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A DESIGN OF THE MINIMUM COST RING-CHAIN NETWORK WITH DUAL-HOMING SURVIVABILITY: A TABU SEARCH APPROACH

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Scope and Purpose—The advent of fiber optic technology has increased concerns about the survivability of metropolitan telecommunication networks. The network survivability usually denotes the capability of a network to recover services from its link or node failures. In contrast, the dual homing survivability requires each node to be connected to one foreign hub, in addition to its home hub, to prepare the failure of its home hub. This article proposes a ring-chain architecture for the dual homing survivability. The architecture consists of a ring and multiple chains. The ring contains hubs and ring nodes which have relatively high traffic with bidirectional or unidirectional SHR. The nodes in the chain which have relatively low traffic are connected to the ring with dual homing survivability. Given a ring network, the problem is to construct a set of chains to satisfy the demand requirements and the dual homing constraint such that the network construction cost is minimized.

Abstract—This article discusses a design of the ring-chain architecture with dual homing survivability for metropolitan telecommunication networks. A self-healing ring (SHR) and multiple chains are considered to cover hub, ring nodes and other offices. Offices in a chain are connected to the ring in dual homing fashion to increase the survivability. Given a ring topology, the problem is to minimize the link cost of the chain network which satisfies the dual homing constraint. An integer programming formulation and the NP-completeness of the problem is presented. As a solution procedure, a tabu search is proposed with two types of moves; insert and swap. To increase the efficiency of the search procedure, tabulists, aspiration criteria, and diversification strategy are discussed. The computational results show that the proposed tabu search provides near optimal solutions within a few seconds. Approximately 1%–4% gap from the optimum is experienced in problems with reasonable size of metropolitan area networks. © 1997 Elsevier Science Ltd

1. INTRODUCTION

The advent of fiber optic technology has increased concerns about the survivability of metropolitan telecommunication networks. The network survivability usually denotes the capability for a network to recover services from link or node failures. In contrast, the dual homing survivability, requires each node to be connected to another foreign hub, in addition to its home hub, in the event of its home hub failure.

While there have been a lot of studies on the survivable network with fiber-hubbing, the study on the dual homing architecture and its topological design has not been made enough. Most researchers have focused on the self healing ring (SHR) and the point to point diverse protection (DP) architecture under single homing constraint [1–12]. A survivable communication network design is divided into two subproblems [9]: topology selection and network architecture design. Given the connectivity requirement, the topology selection problem is to determine the physical link layout among switching offices such that the installation cost of fiber links is minimized. In the related studies [3–5,8], efficient algorithms such as a tabu search or a cutting plane method are developed to design the survivable network with two connectivity requirement. The network architecture design relates to the demand requirement. In the design, the survivable network architectures such as a ring or DP are deployed to restore services in the event of a link or node failure. Doverspike *et al.* [2] and Wu *et al.* [10,12] studied

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the feasibility and economic advantages of the SHR architecture in the broadband fiber optic network. Some researchers studied the minimum-cost ring network design such that the demand requirements are satisfied [7,11]. In the study, a fiber-hubbing network including a hub office is constructed as the SHR network that connects the ring offices in a cost-effective manner. However, there has been no research on the design of ring-chain network with dual homing survivability in the literature.

In contrast to the single homing approach, the dual homing designates two hubs for each office which requires high survivability. To provide the dual homing survivability in the communication network, two approaches may be considered. The first one is to cover the network with multiple SHRs. The second is to connect each node to two hubs through point to point diverse protection facilities. The multiple SHRs require high equipment costs because of the expensive add-drop multiplexers (ADM). The point to point diverse protection is also expensive as a large amount of fiber materials should be placed between each pair of hub and other nodes which require the dual homing survivability.

Our study on the dual homing is motivated by Lee [13]. In his study the node set is classified into ring nodes, hub nodes and terminal nodes. A set of hub nodes that concentrate traffics from terminal nodes are connected to the ring nodes in a dual homing fashion. Then the dual homing problem seeks to find an optimal ring topology and traffic routing among nodes while satisfying the dual homing pattern constraints. This article proposes a ring-chain architecture for the dual homing survivability. The architecture consists of a ring and multiple chains. The ring contains hubs and ring nodes which have relatively high traffic with bidirectional or unidirectional SHR. The nodes in the chain which have relatively low traffic are connected to the ring with dual homing survivability (see Fig. 1). ADM-fiber chains [9,12], which provide connections between a group of ADM offices, are considered to connect each node in the chain to the SHR. Given a ring network, the problem is to construct a set of chains to satisfy the demand requirements and the dual homing constraint such that the network cost is minimized.

The remainder of this article is organized as follows. In Section 2, we consider the design problem of ring-chain network with dual homing survivability. We present an integer programming formulation of the problem. The NP-completeness of the ring-chain problem is also proved. In Section 3, a tabu search procedure is proposed to solve the problem efficiently. Various operators of the tabu search such as *move*, *tabulist*, *aspiration criteria* and *diversification strategy* are examined. The efficiency of the proposed tabu search is illustrated by comparing with an exact solution method in Section 4. The performance of various tabu operators are also discussed. Finally, we conclude this article in Section 5.

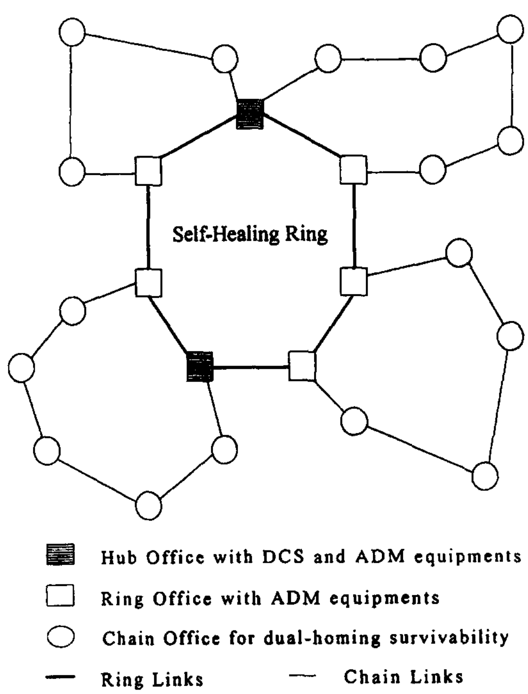


Fig. 1. Ring-chain architecture for dual homings survivability.

2. RING-CHAIN DUAL HOMING PROBLEMS

In this section we first discuss the ring-chain design process for dual homing survivability in a metropolitan telecommunication network. We also propose a demand routing scheme for dual homing chain against a network failure. The ring-chain dual homing problem (RCDH) is formulated as an integer programming model and shown to be a NP-complete problem. To get an exact solution for the problem, a cutting plane procedure is described.

2.1. *Ring-chain design process in a metropolitan network*

We consider a metropolitan network that is usually covered with single SHR and several ADM fiber chains that are incident to the SHR. Then the ring-chain design process is divided into two phases; the SHR design and the design of dual homing chains.

2.1.1. Self healing ring design. In most of the metropolitan telecommunication networks, demand patterns of central offices are irregular and nonhomogeneous. The total amount of demand, peak time and night demands, patterns in a week may be different at each office. Given a set of nodes in the network, the ring design phase first classifies each node either as a ring node or as a chain node. The classification usually depends on the following rules:

(a) A node with high demand is assigned to a ring, while the one with low demand to a chain.

(b) The sum of demands routed on the ring should not exceed the *ring capacity* (e.g. OC-48 or 192). The rule (b) relates to the technology of ADM equipments, whereas the rule (a) depends on the priority of service requirement that a network provider considers. Thus these rules may be different according to the technological level and the service requirement to be considered.

After classifying each node into a ring or a chain node, we must construct a reasonable ring topology that spans all ring nodes. This procedure is performed by solving the well-known traveling salesman problem or the ring routing problem [7,8].

2.1.2. Dual-homing chain design. In this phase, we construct a set of dual homing chains incident to the SHR. We assume that the set of ring nodes and their connectedness are obtained in the ring design phase. Then the origin-destination pair of each demand is mapped into two classes; ring to ring demand (both end nodes are on the ring) and chain to ring demand (one node is on a chain and the other is on the ring). Any chain to chain demand can be considered as the combination of the two demands. The dual homing requires each chain node to be connected to at least two different ring nodes through different paths. The sum of traffics routed on a chain link should not exceed the chain link capacity.

2.2. *Demand routing scheme for dual homing chains*

Given the demand requirements, the ring capacity C_R and the chain link capacity C_L should be given a priori or estimated from demand requirements of nodes in the network. In the unidirectional SHR case, the ring capacity is given as the sum of all the traffics routed on the ring in the network. The capacity of the bidirectional ring can be estimated by solving the so-called *load-balancing* problem [14,15]. In this article, the ring capacity C_R is given as the sum of all demand requirements in the network, which easily provides a feasible routing on the ring. Note that the ring capacity is large enough to allow all the traffics routed on the ring. Thus this article focuses on the design of chain networks. The capacity of chain link C_L is obtained by considering the demands of chain nodes and a set of OC line rates (OC-3 or 6).

Given the chain link capacity C_L, the chain to ring demands are routed as follows [9,12]. In the network, let R and C be a set of ring nodes and a set of chain nodes, respectively. For each chain node $v \in C$, we consider the node demand $d(v)=\Sigma_{w \in R} d(v,w)$, where $d(v,w)$ is the demand from origin v to destination w. Under normal operations, each demand $d(v)$ is routed such that one half of the demand to one direction and the other half to opposite direction (See Fig. 2(a)). Let S be a chain, then the constraint of chain link capacity requires the sum of node demands in S, not to be greater than the chain link capacity C_L. The demand routing schemes for failure in a hub and a link are also shown in Figs 2(b) and (c), respectively. In the event of a hub failure (see Fig. 2(b)), another alternate routing is made in the opposite direction by the path rearrangement of the chain node which is incident to the failure node. For

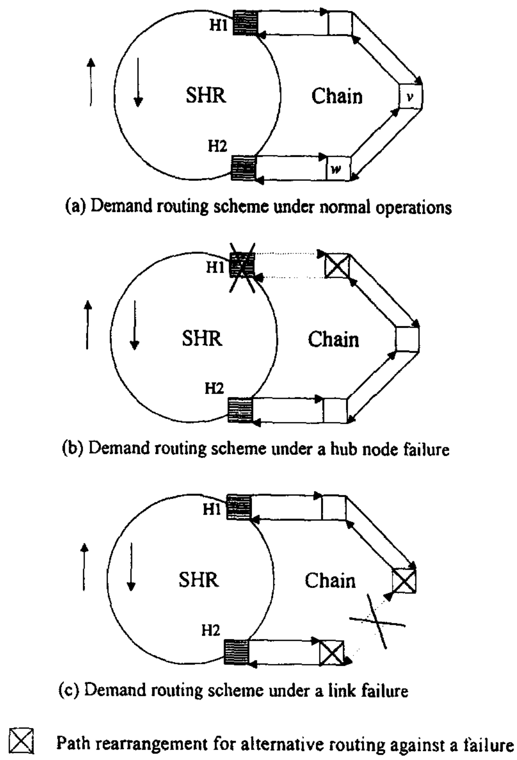


Fig. 2. Demand routing schemes for dual homing chains.

a link failure as in Fig. 2(c), the path rearrangements are required to reroute the traffics on the failed link along two opposite directions.

2.3. *Modeling of ring-chain dual homing problem*

In this section, we propose an integer programming model for the ring-chain dual homing problem which is based on the cut formulation. The node set N in the network is classified into a set of ring nodes R which are covered with a SHR, and another set of chain nodes C which are connected to the SHR through an ADM fiber chain. Given a network $G(N,A)$ and a ring topology, the ring-chain dual homing problem seeks to find the minimum cost chains such that the chain capacity and the dual homing constraints are satisfied. The electronic equipment cost such as ADMs at each chain node is not considered in the problem, since the total node equipment cost becomes constant when the nodes to be included into the chain are decided. Usually the link cost is composed of the cost of fiber materials, placement and repeaters. Thus the model has to reflect these cost components for realistic conditions. In this article, however, it is assumed that the cost of installing a chain link is linear to the distance of the link.

To formulate the problem, let us define the following notations:

$A=\{(v,w):v \text{ or } w \in C\}$: a set of undirected chain links in the network,
$d(w)$: the demand requirement of a chain node $w \in C$,
$d(W)=\Sigma_{v \in W} d(v)$: the demand requirements for a subset of nodes $W \subseteq C$,
C_L: the chain link capacity,
a_{vw} : the cost of installing the chain link $(v,w) \in A$,
x_{vw}: 1 if the undirectional chain link (v,w) is installed, and 0 otherwise for all $(v,w) \in A$,
$r(W)= \left\lceil \frac{d(W)}{C_L} \right\rceil$: the number of chains required to satisfy the demand requirement of a node subset W with the chain link capacity C_L, where $\lceil x \rceil$ is the smallest integer not smaller than x.

Then, the ring-chain dual homing (RCDH) problem is formulated as follows.

$$(RCvDH)\quad \text{Minimize}\quad \Sigma_{(w,v)\in A} a_{wv} X_{wv} \tag{1}$$

$$\text{subject to}\quad \sum_{v\in N} x_{wv} = 2 \qquad \forall w \in C \tag{2}$$

$$\sum_{w\in W} \sum_{v\in N\setminus W} x_{wv} \geq 2r(W) \qquad \forall W \subseteq C \tag{3}$$

$$\sum_{w\in W} \sum_{v\in N\setminus(W\cup\{z\})} x_{wv} \geq r(W) \qquad \forall z \in R, W \subseteq C \tag{4}$$

$$x_{wv} 0/1 \quad integers \qquad \forall (w,v) \in A \tag{5}$$

In RCDH model, the network cost (1) consists of fiber material cost and placement of each chain link. The degree constraints (2) designate that the degree of each chain node is two to be connected to other nodes through the chain. The constraint (3), which is called as the chain capacity constraint in this article, is similar to the subtour elimination constraint in the vehicle routing problem [16]. The chain capacity constraint designates that a subset of chain nodes W should be connected to the ring through at least $2r(W)$ paths. The constraint (4), which is called as the dual homing constraint, represents the dual homing survivability between the ring and the chain induced by a node subset W. This constraint restricts the two paths from a chain node to have the single homing on the ring that may occur by the constraint (3). Thus each chain node is connected to the ring after a ring node fails.

Given a network $G(N,A)$, let us define the connected polytope for the feasible solution space of the RCDH problem as

$RCDH(G) = \text{conv}\{x \in \{0,1\}^{|A|}$: x satisfies the constraints (2), (3) and (4)$\}$, where conv is the convex hull operator. Then the RCDH problem is to minimize $a^T x$ for all $x \in RCDH(G)$. Since the connected polytope $RCDH(G)$ is composed of a large amount of cut constraints such as (3) and (4), the computational complexity gets larger as the problem size increases. Thus an efficient heuristic is necessary to solve the problem.

2.4. *NP-completeness of RCDH problem*

In this section, we prove the NP-completeness of the RCDH problem by transforming from the well-known Hamiltonian Path Problem (HPP) [17]. The following theorem states that the RCDH problem is NP-complete.

Theorem 1. *RCDH problem is NP-complete.*

Proof. It can be shown easily that the decision problem version of RCDH problem is in the class of NP. We prove that the problem is NP-complete by transforming the HPP into it. Consider an instance of HPP defined on a network $G(N,A)$. Then HPP asks whether there a path exists in G which spans all of the nodes in N. Figure 3(a) illustrates the original graph G for the HPP. In the figure a Hamiltonian path is shown.

From the network $G(N,A)$, we construct a new network $G^*(N^*,A^*)$ such that $N^* = N \cup \{r_1, r_2\}$ and $A^* = A \cup \{(r_i, v) | i = 1, 2, v \in N\}$, where r_1 and r_2 are any two different ring nodes and N are the set of chain nodes. Figure 3(b) shows the new graph G^* which is constructed by transformation from G. Now we consider an instance of the RCDH problem on the new graph G^*. Let a link cost $a_e = 1$ for all $e \in A^*$ and $n = |N|$. We also set the chain capacity $C_L = n$ and the node demand $d(v) = 1$ for all $v \in N$.

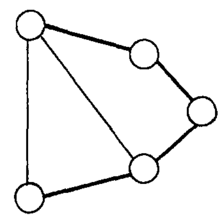
Consider the following instance of the decision problem version of RCDH which is defined on a newly constructed network G^*.

2.5. P *Is there a feasible solution of RCDH with a network cost less than or equal to* $n + 1$?

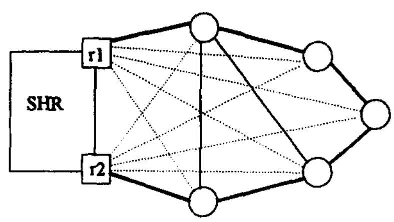
Let a feasible solution of RCDH with k chains be given and let $n_1, \ldots, n_k$ be the number of chain nodes in each chain. Then the network cost is $n + k$. Hence the answer to (**P**) is "yes" if and only if a feasible solution exists to RCDH with exactly one chain. Since the chain in G^* corresponds to a Hamiltonian path in G, we complete the proof. Note that a Hamiltonian path in Fig. 3(a) corresponds to a feasible solution to RCDH with exactly one chain in Fig. 3(b). Q.E.D.

2.6. *Cutting plane procedure for exact solutions*

In spite of the NP-completeness of the RCDH problem, we sometimes need to find an exact solution, which is necessary to measure the solution quality of a heuristic procedure. With the cut-based integer programming model in Section 2.3, we propose a cutting plane procedure to obtain an exact solution for



(a) Original Graph in Hamiltonian Path Problem



(b) Reduced Graph by Transformation from HPP

Fig. 3. Graphical illustration of the theorem.

the RCDH problem. The cutting plane procedure presented in this article is based on the simple *separation routine*. Starting from an initial integer linear program with the constraints (2) and (5), we solve it by minimizing the network cost. In the separation routine, the constraints for the *RCDH(G)* polytope, which is violated by the current integer solution, are generated and added into the integer program. These steps are repeated until an optimal solution is obtained which satisfies the *RCDH(G)* polytope.

2.6.1. Cutting plane procedure.

Step 1. Optimization routine

1-1. Solve the following integer program (IP);

Minimize $\{a^T x: x \in \{0,1\}^{|A|}$ satisfies the constraints (2) and the constraint (3) with $W=C\}$.

/* The integer program can be solved by using a commercial IP solver such as CPLEX [18] */

1-2. Let $x^* = \{(w,v) \in A | x_{wv} = 1\}$ be the optimal integer solution of the integer program.

Step 2. Separation Routine

Find the constraints (3) and (4) that are violated by the solution x^* as the following cases [21];

A. Subtour elimination constraints (Case A of Fig. 4)

A-1. **For** all $v \in C$, Mark[v]=0./* Mark[v] identifies whether the node v is searched or not */
Do the following search process **until** Mark[v]=1 for all $v \in C$.

A-2. Select a chain node v with Mark[v]=0 and set $S=\{v\}$./* a subtour S is a list of nodes */

A-3. **For** $(v,w) \in x^*$,
If Mark[w]=0 and $w \in C$, **then** Mark[w]=1, $S=S \cup \{w\}$, $v=w$. Go to A-3.
Else if $w \in R$, **then** S is not a subtour. Set $S=\emptyset$. Go to A-2.
Else if Mark[w]=1, **then** generate the constraint (3) for S, insert it into IP. Go to A-2.

B. Dual homing (Case B of Fig. 4) and chain capacity constraints (Case C of Fig. 4)

B-1. **For** all $v \in R$, Mark[v]=0. **Do** the following search **until** Mark[v]=1 for all $v \in R$.

B-2. Select a ring node v with Mark[v]=0 and $(v,w) \in x^*$ for a chain node w.

B-3. Mark[v]=1, $z=v$ and set $S=\{v\}$./*z is the starting node of the chain S*/

B-4. **For** $(v,w) \in x^*$
If $w \in C$, **then** $S=S \cup \{w\}$, $v=w$ and go to B-4.
Else if $w \in R$ {
If $w=z$, **then** generate the constraint (4) for S and insert it into IP.
Else if $w \neq z$ (In this case, the chain S satisfies the dual homing constraint) {
If $r(S)=1$, **then** the chain S is a normal chain.
Else if $r(S)>1$, **then** generate the constraint (4) and insert it into IP.

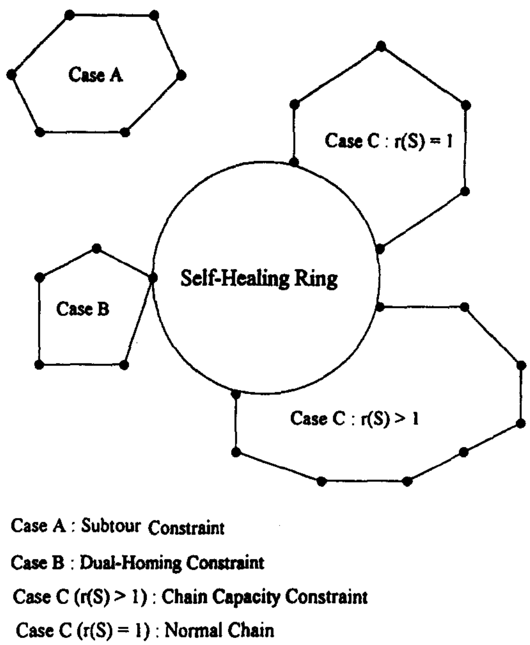


Fig. 4. Illustrative examples of the separation procedure.

}
Go to B-2.
}
Step 3. Stopping routine
If $x \in RCDH(G)$, that is, no violated constraint is generated in Step 2, **then** stop.
Otherwise, go to Step 1.

Let x^* be an optimal solution obtained by solving the initial IP in Step 1. Clearly, x^* is an integer solution which satisfies the degree constraints (2). This implies that the network induced by the solution x^* is composed of subtours and chains. The subtour designates a cycle which is not connected to the ring. The chain represents an incident cycle which is connected to the ring. Each subtour is removed by adding the constraint (3) as Case A of Step 2. The chain, which is connected to the ring with only one ring node, is removed by adding the constraint (4) as Case B. Now, consider a chain S which is connected to the ring with two distinct nodes. Note that $r(S)$ is the number of chains required to satisfy the demand requirement of a node subset S. Thus the chain induced by S with $r(S)>1$ should be splitted into more than two chains as Case C. In Fig. 4, the chain of the Case C with $r(S)=1$ is a normal chain which satisfies the dual homing survivability.

3. APPLICATION OF TABU SEARCH

Tabu search techniques are used to solve combinatorial optimization problems. These methods suggested by Glover [19,20] can be sketched as follows: starting from an initial feasible solution, at each step we choose a move to a neighboring solution in such a way that we move stepwise towards a solution giving hopefully the minimum value of some objective function. Up to this point, this is close to a generic steepest decent technique in which tabu search could be implemented as a meta-heuristic.

The interesting feature of tabu search is the construction of a list T (tabulist) of tabu moves: these are moves which are not allowed at the current iteration. The reason for this list is to exclude moves which would bring a current solution back where it was at some previous iteration. A move remains a tabu move only during a certain number of iterations (it is called "tabusize"), so that we have a cyclic list T where at each move $s \rightarrow s'$, the opposite move $s' \rightarrow s$ is added at the end of T while the oldest move in T is removed. Another characteristic of tabu search is "aspiration strategy". For each move labeled as tabu, if it gives a better solution than a predetermined local optimum, the move is taken even if it is in tabu status.

In this section, we present a tabu search procedure and its implementation for the RCDH problem. In particular, the tabu search in this article employs a diversification strategy to explore much better solutions. After a solution region is highly searched by the move and tabulist strategy, the diversification strategy of tabu search drives the search into a new area that has not been explored until then.

3.1. Initial chain construction

Before applying the tabu search, we need to construct an initial chain. Given the ring topology, the following three heuristics are suggested to construct chains that are connected to the ring.

3.1.1. Nearest neighbor. This construction method is based on the well-known nearest neighbor procedure in the traveling salesman problem. The following steps are continued until all chain nodes are connected to the ring.

Step 1. Select a ring node r_1.
Step 2. Find a chain node c_1 such that the link cost of (r_1,c_1) is the minimum among all links connected to r_1.
Step 3. Construct a partial chain $S=\{r_1, c_1\}$ by using one-dimensional array.
Step 4. Set $d(S)=d(c_1)$ and $k=1$.
Step 5. Find a chain node c_{k+1} satisfying $d(S)+d(c_{k+1})\le C_L$ such that the link cost of (c_k,c_{k+1}) is the minimum among all links connected to c_k. Then $S=S\cup\{c_{k+1}\}$ and $k=k+1$. Repeat this step.
Step 6. **If** there is no chain node c_{k+1} satisfying $d(S)+d(c_{k+1})\le C_L$,
then construct a feasible chain S by adding a ring node r_2 to the chain such that the link cost of (c_k,r_2) is the minimum among all links connected to c_k and go to Step 1.

3.1.2. Chain expansion. This procedure first constructs a small chain with a chain node and two ring nodes, and then expands it by adding the other chain nodes. The following steps are continued until all chain nodes are connected to the ring.

Step 1. Select a chain node c_1.
Step 2. Find two ring nodes r_1 and r_2 such that the cost of two links (r_1,c_1) and (r_2,c_1) is the minimum among all links connected to c_1.
Step 3. Construct a chain $S=\{r_1, c_1, r_2\}$ by using one-dimensional array.
Step 4. Set $d(S)=d(c_1)$ and let $S=\{v_1, v_2,...., v_k\}$ where $v_1=r_1$ and $v_k=r_2$.
Step 5. Find a chain node c^* satisfying $d(S)+d(c^*)\le C_L$ such that the cost of two links (v_i,c^*) and (c^*,v_{i+1}) is the minimum for $i=1, 2,..., k-1$. Then $S=S\cup\{c^*\}$. Repeat this step.
Step 6. **If** there is no chain node c^* satisfying $d(S)+d(c^*)\le C_L$, **then** go to Step 1.

3.1.3. Random chains. Based on the chain expansion procedure, this method repeatedly inserts nodes into a chain as far as the chain capacity is satisfied. However, two ring nodes and chain nodes to insert are randomly selected among those that are not included to other chains. Since this method does not use the information about link cost, it usually produces a solution with high cost. However, this procedure is useful for generating random initial solutions to which we apply an improvement heuristic.

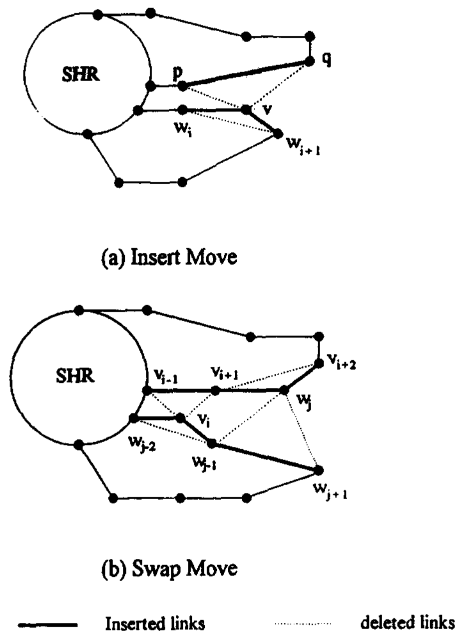
3.2. Design of move

Starting from the initial chain, the solution is improved by applying moves. In this article we define a move as a transformation of a node from a chain into another chain. Let C_1 and C_2 be two incident chains in the network. Then the following two types of moves are considered.

3.2.1. Insert move. Let us consider a chain node v in C_1 and another chain $C_2=\{w_1, w_2,..., w_k\}$. If $d(C_2)+d(v)\le C_L$, then node v is excluded from C_1 and included into C_2. Two nodes w_i and w_{i+1} in C_2 are selected which minimize the difference between the cost of inserted new links $((w_i,v), (v,w_{i+1})$ and $(p,q))$ and that of deleted old links $((w_i,w_{i+1}), (p,v)$ and $(v,q))$ as shown in Fig. 5(a).

3.2.2. Swap move. In the insert move, if $d(C_2)+d(v)>C_L$, it is not possible to take an insert move. In this case, a swap move is considered. Let us consider two chains $C_1=\{v_1, v_2,..., v_m\}$ and $C_2=\{w_1, w_2,..., w_k\}$. Two node pairs v_i and w_j are selected which satisfy the chain link capacity; $d(C_1)-d(v_i)+d(w_j)\le C_L$ and $d(C_2)-d(w_j)+d(v_i)\le C_L$, for $i=1,.., m$ and $j=1,..., k$. Then two nodes v_i and w_j are exchanged which minimize the cost difference between the inserted links and deleted ones. In Fig. 5(b), thick and dotted lines represent the inserted link and deleted one, respectively.

The formal steps for the move procedure in the tabu search are presented as follows.



(a) Insert Move

(b) Swap Move

Fig. 5. Insert and swap move in tabu search.

3.2.3. Move procedure

Step 1. Let $C_1, C_2,..., C_k$ be a set of chains in the current solution.
Step 2. Initialize the variables *move_type*, *cost*, *min*=a larger number.
Step 3. **For** $i=1,..., k$, **do**

```
        For a chain j≠i do {
          For each chain node v in C_i, do {
            If d(v)+d(C_j)≤C_L,
            Then cost=Insert(v,C_i,C_j).
              If cost<0 then insert v into C_j and go to Step 3.
              If cost<min then min=cost, move_type=Insert.
            Else {
              For each chain node w in C_j, do {
                If d(w)+d(C_i)−d(v)≤C_L, and d(v)+d(C_j)−d(w)≤C_L
                Then cost=Swap(v,C_i,w,C_j).
                  If cost<0 then swap v and w and go to Step 3.
                  If cost<min then min=cost, move_type=Swap.
              }
            }
          }
        }
```

Step 4. **If** there is no cost improvement for any chain in the network in Step 3,
Then do the best candidate move (*min*, *move_type*) that has been examined.

3.2.4. Insert(v,C₁,C₂)

Step 1. Let $C_1=\{v_1, v_2,..., p, v, q,...,v_m\}$ and $C_2=\{w_1, w_2,..., w_k\}$.
Step 2. *cost*=the minimum cost of $a_{wi,v}+a_{v,wi+1}+a_{p,q}-a_{wi,wi+1}-a_{p,v}-a_{v,q}$ for $i=1,..., k-1$ (Fig. 5(a)).
Step 3. Return(*cost*).

3.2.5. Swap(v,C₁,w,C₂)

Step 1. Let $C_1=\{v_1, v_2,..., v,..., v_m\}$ and $C_2=\{w_1, w_2,..., w,..., w_k\}$.
Step 2. *cost*=the minimum cost of $a_{vi-1,vi+1}+a_{vi+1,wj}+a_{wj-2,vi}+a_{vi,wj-1}+a_{wj-1,wj+1}-a_{vi-1,vi}-a_{vi,vi+1}-a_{vi+1,vi+2}-a_{wj-2,wj-1}-a_{wj-1,wj}-a_{wj,wj+1}$ for $i=1,... m-2$ and $j=2,..., k-1$ (Fig. 5(b)).
Step 3. Return(*cost*).

3.3. *Tabulist and tabu parameters*

To escape the search from trapping into local optimality, an effective tabulist needs to be designed. The tabulist is a list of forbidden moves. If a candidate move is one of the forbidden moves in the list, the candidate is a tabu move so that the move cannot be chosen unless it satisfies the aspiration criteria. A candidate move that can be chosen is called admissible and the best admissible candidate is finally executed. In this article we consider two tabulists; tabu-add and tabu-delete. Each tabulist keeps a number of predicates in a circular list.

3.3.1. Tabu-add: (node w, chain y). This tabulist restricts a node w to be added back to the chain y. In Fig. 5(a) if the node v in chain 1 was inserted into chain 2 then a predicate (v, C_1) will be enrolled into the tabu-add list. In the following moves, the node v can not be added back into the chain C_1. In a swap move of Fig. 5(b), two predicates (v, C_1) and (w, C_2) are enrolled into the tabulist.

3.3.2. Tabu-delete: (chain y, node w). This tabulist is applied to a move in the reverse form of tabu-add. If a node w was inserted into the chain y, the tabulist restricts the node w to be deleted from the chain y. In case of a swap move, two predicates (C_1, w) and (C_2, v) are enrolled into the tabu-delete list.

Note that the tabu-delete is more restrictive than the tabu-add for a candidate move. In Fig. 5(a), a predicate (C_2, v) in the tabu-delete prohibits the node v to be added into C_1 as well as the other neighboring chain. For the implementation of the tabu moves we also employ a hybrid method which applies tabu-add and tabu-delete in turns. That is, if a move is enrolled into the tabu-add, the next move is enrolled into the tabu-delete.

Tabusize is defined as the number of predicates in tabulist. The determination of a reasonable tabusize gives an impact on the performance of tabu search. If the size is too small, cycling behavior which revisits some earlier solutions may occur during the search. If it is too large, it may induce the search to follow new trajectory too frequently. Thus a reasonable number of tabusize needs to be considered depending on the problem size.

3.4. *Aspiration criteria*

Compared with the constraining effect of tabu restrictions, aspiration criteria make the search process free. An aspiration criterion is designed to overrule tabu status and make a candidate move in tabu status admissible. In this article, we use two aspiration criteria. For a candidate move which is in tabu status, if the network cost is less than the following aspiration criteria, the search overrules the tabu status.

(1) global aspiration criterion: the network cost is less than the current best solution.

(2) local aspiration criterion: the network cost is less than the local minimum obtained most recently.

In the local criterion, the local minimum is updated whenever an uphill move occurs. Since the local criterion is less restrictive than the global one, more explorative search is expected by the local criterion. However, it may produce unnecessarily many moves compared to the global criterion. We thus compare the two criteria in Section 4.

3.5. *Diversification strategy*

The diversification strategy is helpful for the search to explore new regions of the solution space. It thus enables the search process to escape the trap of local optimality. In this study, a spilt-merge operation is presented for the diversification strategy. The split-merge operation divides a chain into two chains or merge two separate chains into one. Any chain, the demand of which is larger than $C_L/2$, is splitted into two by deleting the most expensive link of the chain. Also, each splitted chain can be merged into other chain as far as the chain capacity constraint is satisfied. Figure 6 illustrates the split-merge operation. In the figure chain 1 and 2 are splitted into two chains respectively. One splitted part of chain 2 is then merged to chain 3.

3.6. *Tabu search procedure*

Based on the previous discussion, we present a tabu search procedure for the RCDH problem. For termination criteria, Short-Term and Long-Term are used for pure tabu search and diversification phase, respectively.

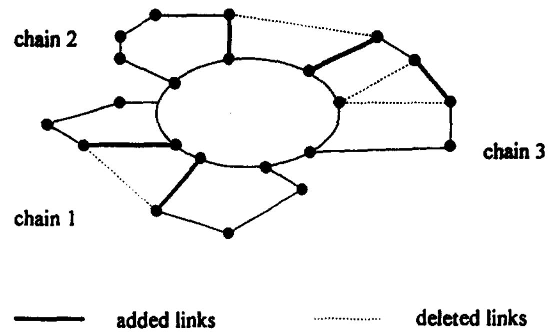


Fig. 6. Split-merge operation in diversification.

Tabu search procedure

Step 1. Initialization phase
1.1. Construct an initial chain for a given ring topology.
1.2. Initialize the tabulist and aspiration criteria.
1.3. Short_Term = Long_Term = 5 and short_term = long_term = 0.

Step 2. Pure tabu search phase
2.1. For each chain in the network, do the move procedure in Section 3.2 by checking tabu status and applying aspiration criterion.
2.2. **if** a new best solution is found by the move, **then** short_term = 0.
else short_term = short_term + 1.
2.3. **if** short_term ≤ Short_Term, **then** go to Step 1.
else go to diversification phase.

Step 3. Diversification phase
3.1. long_term = long_term + 1;
3.2. **if** long_term > Long_Term, **then** stop the tabu search.
else do the split-merge operation and initialize tabulist.
3.3. Go to pure tabu search phase.

4. COMPUTATIONAL RESULTS

To test the performance of the proposed tabu search algorithm for the RCDH problem, two types of problems are considered: fixed demand and random demand. In each type 25 problems are generated such that each set of five problems has different number of chain nodes. The numbers of chain nodes examined are $|C| = 10, 20, 30, 40, 50$. The number of ring nodes $|R|$ is fixed to 10 and the ring topology is given. All the computational results in this section are coded by C language and tested on WorkStation HP/9000 Series.

Table 1 specifies problem to be tested. In the table $d(v)$ and C_L respectively represent the demand of a chain node v and the chain link capacity. In problems with fixed demands, a fixed demand is given for each node in the network, while in problems with random demands the demand at each node follows uniform distribution over 0.2, 0.4, 0.6, 0.8 or 1.0 with equal probability. Note that the problems with random demands are more difficult than those with fixed demands. When the demands are fixed, the number of nodes to be inserted into a chain can be predetermined. However, when demands are random,

Table 1. Test problems

	Problem Set	$\|C\|$	$d(v)$	C_L
Fixed demands	Set 1	10.00	1.00	OC-3
	Set 2	20.00	1.00	OC-6
	Set 3	30.00	0.50	OC-3
	Set 4	40.00	0.50	OC-6
	Set 5	50.00	0.40	OC-6
Random demands	Set 1	10.00	Uniform*	OC-3
	Set 2	20.00	Uniform*	OC-3
	Set 3	30.00	Uniform*	OC-6
	Set 4	40.00	Uniform*	OC-6
	Set 5	50.00	Uniform*	OC-6

*Demands are generated uniformly over 0.2, 0.4, 0.6, 0.8 and 1.0.

Table 2. Comparison of initial chain construction methods

Number of nodes	10.00	20.00	30.00	40.00	50.00
Nearest neighbor	1375.00	2118.00	2960.00	3156.00	3427.00
Chain expansion	1406.00	2363.00	2997.00	3335.00	3464.00
Random chains	1380.00	2319.00	3008.00	3514.00	3740.00

Each value is averaged over five instances.

each chain might have different number of nodes. Thus, in problems with random demands, additional move steps are necessary to decide the nodes that can be inserted into a given chain capacity. This clearly makes the tabu search difficult in steps with insert and swap moves.

In the experiments, chain nodes are randomly generated in the 300 by 300 Euclidean plane. A set of potential links are also generated in the underlying network with each node degree ranged from 6 to 10. Each link cost is given as the Euclidean distance between two end nodes in the network.

Table 2 shows the performance of three initial chain construction methods in the problems with fixed demands. In the table, random chains means the network cost of the best solution obtained by applying the random chain construction method. The nearest neighbor method gives better solutions than two other methods in all problems. Thus the nearest neighbor is employed as an initial chain construction method for all experiments to follow.

To solve the RCDH problem we performed the tabu parameter tuning experiments for various tabu operators and tabusizes. The experimental results for the problems with fixed demands are illustrated in Figs 7–10.

In Fig. 7, three tabulists, tabu-add, tabu-delete and hybrid method, are compared with a simple local search in which only moves are applied without tabulists, aspiration criterion and diversification strategy. The hybrid method is the combination of the two tabulists discussed in Section 3.3. From the figure we conclude that tabu-add is the most appropriate tabulist for the RCDH problem.

Figure 8 shows the tabu search with different tabusizes. Tabu-add is employed as a tabulist for each problem. From the figure, it seems reasonable to use tabusize of 3 for the 10 node problems, 5 for 20, 30 and 40 node problems and 7 for 50 node problems.

In Fig. 9 we compare the performance of tabu search using two aspiration strategies; local and global aspiration criteria. The network cost and number of moves generated by each method are compared with the method without an aspiration strategy. The local criterion gives better performance than the global one at the expense of more number of moves. However, since the number of moves generated is not explosive, the local aspiration strategy is employed in the experiments to follow.

In Fig. 10, the diversification strategy and the multiple startings with random initial solutions are compared with the pure tabu search without the diversification. The power of the diversification strategy is prominent compared with the multiple starting strategy in problems with large number of chain nodes.

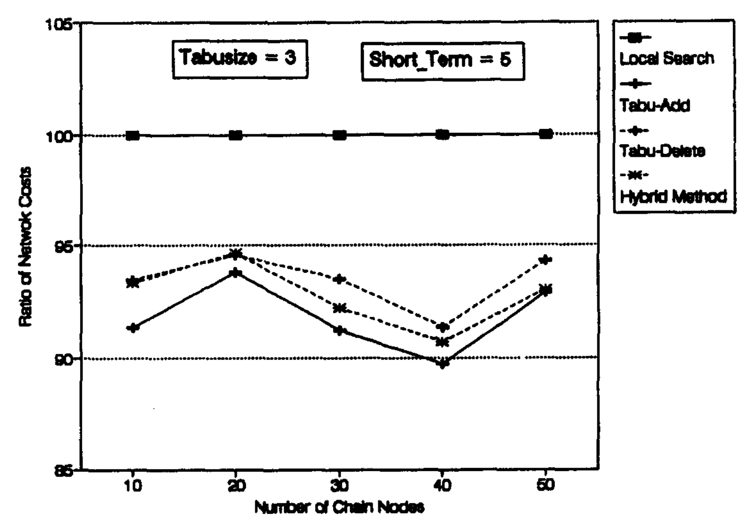


Fig. 7. Determination of tabulist.

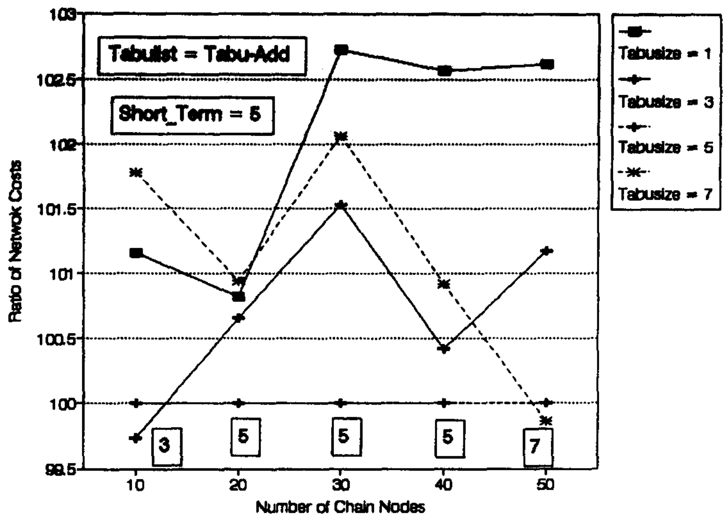


Fig. 8. Determination of tabusize.

Tables 3 and 4 show the performance of the tabu search procedure with operators and parameters as recommended above. The CPLEX [18] is used to obtain optimal solutions of the RCDH problem by employing the cutting plane procedure of Section 2.5. The network cost in the table represents a relative percentage compared with the optimal solution. Unfortunately, for problems with 40 and 50 nodes, the RCDH problem cannot be solved within three hours. For those cases, we only present the lower bound for each instance.

From the tables, it is clear that the proposed tabu search is very effective both in solution quality and CPU seconds. The gap from the optimal solution is approximately 1%–4% for problems with 10, 20 and 30 nodes. Even if the effectiveness of the proposed tabu search could not be verified in problems with more than 40 nodes, it is clear that the gap is approximately 10% from the lower bound.

5. CONCLUSIONS

A ring-chain architecture with dual homing survivability is considered for metropolitan telecommunication networks. In the architecture, hub and high traffic nodes are covered with a SHR and other nodes with chains. Given a ring topology, the ring chain dual homing problem is formulated as an integer programming model which minimizes the link cost of chains while satisfying the dual homing constraint. It is shown that the problem is NP-complete.

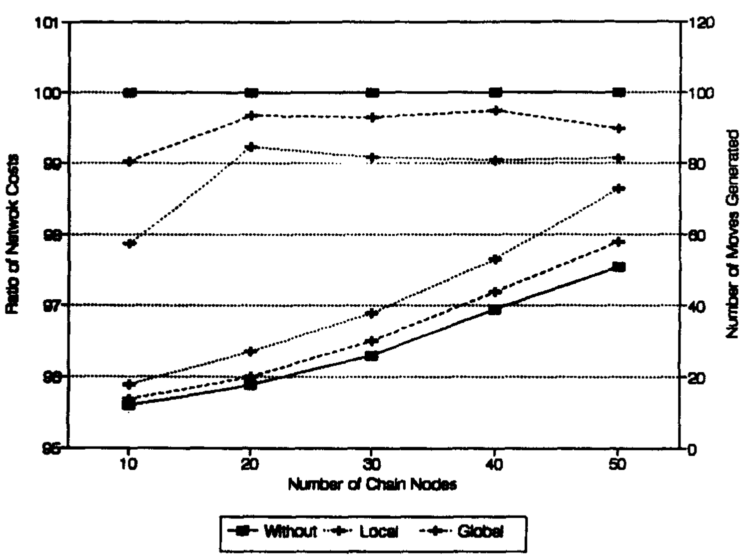


Fig. 9. Aspiration strategy.

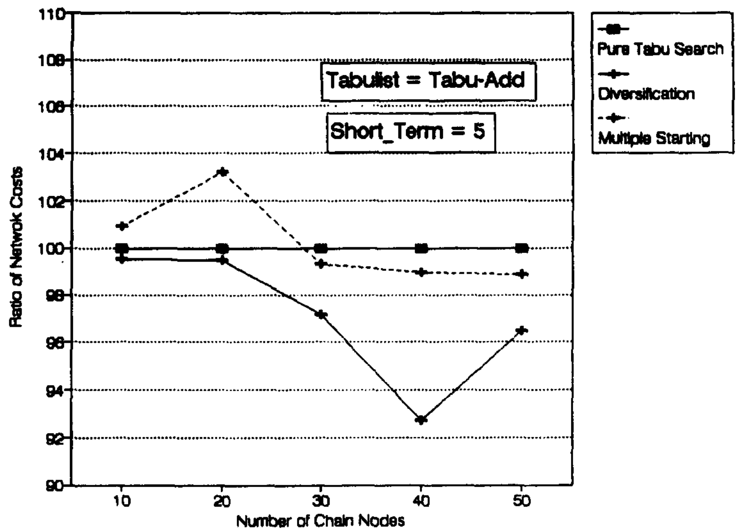


Fig. 10. Diversification.

Table 3. Computational results of tabu search in problems with fixed demands

Number of nodes	10		20		30		40		50	
	Tabu search	Optimal solution	Tabu search	Optimal solution	Tabu search	Optimal solution	Tabu search	Lower bound	Tabu search	Lower bound
Problem 1	101.88	100.00	100.00	100.00	101.81	100.00	103.36	100.00	111.66	100.00
Problem 2	100.00	100.00	100.00	100.00	104.01	100.00	104.11	100.00	105.45	100.00
Problem 3	100.74	100.00	100.95	100.00	104.42	100.00	102.09	100.00	112.33	100.00
Problem 4	100.00	100.00	100.71	100.00	100.26	100.00	110.75	100.00	112.34	100.00
Problem 5	100.00	100.00	101.65	100.00	101.92	100.00	109.39	100.00	107.07	100.00
Average	100.53	100	100.66	100	102.55	100	105.86	100	109.78	100
	(1.41)	(38.20)	(4.60)	(782.40)	(8.77)	(9766)	(10.60)	(3 h)	(16.22)	(3 h)

The values in the parenthesis are the CPU seconds.

Table 4. Computational results of tabu search in problems with random demands

Number of nodes	10		20		30		40		50	
	Tabu search	Optimal solution	Tabu search	Optimal solution	Tabu search	Optimal solution	Tabu search	Lower bound	Tabu search	Lower bound
Problem 1	100.00	100.00	102.13	100.00	103.76	100.00	106.34	100.00	111.92	100.00
Problem 2	102.65	100.00	101.39	100.00	103.69	100.00	105.21	100.00	108.69	100.00
Problem 3	101.18	100.00	102.56	100.00	104.69	100.00	107.78	100.00	110.38	100.00
Problem 4	101.28	100.00	102.43	100.00	104.34	100.00	107.48	100.00	111.21	100.00
Problem 5	100.33	100.00	101.76	100.00	103.56	100.00	108.42	100.00	109.31	100.00
Average	101.09	100	102.05	100	104.01	100	107.05	100	11031	100
	(3.21)	(88.23)	(7.43)	(1131.89)	(18.93)	(10032)	(64.28)	(3 h)	(105.14)	(3 h)

The values in the parenthesis are the CPU seconds.

An efficient tabu search procedure is proposed to solve the problem. Two types of moves, insert and swap, are employed to improve the solution starting from an initial chain construction. To avoid the cycling of the search, two tabulists, tabu-add and tabu-delete are proposed and examined. As a diversification strategy, the split-merge procedure is employed to help the search explore new regions of solution space.

Computational results show that the proposed tabu search provides near optimal solution within a few seconds. The difference is at most 4% from the optimum in problems with 10, 20 and 30 nodes. Even in 40 node problems the average gap is 7% from the lower bound.

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