Tạp chí Tin học và Điều khiển học, T. 19, S. 3 (2003), 281–289

OPTIMIZATION PROBLEMS IN TELECOMMUNICATION NETWORKS: A CLASSIFICATION STUDY

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Abstract. In this paper, we present a classification method for optimization problems, which are proposed by some other authors, related to telecommunication networks on the basic of their characteristics, objects and applied ranges. Then we illustrate this on typical optimization problems.

Tóm tắt. Trong bài này, chúng tôi trình bày một phương pháp phân loại các bài toán tối ưu do các tác giả khác đề xuất liên quan đến mạng viễn thông trên cơ sở của đặc tính, mục tiêu và phạm vi áp dụng của các bài toán. Tiếp đó, chúng tôi minh họa phương pháp phân loại này bằng các ví dụ tiêu biểu.

1. INTRODUCTION

In recent years, optimization has taken an important role in telecommunication networks. For a given problem, the choice of technique for optimization is not an easy task. Therefore, we shall first present a brief classification of optimization problems, which can give indications (but not definite guidelines) for the choice of the optimization technique to solve problems in telecommunication networks. Then we shall illustrate this on typical optimization problems.

Before using an optimization method, a criterion function has to be defined along with different constraint conditions to be used. However, it is not always possible to solve a problem within framework of an optimization process ([1]). In some cases, certain subproblems, in which specific aspects are solved, are needed. Then overall optimizations are performed to get the final solution of the problems. In cases where the problems can not be formulated mathematically, it is impossible to use an optimization method to solve the problem.

There are many documents and study works on the subjects related in telecommunication network using the optimization techniques as the fundamental tools to achieve a satisfied solution. However, the use of optimization tools with the aim at finding out the optimal solution for the problems has not unified from document to document and has yet been systematized into the classes of typical problems.

By studying a series documents using optimization tool, we have found that the scope of applying of optimal problems are very various. There exist many different types of optimization problems in telecommunication network. They differ in many respects, depend on the problems as well as the QoS requirements. Linear and integer programming are the most well known optimization approaches and are widely used. These solution approaches are the main optimization techniques used throughout series of documents.

Costs in terms of currency units are the objective criterion which is used most, but not necessarily the best. In some situations, a tradeoff between two contradictory goals is sought. This might be the case if the designer looks for obtaining good QoS for a reasonable amount of money and there are a restrictive hard constraint on the amount of money to spend or on the QoS which has to be guaranteed. Obviously, minimizing costs while maximizing QoS is contradictory.

The rest of this paper is organized as follows. Section 2 introduces a brief classification of optimization problems in telecommunication networks. To illustrate this, in Section 3, some typical exames are showed. Finally, Secsion 4 will conclude the problem.

2. CLASSIFICATION OF OPTIMIZATION PROBLEMS IN TELECOMMUNICATION NETWORKS

In general, optimization problems in telecommunication networks are very specified ones. However, there exists several methods for categorizing them.

From the network management point of view, the optimization problems can be divided into optimal investment ([9]), optimal expense in operation and maintenance ([7]), optimal expense in expansion and development the networks ([1]).

According to characteristics of network optimization problems can be classified into groups of fixed-network ([1]), mobile network ([5]); wired network ([1]) or wireless network ([5]).

In term of services which are supported, the problems can be divided into single service network group ([8]), multiple service network group ([3,8]).

From the mathematical viewpoint, the optimization problems can be divided into linear programming ([4]), integer programming ([10]), multi-objective programming ([11]) or exact methods and heuristic ones.

- In this article, we introduce a classification method on basics of subjects to be achieved, which are:
- The first class includes optimal topology network designing problems based on available forecasts ([1,7,10,12]).
- The second class solving the requirements of optimal allocating and accessing into network resource for every customers with the constraints of quality of service ([2,3,4,5,8,9]).
- The last class relates to the network survivable problems and self-healing capablities in face of both network component failures and unexpected traffic partern [7].

Althought they are classified into separate categories for simplicity and similarity in studying, the problems in these categories are highly inter-related with each other and involve in quality of services characteristic of system.

As a nice result, the classification of problems above-mentioned is also the classification according to categories of problems. In each class, because of having the same goal, the objective function and the constraints of problem often have similar forms. Consequently, problems in each class is often solved by some similar methods.

3. OPTIMIZATION PROBLEMS IN TELECOMMUNICATION NETWORKS

3.1. Optimization problems in designing telecommunication network

Telecommunication network designing is one of the most important problems in telecommunication, having a role of setting the foundation for managing, exploring and developing network afterward. The purpose of designing telecommunication network is building an optimal network structure, fulfilling traffic requirements and service providing.

Some network designer often choose some criteria that is, according to them, the most important. Someone specially concern about cost issue ([12]), someone concerns about performance ([7]), meanwhile some others concern about management ability of systems ([1]). Each above criterion has its own certain importance, depending on specific conditions and requirements.

In practice, it is often the case that already parts of a network or even a complete network does exist. In this case it is meaningful to ask how one can improve the old network by adding connections or increasing capacities rather than wasting the money already invested in the network. Network optimization design is usually to minimize the cost while satisfy requirement of traffic and system effectiveness (limit of delay and loss). The objective function is a weighted sum of costs. Constraints include the limit of traffic, bandwidth , number of node ([1]).

Consequently, the network optimal designing problem is often stated as a form of linear optimization problem (LP). One often use simplex method to solve the linear optimization problems with an ensuring of reaching to optinum after a reasonable time. Whenever there are integer conditions imposed on the problem, the LP becomes an Integer Linear Program (ILP). The decision whether a facility should be deployed or not is an example of such an integer condition in a model. Solvers for ILP problems are e.g. Branch and Bound or Branch and Cut ([1]). Techniques that combine heuristics with ILP are expected to produce very good results in network design but due to their complexity are limited to medium sized problems ([1]).

Although the real telecommunication networks are usually structured in too many layers, most design problems concern only a part of the overall network ([12]). The net work is modeled by a graph, which comprise a set of nodes (vertices) and a set of links (edges). The problens start with a geographical context for the nodes. We are given an existing (or possible) connected graph, in which each link has a distance or cost. The costs in this case do not necessarily correspond to geographical distances.

Several methods have already been applied to this problem, both exact ([1]) and heuristics ([8,10]). The typical and simplest optimal problem in topological design of telecommunication networks is stated as Constraint Minimum Spanning Tree (CMST) problems ([1]). CMST deals with finding a tree that spans all the nodes of the graph and minimizes the overall weight of the edges in the tree. This problem can be solved by several greedy algorithm such as Kruskal's algorithm, Prim's algorithm, Sharma's algorithm ([8]). Although these heuristics solve exprimental size problems, the performance deteriorates when problem size get larger. In this case, they prefer to use genetic algorithm ([13]). According to the simulation results which are presented in ([8,12,13]), we can say that for the small problem, heuristic is quick and successful, but for larger problem, genetic algorithm is more efficient.

The basic topological design problem - the Optimal Network Design Problem was widely studied in ([1,12]). Optimal Network Design Problems are able to be classified into two main classes of typical problems:

- Access network optimization.
- Backbone network optimization.

3.1.1. Access network optimization

Most excisting local access telecommunication networks (LATN) have a tree or star structure. Each customer node associates with a demand representing the required capacity of connection from that node to the switching center. This demand can be satisfied by either connecting the node through a cable along the unique path to the switching center, or routing it first to a concentrator which compress the incoming traffic into a higher frequency line. The objective of the LATN design problem is to make a trade-off between cable expansion and concentrator installation to minimize total cost.

Given a set $\mathcal{N}$ of terminals and a set $\mathcal{M}$ of concentrators. The cost of connecting terminal i to concentrator j is c_{ij}. The capacity of concentrator j is b_j. The terminal i has a demand of d_i. The optimal terminal assigment problem is to minimize the cost of connecting the terminals to the concentrators, subject to the capacity constraint:

$$\underset{x_{ij}}{\text{Minimize}}\ Z = \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{M}} c_{ij}x_{ij} \tag{1}$$

$$Subject \qquad to$$

$$\sum_{j\in\mathcal{M}} x_{ij} = 1, \quad i \in \mathcal{N} \tag{2}$$

$$\sum_{i\in\mathcal{N}} d_i x_{ij} \le b_j, \quad j \in \mathcal{M} \tag{3}$$

$$x_{ij} \in \{0,1\}, \quad d_i \ge 0, \quad c_{ij} > 0 \ \forall i \in \mathcal{N}, j \in \mathcal{M} \tag{4}$$

where x_{ij} is 1 if terminal i is assigned to concentrator j. The first constraint guarantees that each terminal is connected to a concentrator. The second one ensures that the capacity are not violated.

In case the locations and numbers of concentraters must be determined, let $\mathcal{M}$ is the possible locations for the concentrators. We denote by y_j the decision variable which equals 1 if a concentrator is installed at location $j \in \mathcal{M}$ and equals 0 othewises. Let e_j denotes the cost of placing and installing a concentrator at location j. These costs include the cost of establishing links which connect transit nodes to root. The formal statement of the uncapacitated concentrator location problem is:

$$\underset{x_{ij},y_j}{\text{Minimize}} \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{M}} c_{ij}x_{ij} + \sum_{j\in\mathcal{M}} e_j y_j \tag{5}$$

$$Subject \quad to$$

$$\sum_{j\in\mathcal{M}} x_{ij} = 1, \ \forall i \in \mathcal{N} \tag{6}$$

$$x_{ij} \le y_j, \ \forall i \in \mathcal{N}, \ \forall j \in \mathcal{M} \tag{7}$$

$$\sum_{i\in\mathcal{N}} d_i x_{ij} \le b_j y_j, \ \forall j \in \mathcal{M} \tag{8}$$

$$x_{ij} \in \{0,1\}, \ y_j \in \{0,1\}, \ \forall i \in \mathcal{N}, \ \forall j \in \mathcal{M} \tag{9}$$

Constraint (6) states that each terminal should be assigned to exactly one concentrator. Constraint (7) states that a terminal can be assigned to a concentrator only if this concentrator is installed. Constraint (8) ensures that there will be no capacitated violation in the network.

These two problems can in principle be solved using Tree Knapsack problem (TKP) as described in [1] and [13]. However, TKP does not guarantee the optimal solution for the problem. As mentioned, for small and medium problems, it is better to use exact or heuristic algorithms . For larger problem, genetic algorithm is more successful.

3.1.2. Backbone network optimization

The topologies of backbone networks may vary depend on the types of connections. It may be a star or a tree or a mesh. In general, in backbone networks there is no central unit and the concentrators are connected to each other forming a mesh.The content of backbone network optimization problem is that: For a given set of access nodes and the demands between each pair of access nodes, we find number and locations of the actually installed transit nodes, capacity of links connecting access nodes to transit nodes and capacity of links interconnecting transit nodes. This problem is known as Mesh Network Topology Optimization (MNTO).

The network consists of two disjoint sets of nodes: a set $\mathcal{V}$ of access nodes and a set $\mathcal{H}$ of transit nodes. The nodes are connected by undirected links. The links connecting access nodes to transit nodes are called access links, and transit links is the links that interconnect transit nodes. There are no links between the access nodes. Let $x_{ij} = 1$ if access node i is connected to the transit node at location j, otherwise $x_{ij} = 0$. Let $u_{jm} = 1$ if there is a link that connect transit node at location j to transit node at location m, and $u_{jm} = 0$ otherwise. The access nodes are given and cost nothing. A transit node can be provided or not. Let y_{jk} be decision variable which equals 1 if a transit node type k is installed at location j (and costs e_{jk}); equals 0 otherwise. Any transit or access link can also be provided or not. Denote by ca_{ij} the installation cost of access link that connects access node i to transit node j. Denote by ct_{jm} the installation cost per unit of capacity of transit link that connects transit node j to transit node m.

Let b_{jm} is the capacity of the link connecting the transit node at location j to the transit node at location m. The MNTO is stated as follows:

$$\underset{x_{ij}, y_{jk}}{\text{Minimize}} \sum_{i\in\mathcal{V}}\sum_{j\in\mathcal{H}} ca_{ij}x_{ij} + \sum_{j\in\mathcal{H}}\sum_{k\in\mathcal{K}} e_{jk}y_{jk} + \sum_{j\in\mathcal{H}}\sum_{m\in\mathcal{H},\, l>j} ct_{jm}b_{jm}u_{jm} \tag{10}$$

Subject to

$$\sum_{j\in\mathcal{H}} x_{ij} = 1,\ \forall i \in \mathcal{V} \tag{11}$$

$$\sum_{k\in\mathcal{K}} y_{jk} \leq 1,\ \forall j \in \mathcal{H} \tag{12}$$

$$\sum_{i\in\mathcal{V}} d_i x_{ij} \leq \sum_{k\in\mathcal{K}} y_{jk} \sum_{m\in\mathcal{H},\, i\neq j} b_{jm},\ \forall j \in \mathcal{H} \tag{13}$$

$$x_{ij} \in \{0,1\},\ y_{jk} \in \{0,1\},\ e_{jk} \in \{0,1\},\ u_{jm} \in \{0,1\},\ \forall i \in \mathcal{V},\ \forall j \in \mathcal{H},\ k \in \mathcal{K},\ m \in \mathcal{H} \tag{14}$$

Mesh topologies introduce the problem of routing traffic in the network. According to [1], this problem can be solved using MENTOR (Mesh Network Topological Optimization and Routing) and MENTOR II.

3.2. Optimal resource allocation problems

Telecommunication networks are designed and built in order to share resources. If interconnecting systems and bandwidths were available at no cost, then the solution to the problem would be to assign dedicated links (channels) of sufficient capacity to every pair of conceivable users to meet their needs. In fact, because of the limittation of network resources, the solution to the problem must be done more strictly.

Lots of research has been done on resource allocation problems. In [5], the resource reservation algorithms were studied. Though resource reservation can provide QoS, it is time consuming and can not optimally utilize the resources. Several research works concentrated on adaptive allocation of network resources ([6,9]), in which, resource can be dynamicaly renegotiated according to changes in the network.

Optimal resource allocation problems are concerned with the allocation of limitted resources among users so as to achieve the best overall performances of the system. This kind of problem can be repesented by a set of decision variables, the set of constraints to be satisfied and the approriate objective functions or, equivalently, the set of weighted goals.

In multimedia networks, the most common problem is how to allocate the limitation network's resources in order to maximize the network throughput. Consider a multimedia network that consist of a set $\mathcal{L}$ of links and a set $\mathcal{N}$ of nodes. There is also a set $\mathcal{K}$ of network's resources that the network allocates at each link in order to meet the QoS requirements. Services are distributed to users through a set $\mathcal{J}$ of connection types (routes), each of which is established on several links.

We denote by x_{ij}^{km} the amount of resources type k that is allocated at link m for connection j requested by node i. The maximum amount of resource type k that can be allocated on link m is denoded by $b_{km}^{\max}$. Let a_{jm} is the number of connections type j that is established on the links m. Denode by d_{ik} the demand of node i for the resource type k. Total demand on the network is $D = \sum_{i \in \mathcal{N}} \sum_{k \in \mathcal{K}} d_{ik}$.

Let $y_{ij} = f_{ij}(x_{ij}^{km})$ is the flow generated by node i on route j, thanks to the allocated resource x_{ij}^{km}. The objective of the optimization problem is to determine the amount and required resources for each type of service to maximize the total flows on the network. The problem is stated as follows:

$$\text{Maximize } \{f_{ij}(x_{ij}^{km})\} \tag{15}$$

$$\textit{Subject} \quad \textit{to}$$

$$\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{J}} a_{jl} x_{ij}^{km} \leq b_{km}^{\max}, \ \forall k \in \mathcal{K}, \ m \in \mathcal{L} \tag{16}$$

$$\sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{J}} y_{ij} = D \tag{17}$$

$$x_{ij}^{km} \geq 0, \ \forall i \in \mathcal{N}, \ \forall m \in \mathcal{L}, \ \forall k \in \mathcal{K}, \ \forall j \in \mathcal{J}$$

Constraint (16) guarantees that the allocated amount of resource type k not exceed the maximum amount. Constrant (17) guarantees that all demands are satisfied.

According to [8], objecctive functions is continuous, differentiable and strictly concave in x. So that the problem has a unique optimal solution. We can solve it using Lagrangean multiplier method.

In [14], they proposed an optimal bandwidth allocation problem for cellular networks, which aims to minimize the amount of resource used to provide a given QoS (defined by the maximum drop probability). This problem is formulated as a binary linear integer program and is solved by a computationally efficient algorithm based on the Lagrangean relaxation procedure.

One important aspect of resource allocation is routing. The goal of routing in telecommunication networks is to direct user traffics from source to destination in accordance with the traffic's service requirements and the network's service restrictions. Given a network consist of a set of nodes connected by a set of links. Routing is to find out a path connecting the source node to the destination node among a set of all possible such paths. The simplest method is to find out the shortest path in term of "length" assigned to each link. The most famous shortest path algorithms are the Dijkstra algorithm and the Bellman-Ford algorithm. However, in practice, the shortest path may not be the best path. We need to plan the whole network while allowing the possibility of multiple paths to a destination and considering all transmission requests in the network simultaneously. This approach is called the optimal routing. This approach generates optimal solutions for the whole network.

We focus on the problem of selecting path from the source to the destination. This path should be selected optimally to improve the efficiency of the network. Two most important measures of performance are the throughput and the delay. The throughput is related to the efficiency of the whole network and delay is related to the quality of each service. Several optimal routing procedure with QoS constraint are proposed in [1,15]. Usually, they optimize a cost function while sastifying only a subset of QoS requirements. In [16], the authors propose a routing technique that minimizes call bloking probability by minimizing the number of hops between the source and destination, while ensuring end-to-end delay (but without ensuring the requested delay). In [1], there is an another routing technique that minimizes the average total delay while satisfying only banhwidth requirements. In a network with given topology and given origin-destination node pairs (OD) with associated input traffic levels at a certain point of time, the question was to determine the optimal routing paths that yield minimum weighted total average delay. Assume that the capacity of each directed arc is given.

Let $\mathcal{W}$ is the set of all OD pairs and $\mathcal{A}$ is the set of all arcs in the network. A traffic request is described a random arrival of packets with given average data rate r_i, $i \in \mathcal{W}$. Assume that each traffic request is a Poisson arrival of packets with mean data rate r_i. Let c_l be the capacity of arc l. Let $\mathcal{P}_i$ be a set of all paths connected O-D pair i and $\mathcal{Q}_l$ be the set of all paths which contains arc l. Assume that $\mathcal{P}_i$ and $\mathcal{Q}_l$ are known for each $i \in \mathcal{W}$ and $l \in \mathcal{A}$. Let x_p be the traffic flow which is allocated to a path p. Then, the following equation should be satisfied:

$$\sum_{p \in \mathcal{P}_i} x_p = r_i, \ \forall i \in \mathcal{W} \tag{18}$$

Also, a traffic flow cannot be negative. Hence,

$$x_p \geq 0, \ \forall p \in \mathcal{P}_i, \ i \in \mathcal{P} \tag{19}$$

The flow of an arc a is $f_l = \sum_{p \in \mathcal{Q}_l} x_p$. Also, the flow through an arc l should be less than or equal to the capacity of the link. Hence the capacity constraint is $f_l \leq c_l, \ \forall l \in \mathcal{A}$, or

$$\sum_{p \in \mathcal{Q}_l} x_p \leq c_l, \ l \in \mathcal{A}. \tag{20}$$

The objective function is

$$\text{Minimize } D(x) = \sum_{l \in \mathcal{A}} D_l(f_l) \tag{21}$$

where $D_l(f_l) = \dfrac{f_l}{c_l - f_l} + d_l f_l$ is the average delay of flow f_l on arc l. Note that d_l is the propagated delay on arc l.

This function has rich interpretation since it has been derived from the theoretical queuing theory. The first property is that this is a differentiable function. So we can use derivatives in describing its optimal properties and developing its algorithms.

3.3. Optimization approach to servivability and realiability of network

Network reliability and servivability mean that in case of a link or node failure network resources still remain for the incurred demand.

Several researchers have previously examined the network restoration problem using different models and assumptions. [1] propose a linear programming based scheme for solving the line restoration problem. The linear programming model is derived from the cutsets of the remaining networks after each possible span failure. The objective function is the sum of the spare capacity on all links. It is minimized subject to a system of constraints in terms of cutset flows through the spares of the network with respect to the working capacity (or service capacity) on each link.

The problem is to find out a spare capacity assignment solution in order to ensure network's capability of self-healing from failures. Given point-to-point traffic demands and a cost/capacity function for each link, we wish to find the minimum cost capacity satisfying the given demands and the survivability requirements. Capacity and flow assignments are jointly optimized. For link failures, only the interrupted traffic is rerouted between its extremities (end-to-end rerouting).

Consider a directed graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$ where $\mathcal{N}$ and $\mathcal{L}$ are the node set and the link set of the network. For each unit of spare capacity on link $j \in \mathcal{L}$, we have to pay a cost c_j. Assume that the demands in the network generate a set $\mathcal{D}$ of traffic flows, with $\mathcal{D} \subset (\mathcal{N} \times \mathcal{N})$. Each traffic flow $i \in \mathcal{D}$ needs a capacity of b_i. The traffic flows in the network are satisfied by a set $\mathcal{P}$ of paths.

To prevent from any link failures causing disjunction of traffic flow i, we establish a set $\mathcal{Q}_i$ of paths which denote a candidate set of loop-free backup paths. $\mathcal{Q}_i$ is precalculated from the network topology and the working paths selected. It is represented by a matrix (a_{ijm}) where $a_{ijm} = 1$ if path $m \in \mathcal{Q}_i$ uses link j for affected flow i. Denote by $\mathcal{E}_k$ the set of traffic flows affected upon the failure of link k. $\mathcal{E}_k$ is easily determined from the set of working path traffic using link k.

Let x_{im} be a binary variable which equal one when path m in $\mathcal{Q}_i$ is used to protect the working traffic of flow i. Let y_j denote the required spare capacity unit on link j to protect against any single link failure.

The optimal problem is stated as follows:

$$\underset{x_{im},\, y_j}{\text{Minimize}} \sum_{j \in \mathcal{L}} c_j y_j \tag{22}$$

$$\textit{Subject} \quad \textit{to}$$

$$\sum_{m \in \mathcal{Q}_i} x_{im} = 1, \ \forall i \in \mathcal{D} \tag{23}$$

$$y_j \geq \sum_{i \in \mathcal{E}_k} (b_i \sum_{m \in \mathcal{Q}_i} a_{ijm} x_{im}), \ \forall j, k \in \mathcal{L}, \ j \neq k \tag{24}$$

$$y_j = \text{integer}, \ x_{im} \in \{0, 1\}$$

The objective function is to minimize the total cost of spare capacity in the network. Constrant (23) guarantees that there is only one link disjoint backup path selected for each flow for each failure case. Constraint (24) determines the total spare capacity needed on each link.

4. CONCLUSION

Optimization techniques are becoming valuable tools for solving problems in telecommunication networks. Use of optimization techniques forces the researcher to formulate the problem mathematically. There are many examples in applications of optimization methods in telecommunication networks. As each optimization method has different properties suited for different type of problems, there is no simple answer to which method to classify them into typical class. However, a brief classification above-mentioned might be the best choice.

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Receied April 15, 2003