Design and Configuration of Reconfigurable ATM Networks with Unreliable Links

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This paper considers a problem of configuring both physical backbone and logical virtual path (VP) networks in a reconfigurable asynchronous transfer mode (ATM) network where links are subject to failures. The objective is to determine jointly the VP assignment, the capacity assignment of physical links and the bandwidth allocation of VPs, and the routing assignment of traffic demand at least cost. The network cost includes backbone link capacity expansion cost and penalty cost for not satisfying the maximum throughput of the traffic due to link failures or insufficient link capacities. The problem is formulated as a zero-one non-linear mixed integer programming problem, for which an effective solution procedure is developed by using a Lagrangean relaxation technique for finding a lower bound and a heuristic method exploited for improving the upper bound of any intermediate solution. The solution procedure is tested for its effectiveness with various numerical examples.

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I. INTRODUCTION

Broadband integrated services digital network (B-ISDN) has been intensively studied [4], [6], [10], [15]–[17], [19], [20], [23], and it is expected that it will dominate data networking activities in the future due to its capability to serve a wide variety of traffic such as video, voice and data. Among different transport techniques proposed to implement B-ISDN, ATM is considered to be the most promising one due to its efficiency and flexibility.

ATM is a switching and multiplexing technique developed for B-ISDN that makes it possible to achieve the multiplexing of different kinds of traffic while keeping individual quality of service required for each traffic type [13], [14], [22]. The International Telecommunications Union (ITU) standard for the ATM interface defines two types of connections: virtual channel (VC) connections and virtual path (VP) connections [14], [22]. The concept of a VC is similar to that of a virtual circuit in traditional networks, namely, a logical unidirectional association that defines a connection between an origin and its destination. To establish a VC, the source node sends a request that propagates through intermediate nodes to the destination requesting allocation of the required bandwidth. Because of the propagation delay (an important issue in this high speed era) and the processing delay at each node of the network, such a VC establishment may be too slow and unacceptable for real-time needs, particularly when connections are established on a per-burst basis. In ATM networks, VPs can solve such problems by providing a pre-defined route with a pre-defined bandwidth between an origin-destination (O-D) pair. A VP is commonly defined as a bundle of virtual channels delimited by two VP terminators. Multiple VCs, conveying different amounts of bandwidth each, may exist simultaneously within a VP between a given O-D pair. VCs are allowed to share the bandwidth pre-allocated to the VP which they belong to. The VP concept provides several advantages such as allowing simpler network architectures, eliminating the need for call-by-call routing and allowing easier implementation of dynamic bandwidth allocation schemes [5], [20], [21]. Each VP provides a logical link with a fixed bandwidth for a certain service for an O-D pair, and the VCs in the same VP are statistically multiplexed on that VP. For easy management and network control, VPs may be defined for dissimilar traffic types and can be deterministically multiplexed. The deterministic multiplexing of different VPs allocates a fixed bandwidth to each VP, which can use the resource as it has traffic to send. It is likely to result in requirements of more network capacity than any statistical multiplexing. However, dynamic bandwidth control and VP rearrangement can be provided by using the VP concept with a less complex admission control scheme. Thus, we consider here the deterministic multiplexing of various paths along with dynamic bandwidth control and VP reconfiguration.

Once a VP is set up with a specified bandwidth, the origin node must decide on each call request whether or not that call can be carried by the VP. In doing so, it is useful to refer to the term “equivalent capacity” (or equivalent bandwidth) which is the amount of bandwidth necessary to accommodate the aggregate traffic of a set of bursty sources while complying with a specific quality of service (QoS) [1], [2], [9]. The concept of the equivalent capacity will be discussed in detail in the later section.

An ATM network can be considered a reconfigurable network where effective topology and capacities can be adapted dynamically to changes in the traffic requirements or to changes in the physical network due to failures. Figure 1 shows the concept of a reconfigurable ATM network. There are six VPs, from VP_1 to VP_6, shown in the figure. VP_2 is a virtual path between nodes N_2 and N_4. Node N_1 is a transit node of VP_2. VP cross-connect systems located at the nodes provide the capability of concatenating VCs in the same VP. For example, a VP cross-connect system at node N_1 enables the concatenation of VCs in each of physical links (N_4, N_1) and (N_1, N_2) to form a logical link, VP_2, between node N_4 and N_2.

The idea of changing the topology and capacity of a network by setting up or releasing cross-connections was proposed in the early 70’s [24], [25]. Since then, the problem of configuring logical networks in such a reconfigurable network has been extensively studied in the past decade [26]–[34]. In those studies, it was assumed that the capacities of the backbone links were fixed. However, no attention was paid to the issue of trade-off between backbone link capacity expansion cost and inferior network performance penalty in a situation where the associated networks were subject to failures. Moreover, they have not

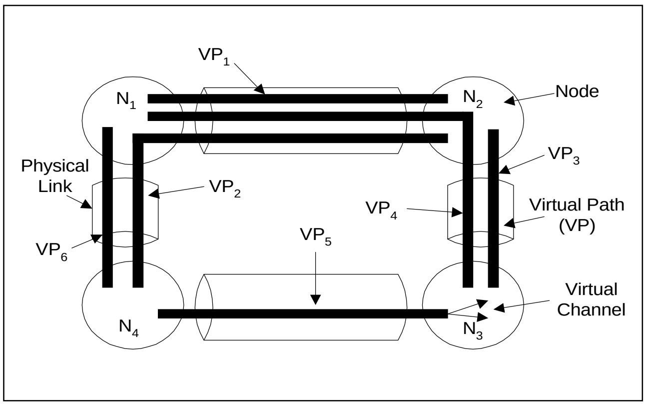

Fig. 1. A Reconfigurable ATM Network.

analytically treated the network reliability issue for any logical network design. This provides us with the motivation of considering a problem of configuring both backbone and logical networks in a reconfigurable network with link failures allowed.

Pazos-Rangel and Gerla [33] investigated a design problem of express pipe networks (logical packet networks) and formulated a nonlinear optimization problem for finding the best capacity and routing assignment. Due to the non-convexity of the associated objective function, their algorithm based on a steepest descent and flow deviation approach found only a local optimum. Gerla *et al.* [26] have addressed the topological reconfiguration issue of an ATM network embedded into a backbone network using digital cross-connect systems (DCSs). They formulated the problem as a nonlinear mixed integer programming problem to minimize a congestion measure based on the average packet delay, for which they applied the algorithm of the work [33]. Lee and Yee [30] formulated the configuration and routing problems for a logical network as a nonlinear mixed integer programming problem to minimize the average packet delay. In 1991, they extended the problem to convert the continuous solution to an integer solution by employing a partial branch and bound algorithm [31]. They also investigated a logical network configuration problem in the environment of ATM networks [32]. Ghosh and Mitra [27] considered the application of DCSs for packet switched networks in formulating a zero-one nonlinear integer programming problem to minimize overall network delay, and presented Lagrangean relaxation-based solution procedures for the problem. Sung and Park [34] addressed the problem of configuring the embedded networks of a telecommunication network carrying voice-grade calls at least cost. They formulated the problem as a mixed zero-one nonlinear programming approach for which lower bounds were found in a Lagrangean relaxation approach embedded in a hybrid search procedure for the associated dual problem. Gopal *et al.* [28], [29] formulated the problem of determining the capacities of the logical paths as a nonlinear integer programming to minimize the average call blocking probability under the assumption that the set of different paths for each node pair was predetermined and given as input. They developed a heuristic algorithm based on the greedy principle, but it was incapable of establishing any lower bounds on the solution.

For traditional networks having no configuration capability, there have been some research works incorporating reliability considerations in design procedure. For example, the subject of designing circuit-switching networks under reliability constraints was studied by Gavish *et al*. [35], where the problem of establishing node and link capacities to satisfy traffic demand under a failure-allowing environment was formulated as a mixed integer programming problem but only partially solved. Sanso *et al*. [36] considered a methodology to adjust link capacities in circuit-switched networks by taking into account both a routing policy and reliability theory. They formulated the problem by use of two subproblems, a routing subproblem and a link capacity adjustment subproblem, and developed a cyclic decomposition algorithm alternating between two subproblems. They extended the basic concept which considers reliability as a measure of network performance in the event of failures into the packet-switched network [43] and broadband ATM network [44]. The problem of finding a reliable routing in packet-switched networks has been investigated by Gavish and Neuman [37] under the assumption that more than one link could not fail at the same time. For this problem, Lagrangean relaxation and subgradient optimization techniques have been used to attain heuristic solutions.

Recently, Sung and Lee [38], [39] addressed the problem of configuring both backbone and logical networks in a reconfigurable circuit-switched network or packet-switched network where links are subject to failures. These problems were formulated as a zero-one non-linear mixed integer program, for which solution procedures were developed by use of Lagrangean relaxation techniques and heuristic methods exploited for improving the lower and upper bounds of any intermediate solution.

In this paper, we investigate the problem of configuring both backbone and logical VP networks in ATM networks with unreliable links. In this problem, two issues (reliability and economic trade-off issues) are explicitly incorporated. The network reliability issue, as well as the capacity expansion issue, is analytically treated to take into account routing and rerouting polices desired at each link failure occurrence. Moreover, this paper considers the issue of economic trade-off between backbone link capacity expansion cost and inferior network performance penalty in a situation where the associated networks are subject to failures. Incorporating these two issues, we investigate the problem of determining jointly the VP assignment, the capacity assignment of physical links and the bandwidth allocation of VPs, and the routing assignments of traffic demands to minimize the total network cost in a reconfigurable ATM network subject to link failures. Such link failures dynamically reflect the network operation conditions which are described by a set of network states each representing a subnetwork of the original network with every failed link excluded. This problem is an extension of the previous works for a reconfigurable circuit or packet-switched networks [38], [39].

The proposed problem is modeled as a zero-one nonlinear mixed integer programming problem in Section II. In Section III, a solution procedure is derived based on the Lagrangean relaxation method and a subgradient method. A heuristic procedure is developed for finding a better feasible solution of the problem. Computation experiments on test networks are presented in Section IV. This paper is summarized in Section V.

II. A NETWORK DESIGN MODEL

The ATM backbone network is represented by a graph $G_b = (N, B)$ where N is the set of nodes and B is the set of backbone links. The associated logical (VP) network is represented by a graph $G_\ell = (N, L)$ with the node set N and the set of logical links L. Both G_b and G_ℓ have the common node set N. A logical link and a VP will be used interchangeably as having the same meaning throughout this paper.

The backbone network is assumed to be subject to failures such that only link failures are considered, each link being in either failed or operating state, and these failures are independent of one another. It follows that the network with i links has 2^i possible states, so that for any real sized network it may not be practical to consider every possible state. In this paper, we consider a network state space $K = \{0, 1, 2, \ldots, e-1\}$, implying that K would consist of the e most probable states [36], [45]. Each network state $k \in K$ can then be characterized by use of the sets of $B(k)$ and its associated $L(k)$ representing the sets of available backbone links and logical links at network state k, respectively, where $B(k) \subset B$ and $L(k) \subset L$. All backbone links are initially assumed to be in the operating state (network state 0), i.e., $B = B(0)$ and $L = L(0)$.

A VP provides a logical direct link between VP terminators. Using VPs, an ATM network can be better managed by grouping VCs into bundles. Using VPs, flexibility in traffic management is possible due to separation of the logical transport network from the physical transmission network. In this paper, it is assumed that the VCs having similar traffic characteristics and QoS requirements are statistically multiplexed on a VP. This traffic will be referred to as a service class. Different VPs for each different service class are deterministically multiplexed on a physical link. Note that more than one service class may be preferable between an O-D pair for traffic having significantly different traffic characteristics and requirements.

To state the problem more precisely, the following notation is introduced:

W set of communicating O-D pairs,

S set of service classes,

q_w^s stimated bandwidth requirement for the offered traffic in Erlangs for service class $s \in S$ and O-D pair $w \in W$ (we will discuss later how the quantity q_w^s can be estimated),

a_w^s minimum acceptable amount of bandwidth to be carried for traffic type $s \in S$ and O-D pair $w \in W$ (obtained simply by adding the average rate of each source for $s \in S$ and O-D pair $w \in W$),

$P(k)$ set of all possible VPs at network state $k \in K$,

$P_w^s(k)$ set of VPs for service class $s \in S$ connecting O-D pair $w \in W$ at network state $k \in K$,

y_b cost of adding one unit of capacity to backbone link $b \in B$,

t penalty cost per unit of the ratio, [estimated bandwidth requirement - actual flow]/actual flow,

D_b capacity already allocated for backbone link b,

U_b capacity expansion limit for backbone link b (to be defined in Section III),

g fixed bandwidth capacity of a transmission path (e.g., 155 Mbits/sec),

$\delta_{pb}(k)$ $\begin{cases} 1 & \text{if backbone link } b \text{ is on VP } p \in P(k) \\ 0 & \text{otherwise,} \end{cases}$

$\Pr(k)$ state probability at network state $k \in K$ (i.e., $\Pr(0) \ge \Pr(1) \ge \cdots \ge \Pr(e-1)$ in the case of $|K| = e$).

The decision variables are also introduced as

n_b number of transmission paths in backbone link $b \in B$,

$F_p^s(k)$ flow amount on VP p chosen to carry the service class $s \in S$ of its associated O-D pair $w \in W$ at network state $k \in K$,

$X_p^s(k)$ $\begin{cases} 1 & \text{if VP } p \in P(k) \text{ is chosen to carry the service class } s \in S \text{ of its associated O-D pair } w \in W \text{ at network state } k \in K \\ 0 & \text{otherwise} \end{cases}$

The following model, to be referred to as Problem IP, can be used for multi-state, multi-service type network configuration of a dynamically reconfigurable ATM network. The problem is formulated as the following optimization problem.

Problem IP:

$$Z_{\text{IP}} = \text{Min} \sum_{b \in B} y_b (n_b - D_b) + t \sum_{k \in K} \Pr(k) \left[\sum_{w \in W} \sum_{s \in S} \left(\frac{q_w^s}{\sum_{p \in P_w^s(k)} F_p^s(k)} - 1 \right) \right] \quad (1)$$

subject to

$$\sum_{p \in P_w^s(k)} X_p^s(k) = 1, \quad \forall s \in S, \forall w \in W, \forall k \in K \quad (2)$$

$$X_p^s(k) \in \{0, 1\}, \quad \forall p \in P_w^s(k), \forall s \in S, \forall k \in K \quad (3)$$

$$F_p^s(k) \le q_w^s X_p^s(k), \quad \forall p \in P_w^s(k), \forall s \in S, \forall k \in K \quad (4)$$

$$\sum_{p \in P_w^s(k)} F_p^s(k) \ge a_w^s, \quad \forall s \in S, \forall w \in W, \forall k \in K \quad (5)$$

$$\sum_{w \in W} \sum_{s \in S} \sum_{p \in P_w^s(k)} \delta_{pb}(k) F_p^s(k) \le g n_b, \quad \forall b \in B(k), \forall k \in K \quad (6)$$

$$n_b \ge D_b \text{ and integer}, \quad \forall b \in B \quad (7)$$

$$F_p^s(k) \ge 0, \quad \forall p \in P_w^s(k), \forall s \in S, \forall w \in W, \forall k \in K \quad (8)$$

In Problem IP, the objective function (1) is to minimize the entire system cost composed of the cost of adding transmission paths to backbone link b and the penalty cost for not satisfying the maximum throughput of the traffic due to link failure or insufficient capacity. The first term in the objective function (1) is the capacity expansion cost of the physical links in the backbone network. We consider a public ATM backbone network as a major application field of this backbone network. In the public ATM backbone networks, optical links including optical interfaces with a fixed bandwidth (for example, OC-3, OC-12, or OC-48 etc.) are usually installed in the ATM switching system. OC-3 (155 Mbps) interface is most popular in the ATM backbone network. In this problem IP, y_b can be changed according to g (i.e., the unit capacity of the transmission path). In the mean time, the capacity of a VP p is a real value represented by $F_p^s(k)$. In the last term in the objective function (1), if the flow amount $\sum_{p \in P_w^s(k)} F_p^s(k)$ carrying the traffic for each service class s and O-D pair w at network state k equals the required flow q_w^s, then the penalty cost is not imposed. In this paper, we use the ratio of the estimated bandwidth requirement and the actual flow as a measure of network performance because this ratio increases as the actual flow decreases. Constraint sets (2) and (3) require only one VP for a service class and an O-D pair at each network state; in this problem, one out of several possible VPs is chosen. Constraint set (4) specifies that the bandwidth flow amount, $F_p^s(k)$, on a VP, if chosen, should not be more than the required flow q_w^s; otherwise, these constraints force the flow to be zero for the paths not chosen. Constraint set (5) requires that the total traffic flow should be no less than a minimum amount to satisfy pairwise minimum QoS parameters for each service class. Constraint set (6) is for the bound on link flow for all different traffic streams that use the link. It states that the total aggregate flow on VPs using a backbone link b must not exceed the capacity of the backbone link. Constraint set (7) expresses the condition that the capacity of backbone link $b \in B$ cannot be less than the capacity allocated already. If there are no pre-allocated links, then $D_b = 0$, for all b.

The objective function (1) can be simplified by eliminating the two terms, $\sum_{b \in B} y_b D_b$ and $t|W||S|\sum_{k \in K} \Pr(k)$, that do not intervene in the minimization. Note that $|W|$ stands for the number of O-D pairs and $|S|$ for the number of service-classes in the network. Therewith, Problem IP is re-formulated as

Problem P:

$$Z_{\mathrm{P}} = \mathrm{Min} \sum_{b \in B} y_b n_b + t \sum_{k \in K} \Pr(k) \left(\sum_{w \in W} \sum_{s \in S} \frac{q_w^s}{\sum_{p \in P_w^s(k)} F_p^s(k)} \right) \qquad (9)$$

subject to (2)–(8).

Then, the objective function value of Problem IP, Z_{IP} is calculated as $Z_{\mathrm{IP}} = Z_{\mathrm{P}} - \sum_{b \in B} y_b D_b - t|W||S|\sum_{k \in K} \Pr(k)$.

In the above Problem P, it is assumed that the bandwidth estimate q_w^s for service class s and different O-D pairs is available. For the purpose of the rest of the work here, we consider a service class to have homogeneous traffic with identical QoS requirements. It should be noted that although each conceivable traffic type can be a service class by itself, in practice this would generate too many classes to operate and manage the network. Classifying various traffic types under a single service class or putting them into different service classes is itself a complex problem [18]. We now discuss about how the quantity q_w^s can be estimated. As the first step to estimate q_w^s, the maximum number of connections to be allowed in the network satisfying the connection level grade of service (GoS) should be estimated.

To consider the connection level GoS (i.e., call blocking probability), we assume that requests for connection of service class s for O-D pair w arrive according to a Poisson process with rate λ_w^s, and the holding time is exponentially distributed with a parameter μ_w^s. Then, the offered traffic in Erlangs is $A_w^s \left(= \dfrac{\lambda_w^s}{\mu_w^s} \right)$ for O-D pair w. Given the GoS, B_s, we can use the inverse Erlang-blocking formula [12] $E^{-1}(A_w^s, B_s)$, to estimate the maximum number of VCs that need to be connected for this service class s, i.e., $N_w^s = N(A_w^s, B_s) = \lceil E^{-1}(A_w^s, B_s) \rceil$, where $\lceil x \rceil$ denotes the smallest integer bigger than or equal to x. This puts a limit on the maximum number of connections to be allowed.

On the other hand, if the traffic model for a service class s used in the formulation is characterized by an ON-OFF model, the traffic parameter in this case can be given by $\{R_s, \rho_s, m_s\}$, where R_s = peak bit rate, ρ_s = utilization, and m_s = mean of the burst period.

We now consider the problem of estimating the bandwidth requirement q_w^s of a VP for service classes for O-D pair w with buffer size r_w^s, to achieve a desired buffer overflow probability, ε_w^s, when N_w^s connections are multiplexed on this VP. This estimated bandwidth is called the equivalent capacity (or equivalent bandwidth) [1], [9] denoted by $q_w^s(N_w^s)$. Based on the fluid flow and the Gaussian approximation, Guerin *et al.* [9] propose an analytic form for q_w^s as follows :

$$q_w^s = \min\{N_w^s m_s + \alpha' \sigma, N_w^s \hat{c}_w^s\}, \qquad (10)$$

where $\sigma^2 = N_w^s m_s (R_s - m_s)$, $\alpha' = \sqrt{-2 \ln \varepsilon_w^s - \ln 2\pi}$,

$$\hat{c}_w^s = \frac{\alpha_w^s m_s (1-\rho_s) R_s - r_w^s}{2\alpha_w^s m_s (1-\rho_s)} + \frac{\sqrt{(\alpha_w^s m_s (1-\rho_s) R_s - r_w^s)^2 + 4 r_w^s \alpha_w^s m_s \rho_s (1-\rho_s) R_s}}{2\alpha_w^s m_s (1-\rho_s)},$$

and $\alpha_w^s = \ln\left(1 / \varepsilon_w^s \right)$ and $\hat{c}_w^s$ is the equivalent capacity associated with a single connection in isolation.

It should be noted that if a more detailed traffic descriptor than the on-off model suits some emerging service, then an appropriate bandwidth estimation procedure has to be used instead of the above procedure. This requires only a new module for bandwidth estimation for this emerging service without any change in Problem P.

III. SOLUTION APPROACHES

Problem P is a large-scale mixed integer program which is NP-hard. A problem with $|B| = 42$, $|W| = 65$, $|S| = 2$, $|K| = 15$, $|P_w^s(k)| = 20$, for example, involves approximately 78,000 variables and 82,000 constraints. Therefore, solving Problem P by using any commercially available integer programming software would be prohibitively time consuming. Thus, efficient solution algorithms are needed. We first develop a primal heuristic to find a good feasible solution to Problem P, and then relax a complicating constraint set in Problem P to construct a Lagrangean relaxation, and solve the Lagrangean dual of Problem P. By solving the Lagrangean dual we obtain a lower bound on the optimal value of Problem P.

In general, a Lagrangean relaxation is obtained by identifying from the primal problem a set of complicating constraints whose removal will make it easier to solve the primal problem. Each of the complicating constraints is multiplied by a multiplier and added to the objective function. This mechanism is referred to as that of dualizing the complicating constraints. As seen from the literature, the Lagrangean relaxation approach has been applied to obtain excellent heuristic solutions and tight lower bounds for various NP-hard problems such as the traveling salesman problem [40], the concentrator location problem [41], and a topological design problem in centralized computer networks [42].

We first need to add an artificial bound $U_b,\ b \in B$ on the variables n_b. This will be used later in solving the dual problem. In Problem P, constraint set (6) is complex because it couples the bandwidth flow variables $F_p^s(k)$ with the backbone link capacity variables. If constraint set (6) is relaxed and incorporated into the objective function with Lagrange multipliers, the resulting Lagrangean problem is derived as follows:

Problem L:

$$Z_{\mathrm{D}}(\alpha) = \mathrm{Min} \sum_{k \in B} y_b n_b + t \sum_{k \in K} \Pr(k) \left(\sum_{w \in W} \sum_{s \in S} \frac{q_w^s}{\sum_{p \in P_w^s(k)} F_p^s(k)} \right)$$
$$+ \sum_{k \in K} \sum_{b \in B(k)} \alpha_b(k) \left(g n_b - \sum_{w \in W} \sum_{s \in S} \sum_{p \in P_w^s(k)} \delta_{pb}(k) F_p^s(k) \right) \quad (11)$$

subject to (2)–(5) and (7)–(8), where α is a vector of Lagrange multipliers $\alpha_b(k),\ b \in B(k),\ k \in K.$

It is well known that the solution of Problem L provides a lower bound for the original problem, Problem P, if $\alpha \le 0$. The objective function can be rearranged as follows:

$$Z_{\mathrm{D}}(\alpha) = \mathrm{Min} \sum_{b \in B} \left(y_b + g \sum_{k \in \hat{K}_b} \alpha_b(k) \right) n_b$$
$$+ \sum_{k \in K} \sum_{w \in W} \sum_{s \in S} \left[t \Pr(k) \frac{q_w^s}{\sum_{p \in P_w^s(k)} F_p^s(k)} - \sum_{p \in P_w^s(k)} \left(\sum_{b \in B(k)} \alpha_b(k) \delta_{pb}(k) \right) F_p^s(k) \right] \quad (12)$$

where $\hat{K}_b (\subseteq K)$ denotes the set of network states at which the backbone link b is not failed.

The Lagrangean problem can now be written as

Problem D:

$$Z_{\mathrm{D}} = \max_{\alpha \le 0} \{ Z_{\mathrm{D}}(\alpha) \}$$

For a fixed value of the Lagrange multipliers, the objective function of $Z_{\mathrm{D}}(\alpha)$, (12), is decomposable in n_b and $F_p^s(k)$. This allows us to decompose the problem into two parts. The first set of subproblem is:

Subproblem L1:

$$Z_{\mathrm{D1}}(\alpha) = \mathrm{Min} \sum_{b \in B} \left(y_b + g \sum_{k \in \hat{K}_b} \alpha_b(k) \right) n_b \quad (13)$$

subject to (7) and $n_b \le U_b,\ \forall b \in B.$

This subproblem can be further decomposed according to each backbone link variable since it has only bounding constraints on the backbone link capacity variables, and thus the solution to Subproblem L1 can be easily obtained by setting:

$$n_b^* = \begin{cases} D_b & \text{if} \left(y_b + g \sum_{k \in \hat{K}_b} \alpha_b(k) \right) \ge 0 \\ U_b & \text{if} \left(y_b + g \sum_{k \in \hat{K}_b} \alpha_b(k) \right) < 0 \end{cases} \quad (14)$$

The second set of subproblem is:

Subproblem L2:

$$Z_{\mathrm{D2}}(\alpha) = \mathrm{Min} \sum_{k \in K} \sum_{w \in W} \sum_{s \in S} \left[t \Pr(k) \frac{q_w^s}{\sum_{p \in P_w^s(k)} F_p^s(k)} - \sum_{p \in P_w^s(k)} \left(\sum_{b \in B(k)} \alpha_b(k) \delta_{pb}(k) \right) F_p^s(k) \right] \quad (15)$$

subject to (2)–(5) and (8).

Subproblem L2 is further separable according to service class $s \in S$, each O-D pair and each network state. For each service class $s \in S$ and each O-D pair $w \in W$ at network state $k \in K$, the associated Subproblem L2(k, w, s) is then derived as

Subproblem L2(k, w, s):

$$Z_{\mathrm{D2}(k,w,s)}(\alpha) = \mathrm{Min}\left[t\,\Pr(k)\frac{q_w^s}{\sum_{p\in P_w^s(k)} F_p^s(k)} - \sum_{p\in P_w^s(k)}\left(\sum_{b\in B(k)}\alpha_b(k)\delta_{pb}(k)\right)F_p^s(k)\right] \quad (16)$$

subject to

$$\sum_{p\in P_w^s(k)} X_p^s(k) = 1, \quad (17)$$

$$X_p^s(k)\in\{0,1\}, \qquad \forall p\in P_w^s(k) \quad (18)$$

$$F_p^s(k) \le q_w^s X_p^s(k) \qquad \forall p\in P_w^s(k) \quad (19)$$

$$\sum_{p\in P_w^s(k)} F_p^s(k) \ge a_w^s \quad (20)$$

$$F_p^s(k) \ge 0 \qquad \forall p\in P_w^s(k) \quad (21)$$

The objective value of Subproblem L2 is obtained as $Z_{\mathrm{D2}}(\alpha) = \sum_{k\in K}\sum_{w\in W}\sum_{s\in S} Z_{\mathrm{D2}(k,w,s)}(\alpha)$.

To solve Subproblem L2(k, w, s), it is desired to find first a shortest path $p^* \in P_w^s(k)$ using the arc weight as $-\alpha_b(k)$, $\forall b\in B(k)$ (recall that $\alpha < 0$, so each arc weight is positive). Then, set $X_{p^*}^s(k) = 1$ and $X_p^s(k) = 0$ for $p\in P_w^s(k)$ and $p \ne p^*$. Such a path selection makes the problem simplified as that of determining a value $F_{p^*}^s(k)$ that minimizes a convex function over a simple bound as follows:

$$\min_{a_w^s \le F_{p^*}^s(k)\le q_w^s} t\,\Pr(k)\frac{q_w^s}{F_{p^*}^s(k)} - \sum_{b\in B(k)}\alpha_b(k)F_{p^*}^s(k)$$

This problem of finding $F_{p^*}^s(k)$ is a problem of minimizing a convex univariate function on a simple interval. Therefore, the solution to Subproblem L2 (k, w, s) can easily be found at

$$F_p^s(k) = \begin{cases} q_w^s, & \text{if } Q_w^s(k) > q_w^s \text{ and } p = p* \\ a_w^s, & \text{if } Q_w^s(k) < a_w^s \text{ and } p = p* \\ Q_w^s(k), & \text{if } a_w^s \le Q_w^s(k) \le q_w^s \text{ and } p = p* \\ 0, & \text{otherwise,} \end{cases}$$

where $Q_w^s(k) = \sqrt{\dfrac{t\,\Pr(k) q_w^s}{-\sum_{b\in B(k)}\alpha_b(k)\delta_{p^*b}}}$.

The best bound using the Lagrangean relaxation is derived by calculating Z_{D} which is the optimal objective function value of Problem D. The challenging issue in deriving bounds using Lagrangean relaxation is the computation of a good set of multipliers. In practice a good, but not necessarily optimal, set of multipliers is often located by using either a subgradient optimization method or various multiplier adjustment methods known as dual ascent methods [3]. Multiplier adjustment methods are heuristics for the dual problem which exploit the special structure of the dual problem in an application. Erlenkotter's algorithm [7] for the uncapacitated facility location problem is a highly successful example of the multiplier adjustment method. However, the subgradient method is easy to program and has performed robustly in a wide variety of applications [8].

In this study we use the subgradient optimization algorithm to derive bounds by using Problem L. The subgradient method is an adaptation of the gradient method in which subgradients replace gradients [11]. Given an initial multiplier vector α^0, a sequence of multipliers is generated by using the following rule :

$$\alpha_b^{i+1}(k) = \alpha_b^i(k) + t_i\left(gn_b^i - \sum_{w\in W}\sum_{s\in S}\sum_{p\in P_w^s(k)}\delta_{pb}^i(k)F_p^{si}(k)\right), \quad \forall b\in B(k), k\in K$$

where $n^i\left(=\{n_b^i\}\right)$ and $F^i\left(=\{F_p^{si}(k)\}\right)$ are the optimal solutions to Problem L with multiplier vector $\alpha^i\left(=\{\alpha_b^i(k)\}\right)$, and t_i is a positive scalar step size. It was shown that $\limsup Z_{\mathrm{D}}(\alpha^i)$ converges to $Z_{\mathrm{D}}(\alpha^*)$ if $t_i \to 0$ and $\sum_{i=0}^{\infty} t_i \to \infty$ [11]. Since in general these conditions are very difficult to satisfy, this method is always used as a heuristic. We use the following step size that has been frequently used in practice:

$$t_i = \frac{\zeta^i(\bar{Z}_{\mathrm{P}} - Z_{\mathrm{D}}(\alpha^i))}{\sum_{b\in B(k)}\left(gn_b^i - \sum_{w\in W}\sum_{s\in S}\sum_{p\in P_w^s(k)}\delta_{pb}^i(k)F_p^{si}(k)\right)^2},$$

where $\bar{Z}_{\mathrm{P}}$ is a feasible solution value of Problem P and ζ^i is a scalar satisfying $0 \le \zeta^i \le 2$. This scalar is set to 2 at the beginning of the algorithm and is halved whenever the bound does not improve in a specified number of consecutive iterations. The subgradient algorithm is terminated after a fixed number of iterations (500 in our case) or earlier if the gap between the dual (lower) bound and the best primal feasible solution value is within a user specified tolerance.

A heuristic solution procedure for Problem P is developed in conjunction with the Lagrangean relaxation presented in this section. This procedure attempts to generate a good feasible solution after every iteration of the subgradient optimization algorithm. The best solution is retained when the subgradient algorithm is terminated. The remainder of this section describes the heuristic solution procedure:

Step 1

Compute the left hand side of (6) in Section II using the values $\{F_p^s(k)\}$ derived from the solution to Subproblem L2 and set $\{n_b\}$ at their largest value. Thus,

$$n_b = \left\lceil \max_{k \in K} \left\{ \sum_{w \in W} \sum_{s \in S} \delta_{P^* b}(k) F_{p^*}^s(k) \right\} \right\rceil \text{ for each } b \in B,$$

where p^* is the path index associated with $X_{p^*}^s(k) = 1$.

Step 2

In each $k \in K$, compute $E_{\min}(s,w) = \min_{b \in B_w^s(k)} \{gn_b - \sum_{w \in W} \sum_{s \in S} \delta_{p^* b}(k) F_{p^*}^s(k)\}$ for each service class s and O-D pair w, where $B_w^s(k)$ is the set of backbone links selected to transmit the traffic of s and w. If $E_{\min}(s,w)$ is positive, then add $\min\{E_{\min}(s,w), q_w^s - F_{p^*}^s(k)\}$ to $F_{p^*}^s(k)$ respecting the condition $F_p^s(k) \le q_w^s$ from (4) in Section II. When the $\{n_b\}$ are fixed, the objective function can be decreased by increasing the flow $F_{p^*}^s(k)$ if possible. Because in Step 1, we set n_b at the largest value of the left hand side of (6) in Section II for each $b \in B$, we may have a chance to find a path satisfying $E_{\min}(s,w) > 0$ for some k.

Step 3

If a decrement in the penalty cost of the shortage throughput incurred by increasing the bandwidth flow $F_{p^*}^s(k)$, by $\min\{g, q_w^s - F_{p^*}^s(k)\}$ is greater than the increment in the capacity cost of the backbone links incurred due to the increase of n_b, then add min $\{g, q_w^s - F_{p^*}^s(k)\}$ to the bandwidth flow $F_{p^*}^s(k)$ and its associated backbone links. Return Step 2. If no service class and O-D pair have the total network cost decreased by increment of the bandwidth flow of any service class and O-D pair and its associated backbone links, then stop.

IV. COMPUTATIONAL RESULTS

We have a numerical example solved with our algorithm. An artificial backbone network with 4 nodes and 5 links is shown in Fig. 2. In this example, we consider two service classes: POTS-voice and NTSC-quality-video. POTS and NTSC are the abbreviations of Plain Old Telephone Service and National Television System Committee, respectively. The equivalent bandwidth calculated from the given traffic demand of each O-D pair is assumed as follows:

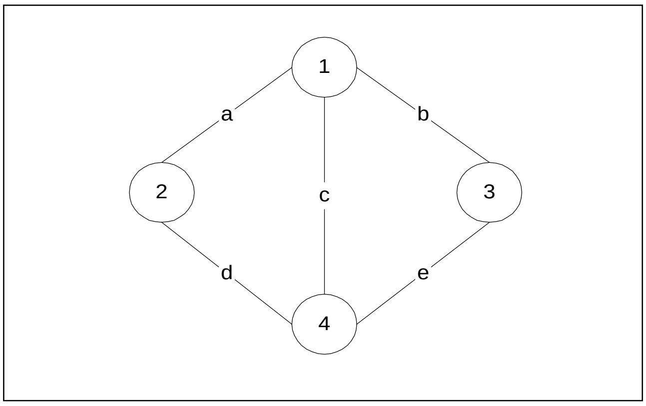

Fig. 2. 4-node backbone network.

Service Classes	O-D pairs	Equivalent Bandwidth
POTS	1 ↔ 4	40 Mbits/sec
	2 ↔ 3	40 Mbits/sec
	3 ↔ 4	40 Mbits/sec
NTSC-video	1 ↔ 3	100 Mbits/sec
	1 ↔ 4	100 Mbits/sec
	2 ↔ 4	100 Mbits/sec

For simplicity, we assumed that the VPs transmit the required traffic symmetrically for each O-D pair. It is also assumed that the most probable network states are $K = \{0, 1, 2\}$. The probability of network state 0 (all backbone links are in the operating state) is set to 0.95. Network states 1 and 2 mean that the links 'c' and 'a' are failed in the backbone network, respectively, and each of these network state probabilities is set to 0.02. In this example, the capacity expansion cost, the performance penalty cost, and the capacity unit of a backbone link are fixed at 20, 2,000, and 155 Mbit/sec, respectively. The backbone link capacities already allocated are 1 unit (155 Mbits/sec) for all links. For the given example problem, we obtained a solution in Fig. 3 through our algorithm.

Figure 3(a) shows the resulting backbone network, where each backbone link is labeled with its capacity expressed in the number of transmission paths. Figures 3(b)–3(d) show VP configurations for each network state 0, 1 and 2. In these figures, VPs to transmit POTS and NTSC-video service classes between the given O-D pairs are represented by solid arrow lines and dotted arrow lines, respectively. In this example, the total minimum cost of the problem P, Z_P, 12,000 and its lower bound is 11,983 so that the duality gap is 0.14 %.

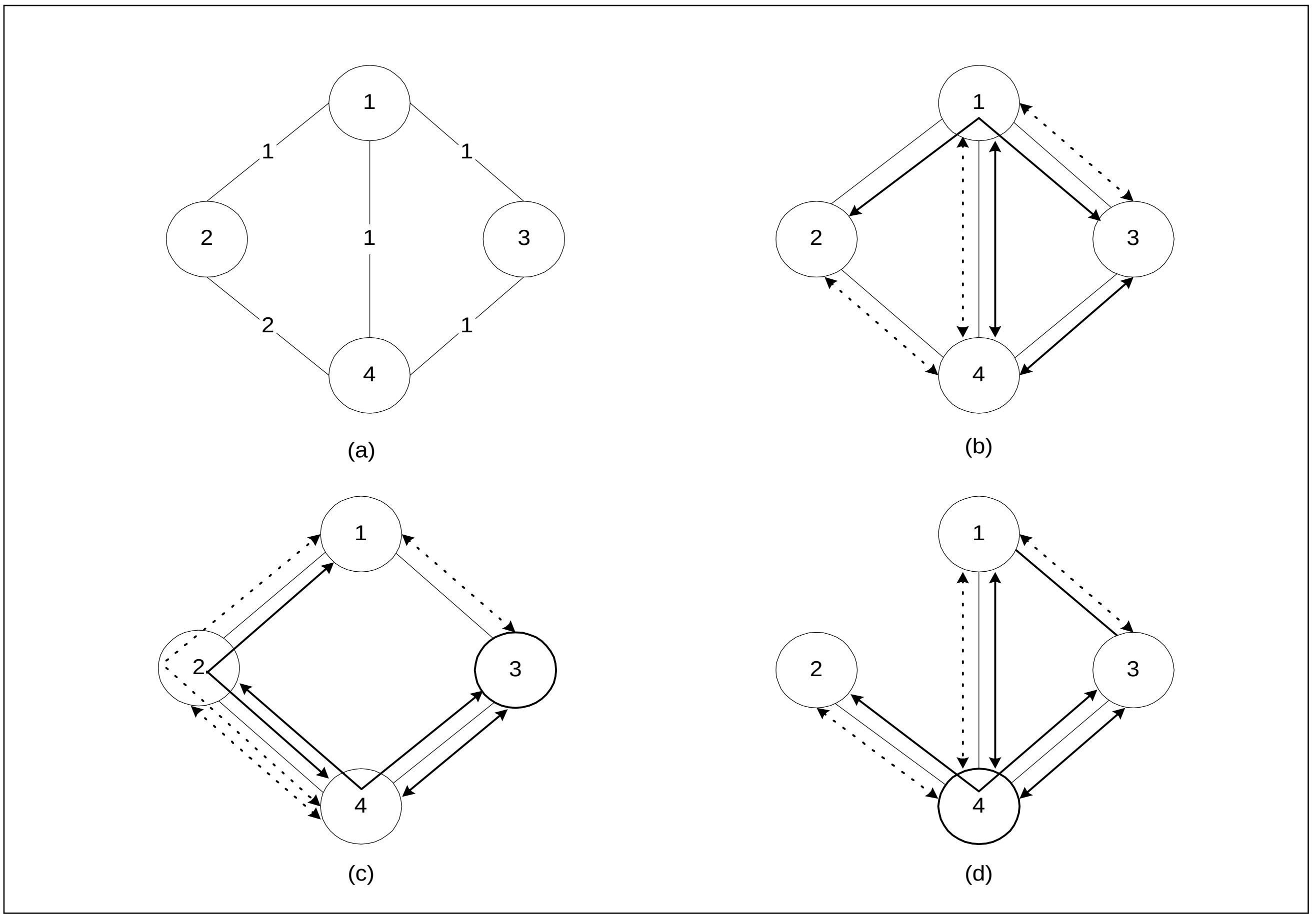

Fig. 3. Final backbone and VP networks: (a) backbone network; (b) VP network at state 0; (c) VP network at state 1; (d) VP network at state 2.

Table 1. Traffic parameters for service classes.

Traffic parameters	POTS-voice service class 1	NTSC-quality-video service class 2
peak rate: R_s (Mbits/sec)	0.064	45
utilization: ρ_s	0.6563	0.2
mean of burst period: m_s (sec)	0.352	0.029
buffer overflow probability: ε_w^s	10^{-4}	10^{-11}
buffer size: r_w^s (Mbits/sec)	1	1

Table 2. Topological Information for Networks.

Test Networks	Number of Nodes	Number of Backbone links	Number of O-D pairs
DCS-5	5	14	10
USA-DCS	10	28	45
TRANSPAC	12	42	65
TELENET	18	44	153

For our various computational tests, we use service classes, each with one homogeneous traffic type. Different on-off traffic descriptor values and QoS requirements of each class are given in Tables 1 and 7. These values are used in computing bandwidth requirement with (10) in Section II. The number of the connections of service-classes 1 and 2 is assumed to be fixed at 1,000 and 50, respectively. The proposed algorithm was tested for networks which were used in other works [15], [17]. Topological information for these networks is given in Table 2 and Figs. 4–7.

In all the cases, each undirected link represents two directed links oriented in opposite directions to each other. In these examples, the capacity expansion cost, y_b , and the capacity unit, g, of a backbone link are fixed at 20 and 150 Mbits/sec, respectively. The results of the computational experiments are summarized in Tables 3–6. The solutions generated by the algorithm are described in terms of the upper bound value of the objective function corresponding to the best feasible solution and the

Table 3. Computational results for different network conditions (DCS-5).

MLFT	# of States	Performance Penalty Cost	Lower Bound	Upper Bound	Gap (%)
30	3	2,000	41,397	41,610	0.51
		5,000	100,245	100,423	0.18
		10,000	198,274	198,452	0.09
		30,000	590,145	590,638	0.08
		50,000	981,918	982,700	0.08
50	5	2,000	41,386	41,684	0.72
		5,000	100,216	100,517	0.30
		10,000	198,180	198,530	0.18
		30,000	589,258	590,780	0.26
		50,000	979,903	980,880	0.10
100	7	2,000	41,615	41,946	0.79
		5,000	100,549	101,132	0.58
		10,000	198,254	198,744	0.25
		30,000	588,454	589,000	0.09
		50,000	978,535	979,340	0.08

Table 4. Computational results for different network conditions (USA-DCS).

MLFT	# of States	Performance Penalty Cost	Lower Bound	Upper Bound	Gap (%)
30	1	2,000	187,908	188,092	0.10
		5,000	445,177	445,510	0.07
		10,000	873,747	874,540	0.09
		30,000	2,588,573	2,590,920	0.09
		50,000	4,304,693	4,307,040	0.05
50	7	2,000	187,474	190,121	1.41
		5,000	446,524	448,545	0.45
		10,000	877,239	879,765	0.29
		30,000	2,594,689	2,598,518	0.15
		50,000	4,310,166	4,314,350	0.10
100	11	2,000	188,417	191,856	1.83
		5,000	447,087	452,515	1.21
		10,000	874,810	881,904	0.81
		30,000	2,584,273	2,591,590	0.28
		50,000	4,293,733	4,301,030	0.17

Table 5. Computational results for different network conditions (TRANSPAC).

MLFT	# of States	Performance Penalty Cost	Lower Bound	Upper Bound	Gap (%)
30	8	2,000	268,458	274,704	2.33
		5,000	642,275	646,113	0.60
		10,000	1,262,757	1,266,264	0.28
		30,000	3,740,561	3,744,927	0.12
		50,000	6,215,790	6,221,966	0.10
50	15	2,000	260,186	281,903	8.35
		5,000	637,375	662,124	3.88
		10,000	1,260,141	1,288,721	2.27
		30,000	3,748,094	3,777,250	0.78
		50,000	6,236,034	6,265,190	0.47
100	19	2,000	226,039	285,108	26.13
		5,000	598,757	662,432	10.63
		10,000	1,216,168	1,280,760	5.31
		30,000	3,685,648	3,750,240	1.75
		50,000	6,155,128	6,219,720	1.05

Table 6. Computational results for different network conditions (TELENET).

MLFT	# of States	Performance Penalty Cost	Lower Bound	Upper Bound	Gap (%)
30	8	2,000	657,122	680,849	3.61
		5,000	1,539,856	1,556,371	1.07
		10,000	3,002,198	3,015,194	0.43
		30,000	8,832,693	8,843,562	0.12
		50,000	14,653,209	14,668,366	0.10
50	15	2,000	633,822	697,572	10.06
		5,000	1,531,187	1,587,398	3.67
		10,000	2,996,695	3,060,457	2.13
		30,000	8,824,637	8,900,480	0.86
		50,000	14,650,877	14,726,720	0.52
100	20	2,000	557,719	718,329	28.80
		5,000	1,471,648	1,612,966	9.60
		10,000	2,929,906	3,082,365	5.20
		30,000	8,750,065	8,904,200	1.76
		50,000	14,570,185	14,724,320	1.06

lower bound value provided by the associated best Lagrangean value. The tolerance measures the duality gap between the upper and lower bounds, and is computed by (upper bound—lower bound) × 100/lower bound. In Tables 3–6, the number of the most probable network states are calculated by use of the mean link failure time (MLFT) to cover 95% of the network state probability. MLFT is the average link down time throughout one year in hours per year and can be translated into the link

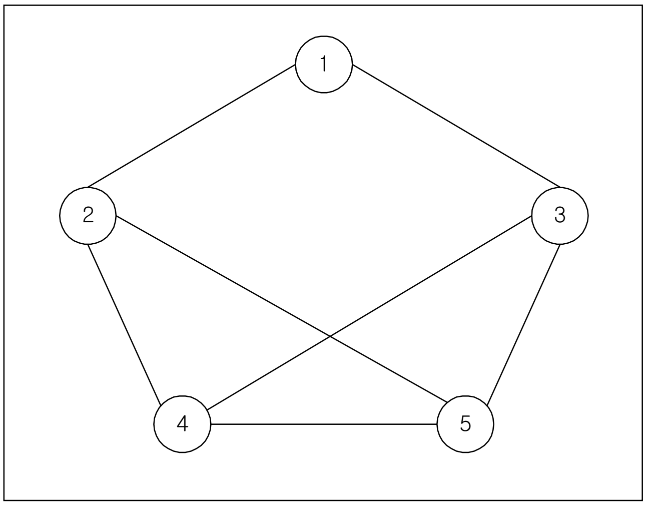

Fig. 4. Topology for the DCS-5 network.

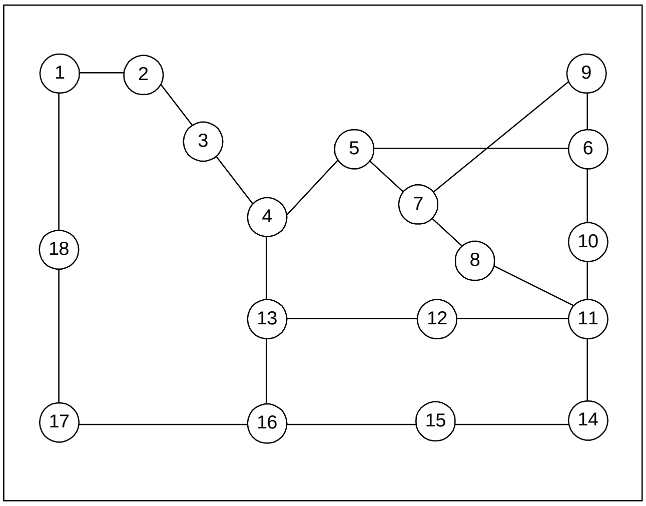

Fig. 6. Topology for the TELENET 1973.

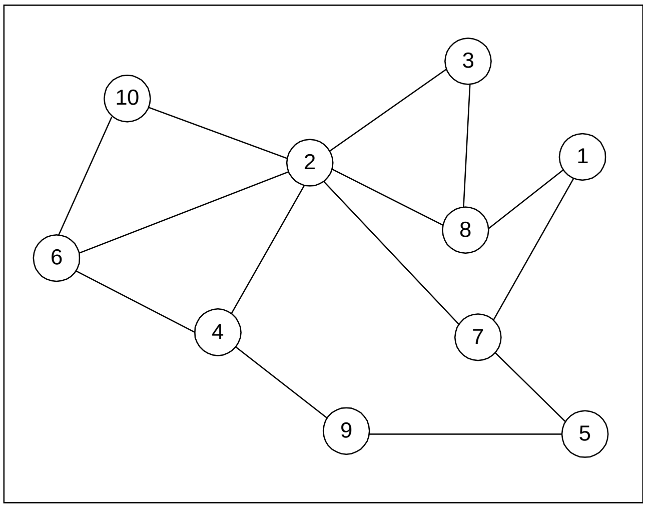

Fig. 5. Topology for the USA-DCS network.

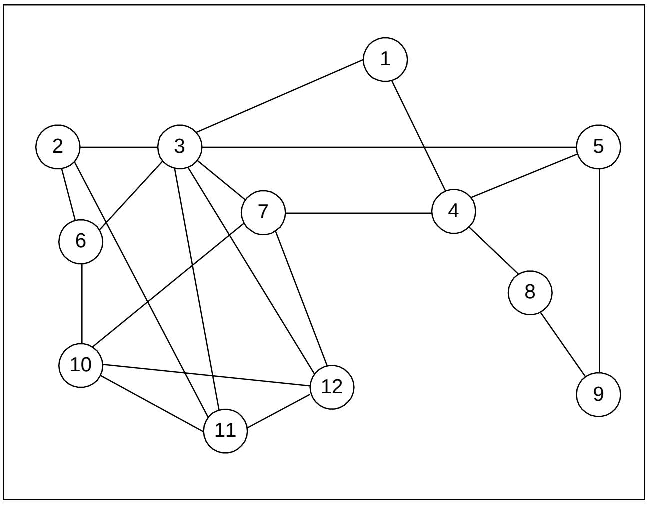

Fig. 7. Topology for the TRANSPAC network.

failure probability. Therefore, the number of network states is the smallest value κ that satisfies $\sum_{k=0}^{\kappa} \Pr(k) \geq 0.95.$ The penalty cost is occurred for not satisfying the maximum throughput of the traffic due to link failure or insufficient capacity.

The heuristic algorithm based on the Lagrangean relaxation appears to provide reasonable results in most cases as the tolerance is bounded by much less than 10 % for the objective function value for Problem P. The tolerance is also reduced mostly as the performance penalty cost increases and the number of network states decreases due to the reduction of the problem uncertainty. The Fig. 8 summarizes the results of Tables 3–6 and shows the impact of different network topologies and different network states on the duality gap. Table 8 shows the computational results for the varying number of service classes described in Tables 1 and 7. In Table 8, we can show that though the number of service classes is increased, the accuracy of the problem is maintained within a small gap percentage. Finally, Table 9 shows the comparison results of the varying case $(n_b \geq D_b)$ against the fixed case $(n_b = D_b)$ of the backbone

Table 7. Traffic parameters for additional service classes.

Traffic parameters	service class 3	service class 4	service class 5
peak rate: R_s (Mbits/sec)	10	0.5	20
utilization: ρ_s	0.4	0.8	0.1
mean of burst period: m_s (sec)	0.8	0.1	0.5
buffer overflow probability: ε_w^s	10^{-8}	10^{-6}	10^{-9}
buffer size: r_w^s (Mbits/sec)	2	0.5	1

Table 8. Computational results for varying number of service classes (USA-DCS Network, MLFT = 50 hours/year).

Performance Penalty Cost	# of Service Types	Lower Bound	Upper Bound	Gap (%)
2,000	1	231,414	233,812	1.03
	2	187,414	190,410	1.57
	3	287,376	292,271	1.67
	4	374,817	379,551	1.23
	5	467,683	473,405	1.21
5,000	1	231,414	233,812	1.03
	2	446,476	448,631	0.48
	3	676,421	680,683	0.63
	4	892,711	897,149	0.49
	5	1,115,218	1,120,798	0.50
10,000	1	447,660	450,208	0.57
	2	877,239	879,765	0.33
	3	1,323,216	1,328,044	0.36
	4	1,754,073	1,759,197	0.29
	5	2,191,873	2,198,359	0.30
30,000	1	1,307,136	1,311,284	0.32
	2	2,594,620	2,598,930	0.17
	3	3,899,810	3,906,824	0.18
	4	5,188,302	5,196,135	0.15
	5	6,484,003	6,493,114	0.14
50,000	1	2,164,957	2,168,955	0.18
	2	4,310,110	4,314,530	0.10
	3	6,473,092	6,480,565	0.12
	4	8,619,067	8,627,340	0.10
	5	10,772,788	10,783,535	0.10

link capacities in terms of the total cost representing the objective function value of the best feasible solution. Specifically, we found that, for the test problems, the total cost can be reduced by considering the expansion of the backbone link capacities in comparison with the fixed case.

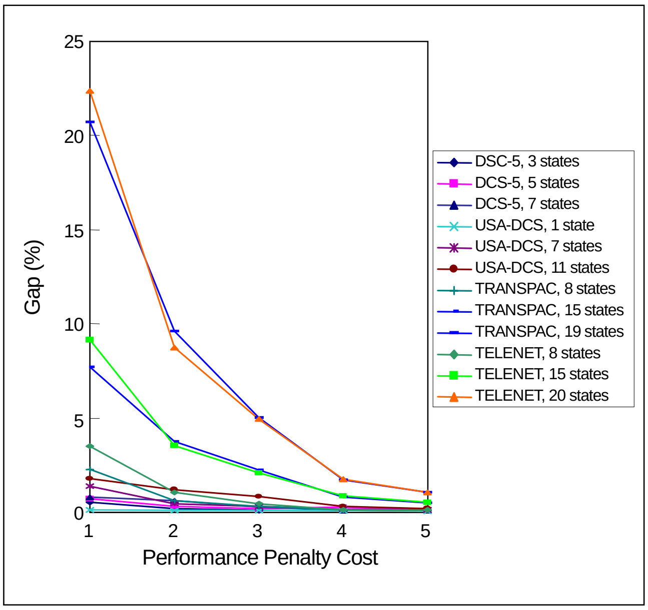

Fig. 8. Gap percentage variations over various network situations.

V. CONCLUSIONS

In this paper, we presented an approach for determining jointly the VP topology, the capacity assignment of physical backbone links and the bandwidth allocation of VPs and the routing assignments of traffic demand in a reconfigurable ATM network subject to link failures. A mixed integer programming model was developed to minimize the cost of adding capacities to backbone links and the penalty cost of the throughput shortage due to link failure or insufficient capacity. A Lagrangean relaxation of the model was developed to derive tight lower bounds on the optimal solution value, and then to develop a procedure for generating feasible solutions.

Table 9. Cost savings by backbone link capacity consideration (Network = USA-DCS with 10 nodes, D_b = 48, MLFT = 50 hours/year, y_b = 20).

Performance Penalty Cost (unit penalty cost *t*)	Best Cost when $n_b \geq D_b$			Best Cost when $n_b = D_b$			Saving Ratio (%)
	Backbone Link Cost	Penalty Cost	Total Cost	Backbone Link Cost	Penalty Cost	Total Cost	
10	13,440.0	1,137.8	14,577.8	13,440.0	1,152.7	14,592.7	0.1
100	14,400.0	9,773.4	24,173.4	13,440.0	13,075.6	26,515.6	8.8
1,000	17,220.0	87,284.1	104,504.1	13,440.0	109,008.0	122,448.0	14.7
2,000	17,300.0	172,665.2	189,965.2	13,440.0	250,948.7	264,388.7	28.1
5,000	17,600.0	431,089.0	448,689.0	13,440.0	645,248.3	658,688.3	31.9
10,000	18,960.0	860,643.5	879,603.5	13,440.0	1,290,253.6	1,303,693.6	32.5

The experimental results were reported. The solution procedure developed is found to be effective, with relatively small gaps between feasible solution values and lower bounds (generally within 10 %). Furthermore, it is shown that considering the backbone link capacities as decision variables can save significant network cost in comparison with the case where the backbone link capacities are fixed.

This work may be immediately extended to considering traffic demand uncertainty. Furthermore, it may be desirable to consider design and configuration of multichannel multihop lightwave networks. In facts, telecommunication networks using lightwave technology become very attractive because of the large bandwidth potential of the optical fiber. One of the promising architectures is the multihop lightwave network based on the Wavelength Division Multiplexing (WDM). Because of technical limitation on the number of transmitters and receivers at each node, it is not feasible to have any direct channel between every node pair. This implies that any information arrived at a node may reach its destination by a mechanism of hopping through a sequence of intermediate nodes. Separate channels created by assigning different wavelengths to various receiver-transmitter pairs define their respective logical connectivity. This logical topology is independent of the underlying physical topology and can be changed by a different wavelength assignment. The design of a reconfigurable lightwave network will appear as a practical issue in the near future, which is another interesting subject for further study.

REFERENCES

[1] H. Ahmadi and R. Guerin, "Bandwidth Allocation in High-Speed Networks Based on the Concept of Equivalent Capacity," *Proceedings of International Teletraffic Congress,* Vol. 13, 1991.

[2] D. Anick, D. Mitra, and M. M. Sondhi, "Stochastic Theory of a Data-Handling System with Multiple Sources," *The Bell Systems Technical Journal,* Vol. 61 No. 8, 1982, pp. 1871−1894.

[3] M. S. Bazaraa and J. J. Goode, "A Survey of Various Tactics for Generating Lagrangean Multipliers in the Context of Lagrangean Duality," *European J. of Oper. Res.,* Vol. 3. 1979, pp. 322−338.

[4] J. Burgin, "Broadband ISDN Resource Management," *Computer Networks and ISDN Systems,* Vol. 20, 1990, pp. 323−331.

[5] J. Burgin and D. Dorman, "Broadband ISDN Resource Management: The Role of Virtual Paths," *IEEE Communications Magazine,* Vol. 29, No. 9, 1991, pp. 44–48.

[6] *CCITT Recommendation I.121, Broadband Aspects of ISDN*, Melbourne, 1988.

[7] D. Erlenkotter, "A Dual Based Procedure for Uncapacitated Facility Location," *Operations Research,* Vol. 26, 1978, pp. 992−1009.

[8] M. L. Fisher, "The Lagrangean Relaxation Method for Solving Integer Programming Problems," *Management Science,* Vol. 27, 1981, pp. 1−18.

[9] R. Guerin, H. Ahmadi, and M. Naghshineh, "Equivalent Capacity and Its Application to Bandwidth Allocation in High-Speed Networks," *IEEE Journal on Selected Areas in Communications*, Vol. 9, No. 7, 1991, pp. 968–981.

[10] S. Gupta and K. W. Ross, "Routing in Virtual Path Based ATM Networks," *Proceedings of IEEE GLOBECOM '92,* 1992, pp. 571−575.

[11] M. Held, P. Wolfe, and H. Crowder, "Validation of Subgradient Optimization," *Mathematical Programming,* Vol. 6, 1974, pp. 62−88.

[12] D. L. Jagerman, "Methods in Traffic Calculations," *AT&T Bell Labs Technical Journal,* Vol. 63, No. 7, 1984, pp. 1283−1310.

[13] M. Kawarasaki and B. Jabbari, "B-ISDN Architecture and Protocol," *IEEE Journal on Selected Areas in Communications,* Vol. 9, No. 9, 1991, pp. 1405−1415.

[14] J. Le-Boudec, "The Asynchronous Transfer Mode: A Tutorial," *Computer Networks and ISDN Systems,* Vol. 24, No. 4, 1992, pp. 279–309.

[15] M. J. Lee and J. R. Yee, "A Design Algorithm for Reconfigurable ATM Networks," *Proceedings of IEEE INFOCOM '93,* 1993, pp. 144−151.

[16] M. Logothetis, S. Shioda, and G. Kokkinakis, "Optimal Virtual Path Bandwidth Management Assuring Network Reliability," *Proceedings of ICC '93,* 1993, pp. 30–36.

[17] D. Medhi, "Multi-Hour, Multi-Traffic Class Network Design for Virtual Path-based Dynamically Reconfigurable Wide-Area ATM Networks," *IEEE/ACM Transactions on Networking*, Vol. 3, No. 6, 1995, pp. 809–818.

[18] S. Monteiro, M. Gerla, and L. Fratta, "Statistical Multiplexing in ATM Networks," *Performance Evaluation,* Vol. 12, 1991, pp. 157−167.

[19] M. D. Prycker, "ATM Switching on Demand," *IEEE Network,* Vol. 6, No, 2, 1992, pp. 25–28.

[20] K. I. Sato, S. Ohta, and I. Tokizawa, "Broad-Band ATM Network Architecture Based on Virtual Paths," *IEEE Transactions on Communications,* Vol. 38, No. 8, 1990, pp. 1212−1222.

[21] Y. Sato and K. Sato, "Virtual Path and Link Capacity Design for ATM Networks," *IEEE Journal on Selected Areas in Communications,* Vol. 9, No. 1, 1991, pp. 104−111.

[22] E. Sykas, and K. Vlakos, and M. Hillyard, "Overview of ATM Networks: Functions and Procedures," *Computer Communications,* Vol. 14, No. 10, 1991, pp. 615−626.

[23] B. H. Ryu, C. H. Cho, and J. H. Ahn, "Design of ATM Networks with Multiple Traffic Classes," *ETRI Journal*, Vol. 20, No. 2, June 1998, pp. 171−191.

[24] J. C. Bellamy, *Digital Telephony*, New York, Wiley, 1982.

[25] A. A. Collins and R. D. Pederson *Telecommunications: A Time for Innovation*, Merle Collins Foundation, Dallas, Texas, 1973.

[26] M. Gerla, J. A. S. Monteiro, and R. Pazos, "Topology Design and Bandwidth Allocation in ATM Nets," *IEEE Journal on Selected Areas in Communications*, Vol. 7, 1989, pp. 1253−1262.

[27] D. Ghosh and S. Mitra, "Configuring Express Pipes in Emerging Telecommunication Networks," *working paper,* 1992.

[28] G. Gopal, C. K. Kim and A. Weinrib, "Dynamic Network Configuration Management," *Proceedings of IEEE ICC '90*, 1990, pp. 295–301.

[29] G. Gopal, C. K. Kim and A. Weinrib, "Algorithms For Reconfigurable Networks," *13th International Teletraffic Congress*, 1991, pp. 341–347.

[30] M. J. Lee and J. R. Yee, "An Efficient Near-Optimal Algorithm for the Joint Traffic and Trunk Routing Problem in Self-Planning Networks," *Proceedings of IEEE INFOCOM '89*, 1989, pp. 127–135.

[31] M. J. Lee and J. R. Yee, "A Partial Branch and Bound Design Algorithm for Reconfigurable Networks," *Proceedings of IEEE ICC '91*, 1991, pp. 682–686.

[32] M. J. Lee and J. R. Yee, "A Design Algorithm for Reconfigurable ATM Networks," *Proceedings of IEEE INFOCOM '93*, 1993, pp. 144–151.

[33] R. A, Pazos-Rangel and M. Gerla, "Express Pipe Networks," *Proceedings of Global Telecommunication Conference*, 1982, pp. 293–297.

[34] C. S. Sung and S. K. Park, "An Algorithm for Configuring Embedded Networks in Reconfigurable Telecommunication Networks," *Telecommunication Systems*, Vol. 4, 1995, pp. 241–271.

[35] B. Gavish, P. Trudeau, M. Dror, M. Gendreau, and L. Mason, "Fiberoptic Circuit Network Design under Reliability Constraints," *IEEE Journal on Selected Areas in Communicatins*, Vol. 7, No. 8, 1989, pp. 1181–1187.

[36] B. Sanso, M. Gendreau, and F. Soumis, "An Algorithm for Network Dimensioning under Reliability Considerations," *Annals of Operations Research*, Vol. 36, 1992, pp. 263–274.

[37] B. Gavish and I. Neuman, "Routing in a Network with Unreliable Components," *IEEE Transactions on Communications*, Vol. 40, No. 7, 1992, pp. 1248–1258.

[38] C. S. Sung and J. H. Lee, "Configuring Both Backbone and Logical Networks of a Reconfigurable Network with Link Failures Allowed," *Engineering Optimization*, Vol. 26, 1996, pp. 227–249.

[39] J. H. Lee and C. S. Sung, "Joint Configuration of Backbone and Logical Networks of a Reconfigurable Packet-Switched Network with Unreliable Links," *Engineering Optimization*, Vol. 30, 1998, pp. 309–331.

[40] M. Held and R. M. Karp, "The Traveling Salesman Problem and Minimum Spanning Trees," *Operations Research*, Vol. 18, 1970, pp. 1138–1162.

[41] A. Mirzaian, "Lagrangean Relaxation for the Star-Star Concentrator Location Problem: Approximation Algorithm and Bounds," *Networks*, Vol. 15, 1985, pp. 1–20.

[42] B. Gavish, "Topological Design of Centralized Computer Networks: Formulations and Algorithms," *Networks*, Vol. 12, 1982, pp. 355–377.

[43] A. Girard and B. Sanso, "Multicommodity Flow Models, Failure Propagation, and Reliable Loss Network Design," *IEEE/ACM Transactions on Networking*, Vol. 6, No. 1, 1998, pp. 82–93.

[44] A. Girard, B. Sanso, and F. Mobiot, "Integrating Reliability in ATM Network Synthesis," *4th INFORMS TELECOM*, Session TA-3, 1998, p. 36.

[45] V. O. K. Li and J. A. Silvester, "Performance Analysis of Network with Unreliable Components," *IEEE Transactions on Communications*, Vol. 32, No. 10, 1984, pp. 1105–1110.

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