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A Decomposition Approach to Assign Spare Channels in Self-Healing Networks

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Abstract

Intelligent transmission network elements such as Digital Cross Connect Systems and Add/Drop Multiplexers enable network restoration by dynamic reconfiguration of the network during failure events. Fast line and path restoration is possible by pre-assigning spare capacity to network links. The paper suggests a decomposition approach for the task of finding an economic placement of spare channels in trunk networks to cope with single link failures. The approach is based on a set of properties derived from a Linear Programming network model which was published in this area. Under reasonable assumptions, the decomposition approach often leads to an optimal solution. A numerical example, considered already in the literature, is analysed by network decomposition to illustrate the merits of the approach developed.

1 Introduction

The introduction of new transmission standards of Synchronous Digital Hierarchy (SDH) and Synchronous Optical Network (SONET) opens new capabilities for improved management and utilization of network resources.

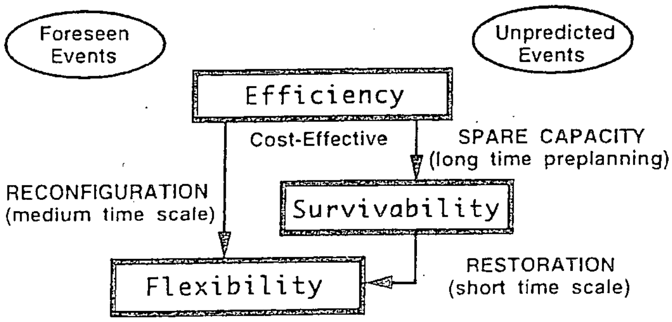


Fig. 1 - Relationship of Functional Capabilities

Three key issues related to functional capabilities of SDH/SONET networks can be specified (Chujo *et al.* [3]): (i) **Flexibility** - derived from the use of new intelligent, remotely controlled, devices such as Digital Cross Connect Systems (DCSs) and Add/Drop Multiplexe: (ADMs) for network reconfiguration; (ii) **Survivabi ity** - due to the instigation of restoration procedur during failures events and the preplanning of spare c: pacity; (iii) **Efficiency** - cost-effective implementatic of (i) and (ii). Efficiency has the potential to direct] affect network reconfiguration in the case of foresee events such the daily changes in traffic load. It als plays an important role in restoration schemes and th preplanning of spare-capacity. The relationship amon these network capabilities is illustrated in Figure 1.

Survivability studies have led to the creation of var: ous self-healing strategies, suitable for the loop, inte office and trunk networks. Distributed Self-Healin Rings (Wu *et al.* [8], [9]), which mainly rely on relativel inexpensive ADM components, were found cost-effectiv solutions for metropolitan areas. For the long-distanc networks, inter-hubbed highly connected topologies ar usually considered. An inter-hubbed network is ofte: composed of high capacity links connecting the DC: hubs. Any link failure of this network may cause a se vere degradation of service quality. Two main researc] areas are related to such networks: (i) Economic place ment of spare channels across the network which wil be utilized under failure conditions (Sakauchi *et al.* [7] Grover *et al.* [6]); and (ii) Effective and fast restoratioı procedures at failure events. The control of restora tion algorithms can be distributed (Grover [5], Yang anc Hasegawa [10] and Chujo *et al.* [4]), centralized (Bellar) and Mizushima [1]) or a hybrid of the two (Baker [2]).

This paper concentrates on the economic pre assignment of spare channels in inter-hubbed networks More precisely, the paper explores the procedure developed by Sakauchi, Nishimura & Hasegawa [7], called henceforth in this paper the SNH procedure, for the assignment of spare capacity. The purpose of this study is: (i) to utilize the SNH procedure for several possible variants; (ii) to derive a set of useful properties by which one can simplify various considerations of analysed networks, and (iii) to obtain new insights into the relationship between spare capacity and network topology.

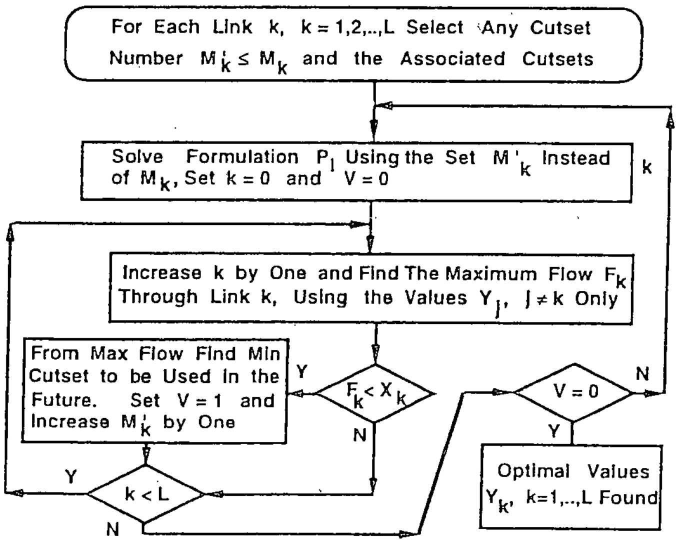
Section 2 briefly describes the SNH procedure and suggests several variants to it. Section 3 presents a decomposition approach of the SNH procedure for typical subnetworks and derives some useful properties. In Section 4 we apply the decomposition approach to a network considered by [10], [7] and [6].

2 Spare-Channel Assignments

Here we present several optimal spare-channel assignments schemes. Consider an inter-hubbed network for which we define:

- N – Total network nodes (DCC hub sites) indexed $k = k, 2, .., N$.
- L – Total physical network links connecting the hubs, indexed $k = 1, 2, .., L$.
- X_k – Number of working channels of link k, $k = 1, 2, .., L$.
- Y_k – Number of spare channels of link k, $k = 1, 2, .., L$.
- M_k – Number of cutsets associated with link k, $k = 1, 2, .., L$.
- $S_{j,k}$ – The jth cutsets associated with link k, $j = 1, 2, .., M_k$, $k = 1, 2, .., L$. The symbol $i \in S_{j,k}$ implies that link i is an element of the cutset $S_{j,k}$.

2.1 The SNH Procedure



Flow Chart for the SNH Procedure

An optimal spare-capacity assignment for network restoration following any single link failures can be obtained by solving the following Linear Programming (LP) model:

$$P_1: \qquad Min \left\{ \sum_{k=1}^{L} Y_k \right\}$$

S.t.

$$\sum_{i \in S_{j,k}} Y_i \geq X_k, \qquad j = 1, .., M_k, \quad k = 1, .., L$$

$$Y_k \geq 0, \qquad k = 1, .., L$$

The above P_1 model has L unknowns and $\sum_{k=1}^{L} M_k$ constraints. The flow chart illustrates the SNH procedure which aims to avoid the search for all cutsets $S_{j,k}$ and their associated constraints. (This task may be complex when analysing large scale networks.)

2.2 Other Related Procedures

The SNH procedure can be extended in several ways Consider the case where the cost of the spare channels is link dependent and partial restoration is allowed. In addition, there might be power processing limitations at certain nodes which limit the number of spare channels those nodes can handle. For such cases we define:

- C_k – The cost of a spare channel assigned to link k, $C_k > 0$, $k = 1, 2, .., L$.
- q_k – The partial restoration level required for link k, $1 \geq q_k \geq 0$, $k = 1, 2, .., L$.
- I_j – Maximum number of spare channels node j is capable of handling, j=1,2,.., N.
- R_j – The set of links connected to node j.

The LP formulation for such cases would be:

$$P_2: \qquad Min \left\{ \sum_{k=1}^{L} C_k Y_k \right\}$$

S.t.

$$\sum_{i \in S_{j,k}} Y_i \geq q_k X_k, \qquad j = 1, .., M_k, \quad k = 1, .., L$$

$$\sum_{i \in R_j} Y_i \leq I_j, \qquad j = 1, .., N$$

$$Y_k \geq 0, \qquad k = 1, .., L$$

The SNH procedure for this general variant is still valid using the formulation P_2 instead of P_1.

For a given network, the addition of physical links may lead to a reduced need for spare channels on the existing links. The SNH procedure can still be used for evaluating such cases. The procedure is used by assigning zero working channels to the added links and updating the values M_k and the appropriate cutsets $S_{j,k}$. The

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cost of adding physical links to an inter-hubbed network might therefore be compensated by a lower overall value of spare channels in the network. This derives from the fact that the network becomes more connected. The relationship between connection degrees and spare channels is discussed further in the next section.

3 The Decomposition Approach

The SNH procedure relies on the requirement that any value X_k should not exceed the spare capacity of *every* cutset associated with the link k. For practical purposes it is important to try and define typical subnetworks for which the above requirement is alleviated. Such an approach has the potential to simplify analysis of a network to a level that either a near or even an optimal solution can be found with less effort when it is compared to the original SNH procedure. Moreover, this approach may lead to new insights to the issue of spare-channel assignment.

3.1 Bypass Subnetworks

Consider a bypass subnetwork having two bypass links with working channels X_1 and X_2 and spare channels Y_1 and Y_2 respectively as in Figure 2. The base link is connected via the base nodes to the rest of the network (part A). Part B presents an equivalent subnetwork for the task of spare-channel assignment. The representation of the bypass by an equivalent link with the values X_E and Y_E (part C) can be further converted to a single link with values which also take into account the dimension of the base link (part D). The representation of the network shown in D is simpler to analyse than the original network shown in A since the network now has less links and nodes.

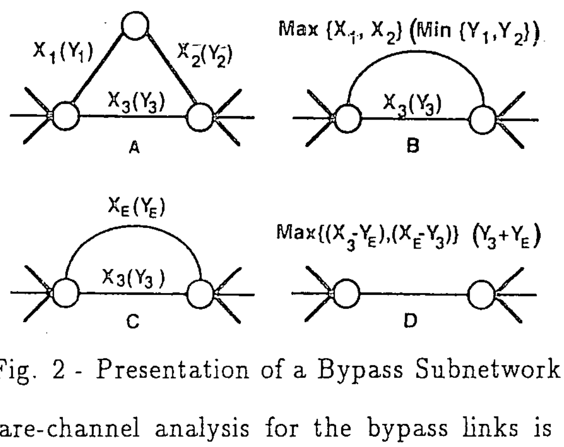

Fig. 2 - Presentation of a Bypass Subnetwork

Spare-channel analysis for the bypass links is very simple, as link 1 has a cutset which is composed of link 2 only and vice versa. Thus, $Y_2 \geq X_1$ and $Y_1 \geq X_2$. Assigning the lower bound $Y_1 = X_2$ and $Y_2 = X_1$ usually leads to an optimal solution for the bypass subnetwork. Recall that Y_3 has not yet been found. This value depends on the rest of the network (when keeping the value Y_1 and Y_2 unchanged). Bypass subnetworks with $K \geq 3$ bypass links have a very similar representation. For such cases X_E (Y_E) is the largest (second largest) value among the working channels of the bypass links.

3.2 Triangular Pyramid Subnetworks

In highly connected networks pyramid subnetworks can often be seen. Consider a triangular pyramid whose base is fully connected, as shown in Figure 3.

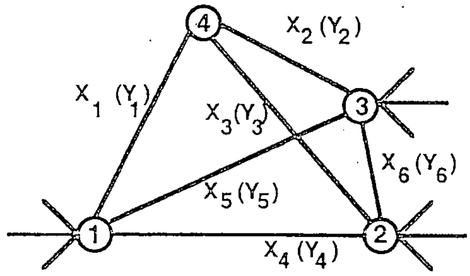

Fig. 3 - A Triangular Pyramid Subnetwork

In the above subnetwork, one may recognise cutsets associated with the links connecting the top of the pyramid to the base (links 1,2 and 3). For these links we suggest finding a spare-channel assignment based on the following LP formulation:

$$P_3: \qquad Min \quad \left\{ \sum_{k=1}^{3} Y_k \right\}$$

S.t.

$$\sum_{k=1,\ k\neq j}^{3} Y_k \geq X_j, \qquad j = 1,2,3$$

$$Y_k \geq 0, \qquad k = 1,2,3$$

The above formulation has a simple optimal solution:

$$Y_j = [\sum_{k=1}^{3} X_k]/2 - X_j \geq 0, \quad j = 1,2,3 \qquad (1)$$

Getting a negative value Y_j (when the value $X_j > \sum_{k=1,k\neq j}^{3} X_k$) represents the degeneracy case, for which we set $Y_j = 0$. The other two Y_j values still can be simply derived from the constraints. The solution for this case is usually not unique. In case where Eq. (1) leads to non-integer values Y_j, it is still possible to get an optimal integer solution by increasing two Y_j values by 0.5 and decreasing the other Y_j value by 0.5. The analysis of Figures 4 and 5 will help in selecting the preferred solution for these special cases.

Assuming that the values Y_k, $k = 1,2,3$ are known then the next step in the decomposition approach is to simplify the network. This will be done in two stages which are illustrated by Figures 4 and 5. Figure 4 presents restoration considerations following a single failure at each of the links 1, 2 and 3.

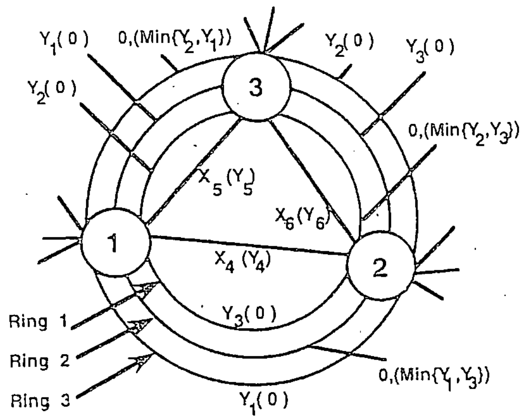

Fig. 4 - Restoration Considerations

First, consider the case where link 1 in Figure 3 is under failure conditions. For this case the restoration scheme is looking for Y_2 spare channels between nodes 1-3 and Y_3 spare channels between nodes 1-2. Satisfying these requirements and using the spare channels Y_2 and Y_3 of links 2 and 3 respectively, ensures full restoration of link 1 as $Y_2 + Y_3 = X_1$ (see Eq. (1)). In addition, there are Min $\{Y_2, Y_3\}$ spare channels available between nodes 2-3 under normal conditions of the network. These considerations are depicted by ring 1 of Figure 4. Similarly, rings 2 and 3 of Figure 4 represent the restoration aspects of links 2 and 3, respectively.

It is readily seen that bypass subnetwork rules can now be applied to simplify the network obtained. Figure 5 presents the simplified network under the reasonable assumption that the pyramid base link values X_k, $k = 4,5,6$ are greater than the values Y_k, $k = 1,2,3$ as $\sum_{k=1}^{3} Y_k = \sum_{k=1}^{3} X_k/2$ (see Eq. (1)). If this is not the case a similar simplification can still be achieved.

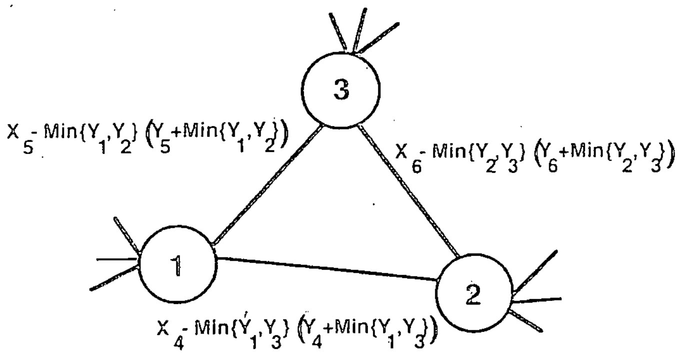

Fig. 5 - Simplification of the Pyramid Subnetwork

Analysing the network in Figure 5 is significantl simpler than analysing the original network as the ba links represent now the entire pyramid subnetwork.

3.3 General Pyramid Subnetworks

The triangular pyramid analysis can be generalize. Consider a subnetwork composed of n, fully-connected base nodes and a set of n links, links k, $k = 1,2,..$ which connect the top node of the pyramid to the ba nodes. The number of links connected to a base node is usually greater than n as additional links may co nect the node to the rest of the network. For this case, one can identify n cutsets, each of which is associated with a certain link k. Spare-channel assignment for t pyramid set of links can be found by the following LI .

$$P_4: \quad Min \left\{ \sum_{k=1}^{n} Y_k \right\}$$

S.t.

$$\sum_{k=1,\ k\neq j}^{n} Y_k \geq X_j, \qquad j = 1,2,..n$$

$$Y_k \geq 0, \qquad k = 1,2,\ ..,\ n$$

Overlooking degeneracy cases this formulation has the following simple solution:

$$Y_j = [\sum_{k=1}^{n} X_k]/(n-1) - X_j \geq 0, \quad j = 1,2,..n \qquad (2)$$

Eq. (2) is, in essence, a generalization of Eq. (for which $n = 3$. Based on this solution, the objective function obtained is:

$$\sum_{k=1}^{n} Y_k = [\sum_{k=1}^{n} X_k]/(n-1) \qquad (3)$$

The dual LP of P_4 can be presented as follows:

$$P_5: \quad Max \left\{ \sum_{k=1}^{n} X_k U_k \right\}$$

S.t.

$$\sum_{k=1,\ k\neq j}^{n} U_k \leq 1, \qquad j = 1,2,..n$$

$$U_k \geq 0, \qquad k = 1,2,..,n$$

Consider $U_k = 1/(n-1)$, $k = 1,2,..,n$ as a soluti for P_5. The objective function obtained would be:

$$\sum_{k=1}^{n} X_k U_k = [\sum_{k=1}^{n} X_k]/(n-1) \qquad)$$

It can be seen that Eqs. (3) and (4) have the same objective function, which indicates that the soluti s obtained for P_4 and P_5 are optimal. The values $U_k = 1/(n-1)$, $k = 1,2,..,n$ represent "shadow prices" of the primal constrains. More specifically, these values represent the additional cost in terms of spare channels one pays when a certain X_k value is increased by one. This seems to be a valuable indication about the relationship between spare capacity and connectivity for full restoration of meshed networks following a single link failure. This relationship was observed by Chujo *et al.* [4] but a more rigorous proof is obtained here.

4 A Numerical Example

In this section we apply the approach developed above to a well known network analysed by [10], [7], [6].

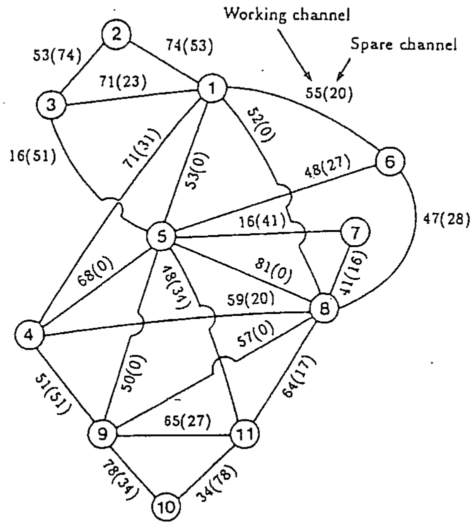

Fig. 6 - The Network Considered

Figure 6 presents the network and the optimal solution found by the SNH procedure. The network has 11 nodes, 23 links and thus 23 unknown spare channels. It is not difficult to recognize 3 bypass subnetworks: nodes (1, 2, & 3); (5, 7 & 8); and (9, 10 & 11) in addition to a triangular pyramid subnetwork, nodes (1, 5, 8 & 6). Applying the decomposition approach to these subnetworks, one can immediately find optimal values for 9 out of the 23 unknowns as follows: $Y_{1,2} = X_{2,3} = 53$, $Y_{2,3} = X_{1,2} = 74$, $Y_{5,7} = X_{7,8} = 41$, $Y_{7,8} = X_{5,7} = 16$, $Y_{9,10} = X_{10,11} = 34$, $Y_{10,11} = X_{9,10} = 78$. Let $Z = (X_{1,6} + X_{5,6} + X_{6,8})/2 = (55 + 48 + 47)/2 = 75$, thus, $Y_{1,6} = Z - X_{1,6} = 75 - 55 = 20$, $Y_{5,6} = Z - X_{5,6} = 75 - 48 = 27$, $Y_{6,8} = Z - X_{6,8} = 75 - 47 = 28$. Moreover, presenting the above subnetworks in a simplified representative manner, as described, creates two triangular pyramids (nodes 1, 4, 8 & 5 and 5, 8, 9 & 11) and another bypass network (nodes 1, 3 & 5). Applying decomposition to the bypass (1, 3 & 5), one gets $Y_{3,5} = Max(71 - 53, 74 - Y_{1,3})$. Simplification of this bypass leads to another triangular pyramid, (nodes 4, 5, 8 & 1), for which we get $X_{1,4} = 71 = Min(Y_{3,5}, 53$ $Y_{1,3}) + Y_{1,5} + Y_{1,8} + 20$. Simple minimization for the unknowns yields the solution: $Y_{1,5} = 0, Y_{1,8} = 0, Y_{3,5}$ $71 - 20 = 51, Y_{1,3} = 74 - Y_{3,5} = 74 - 51 = 23$ and th $Y_{1,4} = 74 - Y_{1,3} - 20 = 74 - 23 - 20 = 31$. The read may find the last 9 unknowns as an exercise.

ACKNOWLEDGEMENTS

The author would like to thank David Gates from Tel com Australia Research Labs for useful comments. Th permission of the Director of Research, Telecom Au tralia, to publish this paper is hereby acknowledged.

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