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Telecommunication Network Optimization : Current Status and Challenges

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통신망 최적화 연구 동향

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This paper gives reviews on current research status in telecommunication network design. Two problems are identified as major research issues. One is the WDM network design problem, where traffic grooming, virtual topology design and routing and wavelength assignment problems are considered. The other is the OSPF weight setting problem which was proposed as a practical method to implement traffic engineering capability in IP networks. After presenting surveys on those problems, we discuss potential challenging research issues in telecommunication network design.

Keywords: Telecommunication Network, Optimization, Operations Research

1. Introduction

Telecommunication network optimization has been one of the major research issues in Operations Research community. In PSTN (Public Switched Telephone Network), the first widely-deployed public communication service network, many optimization techniques have been routinely used to determine the optimal link capacities and the routing strategies. Also from the early stages of wireless networks, cell planning and other related network design problems were usually formulated as optimization problems and have been studied extensively. Now optimization methods are considered as a viable tool in designing telecommunication networks and being used by many practitioners in this field.

The purpose of this paper is to give a brief summary on the current status of telecommunication network optimization and also to present new challenges. Though there are many important research issues in wireless networks, we limit the scope of this paper to wired networks. Also we will focus on network optimization problems. However, we want to mention that there are many dimensions in telecommunication industry which need contributions by OR community. For example, due to market saturation and severe competition, the customer relationship management is an important issue in many telecommunication companies. Customer churn analysis based on data mining techniques can be an area where OR plays a very important role.

Telecommunication network usually has a hierarchy for efficient network management and oper-

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ation. Roughly speaking, three layers can be identified in telecommunication network, that is, the physical layer, transport layer, and application layer. The physical layer consists of various transmission mediums such as optical fiber. The transport layer offers transport facility for higher layer services and is composed of various transmission equipments whose function is to multiplex and de-multiplex different speeds of signals. The application layer is the service network. In today's telecommunication environment, the most important application layer network is the Internet and almost all of the telecommunication services will be integrated to be offered on the Internet, giving rise to a broadband converged network (BcN).

In 1990s, the major research issue was to design the survivable transport network. At that time, the optical fibers was being widely installed to accommodate the increase in traffic volume. Due to their high capacity offered and expensive cost of installation, fiber networks should be designed in a resilient and cost-effective way. Survivable network topology design was a major issue in physical layer network which can be posed as a problem of finding the minimum cost 2-connected or 2-edge-connected network. Capacitated network design of various topology was also a major research issue where the objective is to design dependable transport network where the service should not be disrupted upon failures in some network elements. Large-scale integer programming techniques were used to solve the problems successfully.

Few research were done in the field of application layer network design. The major difference of the application layer networks compared to transport layer networks lies in the routing technology used. In Internet, routing is usually dynamic and is based on standard routing protocols such as OSPF (Open Shortest Path First) and IS-IS (Intermediate System to Intermediate System). When used with default setting, those routing protocols automatically determine the routes between any source and destination pair using link metrics calculated based on the installed capacity. Unlike transport layer where we can safely assume that the routes can be preconfigured in design stage, the routing and capacity design in Internet are dependent on each other so that it requires a different modeling and solution approaches. Since Internet will play as a unified network for integrated services, the cost-effective design of the network is certainly an important issue, which will be further clarified in later sections.

Horizontally, a telecommunication network viewed at the same layer, can be partitioned into various sub-networks. Roughly speaking, a network is composed of access network and backbone network where backbone network can be further partitioned to smaller component networks. Traffic volumes are concentrated before entering the backbone network. So the capacity requirement in the backbone network usually much higher than in the access network. Different criteria are chosen in designing access networks and backbone networks. In the case of access network, cost-effectiveness is the major design criteria and tree or ring topology is usually a choice of network topology. In backbone network, high level of flexibility is required for capacity expansion and fast reconfiguration, and so usually mesh topology is used. Different transport equipments are installed in each network. Combined with different topology and network equipments used, different network design models are used. In general, network design models can be classified according to the topology that result in star, tree, ring and mesh network design models.

Recently, most research effort is made to develop the cost-effective design methods for WDM (Wavelength Division Multiplexing) network which can be considered as an intermediate layer lying between physical and legacy transport layers. As mentioned earlier, few results were presented in designing Internet except some specific problems related to MPLS (Multi-Protocol Label Switching) technology which can also be viewed as an intermediate layer lying between transport and Internet layers. Hence the review on the current research issues is mainly focused on the WDM network design. After presenting other currently addressed research issues, we will present some new challenges in designing networks.

The structure of the paper is as follows. In section 2, we will give a summary on the WDM network design. Section 3 deals with OSPF weight setting problem. In section 4, we will present some research directions and challenges which we think important. Finally, section 5 gives concluding remarks.

2. WDM Network Design

WDM is a method to multiplex multiple wavelengths to a single fiber. It can be considered as an FDM (Frequency Division Multiplexing) applied to optical network. In WDM, the optical spectrum is partitioned into wavelength channels which can be viewed as virtual multiple fibers in a single physical fiber. For technical background on WDM network, see Ramaswami and Sivarajan (2002). Currently, commercially available optical fibers can support over a hundred wavelength with up to speed of 10 Gbps per each channel.

In this section, first we give some terminologies related to technical aspects of WDM networks. Then we will present a general WDM network design problem which contains many important models in WDM network design as subproblems. Then we will give a summary on current research activities and discuss some further research directions.

As in SDH/SONET networks, WDM equipments can be classified based on their switching capability. A point-to-point WDM equipment is the simplest one and its function is to multiplex or demultiplex multiple optical channels in a single fiber. Optical ADM (Add Drop Multiplexer) can bypass some optical channels in an incoming link to an outgoing link and also can terminate subset of incoming channels or add new channels to outgoing link. OADM is used to construct a WDM ring. In mesh network, optical cross-connect (OXC) is used to switch channels in multiple incoming fibers to multiple outgoing fibers.

WDM nodes are also classified based on the domain where switching occurs. When all switching takes place in optical domain, the node is called a *transparent* node. Otherwise, when switching is done only in electronic domain, the node is termed *opaque*. *Translucent* node lies in between transparent and opaque node where subset of channels can be switched in optical domain while others are switched in electronic domain. Similarly, a network is termed transparent, opaque or translucent according to the node types in the network. Some WDM nodes have channel copying capability so that they can support multicasting in optical domain. Wavelength converters are used to switch channels with different wavelengths. If wavelength conversion is not allowed, a light-path (which is a path in the physical network with an assigned wavelength in each fiber on the path) from a source node to a terminal node should have the same wavelength along the physical path.

2.1 The General WDM Network Design Problem

The general WDM network design problem can be stated as follows. Given a physical network, traffic demands and available set of wavelength, find set of light-paths installed with their routing and wavelength assignments and traffic routing over the light-paths which optimizes a given objective function. Note that the set of light-paths defines a virtual (logical) network on which the traffic demands are routed. To give a mathematical formulation of the problem, we need some notations presented in <Table 1>.

The above notations correspond to input to the problem. The graph G denotes the physical network where we assume the graph can have multiple links (multiple fibers) for a given pair of nodes. The decision variables are summarized in <Table 2> Note that the decision variables can be partitioned

Table 1. Notations

- $V = \{1, \cdots, M\}$: the set of nodes, where each node corresponds to the location where equipment is installed.
- $E = \{1, \cdots, N\}$: the set of directed links, where each link corresponds to a fiber cable in the physical network.
- $G = (V, E)$: the physical network
- $\delta^+(v), \delta^-(v), v \in V$: the set of outgoing/incoming links for a node v
- $\Lambda = \{1, codts, W\}$: the set of wavelengths available
- $K = \{(i, j) | i, j \in V\}$: the set of all ordered pairs of nodes in G
- $s_k, d_k, k \in K$: the source and destination of an ordered pair k, $k = (s_k, d_k)$
- $T = [t^k]_{k \in K}$: the traffic demand for ordered node pair k
- C : the capacity of a single channel (measured on the same scale as the traffic demands)

Table 2. Decision Variables

- $y_k \in Z_+,\ k \in K$: the number of light-paths in stalled for no de pair k
- $y_k^\lambda \in Z_+,\ k \in K,\ \lambda \in \Lambda$: the number of light-paths installed for node pair k with assigned wavelength λ
- $x_{ke}^\lambda \in \{0,1\}, k \in K,\ e \in E,\ \lambda \in \Lambda$: indicator variable whether a light-path for node pair k passes through a link e with assigned wavelength λ
- $f_k \in R_+,\ k \in K$: total amount of traffic carried on the logical link k
- $f_k^l INR_+,\ k,\ l \in K$: the amount of traffic of node pair l carried on the logical link k

into two sets, the first set (*x* and *y*) which defines the light-path routing and wavelength assignment in the physical network and the second set (*f*) which defines the traffic routing in the logical network formed by the light-path chosen.

Now we can formulate the general WDM network design problem and it is given in <Table 3>.

Table 3. Formulation of General WDM Network Design Problem

- Objective Function : Minimize one of the following functions

$$\sum_{k \in K} y_k \text{ : total number of the light-paths} \tag{1}$$

$$\sum_{k \in K} \sum_{l \in K} f_k^l - \sum_{k \in K} f_k^k \text{ : total amount of electronically switched traffic} \tag{2}$$

$$\max_{v \in V}\left(\max\left(\sum_{\{k \in K | s_k = v\}} y_k,\ \sum_{\{k \in K | d_k = v\}} y_k\right)\right) \tag{3}$$

- Constraints

Logical Network Configuration

$$\sum_{k \in K} x_{ke}^\lambda \le 1, \text{ for all } e \in E,\ \lambda\ \Lambda, \tag{4}$$

$$\sum_{e \in \delta^+(v)} x_{ke}^\lambda - \sum_{e \in \delta^-(v)} x_{ke}^\delta = 0,$$

$$\text{for all } v \in V \setminus \{s_k,\ d_k\},\ k \in K,\ \lambda \in \Lambda \tag{5a}$$

$$\sum_{e \in \delta^+(s_k)} x_{ke}^\lambda = y_k^\lambda, \text{ for all } k \in K,\ \lambda \in \Lambda \tag{5b}$$

$$\sum_{e \in \delta^-(d_k)} x_{ke}^\lambda = y_k^\lambda, \text{ for all } k \in K,\ \lambda \in \Lambda \tag{5c}$$

$$x_{ke}^\lambda = 0 \text{ for all } e \in \delta^-(s_k),\ e \in \delta^+(d_k),\ k \in K \tag{5d}$$

$$y_k = \sum_{\lambda \in \Lambda} y_k^\lambda \text{ for all } k \in K \tag{6}$$

Traffic Routing Constraints

$$f_k \le Cy_k \text{ for all } k \in K \tag{7}$$

$$f_k = \sum_{l \in K} f_k^l \text{ for all } k \in K \tag{8}$$

$$\sum_{\{k \in K | s_k = v\}} f_k^l - \sum_{\{k \in K | d_k = v\}} f_k^l = \begin{cases} 0, \text{ if } v \in V \setminus \{s_l,\ d_l\} \\ t^l, \text{ if } v = s_l \\ -t^l, \text{ if } v = d_l \end{cases}, \text{ for all } l \in K \tag{9}$$

The formulation given in <Table 3> is a simplified version of the one given in Dutta *et al*. (2002a). Note that the formulation is for explanatory purpose and is subject to further improvement. Specifically some of the variables can be eliminated in the formulation.

Though the formulation is mostly self-explanatory, some clarification is in order. First, consider the objective functions. Since each light-path requires transceivers at both end points, (1) attempts to minimize the cost of line terminating equipments (LTEs). Similarly, (2) attempts to minimize the amount of traffic which needs electronic switching (traffic which is neither terminated nor originated at the node), and so also attempts to minimize the cost of LTEs. The objective function (3) aims to design networks with equipments of similar capacities, which is important in practical design problems. These objective functions differ from those considered in many previous studies. The most commonly used objective function is related to the number of wavelengths. However, as Dutta *et al.* (2002b) pointed out, the cost of network components is more appropriate metric for WDM network design.

The constraint (4) tells that for each physical link, only one light-path of a given wavelength can be installed. The constraints (5a) to (5d) are wavelength continuity constraints which are needed since we assume no wavelength conversion in the formulation. The set of constraints are modified to prevent possible loops of light-paths. Note that the variables in (5d) should be eliminated before solving the model. The constraint (7) represents the total capacity offered by each logical link and (9) is the usual flow conservation equation for multi-commodity flows.

Note that the size of the formulation can be very large even for small sized networks. In ring network, the formulation can be greatly simplified and so most of the research was focused on the ring network and interconnected ring network (Dutta and Rouskas 2002b; Zhang and Qiao 1999; Gerstel *et al*., 2000; Colburn and Ling, 2003; Wan *et al*., 2000; Zhang and Qiao 2000; Berry and Modiano 2000). Few results can be found in the case of general mesh network. Almost all of the proposed methods are heuristic or meta-heuristic such as simulated annealing. In the literature, the problem presented above is called a “traffic grooming problem” since it explicitly considers multiplexing of low-speed traffics to high speed optical channels. A good survey on the traffic grooming problems (especially in the case of ring networks) can be found in Dutta *et al*. (2002) and Zhu and Mukherjee (2003).

Subproblems which can be obtained by decomposing the general WDM network design problem have been studied extensively. In particular, there can be identified three interesting subproblems, that is, the virtual topology design problem, the routing and wavelength assignment (RWA) problem and the traffic routing problem. In the following, we will consider each subproblem except the traffic routing problem which can be viewed as a well-known multi-commodity network flow problem.

2.2 Virtual Topology Design Problem

The virtual topology design problem is to find the set of light-paths installed in the physical network. The problem is similar to the traffic grooming problem presented above except that the capacity of the optical channel is assumed to be virtually unlimited. Also different objective function such as minimizing the maximum amount of traffic carried on a light-path (called congestion) is used. A comprehensive survey on this problem can be found in Dutta and Rouskas (2000). Recently, the virtual topology design problem was incorporated into the traffic grooming problem.

2.3 Routing and Wavelength Assignment Problem

In RWA, the set of light-paths are pre-specified and traffic demands are assumed to be comparable to the capacity of the optical channel. Hence in this problem, traffic routing is not considered explicitly. The output is the structure of the virtual network, that is, specification of routing and wavelength assignment for (the subset of) light-paths in the physical network. Also the objective function is either to maximize the number of light-paths installed (under the constraint of a given number of wavelengths) or to minimize the number of wavelengths needed (under the constraint that all the light-paths should be set up).

This problem is the most extensively studied problem in WDM network design. In the early stage of WDM network design, the wavelength was considered as a scarce resource and it was a major source of capital investment, though, now it is generally accepted that the cost of LTEs is more substantial.

Good surveys on this problem can be found in Dutta and Rouskas (2002) and Zang *et al*. (2000). RWA in itself is a very hard problem and it was proved that even in the binary tree network case, the problem is NP-hard (Corteel *et al*., 2003). Note in the tree network, the problem reduces to the well-known node coloring problem in graph theory. There are some results on approximation algorithms with worst case performance guarantees in specially structured networks, for instance, see Wolfgang and Winkler (1998).

Recent surveys can be found in Jaumard *et al*. (2004) where they gave comprehensive analysis of different IP formulations previously proposed by various researchers. Also surveys on simple greedy heuristic and meta-heuristic approaches can be found there. Two types of formulations were proposed for RWA problem, the first one using flow variables (Krishnaswamy and Sivarajan 2001; Ozdaglar and Bertsekas 2003) and the second one using path variables (Lee *et al*., 2002; Tornatore *et al*., 2002; Saad and Luo 2002; Ramaswami and Sivarajan 1995; Lee *et al*., 2000). In general, the bounds of LP relaxations of both the flow-based formulation and the path-based formulation are the same. However, path-based formulation has some advantage in dealing with additional constraints on the light-paths such as hop limit. Exact solution approaches include column generation (Lee *et al*., 2000) and Lagrangian relaxation (Saad and Luo 2002).

When there are wavelength converters installed at all the nodes, the problem reduces to integer multi-commodity flow problem. Though the problem remains NP-hard in general network, it can be polynomially solvable in ring networks, see (Myung 2001; Wang 2005). Some studies showed that even with very limited wavelength conversion, the traffic-carrying capacity of the network improves greatly, see Ramaswami and Sasaki (1998). Also if multiple fibers are used (called multi-fiber networks), the results in Li and Simha (2001) showed that considerable degree of improvement can be achieved.

2.4 Dynamic Demands

The problems considered so far assumes static traffic demands. When connection request arrives dynamically, the light-paths should be dynamically set up and torn down. In this case, the appropriate measure of network performance will be the connection blocking probability. Thiagarajan and Somani (2001) addressed the problem of fairness and showed that high speed connections will have higher blocking probabilities compared to low speed connections. They proposed a connection admission control (CAC) to resolve the problem.

Another line of research in dynamic demand case models the traffic as a set of traffic matrices where each traffic matrix can be considered as a particular traffic pattern in for example, a day or an hour. The traffic grooming problem in this case was studied by Zhu and Mukherjee (2002), where they presented an IP formulation and two heuristic algorithms. Different approaches were considered by Berry and Modiano (2000). Instead of a set of predefined traffic patterns, they introduced new concept called "t-allowable" traffic matrix model which can be considered a set of traffic matrices with specific properties. Similar approach was used in Gerstel *et al*. (2000).

2.5 Multicast Traffic

Multicast traffic is defined by a traffic among single source and several destination nodes. Video conference and IP TV are primary examples of multicast applications. In WDM network, multicasting can be realized by setting up so-called "light-trees" which can be considered as a generalization of the light-paths to the case of point-to-multipoint communication.

Traffic grooming and RWA problems have been studied to support multicast traffic in WDM networks. For a survey on multicasting in WDM networks, see Zhou and Poo (2005). Singhal and Mukherjee (2001) presented an IP formulation for multicast traffic grooming problems in WDM mesh networks. Similar to unicast RWA problems, multicast RWA in ring networks can be handled in a much simpler way. Jia *et al*. (2002) and Din (2005) presented heuristic methods where they decomposed the problem into two subproblems, that is, routing problem and wavelength assignment problem. Recently, Lee *et al*. (2007) proposed an optimization algorithm based on branch-and-price for multicast RWA problem in ring network.

2.6 Protection Design in WDM Networks

Ring networks have a built-in protection mechanism and so protection issues in them need not be considered separately. However, in mesh networks, protection design is an important issue. As is the case with SDH mesh network, there are two protection schemes; link-wise protection and path-wise protection. The protection can be dedicated or shared among multiple connections.

Lardies *et al*. (2001) studied various protection requirements (no protection, 1+1 protection, m:n protection, etc) and proposed an IP formulation and a simple heuristic method with an objective of minimizing network cost. Ou *et al*. (2004) studied the shared-path protection schemes more deeply and proposed an efficient heuristic method. However, protection design in WDM mesh networks still needs further research.

2.7 Summary and Discussion

WDM network design problem has attracted a great interest in network design community. Though several useful heuristic methods were proposed, the optimization methods for solving practically-sized problems still need further research. Since investment in WDM network deployment will increase steadily as the volume of Internet traffic grows, the optimization methods or methods which can guarantee near optimal solution will become much more important. So developing an efficient solution method for traffic grooming problems is one of the current challenging research issues.

However, the most important problem is to design integrated IP/WDM networks. Today's Internet routers can terminate optical signals and even some of the commercial products also support WDM functionalities. Hence Internet routers will be major LTEs in WDM network. For IP networks, lightpaths set up by WDM network are viewed as transport links. The problem is that IP network uses dynamic routing protocols such as OSPF and IS-IS for unicast traffic and PIM-SM (Protocol Independent Multicasting-Sparse Mode) for multicast traffic, whereas traffic routing in WDM network is usually assumed to be manually configurable. The mismatch between two routing schemes can result in inefficient network utilization. Cross-layer network design models and solution approaches will be a real challenge in IP/WDM network design in near future.

3. Metric Setting Problem for Internet Routing Protocol (OSPF Weight Setting Problem)

In large-scale Internet, usually two routing protocols are used to determine the routes for a given source-destination pair. One is the inter-domain routing protocol (called EGP, Exterior Gateway Protocol) which is used for Inter-AS (Autonomous System) routing. The other is the intra-AS routing protocol (called IGP, Interior Gateway Protocol) which is mainly responsible for determining routes in an AS. In most IP networks, BGP (Border Gateway Protocol) is the only choice for EGP, while either OSPF or IS-IS is used as IGP.

OSPF (and IS-IS) determines the shortest path between any pair of nodes by using the Dijkstra's algorithm. The metric (cost) on the link is preset when the link is firstly installed and never changes until externally configured if the link remains alive. Usual choice of the metric is inversely proportional to the capacity of the link. Thus if there is no failure in the network, the routing table in a router doesn't change even when some of the available links are congested while others are under-utilized.

Though simple and scalable, such a property of IGP can lead to inefficient use of network resources and can make it difficult to offer differentiated quality of service for premium services. To resolve the problem, traffic engineering (TE) has been extensively studied in IETF (Internet Engineering Task Forces). The essential feature of TE can offer the network operator a degree of freedom in controling the routing. However, to fully implement it, it requires both the change in routers and modification of routing protocols.

OSPF weight-setting problem was introduced as a practical alternative to provide TE functionality within a network without modifications in the installed network bases. The basic idea is to dynam-

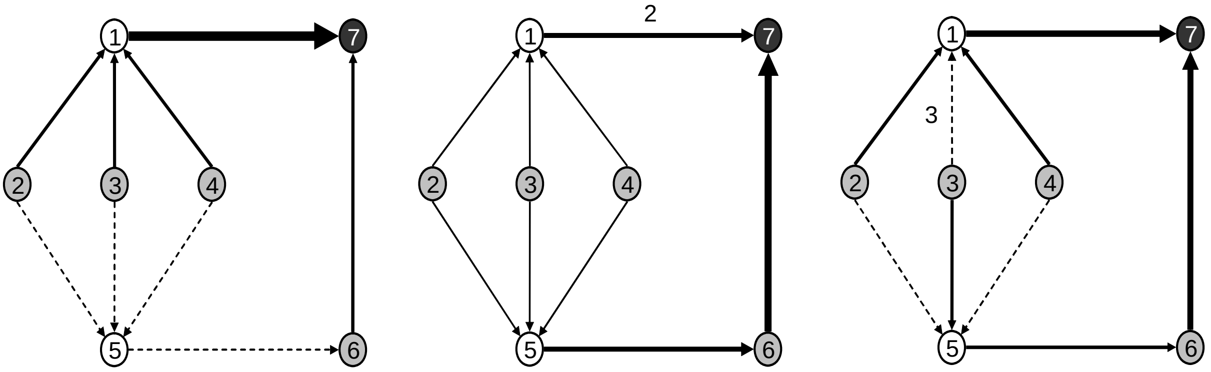

Figure 1. (Fortz *et al.*, 2002) Example of OSPF weight setting : Unit demand is given on the pairs (2,7), (3,7), (4,7), (6,7) only. Links with no numbers are of weight 1. The thickness of a link is proportional to the load on the link.

ically change the weights of the links according to the traffic load in the network. Though it seems to be very limited, the change in link weights can lead to efficient utilization of the network resources while still using the functionality of the legacy routing protocols and routers. The idea can be best explained by an example. The <Figure 1> (Fortz *et al*., 2002) shows how we can fully utilize the link capacities by changing the link metrics.

The general framework for applying dynamic weight setting is presented in Fortz *et al*. (2002). Since frequent changes in weights can lead to network instability, weight changes are usually made only when there is a considerable change of traffic patterns. The OSPF weight setting problem can be formulated as an MIP (Mixed Integer Programming) problem, see Pioro *et al*. (2002). The objective function is to minimize the maximum load of the links where the load of a link is defined as a utilization of the link capacity. Since only the shortest paths should be used for traffic flow between any pair of nodes, variables corresponding to the distance label per each node were introduced in the formulation. One can note that the node variable corresponds to the dual variable in the LP formulation of the shortest path problem. For formulation details, see Pioro *et al*. (2002).

Bley (2005) showed that we cannot find even a constant factor approximation scheme for the restricted version of the problem unless $P = NP$. Thus usually heuristic or meta-heuristic methods were studied to solve the problem. Pioro *et al*. (2002) presented solution methods based on local search, simulated annealing and Lagrangian relaxation. Erricsson *et al*. (2002) proposed a genetic algorithm and it was extended to a memetic algorithm by Buriel *et al*. (2002). Retvari and Cinkler (2004) presented an approximation algorithm based on LP relaxation.

Exact solution approaches were studied by Parmar *et al*. (2006). There they proposed some classes of valid inequalities which can be used to strengthen the LP relaxation and presented some computational experiments. However, the exact solution of the problem still seems to be very difficult. Since the problem should be solved in a real time, it would be more desirable to find an approximation algorithm with possible performance guarantees such as branch-and-bound methods with limited branching together with good primal heuristic.

4. New Challenges in Telecommunication Network Design

In the previous two sections, we considered two widely studied design problems in telecommunication networks. In this section, we present some potential future research directions.

Telecommunication industry is very dynamic in nature. Since the late 1990s, we have witnessed emergence of new services and rapid evolution of technologies in this area. Though it can be thought as a new opportunity, the technological innovation together with fast changes in market environment poses difficult challenges for the network service providers. Especially, almost all of the today's networks can be viewed as an Internet. The Internet is very flexible, scalable and distributed. However, due to the very nature of Internet itself, network operating companies are losing their control over the telecommunication industries. To survive in this difficult circumstances, many network companies are trying to develop new services and change their network infrastructure as flexible as possible in a cost-effective manner.

Despite of the rapid change in the telecommunication network environment, the current status of research in this field seems to be too slow. New problems occur very fast, but most research by OR community is still confined to somewhat old, well-defined problems. For instance, these days, many telecommunication companies in Korea are deploying networks which can offer IP TV services. To provide predictable quality for IP TV, it is necessary to limit the multicast traffic flow to a single path. The usual method of capacity expansion by installing additional links between two routers can be problematic in this case, since it can lead to traffic splitting. So new models for network capacity expansion need to be developed which also can reflect the dynamic nature of Internet multicasting protocol. We think that closer and more active relationship with the telecommunication companies are very needed and more effort should be made to find models and algorithms which can help them.

As noted previously, WDM network design has been a most actively studied research issue. However, the well-defined RWA problem doesn't seem to be very interesting for practitioners since these days the number of available wavelengths is very plenty. Rather, the traffic grooming and related problems are more qualified for practical research efforts. Though the models are very complex and hard to solve, they have more practical applicability. We think more effort is needed to develop models which capture the real problem characteristics and solution methods for them.

Though Internet is the most important network, there has been very few research effort in the design of IP networks. As previously mentioned, the nature of Internet routing makes it very difficult to develop a well-defined mathematical model for designing an IP network. The OSPF weight setting problem gives some insight in this respect. By clever modeling approach, it will be possible to develop a more tractable model for IP network design.

Cross-layer network optimization is another area which needs more research. Traditional models only consider specific layer, leading to an iterative optimization process to find the final network design. These days, many network equipments are optical-aware and the distinction between service switches and transmission facilities becomes more blurred. New technologies such as GMPLS (Generalized MPLS) will make it possible to directly transport application layer packets on the light channels. Hence cross layer optimization of IP/WDM network will be an important issue in near future.

Another research direction is to incorporate uncertainty in the network design models. As market conditions become more and more unpredictable, the best that can be done by a service provider is to estimate expected traffic with some dispersion measure. Stochastic programming can be very helpful in handling such problems. In particular, two-stage linear models for finite number of scenarios seem to be very useful in decision making for network capacity expansion. One of the advantages in applying the approach is that we can use previous results with some modifications when solving the problem. For instance, Guan *et al*. (2006) studied the stochastic uncapacitated lot sizing problem and proposed a branch-and-cut approach by extending previously studied results on lot sizing models. Similar approach can be applied to many network design problems. Robust optimization can be another possible approach to handle uncertainty. The approach proposed by Bertsimas and Sim (2004) provides a way to extend deterministic linear models to another linear models (of somewhat larger size) which can capture the uncertainty in many parameters.

5. Concluding Remarks

This paper presented a survey on the current research activities in telecommunication network design. Especially, WDM network design problem and OSPF weight setting problem were discussed in some detail. Then we presented some future research directions and issues.

Finally, we want to mention that there are many challenging problems in wireless network design. Especially, sensor network optimization will be a very important issue as USN (Universal Sensor Network) becomes popular. Also there are many potential research issues in other areas in telecommunication industry including CRM (Customer Relationship Management), customized service design and network security. In particular, telecommunication companies have huge amounts of data on their customers, originally collected for billing, which makes them ideal places to apply data mining techniques for service design, market analysis and others.

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