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# Resource Assignment in Multi-service Survivable Networks Based on the Cycle-oriented Approach

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**Abstract:** Service Convergence is a prospective goal to reach considerable economic benefits in a Multi-Service Network (MSN) environment. Elements such as Multi-Service Provisioning Platforms and Multi-Technology Network Management systems together with suitable MSN modeling are the key underlying components supporting that goal. The paper relates to the framework of MSN modeling and specifically addresses the issue of assigning resources in an MSN environment to provide differential survivability. In this paper we specify aspects of MSN survivability, explain the Cycle-oriented approach for Path Protection/Restoration and the survivable traffic types to be supported. We detail two network models for optimal resource allocation with special emphasis on large-network considerations and present some typical results that reflect the strengths of the network models developed.

**Keywords:** Multi-service Networks, Path Protection/Restoration, Optimal Network Planning.

## 1. INTRODUCTION

A unified Multi-Service Network (MSN) has the inherent advantages with respect to service creation and efficient use of resources. Service Convergence (SC) is desirable due to the potential cost savings in both capital and operational expenditures that may be achieved [13].

| | |
|---|---|
| Business/User | 1. SC goal setting |
| Service | 5. Activation of SC |
| Network | 4. Suitable MSN Modeling<br>3. Employing MTNM Systems |
| Network Element (NE) | 2. Use of suitable NEs, e.g. MSPPs |

Table 1 – Components Supporting Service Convergence

Table 1 shows the goal of SC and its underlying components in the layered view of Network Management. It can be seen that SC has to rely on appropriate multi-service elements, e.g. Multi-Service Provision Platforms (MSPPs), associated with the Network-Element (NE) layer. These elements enable the convergence of voice, video and data-centric services on a single platform, using common resources and operational procedures for both provisioning and proper functioning of these services. Developments of the optical technology and the introduction of wavelength services have led to increased convergence in the Network layer by employing advanced Multi-Technology Network-Management (MTNM) systems which manage the various transport network resources and the services in an end-to-end manner. An additional component in the SC framework is the development of suitable MSN models that address various design issues for proper assignment and improved utilization of network resources, naturally associated with the Network layer. While setting the goal of SC belongs to the Business layer, the actual activation of SC is in the Service layer. The serial numbers 1-5 given to the components mentioned, as in Table 1, reflect the chronological order of component setting for SC.

The rest of the paper is organized as follows: Section 2 specifies main survivability considerations with special attention to multi-service aspects. Section 3 explains the Cycle-oriented approach and the survivable traffic types that can be supported by that approach. Section 4 presents an optimal resource-allocation model for MSNs. Section 5 deals with large-network considerations and revises the network model accordingly. Section 6 analyzes a test network and shows some typical results that reflect the strengths of the network models developed.

## 2. MSN – SURVIVABLE CONSIDRATIONS

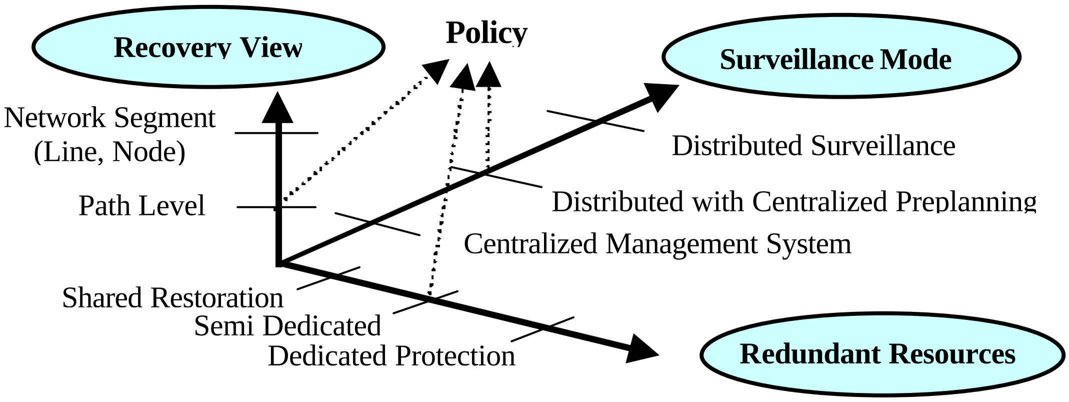

Figure 1 – State Space of Survivability

Strategies for network survivability [17] vary considerably. Figure 1 presents the state-space of survivability, its main dimensions are: scope of recovery view to bypass failure events, mode of surveillance/management and nature of redundant resources. Combined selection from these dimensions determines a **policy** for survivability.

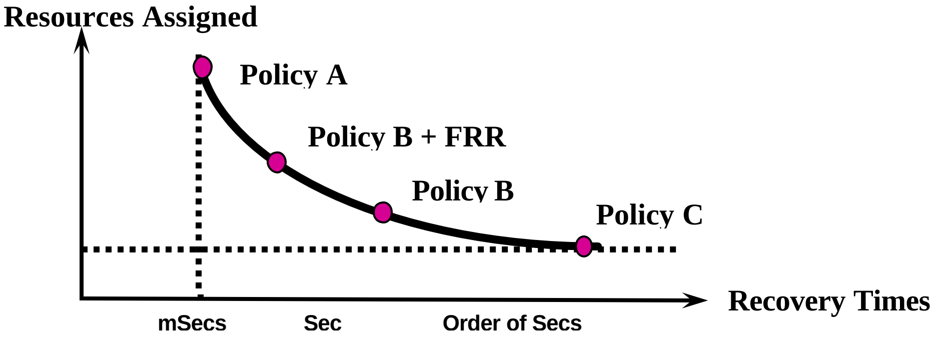

Figure 2 - Tradeoff between Resources Assigned and Recovery Times

Figure 2 illustrates a typical tradeoff between the amount of resources assigned (working + redundant + management) and the expected recovery times for various policies. Policy A represents the case of dedicated protection 1+1, using a distributed surveillance at path ends. Very-fast recovery times are achieved under such a policy while resource allocation is high. Policy B represents Line Restoration with shared redundant resources handled by a central management system. Compared to Policy A, recovery times increases significantly but considerable saving of redundant resources may be accomplished. Enhancement of Policy B is possible by incorporating Fast Re-Routing (FRR) techniques to reduce recovery times at the expense of complexity and additional resources. Policy C represents the most efficient case of resource utilization, using shared redundant resources, Path Restoration and a centralized view at the expense of longer recovery times. Adopting a single policy for survivability in MSNs may lead to mismatching situations, i.e. some services may be over dimensioned in term of resources assigned while other services may experience intolerably long recovery times.

**Previous work**

Resource allocation plays a major role in survivable network design and the proper use of redundant resources is very important. Some different approaches for optimal allocation of shared redundant resources when focusing on Line Restoration are: Cut Sets [14], Hop Limit [7] (both relying on a centralized management system) and p-Cycles (protection cycles) [6] that rely on a distributed surveillance mode at end line sites. Joint optimization of both working and shared redundant resources for Path Restoration has also been considered [8], [11]. Resource allocation designed for survivable Wavelength Division Multiplexing (WDM) networks is presented in [16]. The idea of using backup Virtual Paths (VPs) in Asynchronous Transfer Mode (ATM) networks that are disjoint to the working VPs was proposed and analyzed in [12]; the issue of bifurcation for such cases was studied in [9]. Each of the references mentioned considers a *single* policy for survivability. Papers that refer to multi-service survivable networks and adopt the Line (Span) Protection/Restoration alternative are [2], [5]. Multi-service survivability dedicated to WDM networks for single-link failures, using two service classes, was studied in [14].

## 3. THE CYCLE-ORIENTED APPROACH IN MSNs

Overall objective is to form a network concept with the following capabilities:

- Constitutes a basis for supporting a pre-defined set of policies for survivability so as to meet a variety of service requirements in an MSN environment.
- Enables merging mature and standardized recovery mechanisms for data traffic such as Link Capacity Adjustment Scheme (LCAS) and Rapid Spanning Tree Protocol (RSTP).
- Suitable for implementation by a distributed surveillance mode and still capable of achieving cost-effective use of network resources by centralized pre-planning.
- Optimized for both wide-area networks having mesh-type architectures, for which resource allocation is of high importance, as well as for metro-regional area networks having a mixture of mesh and ring-based network architectures.
- Enables addressing both network-planning and operational considerations. In this paper we concentrate on resource allocation aspects. Operational aspects due to network dynamics when adopting the Cycle-oriented approach are considered in [10].

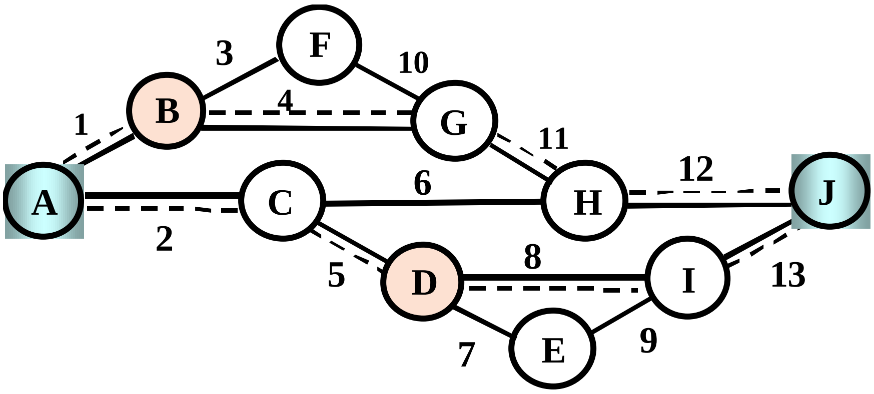

Figure 3 – Basics of the Cycle-oriented Approach

We use Figure 3 to clarify terms of the Cycle-oriented approach (detailed in [10]). Circles represent sites with termination traffic that use MSPP equipment. Striving for survivability at the Path Level, we further assume that for each site pair associated with survivable traffic a non-empty set of *eligible cycles* can be derived, each of which is composed of two end-to-end disjoint paths. Dashed lines highlight one eligible cycle (bi-directional) associated with site-pair A:J that passes through the sequence of links 1-4-11-12-13-8-5-2; its two disjoint paths are: 1-4-11-12 and 2-5-8-13. The highlighted cycle may be associated with other site pairs, e.g. B:D, for which the two disjoint paths are: 1-2-5 and 4-11-12-13-8.

Site-pair survivable traffic may be assigned to one or more cycles, depending on the nature of traffic. If concatenation or splitting is not allowed, site-pair traffic has to be assigned to a single cycle.

Based on the above, we define four survivable traffic types that can be supported by the Cycle-oriented approach, each of which refers to a generic survivable traffic, not restricted to specific telecommunication services. As a result, various application areas, including SDH/SONET, ATM, Ethernet, MPLS and WDM can benefit by using suitable service-dependent mechanisms for survivability associated with the four survivable traffic types.

- **Dedicated Protection Traffic** - Arrangements such as 1+1 or 1:1 at the Path Level can be considered here. Working resources are assigned to one path of the cycle and “hot-standby” resources are allocated to the other path for backup purposes. Considerations of SRLG ensure survivability from any “single point of failure”. End-to-end proper functionality of this traffic type has a distributed management mode, using destination sites for surveillance and protection switching, *regardless* of points of failure along the working path. Failure localization to fix failures can be done after recovery. “Revert to Normal” after failure repair is optional.
- **Semi-dedicated Restoration Traffic** – For dedicated protection traffic, the working and backup paths of a selected cycle are allocated working and protection resources, respectively. This can be termed “fully dedicated” . We define the “semi-dedicated” traffic for which the working path is unchanged while the backup path is only dedicated for recovery. The redundant resources along the backup path are shared with other backup paths. Knowing the restoration path of working trail in advance complies with the cycle-oriented approach and fits well with the mode of distributed management. Failure localization is not required for restoration and surveillance can still be done at destination sites, as before. This is a major alleviating factor that also contributes to reducing recovery times, compared to the more general case of allocating shared resources which require a search for recovery paths upon failures. The “semi-dedicated” case is also called “Fast Mesh”.
- **Split Traffic** - This traffic relies on capacity-concatenation capabilities where a high-rate service stream may be composed of several lower-rate streams. End-to-end site-pair traffic is basically unprotected but some safety margins for survivability can still be achieved. An ideal use of the split traffic relies on Virtual Concatenation (VCAT) incorporated with LCAS that enable acceptable data-service functionality despite failure events. The Cycle-oriented approach fits well with such a scheme. Under normal service conditions site-pair traffic, assigned to a cycle, is split in such a way that both working and backup paths carry live traffic. The two cycle paths mutually back up each other in case of failure events. This means that no more than 50% of site-pair traffic can be affected by any single point of failure. Loss of traffic following a single failure may even be less than 50% in case site-pair traffic is assigned to two or more eligible cycles (number of splits is larger than 2).
- **Group-Connected Traffic** - Maintaining connectivity despite failures, as for the split- traffic, is generalized to a group of site pairs instead of a single site pair. Through capabilities in the Service layer, e.g. VPN, IP or Ethernet, direct as well as indirect communication can be maintained for any site-pair within the group. The Cycle-oriented approach for this traffic type is restricted to form graphically Hamiltonian cycles, traversing through the set of group sites. SRLG considerations are extended to maintain group connectivity despite any single point of failure. This traffic type can meet various data handling specifications, including RSTP, used for Layer 2 data services. The Spanning Tree in this case is automatically formed following any single failure of the affected Hamiltonian cycle, while under normal network conditions, the Spanning Tree is established by arbitrarily deactivating one section of the Hamiltonian cycle.

## 4. RESOURCE ALLOCATION NETWORK MODELING

In this network model we only consider three out of four survivable traffic types: The Dedicated protection, the Semi-dedicated restoration and the Split traffic. The following notation is used:

### Model Sets and Parameters

| | |
|---|---|
| $I$ | Number of network fibers, indexed $i=1,..,I$. |
| $N$ | Number of sites, indexed $n=1,..,N$. |
| $J$ | Number of site pairs having survivable traffic requirements, indexed $j=1,..,J$. |
| $t$ | Index for survivable traffic type. Without loss of generality we use: $t$=1, 2 and 3 for Dedicated protection, Semi-dedicated restoration and Split traffic types, respectively. |

| | |
|---|---|
| $T_j^t$ | Total traffic demand of traffic type *t* associated with site pair *j*, $t=1,2,3$, *j=1,..,J.* |
| $l_j^t$ | Modeling traffic demand of type *t* and pair *j*, $t=1,2,3$, *j=1,..,J;* <br> $l_j^t = \begin{cases} T_j^t, & t=1,2 \\ 0.5 \cdot T_j^t, & t=3 \end{cases}$ |
| $R_j$ | Number of eligible cycles considered for connecting pair *j*, indexed *r=1,.., R j.* |
| $K$ | Number of failure scenarios considered, including single-link, multi-link and node failures. Without loss of generality, we use the index *k=1,2,,..,I* for link failures, *k=I+1,I+2,..,I+N* for node failures and *k=I+N+1,..,K* for multi-link failures. Clearly: <br> $k=\begin{cases} i & ,1 \le i \le I \quad \text{Failure in link } i \\ I+n & ,1 \le n \le N \quad \text{Failure in node } n \end{cases}$ <br> For each compound failure *k, k>I* (node and multi-link failures), it is required to keep the set of links being affected by the failure *k*. |
| $d_{jr}^{wk}$ | Gets the value "1" if working part of cycle *r*, pair *j*, is affected by failure *k* and "0" otherwise, *k=1,2,..K, j=1,2,..,J, r=1,2,..,R j.* Information on failures *k>I* and their affected links, as explained in previous lines, is used here. Failures *k=I+n1, I+n2* are excluded, get values "0", if *n1 & n2* are the termination nodes of site pair *j*, recalling that recovery of traffic affected by these failures is actually impossible. |
| $d_{jr}^{bi}$ | Gets the value "1" if the backup part of cycle *r*, pair *j* uses link *i* and "0" otherwise |
| $C_i$ | Cost per system on link *i* , *i=1,2,..,I* |
| $M$ | Modularity value, total capacity per system. M is related to the nature of capacity resources. For SDH/SONET traffic, it stems from capacity standards, e.g. if capacity units are in terms of STM1 or VC4, and systems represent STM16 pipes then M=16. WDM considerations, for which capacity units are in terms of wavelengths, may yield cases where M=1. |

**Model Variables:**

| | |
|---|---|
| $X_i$ | Number of systems assigned to link *i* . |
| $W_i$ | Total working capacity on link *i* . |
| $D_i$ | Dedicated protection capacity on link *i* (for traffic type 1). |
| $S_i$ | Shared restoration capacity on link *i* (for traffic type 2). |
| $f_{j,r}^t$ | Traffic flow assigned to cycle *r* of pair *j* for traffic type t, $t=1,2,3$. |

## Integer-Programming Model:

$$Min \quad \{ \quad \sum_{i=1}^{I} C_i \cdot X_i \quad \}$$

S.t.

$$W_i + D_i + S_i \le M \cdot X_i \qquad \forall\, i = 1,2..,\ I \tag{1}$$

$$\sum_{r=1}^{R_j} f_{jr}^t \ge l_j^t \qquad \forall\, t = 1,2,3; \quad j = 1,2,..,\ J \tag{2}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R_j} [d_{jr}^{bi} \cdot f_{jr}^3 + \sum_{t=1}^{3} d_{jr}^{wi} \cdot f_{jr}^t] = W_i \qquad \forall i = 1,2,...,\ I \tag{3}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R_j} d_{jr}^{bi} \cdot f_{jr}^1 = D_i \qquad \forall\, i = 1,2,...,\ I \tag{4}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R_j} d_{jr}^{bi}\cdot d_{jr}^{wk}\cdot f_{jr}^{2} \le S_i,\ \forall k=1,..,K; \qquad i=1,..,I \tag{5}$$

$$X_i\ , W_i\ , D_i\ , S_i\ , f_{jr}^{t} \ge 0 \quad and\ \ Integer \quad \forall i, j, r, t \tag{6}$$

The objective function minimizes total equipment cost. Constraints (1) limit consumption of resources to the available level while Constraints (2) meet modeling traffic demands. Constraints (3) and (4) accumulate working and dedicated protection resources, respectively, while Constraints (5) ensure adequate shared resources due to the failures considered. Amount of constraints is quite small, $O(I^2)$. Model relaxation is thus solvable by commercial Linear Programming solvers, even for very large networks, a major advantage to obtain lower bounds and reference values to evaluate quality of results.

## 5. LARGE-NETWORK CONSIDERATIONS

In this section we focus on considerations associated with large networks with the purpose of addressing computational aspects and network data that enable the reduction of computing effort, time and data storage. This is quite significant for large networks, recalling that traffic considerations when selecting the approach of Path Protection/Restoration is directly related to number of site pairs $J \sim O(N^2)$, compared to number of lines $I \sim O(N)$ when adopting the alternative of Line Protection/Restoration.

### 5.1 Excluding Distant Site Pairs from the Model

We first try to exclude selected site pairs with survivable traffic, thus reducing the value *J*. In particular, it is desirable to exclude distant pairs for which: (i) associated cycles are expected to be vulnerable, long and hard to be maintained; (ii) computational effort to obtain associated cycles can be quite high.

Figure 4 presents a non-homogenous network having core and sparse parts. Assume that site A is associated with survivable traffic to various destination sites, including Z1, Z2 and Z3. For pairs A-Z1, A-Z2 and A-Z3 we suggest using intermediate sites as hubs to carry their traffic. Consider site H1 as a hub for survivable traffic between site A and sites Z1, Z2 and Z3. Under such an arrangement site pairs A-Z1, A-Z2 and A-Z3 are excluded from computation and their traffic is "piggybacked" on site pairs A-H1, H1-Z1, H1-Z2 and H1-Z3. For reliability purposes, traffic of the excluded site pairs can be split between the hub sites H1 and H2. Hub sites may have own facility-protection arrangements.

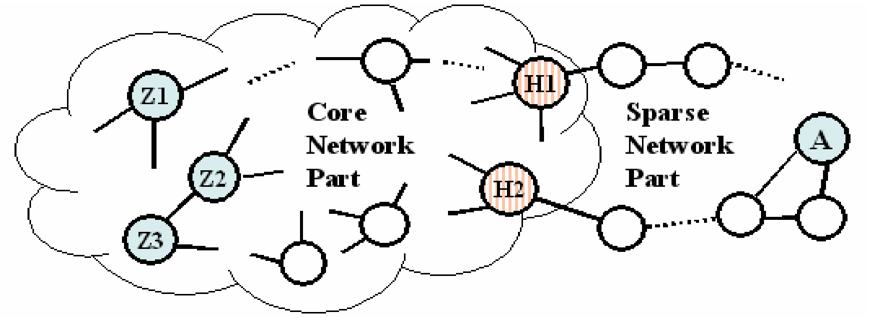

Figure 4 – A Typical Large-Network Situation

### 5.2 Using a "Pool" of Cycles for Network Modeling

The network model presented in the previous section uses for each site pair a group of eligible cycles. As each cycle can be associated with many sites pairs, although not necessarily with all site pairs along the cycle due to SRLG considerations, it is only natural to try using a "pool" of cycles, instead of the individual site-pair cycle groups. Algorithms that enable generating network cycles are in [1], [4]. It is important to note that in large networks the number of network cycles can be one or two orders of magnitude smaller than the sum of cycle groups over all site pairs. Adopting the "pool" of cycles approach requires modifying the network model developed in the previous section in several ways. In order to take full advantage of the "pool" approach, we suggest applying the following two principles:

1. Using a *single* data entry for each cycle, despite being eligible for many site pairs;
2. Keeping a *minimal* set of information for the associates between cycles and site pairs.

We use Figure 3 to illustrate a practical way that complies with the above two principles: The highlighted cycle is recorded as an *ordered* set of links: 1, 4, 11, 12, 13, 8, 5, 2 at the positions 1 to 8, respectively. For pair A:J it is sufficient to indicate that cycle's working and backup paths start at positions 1 and 5, respectively. Similarly, for pair B:D it is sufficient to indicate that cycle's working and backup paths start at positions 7 and 2, respectively.

Based on the above, the model's notation is extended as follows:

**Additional Sets and Parameters for the Revised Model**

| | |
|---|---|
| $R$ | Total number of network cycles considered, indexed $r=1,..,R$. |
| *Set-r* | Set of links associated with cycle $r$. We define *Set-r* as a *Circular* set, where first member follows the last one, a regular feature of math languages, e.g. AMPL [3]. |
| *Card-r* | Cardinality of the *Set-r*. As the *Set-r* is circular, we can rely in the revised model on the term '*p mod_Card-r'* to calculate the actual position of a link in the *Set-r* for any given large integer-position value $p>$*Card-r*. |
| $\Delta^{pi}_{jr}$ | Gets the value "1" if cycle $r$ is associated with pair $j$ and the $p$-th position (member) of *Set-r* represents the link $i$, $i=1,2,..,I$, otherwise gets the value "0". |
| $\Lambda^{k}_{jr}$ | Gets the value "1" if working path of cycle $r$ associated with pair $j$ is affected by failure scenario $k$, $k>0$, and "0" otherwise. We further extend the use of this binary coefficient as follows; it gets the value "1" if cycle $r$ is associated with pair $j$ and "0" otherwise, assigning for this case an artificial value $k=0$. |
| $w(jr)$ | Given starting position of the working path associated with pair $j$ along *Set-r*. |
| $b(jr)$ | Given starting position of the backup path associated with pair $j$ along *Set-r*. |
| $a(jr)$ | Calculated end position of the working path associated with pair j along *Set-r*. |

$$a(jr) = w(jr) + [b(jr) - w(jr) - 1 + Card\text{-}r]\ mod\_Card\text{-}r \tag{7}$$

| | |
|---|---|
| $d(jr)$ | Calculated end position of the backup path associated with pair j along *Set-r*. |

$$d(jr) = b(jr) + [w(jr) - b(jr) - 1 + Card\text{-}r]\ mod\_Card\text{-}r \tag{8}$$

Figure 3 is used once again to clarify results derive from formulas (7) and (8). For site pair A:J, with given cycle positions $w$=1 and $b$=5, we obtain calculated positions of $a$=4 and $d$=8, meaning that working and backup paths use links at the expected positions 1-4 and 5-8, respectively. For pair B:D, with given cycle positions $w$=7 and $b$=2, we obtain calculated positions of $a$=9 and $d$=6, meaning that working and backup paths use links at positions 7, 8, 9 and 2, 3, 4, 5, 6, respectively. As the *Set-r* is circular, the link positions associated with the working path are actually 7, 8, 1, as expected.

**Integer-Programming Revised Model:**

$$Min \quad \{ \quad \sum_{i=1}^{I} C_i \cdot X_i \quad \}$$

S.t.

$$W_i + D_i + S_i \le M \cdot X_i \qquad \forall i = 1,2..,I \tag{9}$$

$$\sum_{r=1}^{R} \Lambda^{0}_{jr} \cdot f^{t}_{jr} \ge l^{t}_{j} \qquad \forall t = 1,2,3; \quad j = 1,2,..,J \tag{10}$$

$$\sum_{j=1}^{J} \sum_{r=1}^{R} [ \sum_{p=b(jr)}^{d(jr)} \Delta^{pi}_{jr} \cdot f^{3}_{jr} + \sum_{t=1}^{3} \sum_{p=w(jr)}^{a(jr)} \Delta^{pi}_{jr} \cdot f^{t}_{jr} ] = W_i \qquad \forall i = 1,2,..,I \tag{11}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R}\sum_{p=b(jr)}^{d(jr)} \Delta_{jr}^{pi}\cdot f_{jr}^{1} = D_i \qquad \forall\, i = 1,2,\ldots, I \tag{12}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R}\Big[\sum_{p=b(jr)}^{d(jr)} \Delta_{jr}^{pi}\Big]\cdot \Lambda_{jr}^{k}\cdot f_{jr}^{2} \le S_i \qquad \forall k = 1,..,K; i = 1,..,I \tag{13}$$

$$X_i\ , W_i\ , D_i\ , S_i\ , f_{jr}^{t} \ge 0 \quad and\ \ Integer \qquad \forall i, j, r, t \tag{14}$$

The revised model follows the previous one. It uses the same objective function, variables and traffic demands, the major differences are related to the binary coefficients. The revised set of constraints can be derived from the original set using the following inter-relationships:

For any given cycle $r$ associated with pair $j$, the equations below are equal to “1” if link $i$ belongs to the working path (and therefore being affected by failure $k=i$) and “0” otherwise.

$$d_{jr}^{wi} = \sum_{p=w(jr)}^{a(jr)} \Delta_{jr}^{pi} = \Lambda_{jr}^{i} \qquad \forall i = 1,2..,I \tag{15}$$

Similarly, for any given cycle $r$ associated with pair $j$, the equations below are equal to “1” if link $i$ belongs to the backup path and “0” otherwise.

$$d_{jr}^{bi} = \sum_{p=b(jr)}^{d(jr)} \Delta_{jr}^{pi} \qquad \forall i = 1,2,..,I \tag{16}$$

In addition, the following holds for all failure scenarios to be considered:

$$d_{jr}^{wk} \equiv \Lambda_{jr}^{k} \qquad \forall k = 1,2..,K \tag{17}$$

All new binary coefficients, except those associated with compound failures $k>I$, are directly derived from network data with the minimal set of parameters $r, j, w,$ and $b$. Binary coefficients associated with compound failures also require information about the set of links being affected by each failure $k$, however, this “pool” amount of information is indeed very small.

## 6. NUMERICAL RESULTS

Figure 5 presents the network used for the analyzing the models derived. The network with 11 sites and 21 fibers is analyzed several times with different cost coefficients and mixtures of traffic types.

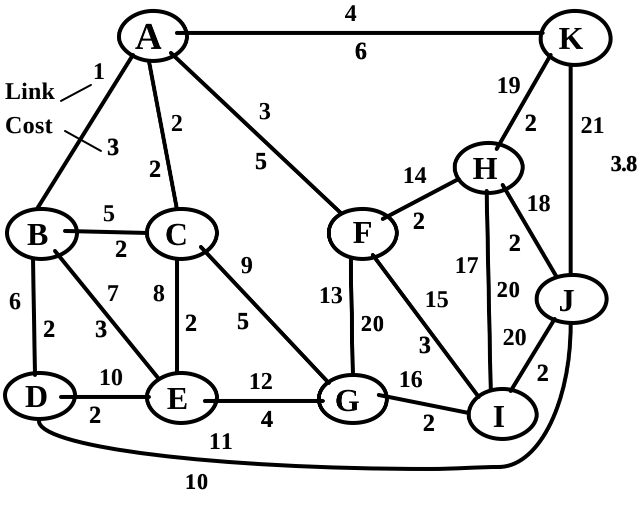

Figure 5– The Network Considered

| From/To | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| A | | | 34 | 38 | 24 | | | 40 | 2 | 6 |
| B | | | 18 | | 26 | 8 | | | | |
| C | | | | 38 | | | 6 | 14 | | |
| D | | | | | 22 | | | 20 | 30 | |
| E | | | | | | 18 | 22 | 18 | 22 | 26 |
| F | | | | | | | | 26 | | |
| G | | | | | | | | 12 | 10 | |
| H | | | | | | | | | | 8 |
| I | | | | | | | | | | 22 |
| J | | | | | | | | | | |

Table 2 – The Traffic Matrix *T* Considered

The cost per system is considered twice: Case 1 uses uniform cost coefficients $C=1$ for all links; Case 2 uses link-dependent cost values, as indicated in Figure 5. $M=28$, single-link and single-node failures are considered for which $K=I+N=11+21=32$. Table 2 is the traffic matrix used. Even values are selected for the analysis so as to ensure Table 2 original values for the case of pure split traffic.

For analysis purposes we use two parameters $\alpha$ and $\beta$ to represent the proportion of split traffic and semi-dedicated traffic, respectively. Various combinations of $\alpha$ and $\beta$, $\alpha + \beta <= 1$, are selected to derive different traffic mixtures. In order to keep the total demand $T$ unchanged we define traffic values:

$$T^3 = 2\lfloor a \cdot T/2 \rfloor, T^2 = \lfloor b \cdot T \rfloor, T^1 = T - T^2 - T^3 \qquad (18)$$

Selecting $\alpha=0$ & $\beta=0$, $\alpha=0$ & $\beta=1$ and $\alpha=1$ & $\beta=0$, leads to pure traffic types 1, 2 and 3, respectively.

Figure 6 demonstrates the impact of cycle hop limit for Case 1 and Case 2. All lines refer to pure traffic types. As hop-limit values less than 6 yield infeasible solutions, we only consider hop-limit values of 6 and above. As expected, increasing cycle hop limits cannot degrade overall results, for both Cases, as the amount of routing alternatives increases. Improvements can be reached until lower bounds are obtained. Lower bounds for Case 1 are reached very rapidly. In fact, for two traffic types the lower bounds are reached even when selecting cycles hop limit = 6. Results here are very much in line with the hop-limit analysis as in [7], originally developed for Line Restoration. For Case 2, higher values of cycles hop limit are required to reach lower bound solutions, derived from the fact that part of longer cycles may now be cheaper than some of the shorter cycles. Also, it can be observed that total cost of pure split traffic is about half the cost of pure dedicated for both cases.

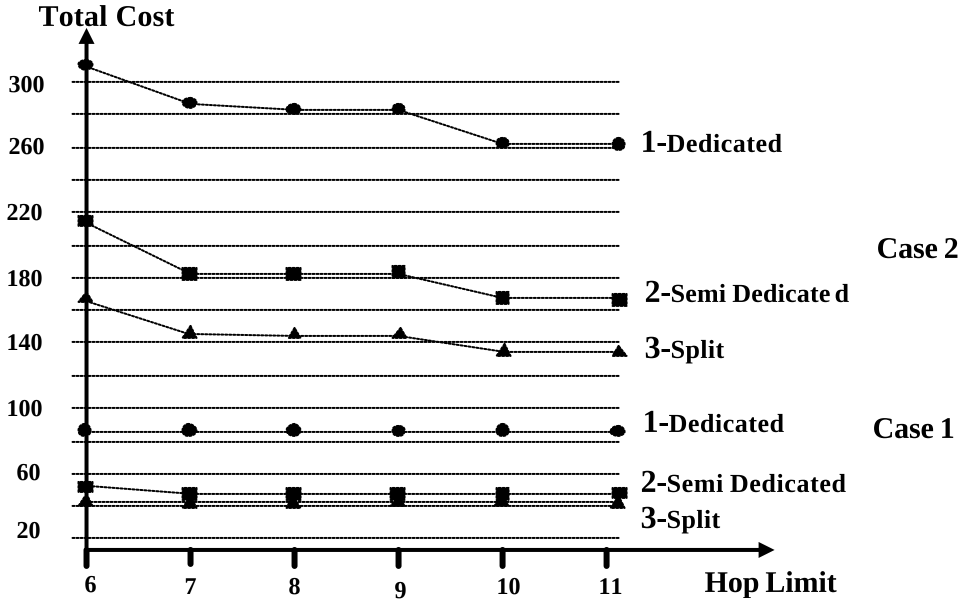

Figure 6 – Cycle Hop-limit Analysis

Figure 7 illustrates the effect of traffic types for Case 2, using 7 as the maximal cycles length. It can be observed that the higher the portion of split traffic (high values of $\alpha$) the lower the overall cost. On the other hand, the higher the portion of dedicated protection traffic (low values of $\alpha + \beta$) the higher the overall cost. The quasi-linear lines obtained indicate that the model results are indeed sound, derived from the relatively dense network where the number of cycles per site pair is fairly large.

Figure 8 analyses the impact of the revised model, using the hop limit as a parameter. Left line is derived from the ratio between the sum group cycles and the "pool" amount. Figures nearby present actual values for several hop limits, e.g., for hop limit = 9 the ratio is 12.3 while actual figures are 4519/367. The dotted line represents the actual amount of data (data load) required, using the total amount for hop limit=11 as a reference of 100%. The dashed line represents the relative data load when using the revised model. Overall saving of data is about 75%.

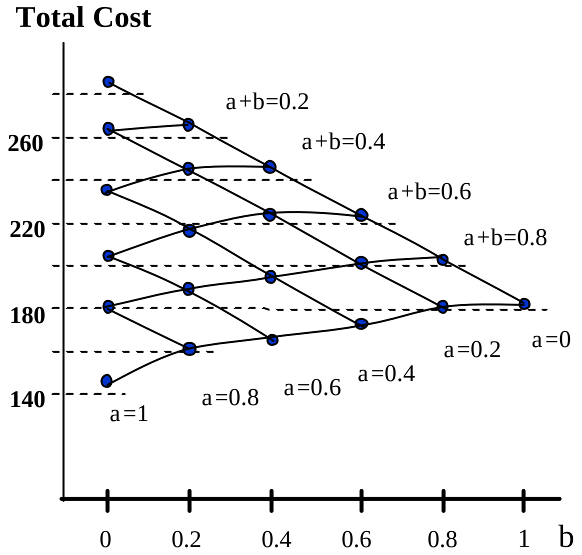

Figure 7 - Impact of Traffic Types for Case 2

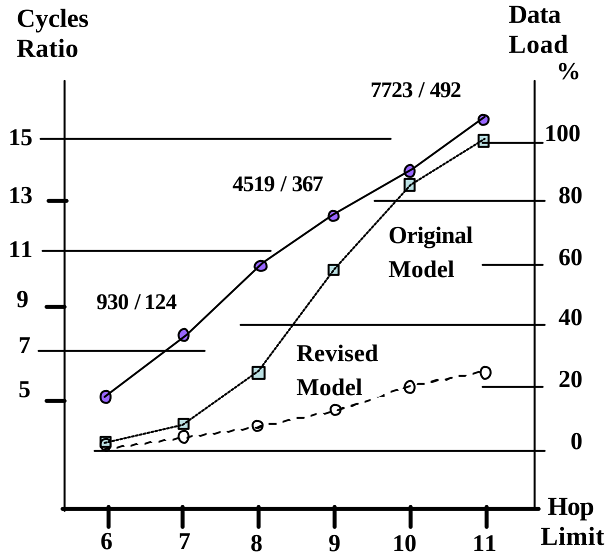

Figure 8 – Impact of the Revised Model

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