Fig. 1, AHP considers the relationship among these elements as a hierarchical structure and link-related elements. Evaluation criteria V can take multiple layers, $V^1, V^2, \ldots$ By calculating the relative strength (weight) for each pair of related elements, AHP derives the score S_i of each alternative plan G_i.

We need to quantify the relative importance of each criterion V against a problem P. This is achieved by comparing the elements on each level in pairs using AHP. For the two elements X_i and X_j in layer c, the numerical value listed in Table 1 selected by the decision maker is set to a_{ij}, the relative importance of X_i against X_j. By defining w_i as the true weight of X_i, we ideally have $a_{ij} = w_i/w_j$. Let $\boldsymbol{A}$ and $\boldsymbol{w}$ denote a matrix of pairwise comparisons a_{ij} and a vector of w_i, respectively. By multiplying $\boldsymbol{A}$ by $\boldsymbol{w}$, we obtain $\boldsymbol{Aw} = n\boldsymbol{w}$, where n is the number of elements in the layer. Therefore, $\boldsymbol{w}$ is the principal eigenvector and n is the maximum eigenvalue.

In practice, consistently setting a_{ij} for all pairs of elements is difficult, so we need to judge the degree of inconsistency. Letting $\lambda_{\max}$ denote the maximum eigenvalue of $\boldsymbol{A}$, we have $\lambda_{\max} \ge n$ [9,20]. We can then judge the degree of inconsistency using the *consistency index* (C.I.) defined by

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n - 1}. \tag{1}$$

$\lambda_{\max}$ decreases as the degree of consistency increases, and $\lambda_{\max} = n$ when $\boldsymbol{A}$ is a consistent matrix. Hence, the degree of consistency increases as C.I. decreases. For each size of matrix n, random matrices are generated and their mean C.I. value, called the *random index* (R.I.), is computed. The *consistency ratio* (C.R.) is defined as the ratio of C.I. to R.I., i.e., C.R. = C.I./R.I., and C.R. is a measure of how a given matrix compares to a purely random matrix in terms of their C.I. A C.R. less than or equal to 0.1 is typically considered acceptable [9].

Let w^c_{ij} denote the weight of the ith element in layer c against the jth element in layer $c-1$. We also define $\boldsymbol{\Phi}^c_i$ as the element set in layer $c-1$ related to X^c_i, the ith element in layer c. S^c_i, the score of X^c_i against problem P, is then derived as

$$S^c_i = \sum_{j; X^{c-1}_j \in \boldsymbol{\Phi}^c_i} w^c_{ij} S^{c-1}_j. \tag{2}$$

In layer 1, S^1_i is equal to the weight of each element against problem P. We can recursively obtain S^c_i in the order of $c = 2, 3, \ldots$ and finally derive S_i, the score of alternative plan G_i. Plans with large S_i are desirable.

[1] A shorter version of this manuscript was presented in [14].