Cost-Minimizing Construction of a Unidirectional SHR with Diverse Protection
Sung-hark Chung, Hu-gon Kim, Yong-seok Yoon, and Dong-wan Tcha, Member, IEEE

Abstract—The widespread use of SONET technology makes the self-healing ring (SHR) architecture the most basic building-block in designing a large fiber-optic network which is not only survivable but also cost-effective. We address the design problem of placing a single SONET unidirectional ring with a single gateway hub in a region administered by a community of interest. Introduced for the purpose of further cost-saving in our problem setting is the flexibility that some offices, instead of being included in the ring, can be homed to the ring via two arc-disjoint paths. Given the set of offices and potential arcs, the objective is then to determine at the minimum total cost both the ring location and the homing to the ring of its nonmember nodes. We formulate the problem as a mixed integer programming model and develop an efficient solution procedure by devising six improvement heuristics. Extensive computational experiments are conducted with input data instances selected from the data ranges of the real-world environments. The practical value of the solution procedure for network planners is well evidenced by its excellent and consistent performance of quickly generated good-quality solutions over various input data instances.

I. INTRODUCTION

The deployment of fiber transmission systems has become pervasive in present-day communication networks in response to the rapid growth in demand and diversity of communication services. Due to the high capacity of the fiber transmission system, even a single isolated failure such as a fiber cable cut in such a network may result in a serious consequence of service disruptions. Thus, the network survivability has become one of the most critical factors to consider in planning and designing fiber optic networks. With emphasis on survivability, the advent of SONET technology has paved the way for several promising network alternatives such as the dual homing system, the point-to-point diverse protection, self-healing rings (SHR's), and the digital crossconnect system (DCS) mesh network, etc. [12]. Some possible combinations of the above-mentioned four kinds of survivable networks are illustrated in [1], [2], and [13].

In this paper, we are concerned with constructing a survivable fiber optic network in a cost-effective manner in a region covered by a single gateway hub and a number of central offices (CO's). The regional network is assumed to have the two-level structure: the upper level of the SHR and the lower level of diverse path protections. The intra-region traffic between CO's in the region is all carried through the SHR. An inter-region traffic, i.e., a traffic destined to or coming from a CO outside the region, has to pass through the regional gateway hub, so that it is viewed as an intra-region traffic between the hub and some CO in the region in our setting. Thus the upper level SHR should have sufficiently large capacity to handle both kinds of traffic. In this traffic estimation, we exclude the requirements on some presupposed CO pairs between which direct point-to-point fiber spans are to be installed due to heavy traffic demands.

As for the architecture, the upper level SHR is unidirectional which is more popular and simpler for implementation than the bidirectional one. A point to note for the unidirectional SHR (USHR) is that its capacity requirement is easily determined by summing all the traffics that enter the ring, since working traffic is carried around the ring in one direction only [12], [14]. In the lower level diverse protection (DP) system, each node is connected to the upper level USHR with a pair of arc-disjoint paths. Thus each constituent CO of the USHR should be equipped with an add–drop multiplexer (ADM), which is called an ADM node, while each of the remaining CO's uses a terminal multiplexer (TM) for diverse protection, which is referred to as a TM node.

The configuration of our target network is now described. The gateway hub and ADM nodes form a single ring, and each TM node is connected to one or two ADM nodes through a pair of arc-disjoint paths, one for working span and the other for protection span. Note that each arc-disjoint path of a TM node should be connected via a plug-in to an ADM node on the ring, where a plug-in represents the equipment necessary to provide the interface between a signal-carrying fiber and an ADM. To save the cable installation costs, we allowed the location of any TM node to be included on the ring path [10]. Thus, in our USHR/DP structure, the communication of every node pair is 100% survivable against any single link failure such as a cable cut. In our setting, a TM node chooses between homing to a common ADM node (single homing) and two different ADM nodes (dual homing) from the cost-minimizing perspective, as shown in Fig. 1. In contrast to our cost-oriented setting, some telecommunication carriers require that a ring be equipped with two gateway hubs (one for normal state and the other for protection), and each TM node be also dual-homed. We will show later on that this architecture of dual-hubbing and dual-homing

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can readily be covered by our USHR/DP model with minor modification.

It is indeed a very complex task to physically implement the USHR/DP architecture in a cost-effective manner. A number of decisions are involved therein, such as the location of ADM’s/TM’s, the configuration of the ring spanning all ADM nodes, the capacity of that ADM ring and the routing of two arc-disjoint paths for each TM node. In this study, we shall integrate these decision factors in a single model and develop its efficient solution methods as well. The major assumptions are now specified to avoid confusion: 1) Given is the underlying network which represents the sites of the gateway hub and CO’s (nodes), and the potential arcs for fiber cables; 2) the underlying network satisfies the two-connectivity such that every pair of nodes has at least two node-disjoint paths between them; 3) all node-to-node demands, except for the ones predetermined to be covered by direct point-to-point fiber spans, are serviced through the USHR to be constructed. Assumption 2 is to ensure the existence of a feasible USHR/DP network. It is Assumption 3 that simplifies the determination of the ring capacity simply by summing all node-to-node demands [14]. The ring capacity uniquely determines the ADM type for the ring, while the fixed cost for a TM node of placing a TM and a pair of plug-ins, one for each of the two arc-disjoint paths, is dependent upon the traffic demand originating from and terminating at the TM node. Therefore, in total, four major cost elements are considered for our cost-minimizing network design problem: two types of node costs, the one for ADM nodes and the other for TM nodes; two types of fiber cabling costs, the one for USHR and the other for diverse protection.

In contrast to the rapid spread of the SONET system, only a few design studies have been reported in the literature. Cosares et al. [1] proposed an architecture, most similar to ours in the literature, which is called the point-to-point ADM network. It is the same as our USHR/DP system except that it forces each TM node to be connected to two different ADM nodes, i.e., does not allow a TM node to be connected to the same ADM node. Any study on formulation and solution methods for the architecture, however, has not been reported as yet in the literature. We will show that the point-to-point ADM network design problem can be formulated as a simple variant of our USHR/DP model, and thus can be effectively solved by our proposed algorithm with minor modification. Wasem [10] presented an enumeration algorithm of constructing a ring spanning the given set of ADM nodes. Her problem can be viewed as a specialized variant of the upper level subproblem of our USHR/DP layout problem. In [7], Lee et al. presented a dual-based algorithm for a two-level hierarchical network in which the upper level backbone network is of ring type, and each of the lower level terminal nodes is connected point-to-point to a backbone node. This architecture, however, did not consider diverse routing for the lower level nodes, but focused instead on the topological aspect of the network design problem with a cost structure much simpler than ours.

This paper is organized as follows: The mathematical model is presented in Section II. Section III proposes some heuristics for constructing an initial feasible solution and for improving a given feasible solution. Section IV provides computational results of our heuristics for several randomly generated test problems. Finally, some concluding remarks are given in Section V.

II. PROBLEM FORMULATION

Consider a graph $G_0 = (I, E)$ representing the underlying network. The node set $I = \{0, 1, \ldots, n\}$ consists of the gateway hub (node 0) and all other nodes, on each of which either an ADM or a TM should be placed. The set of undirected arcs $E$ represents all potential arcs where fiber cables may be installed. To facilitate the model formulation, we transform the original graph $G_0$ into a directed graph $G$ by the following augmentation procedure, which is also depicted in Fig. 2. For notational convenience, the undirected and the directed arcs are represented as $\{i, j\}$ and $(i, j)$, respectively.

1) Add two dummy nodes, denoted by $n + 1$ and $n + 2$. Let $J = I \cup \{n + 1\}$ and $J_1 = J \cup \{n + 2\}$.

2) Define the set $A_1$ as made up of the following directed arcs:

   - For each undirected arc $\{0, j\} \in E$, replace it with a directed arc $(0, j)$ and add a directed arc $(j, n + 1)$.
   - For each remaining undirected arc $\{i, j\} \in E$, replace it with a pair of directed arcs $(i, j)$ and $(j, i)$.

3) Define the set of dummy arcs $A_2$ with a directed arc $(j, n + 2)$ for each node $j \in J \setminus \{0\}$.

4) Let $A = A_1 \cup A_2$.
On the directed graph $G = (J, A)$, we introduce two types of commodities. Let us associate the type-1 and type-2 commodities with the paths to form a ring for ADM nodes and the diverse protection for TM nodes, respectively. Then, a type-1 commodity $k (k \in I)$ originates at node $k$ and is destined to the dummy node $n + 1$, while a type-2 commodity $k (k \in I \setminus \{0\})$ originates at node $k$ and is destined to the dummy node $n + 2$. Fig. 3 illustrates a feasible solution on both graphs $G_0$ and $G$. Note that a path from node 0 to node $n + 1$ on $G$ corresponds to a ring beginning and ending at node 0 on $G_0$, which will be referred to as a ring path. In addition, the following notations are needed:

- $F_i$: fixed cost of placing an ADM at node $i \in J$ ($F_{n+1} = 0$);
- $T_i$: fixed cost of placing a TM and a pair of plug-ins for node $i \in J$;
- $z_i$: 0-1 variable whose value is 1 if an ADM (a TM) is placed at node $i \in J$;
- $R_{ij}$: installation cost of fiber cable on arc $(i, j) \in A_1$ for the ring $(R_{i,n+1} = R_{0i}, \text{for} \ i \in I \setminus \{0\})$;
- $y_{ij}$: 0-1 variable whose value is 1 if arc $(i, j) \in A_1$ is contained in the ring, and is 0 otherwise;
- $f_{ij}^k$: variable denoting the demand fraction of type-1 commodity $k \in I$ flowing on arc $(i, j) \in A_1$;
- $C_{ij}^k$: installation cost of fiber cable on arc $(i, j) \in A$ for an arc-disjoint path from node $k \in I \setminus \{0\}$ to an ADM on the ring ($C_{i,n+2}^k = 0$ for $i \in J \setminus \{0\}, k \in I \setminus \{0\}$);
- $x_{ij}^k$: variable denoting the demand fraction of type-2 commodity $k \in I \setminus \{0\}$ flowing on arc $(i, j) \in A$.

Then, our problem can be formulated as the following mixed 0-1 programming problem ($P$)

$$
\min \sum_{i \in J} F_i z_i + \sum_{i \in J} T_i(1 - z_i) + \sum_{(i, j) \in A_1} R_{ij} y_{ij} + \sum_{k \in I \setminus \{0\}} \sum_{(i, j) \in A_1} C_{ij}^k x_{ij}^k
$$

subject to

$$
\sum_{j \in J} f_{ij}^k - \sum_{j \in J} f_{ji}^k = \begin{cases} z_k, & \text{if } i = k \\ 0, & \text{otherwise} \end{cases}, \quad \sum_{j \in J} f_{ij}^k = \begin{cases} z_k, & \text{if } i = n + 1, \ i \in J, k \in I \\ 0, & \text{otherwise} \end{cases}
$$

$$
0 \leq x_{ij}^k \leq 1, \ (i, j) \in A_1, \ k \in I
$$

$$
\sum_{j \in J} y_{ij} \leq 1, \ i \in J
$$

$$
\sum_{j \in J} y_{ij} \leq 1, \ i \in J
$$

$$
0 \leq z_i \leq 1, \ i \in J
$$

The objective function (1) has four cost terms: the nodal fixed costs of installing ADM's, the nodal fixed costs of installing TM's, the arc costs for installing fiber cables for the ring, and the arc costs for installing fiber cables for diverse paths from TM nodes to the ring. When there is another gateway hub $l \in I \setminus \{0\}$ other than node 0, ($P$) is modified to express such a dual-hubbed ring simply by having $T_l = \infty$.

Constraints (2) require that one unit of type-1 commodity $k$ be shipped to its destination $n + 1$ if $k$ is selected as an ADM node. Constraints (3) ensure a flow of type-1 commodity $k$ to be allowed only if arc $(i, j)$ is contained in the ring. Constraints (4) prevent the ring path from visiting a node more than once. Thus the constraints (2)~(5) guarantee the ring path from node 0 to node $n + 1$ to visit exactly once every ADM node. Note that a ring path may have TM nodes as intermediaries when necessary. Constraints (6) prevent the ring path from containing only one ADM node, thereby taking into account only the legitimate rings on the original graph $G_0$. Constraints (7) show that an ADM should be established on the gateway hub (node 0).

Constraints (8), (9), (12), and (13) guarantee two arc-disjoint paths from each TM node to one or two ADM nodes on the ring. Constraints (8) enforce two units of type-2 commodity $k$ to flow from the origin TM node $k$ to the destination node $n + 2$, while constraints (9) allow them to pass through the same ADM node on their way. If each TM node is required to be connected to exactly two different ADM nodes on the ring like the point-to-dual ADM system suggested in [1], then the constraints (9) should be modified to $x_{ij}^k \leq z_i$. The problem ($P$) is a complex mixed-integer problem, having approximately $3n^2 + 3n + n|A_1|$ constraints, and $n|A_1| + (n + 1)|A_1| + n$ variables, $|A_1| + n$ of which are 0-1 integers. Let $Z$ be a subset of nodes selected for ADM placement, i.e., $Z = \{i \in J : z_i = 1\}$, and let $\bar{Z} = J \setminus Z$. Given $Z$, ($P$) can be decomposed into two independent subproblems:

- the ring path problem ($RP(Z)$) for ADM nodes, and the
shortest arc-disjoint path problem \((DP(Z))\) for TM nodes. The two subproblems are now given.

\[(RP(Z)):\]
\[
\min \sum_{(i,j) \in A} R_{ij} y_{ij}
\]
subject to
\[
\sum_{j \in J} x_{ij} - \sum_{j \in J} x_{ji} = \begin{cases} 1, & \text{if } i = k \\ -1, & \text{if } i = n + 1, j \in J, k \in Z \\ 0, & \text{otherwise} \end{cases}
\]
\[(3), (4), (5), (6), (11), \text{and } (14).\]

\[(DP(Z)):\]
\[
\min \sum_{k \in Z} \sum_{(i,j) \in A} C_{ij} x_{ij}
\]
subject to
\[
\sum_{j \in J_1} x_{ij} - \sum_{j \in J_1} x_{ji} = \begin{cases} 2, & \text{if } i = k \\ -2, & \text{if } i = n + 2, \text{or } i \in J_1, k \in Z \\ 0, & \text{otherwise} \end{cases}
\]
\[
0 \leq x_{i,n+2} \leq 2, \quad i \in Z, k \in Z
\]
\[
0 \leq x_{i,k} \leq 1, \quad (i,j) \in A_1, k \in Z.
\]

The problem \((RP(Z))\) is to find the shortest path from node 0 to node \(n + 1\) on \(G\) with the constraint of visiting exactly once every node in \(Z\). Also it is a general version of traveling salesman problem, which is reduced to one standard when \(Z = J\) [5]. Although this problem has been dealt with by several authors [3], [4], no efficient exact algorithm has been reported owing to its NP-completeness.

\((DP(Z))\) can be decomposed into \(|Z|\) independent subproblems \((DP_k(Z)), k \in Z\). Observe that \((DP_k(Z))\) is a variant of the shortest arc-disjoint path problem that determines a pair of arc-disjoint paths from the origin \(k\) to the destination \(n + 2\), allowing to use twice each arc \((i, n + 2), i \in Z\). We can solve it within \(O(m \log(1 + m/n) n)\) running time using the Suurballe and Tarjan algorithm [9].

III. SOLUTION METHOD

Instead of developing an exact algorithm for \((P)\), we shall propose an approximate solution method which well exploits the interrelations between the three subproblems, the one of locating ADM nodes, \((RP(Z))\), and \((DP(Z))\). The proposed method is composed of two phases: the first phase of generating an initial feasible solution, and the second with several local improvement heuristics. For exposition, we define the following notation:
- \(Y/T\): set of arcs/nodes on the ring path (note \(Z \subseteq T\));
- \(Y_{ij}/T_{ij}\): set of arcs/intermediate nodes, excluding the end nodes, on the ring path from \(i\) to \(j\);
- \(Z_{ij}\): set of intermediate ADM nodes on the ring path from \(i\) to \(j\) (note \(Z_{ij} \subseteq T_{ij}\));
- \(P_{st}/Q_{st}\): set of arcs on the primary/secondary node-disjoint path from \(s\) to \(t\);
- \(U_{st}/V_{st}\): set of nodes on the primary/secondary node-disjoint path from \(s\) to \(t\);
- \(u(\cdot)/u(\cdot)\): an optimal/feasible solution value of problem \((\cdot)\),

A. Generating an Initial Feasible Solution

Select any node \(j \in I \setminus \{0\}\) and temporarily set \(z_j = 1\). The immediate task is to find a ring passing through the gateway hub (node 0) and node \(j\) in the original undirected graph \(G_0\). For that, we obtain a pair of node-disjoint paths from origin \(j\) to destination 0 by applying the Suurballe and Tarjan algorithm [9] with the ring cable cost matrix \((R_{st})\). Let such two paths be \(P_0 = \{(j, k_1), (k_1, k_2), \ldots, (k_i, 0)\}\) and \(Q_0 = \{(j, i_1), (i_1, i_2), \ldots, (i_m, 0)\}\). Then \(Y = \{(0, k_1), \ldots, (k_i, k), (k, j_1), (j_1, j), \ldots, (i_m, n + 1)\}\) for the directed graph \(G\). We set \(Z = \{0, j, n + 1\}\), \(T = \{0, k_1, \ldots, k_i, j_1, j, \ldots, i_m, n + 1\}\) and solve the subproblem \((DP(Z))\). This gives us a feasible solution to the problem \((P)\) with the total cost \(u(P(Z)) = \sum_{k \in Z} F_k + \sum_{k \in Z} T_k + \sum_{i \in V} R_{st} + u(DP(Z))\). We repeat the above procedure for all \(j \in I \setminus \{0\}\), and take the initial solution as the one corresponding to node \(j^*\) that minimizes \(u(P(Z))\).

B. Improvement Heuristics

To improve the current solution without violating feasibility, the following six heuristics based on local transformation [8] are sequentially applied until further cost saving is not possible. These heuristics are general enough to cover a wide range of feasible topologies, yet fast enough to be performed in reasonable time even on a personal computer.

1) Exchange Heuristic (Exch-H): Select \(i \in T \setminus Z\) and \(j \in Z \setminus \{0, n + 1\}\). Set temporarily \(z_i = 1, z_j = 0\). For the updated \(Z\), calculate the total cost \(u(P(Z))\) that is equal to \(\sum_{k \in Z} F_k + \sum_{k \in Z} T_k + \sum_{i \in V} R_{st} + u(DP(Z))\). If the total cost decreases then set \(z_i = 1, z_j = 0\). Otherwise, set \(z_i = 0, z_j = 1\).

2) Drop Heuristic (Drop-H): This heuristic can be applied only when \(|Z\) $\geq 3\). Select \(i \in Z \setminus \{0, n + 1\}\), set temporarily \(z_i = 0\). If the total cost with the updated \(Z\) becomes smaller then set \(z_i = 1\). Otherwise, set \(z_i = 1\).

3) Add Heuristic (Add-H): Select \(i \in T \setminus Z\). Set temporarily \(z_i = 1\). If the total cost decreases then set \(z_i = 1\). Otherwise, set \(z_i = 0\).

4) Ring Path Partial-Exchange Heuristic (RingExch-H): Choose a pair of nodes \(s, t \in Z\) such that \(Z_{st} = \emptyset\). Set \(R_{ij} = \infty\), for all \((i, j) \in A_3\) such that \(i \in (T \setminus T_{st}) \setminus \{s, t, 0\}\). Get the shortest path from \(s\) to \(t\) with arc cost matrix \((R_{st})\). Let \(E_{st}\) be the set of arcs which are located on the shortest path from \(s\) to \(t\). Let \(N_{st}\) be the set of nodes which are located on the shortest path from \(s\) to \(t\). If the shortest path length \(\sum_{(i,j) \in E_{st}} R_{ij}\) is less than \(\sum_{(i,j) \in Y_{st}} R_{ij}\) then set \(Y = (Y_{st} \cup E_{st}) \cup U_{st}, T = (T_{st} \cup E_{st}) \cup N_{st}\). Otherwise, keep \(Y, T\).

5) Ring Path Extension Heuristic (RingExt-H): To check the effect of including node \(k \in I \setminus T\) as an intermediate ADM node, we apply the node-disjoint path algorithm from source \(k\) to destination \(n + 2\). For this, some arc costs are modified as: \(R_{s,n+2} = 0\) for \(s \in T\), \(R_{s,n+2} = \infty\) for \(s \in I \setminus T\). Two such node-disjoint paths from source \(k\) to destination \(n + 2\) are generated as illustrated in Fig. 4(a), while Fig. 4(b) shows the new ring path thus updated. Calculate the total cost \(u(P(Z))\).
with the following updates.
Let
\[ U_{k,n+2} = \{ k, j_1, \ldots, j_{l-1}, j_l, j, n + 2 \}, \]
\[ V_{k,n+2} = \{ k, i_1, \ldots, i_{m-1}, i_m, i, n + 2 \}, \]
\[ U'_k = U_{k,n+2} \setminus \{ n + 2 \}, \]
\[ V'_k = V_{k,n+2} \setminus \{ n + 2 \}. \]

Let
\[ P_{k,n+2} = \{ (k, j_1), \ldots, (j_{l-1}, i_l), (j_l, i), (j, n + 2) \}, \]
\[ Q_{k,n+2} = \{ (k, i_1), \ldots, (i_{m-1}, i_m), (i_m, i), (i, n + 2) \}, \]
\[ P'_k = \{ (k, j_1), \ldots, (j_{l-1}, j_l), (j_l, i) \}, \]
\[ Q'_k = \{ (i, i_1), (i_m, i_{m-1}), \ldots, (i, k) \}. \]

Temporarily set
\[ Z = (Z \setminus Z_{ij}) \cup \{ k \}, \]
\[ Y = (Y \setminus Y_{ij}) \cup P'_k \cup Q'_k, \]
\[ T = (T \setminus T_{ij}) \cup U'_k \cup V'_k. \]

If the total cost \( u(P(Z)) \) decreases then the new topology is adopted [Fig. 4(b)]. Otherwise, keep the original ring path and \( Y, T, \) and \( Z \) [Fig. 4(a)].

6) Ring Path Extension and Drop Heuristic (RingExt&Drop-H): This heuristic is essentially the same as (RingExt-H) plus (Drop-H). It takes into account the possibility of further cost saving by allowing ring path extension, when (RingExt-H) alone fails to make such extensions any further. Consider the case where the candidate extended ring path generated by (RingExt-H) as shown in Fig. 4(b) is such that \( i \in Z \) or \( j \in Z. \) Then apply (Drop-H) focusing on any one node from among the two such nodes. For example if we drop node \( i \in Z, \) set temporarily \( Z = ((Z \setminus Z_{ij}) \setminus \{ i \}) \cup \{ k \}. \)

C. Solution Procedure
All the above heuristics are integrated to form the overall solution procedure (H). Instead of listing the procedure in detail, we provide a flowchart in Fig. 5, which effectively shows the interrelationships between those heuristic subroutines.

IV. COMPUTATIONAL RESULTS
The underlying networks for the test are generated by the code in [6], which was developed to simulate the real network environment. The test networks thus generated are generally sparse and planar, and satisfy the two-connectivity. And they are characterized by two parameters: one is \( \alpha \) denoting the maximum node degree, and the other is \( \beta \) indicating the minimum arc length in terms of Euclidean distance in a square grid plane.

A total of 30 underlying networks were randomly generated on the 450 \( \times \) 450 grid plane with three different sizes = (no. of
nodes \times \text{no. of arcs}, (15 \times 30), (30 \times 60), and (50 \times 90), ten networks for each size. In all networks, we set \( \alpha = 7, \beta = 30 \).

The proposed solution method was programmed in C and run on an HP workstation (9000 series 715/33).

The installation cost of fiber cable on arc \( \{i, j\} \) for a type-2 commodity \( k \) is given the same for all commodities, i.e., \( C_{ij}^{k} = C_{ij} \) for all \( k \). The common cost parameter \( C_{ij} \) is set equal to the Euclidean distance of arc \( \{i, j\} \) (round to the nearest integer). The installation cost of fiber cable for the ring path on arc \( \{i, j\}, R_{ij} \), is obtained by multiplying the corresponding \( C_{ij} \) by the scaling factor 1.5 common to all arcs.

The fixed cost of establishing an ADM at node \( i \), \( F_{i} \), is set at \( F \) common to all nodes. For simplicity, we let a single type of a TM and plug-ins correspond to a given ADM type. Both fixed costs are thus specified as a pair, \((F, T)\), where the

fixed cost of a TM node, \( T \), is generally much smaller than \( F \). Fixing TM nodal cost parameters at a single value as above certainly conflicts with the fact that the capacity of a TM and a plug-in pair should be dependent on the traffic demand at a potential TM node. It requires a large number of additional test runs to accommodate this variations in TM nodal cost, the burden of which vindicates our simple nodal cost structure.

Now placing the focus on finding a trend how sensitive solution time and quality are with respect to varying ADM and TM costs, considered are three different values for each of \( F \) and \( T \). Hence a total of nine different values of \((F, T)\) are tested for each of the above-mentioned 30 underlying networks, ten for each of three network sizes.

The results of the extensive computational experiments are summarized in Table I, each entry of which shows the average

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<td>-</td>
<td>277.7</td>
<td>110.6</td>
</tr>
<tr>
<td>(2000, 1000)</td>
<td>74833.1</td>
<td>68847.9</td>
<td>-</td>
<td>451.1</td>
<td>219.5</td>
</tr>
<tr>
<td>(2000, 500)</td>
<td>50833.1</td>
<td>46575.4</td>
<td>-</td>
<td>377.3</td>
<td>232.6</td>
</tr>
<tr>
<td>(1000, 750)</td>
<td>60833.1</td>
<td>49658.1</td>
<td>-</td>
<td>124.3</td>
<td>38.7</td>
</tr>
<tr>
<td>(1000, 500)</td>
<td>48833.1</td>
<td>40075.4</td>
<td>-</td>
<td>277.7</td>
<td>110.5</td>
</tr>
<tr>
<td>(1000, 250)</td>
<td>36833.1</td>
<td>29718.1</td>
<td>-</td>
<td>355.0</td>
<td>143.5</td>
</tr>
<tr>
<td>(500, 375)</td>
<td>41833.1</td>
<td>23835.1</td>
<td>-</td>
<td>56.3</td>
<td>33.4</td>
</tr>
<tr>
<td>(500, 250)</td>
<td>35833.1</td>
<td>24608.1</td>
<td>-</td>
<td>124.3</td>
<td>38.7</td>
</tr>
<tr>
<td>(500, 125)</td>
<td>29833.1</td>
<td>19985.4</td>
<td>-</td>
<td>200.6</td>
<td>73.9</td>
</tr>
</tbody>
</table>

\( ^a \) Exch-H

\( ^b \) Drop-H

\( ^c \) RingExch-H

\( ^d \) RingExt-H

\( ^e \) RingExt&Drop-H

\( ^{ \% \text{ gap} = 100 \times (\text{Final} - \text{PLEX}) / \text{PLEX} } \)

\( ^{ \text{CPU time in seconds on the HP workstation} } \)
test result over the corresponding ten networks. Table I(a) shows the test results for the networks with size (15 × 30). The 2nd, 3rd, and 4th columns give the values of the initial solutions by our heuristic procedure (H), the final solutions by (H), and the optimal solutions of USHR/DP by CPLEX which is the well-known mixed integer programming solver, respectively. The performances of six improvement heuristics exhibited from the 5th column to the 10th column appear to be data dependent. The levels of improvement are significantly different from one another to be divided into three scales: large by (Add-H) and (RingExt-H), medium by (Exch-H) and (Drop-H), and small by (RingExch-H) and (RingExt&Drop-H).

It is indeed remarkable to find that the solution times with (H) listed in the 11th column are all within 4.0 CPU s, while the CPU times with CPLEX are larger in several orders of magnitude, from 578 (9.6 min) to 35 908 s (598 min) as manifested in the 12th column. The 13th column well demonstrates the impressive quality of the solutions obtained by the heuristic procedure (H) by reporting the percentage gaps as small as from 0.031% to 0.998%.

Table I(b) and Table I(c) exhibit the results for the other two network sizes, (30 × 60) and (50 × 90), respectively. All the remarks made for Table I(a) still hold here except that the improvement levels with six improvement heuristics differ from one another as follows: large by (Add-H) and (RingExt-H), medium by (Exch-H) and (Drop-H), and small by (RingExch-H) and (RingExt&Drop-H). These differences conform with our expectation that the improvement level is generally proportional to the depth of local perturbation conducted by a heuristic. The other point to note is the unavailability of the optimal solutions for these problems of two network sizes owing to the enormously large computation time with CPLEX. Thus the percentage gaps are not reported in these two tables, but we believe that the quality of solutions generated for these networks is almost as good as the one for the previous networks of smaller size, (15 × 30).

For strategic network planning under uncertain cost projection, it would be useful to find how sensitive the location variations of established multiplexers, particularly ADM's, in the generated solutions, are with varying cost structures. As the relative size of ADM costs decreases, the number of established ADM's increases, which certainly conforms with our intuition. But we cannot find any consistent behavior that an ADM site selected in one solution would remain so in another solution having a larger number of open ADM's. Note that node demands determines TM costs in our problem setting, thereby reducing the sensitivity analysis of demand variations on multiplexers location to the case above. These observations on ADM location variations are stated here without listing the associated results simply for exposition brevity.

V. CONCLUDING REMARKS

We have dealt with the problem of designing an optical fiber network based on the SONET self-healing-ring architecture in a region with a single gateway hub and a number of central offices. The attention has been focused on the most promising two-level architecture for such a regional network environment in terms of cost and survivability: the upper level of the unidirectional SHR and the lower level of the diverse protections. The network design problem is so complex as to include three decision subproblems: selecting a subset of nodes to place ADM's, configuring the SHR ring spanning all the ADM's and the gateway hub, and routing a pair of arc-disjoint paths from each TM node to one or two ADM nodes on the ring. Augmenting the given underlying network so as to exploit the interrelations between the three decisions, the problem was successfully formulated as a mixed 0-1 integer program. The structure of the model enabled us to develop an efficient heuristic solution method. Despite the excessive computational complexity with the original design problem, the performance of the proposed method is shown via the extensive computational experience to be very satisfactory in both speed and quality of the solutions generated.

The assumption of a single ring in a region may be restrictive when considering the reality that traffic demand including broadband applications in some region can be too high to be covered by a single ring. Thus in order for the model to be more realistic, more than one ring should be allowed in a region. The demand loading problem, from among additional several problems to resolve, of how to distribute each node-to-node demand among the established rings then arises, complicating the already complex design problem. An immediate extension to the multi-ring case of our study would be to integrate these subproblems in a unified design process.

REFERENCES

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