Network-resource deployment considering both resource amount and operation-risk reductions

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Abstract: Physical-network-resource deployment to meet future traffic growth is a significant issue for network operators because it is related to the ground design of next generation networks. In this paper, we propose an effective heuristic decomposition method of physical-network-resource deployment considering the balance between the amount of additional network resources $Q$ and operation-risk. We focus on decreasing the number of physical links with additional capacity $Nu$ to reduce operation-risk. Numerical evaluations indicate that, with our method, pareto-optimal solutions between $Q$ and $Nu$ can be designed with a smaller $Nu$, more than 50\% smaller, compared with a benchmark method that minimizes $Q$.

Keywords: Pareto optimization, resource deployment, resource allocation, operation-risk, linear programming

Classification: Network

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1 Introduction

There have been a number of significant studies on appropriate network-resource allocation. Most of these have focused on flow management, such as traffic routing, or establishment of logical paths over a given physical-network resource under various types of pipe [1, 2] or hose traffic models [3, 4]. Their aim was to minimize the maximum link-utilization rate over given physical links or to increase robustness against traffic-demand fluctuations.

In this paper, we focus on the effective deployment of physical-network resources (resource deployment) to meet future traffic growth. Resource deployment is a significant issue, in addition to flow management, for network operators because it is related to the ground design of next generation networks.

When considering resource deployment, minimizing the amount of network resources is considered a general objective function. In addition, we insist that it is essential to include another factor, operation-risk, to design effective resource deployment from the network-operation viewpoint. This is because operation-risk, for example, advanced and complex network design, miss configuration of deployed network components, and failures of newly deployed components, will increase the capital expenditures and the operating expenses, and prevent the provision of stable commercial services. Therefore, resource deployment should be designed carefully from the viewpoints of both the amount of additional network resources $Q$ and operation-risk. However, to the best of our knowledge, there have not been any studies that discuss appropriate resource deployment considering both factors.

We propose an effective heuristic decomposition method of resource deployment considering the balance between $Q$ and operation-risk. To reduce operation-risk, we focus on decreasing the number of physical links that require additional capacity.

The contributions of this paper are as follows. First, we discuss resource deployment design considering operation-risk in addition to the amount of network resources. Second, we formulate the resource-deployment problem by mixed integer linear programming (MILP) and introduce our heuristic decomposition method to reduce the computation time. Third, we indicate the effectiveness of our method through numerical evaluations.

The remainder of this paper is organized as follows. In Section 2, we formulate the problem as an optimization problem and, in Section 3, introduce our heuristic decomposition method. In Section 4, we evaluate the performance of our method. Finally, we conclude the paper in Section 5.
2 Basic optimal problem formulation

Our goal is to design effective resource deployment considering the balance between the reduction in the resource amount and operation-risk. To reduce operation-risk, we focus on decreasing the number of physical links that require additional capacity $Nu$ as the first step. This is because the re-configuration in the physical-network layer is a significant operation issue because it generally greatly impacts the upper layers as well, such as the re-establishment of logical paths or re-assignment to different interface cards.

We now provide the basic MILP formulation of the resource deployment problem. Assume a physical network $G (N, E)$, where $N$ is the set of physical nodes that consists of edge and transit nodes, and $E$ is the set of physical links. Set $P$ consists of source-destination edge node pairs, where each pair $p \in P$ consists of a source node $s$ and destination node $t$. The variables are $B_{ij}$ and $x_{st}^i$, where $B_{ij}$ is the additional capacity of link $(i, j) \in E$, while $x_{st}^i$, $0 \leq x_{st}^i \leq 1$ is the portion of the traffic from $s$ to $t$ routed through $(i, j)$. We assume additional resources will be deployed only on physical links.

\[
\begin{align*}
\text{minimize} & \quad \sum_{(i,j) \in E} B_{ij} \\
\text{subject to} & \quad \sum_{j : (i,j) \in E} x_{ij}^s - \sum_{j : (j,i) \in E} x_{ij}^t = \begin{cases} 
1 & \text{if } i = s \\
-1 & \text{if } i = t \\
0 & \text{otherwise} 
\end{cases} \\
& \quad i \in N, (s, t) \in P \\
& \quad \sum_{(i,j) \in P} x_{ij}^s \cdot D_{st}^i \leq C_{0ij} + B_{ij} \cdot \delta_{ij}, \quad (i,j) \in E \\
& \quad \sum_{(i,j) \in E} \delta_{ij} \leq Nu. 
\end{align*}
\]

The objective function in Eq. (1) minimizes the amount of additional resources. Constraint (2) is due to flow conservation considering traffic from $s$ to $t$. Constraint (3) means additional capacity of $(i, j)$, $B_{ij}$, is required for the sum of the fractions of traffic demands, $D_{st}^i$, transmitted over $(i, j)$. The parameter $\delta_{ij}$ is given, where $\delta_{ij}$ is 1 for $(i, j)$ that require additional capacity while $\delta_{ij}$ is 0 for $(i, j)$ that maintain the current capacity $C_{0ij}$. Constraint (4) is due to the maximum $Nu$.

To determine appropriate additional capacity, it is necessary to solve the MILP problem repeatedly by changing all possible combinations of $\delta_{ij}$ bounded by the constraint (4). However, it will take longer computation time to solve the problem in a large-scale network because the number of combinations of $\delta_{ij}$ becomes larger. For example, it is necessary to compute the problem more than $5 \times 10^7$ times repeatedly in a network with sixty directed links and the maximum $Nu$ of twenty.

3 Heuristic decomposition method

To reduce the computation time, we introduce our heuristic decomposition method that divides the problem into two sub-problems (a) and (b). With the heuristic
decomposition method, the computation time for solving the optimal problem can be drastically shortened compared with the basic method discussed in Section 2. This is because only two computations, (a) and (b), are required to determine appropriate additional capacity even in a large-scale network.

(a) Determination of places to deploy additional capacity $\delta_{ij}$: The most adequate group of links where additional capacity is deployed is determined under the constraint that the number of links is less than $N_u$. We call the most adequate group of links as the Artery.

(b) Determination of additional capacity $B_{ij}$: Additional capacity of each link on the Artery is determined to meet future traffic demand, where the amount of additional capacity is minimized.

How to determine the Artery in (a) is the key issue with our method. Once the Artery is determined, it is easy to solve (b) by Eqs. (1) to (3) and $\delta_{ij}$ determined in (a). The Artery will be determined considering both network topology and traffic demand. We set the following two hypotheses. First, from the viewpoint of network topology, the Artery will approach the minimum spanning tree (MST) between all edge nodes when $N_u$ becomes smaller. This hypothesis is useful when a large number of links require additional capacity to meet future traffic growth. The second hypothesis is from the viewpoint of traffic demand. In the Artery, a logical path with larger traffic demand will be allocated on a shorter route to reduce as much network resources as possible.

Based on the hypotheses, we determine the Artery as follows. First, we find connected graph(s) between all edge nodes under the $N_u$ constraint. We call these connected graph(s) as logical CG(s). We then determine the Artery that is the logical CG with the minimum weighted hop counts between all edge nodes. The weight is designed based on traffic demand between pair edge nodes. The Artery is determined using the following simple MILP formulations. We use MILP because the Artery is different from a classical MST such as Kruskal’s and Prim’s algorithms [5].

$$\text{minimize} \quad \sum_{(s,t) \in P} \sum_{(i,j) \in E} w_{st} \cdot y_{ij}^{st}$$  \hspace{1cm} (5)$$

subject to

$$\sum_{j: (i,j) \in E} y_{ij}^{st} - \sum_{j: (j,i) \in E} y_{ij}^{st} = \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (6)$$

$$y_{ij}^{st} \leq \delta_{ij}, \quad (i, j) \in E, (s, t) \in P$$  \hspace{1cm} (7)$$

$$\sum_{(i,j) \in E} \delta_{ij} \leq N_u$$  \hspace{1cm} (8)$$

The $y_{ij}^{st}$ and $\delta_{ij}$ are variables with binary value $\{0, 1\}$. The Artery consists of $(i, j)$ with $\delta_{ij} = 1$. The capacity of $(i, j)$ with $\delta_{ij} = 0$ maintains the current capacity. The value of $y_{ij}^{st}$ is 1 when the traffic of the logical path between edge nodes is routed through $(i,j)$. Equation (5) is the objective function of the minimum weighted hop counts. The parameter $w_{st}$ is the weight of logical path $(s,t)$. 

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Constraint (6) is due to flow conservation. Equation (7), with Eq. (8), indicates the constraint on a logical CG.

4 Performance evaluations

To confirm the effectiveness of our method, we evaluated the relationship between $Q$ and $Nu$. We also evaluated the performance of a method in which the amount of additional resources is minimized as a benchmark. This is because, when network operators consider cost-reduction, minimizing additional resources is one of the most general and basic requirements. The MILP formulations are solved using the GNU Linear Programming Kit Solver.

We prepared three network models with different average node degrees $D$ to understand the dependency on network topology, as shown in Fig. 1(a). A network model consists of six edge nodes, where logical paths are established between all edge nodes. Network 1 is Abilene with $D$ of 2.55 [6]. Network 2 is a random network with $D$ of 3.1 generated using the BRITE topology generator. Network 3 is

![Network models](image1)

(a) Network model

![Evaluation results](image2)

(b) Evaluation results

![Artery and links](image3)

(c) Artery, (1), (2), (3), and links determined by benchmark, (4), in Network 2

Fig. 1. Relationship between amount of additional resources and number of links with additional capacity
Cost239 with $D$ of 4.55 [7]. The current link capacity is assumed to be 5 arbitrary units. Future traffic demand of a logical path is assumed to be proportional, 20 arbitrary units, to understand basic performance. Then the value of $w^{st}$ of every logical path $(s, t)$ is set to 1.

Fig. 1(b) shows the results of the relationship between $Q$ and $Nu$. In our method, the problem was solved with several indicated $Nus$, and the pareto-optimal solutions between $Q$ and $Nu$ were designed with a smaller $Nu$ in all network models with different $D$, compared with the benchmark. The maximum reduction ratio of $Nu$ was 50, 63, and 66% respectively in Networks 1, 2, and 3, where in each network, the minimum $Nu$ is the number of links in an MST between all edge nodes. Fig. 1(c) shows the difference between the Artery and the links that require additional capacity when using the benchmark in Network 2. Though we omit the results with other traffic conditions because of the space limitation, we confirmed the same characteristics of our method.

Through these evaluations, we believe that in a practical network environment, our simple heuristic decomposition method will be useful for designing resource deployment considering the balance between $Q$ and $Nu$ under a condition of fewer $Nus$, and that network operators can design optimal physical-network-resource deployment with smaller operation-risk.

5 Conclusion

We proposed a simple but effective heuristic design method of physical-network-resource deployment considering the balance between $Q$ and the operation-risk to meet future traffic growth. We focused on decreasing $Nus$, that require additional capacity to reduce operation-risk. Through numerical evaluations, we confirmed that our method gives us pareto-optimal designs with a smaller $Nu$, more than 50% smaller, compared with a benchmark method that aims to minimize $Q$. The results indicate that, with our method, network operators can design optimal physical-network-resource deployment with smaller operation-risk.