Mesh/Arc Networking: An Architecture for Efficient Survivable Self-Healing Networks

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Abstract

This paper summarises the results of a study which compares two architectures for survivable self-healing transport networks. Mesh/Ring and Mesh/Arc networks are compared in terms of equipment costs required to achieve fully survivability against single span failure. Heuristic design procedures are developed. The Mesh/Arc network architecture is shown to be superior in all cases studied. Two main contributions to survivable network design/ planning have resulted from this study. The first is the use of the network nodal degree distribution to partition a network into core and access regions. The second is the use of span elimination techniques as a cost-reducing transformation for the access region of networks.

1. Introduction

1.1 Mesh/Ring and Mesh/Arc Architectures for Survivable Transport Networks

Ref. [1] proposed a new architecture for survivable core/access transport networks in which a distributed restoration algorithm (DRA) (e.g. see [2],[3]) is installed throughout the entire network (i.e. in both core and access flexibility nodes). In this architecture the core network consists of a mesh of digital crossconnect (DCS) nodes whilst the access network consists of incomplete rings or 'arcs' of add-drop multiplexors (ADMs) anchored on DCS nodes of the core. The ADMs execute their own version of a DRA and because of the topological constraints imposed by the 'arc' structure (each ADM has only two spans), the restoration response of the DRA is exactly that of a Self Healing Ring (SHR). This new architecture was named the Mesh/Arc network architecture and was proposed as a technical improvement to the Mesh/Ring network architecture which was also considered in [1].

Fig 1a shows an example of a Mesh/Arc network whose core region is a mesh of the DCS nodes (0,3,4,7,9,10,12,13,15,17). The access region comprises 4 'arcs' of ADM nodes (0-19-8-17), (17-14-6-1-18-16-12), (10-5-2-9) and (15-11-7). Both ends of each 'arc' terminate directly on core region DCS nodes.

Fig 1b shows an example of a Mesh/Ring network design which is an alternative to the Mesh/Arc network of Fig 1a. In Fig 1b, the access region consists ADMs arranged in 4 SHR (17-14-6-1-18-16-12), (15-11-7), (0-19-8-17-13-4) and (10-5-2-9-3). Each SHR requires DCS-ADM interface equipment to transfer traffic between itself and the meshed core.
Network resilience considerations would usually make it desirable to inter-connect each SHR with the core at a minimum of two different nodes.

Mesh/Arc networking offers the prospect of network-wide protection using a uniform restoration technology, at a level of investment in spare capacity limited only by the choice of working capacity routing over the network and the network topology. This contrasts to Mesh/Ring networking where one restoration technology (i.e. mesh restoration using DRAs) is used to protect the core and a different restoration technology (SHRs) are used in the access region. Furthermore whilst the core network can be spared efficiently according to mesh restoration sparing procedures [4], the access network is spared according to the usual spare capacity assignment rules for SHRs [5]. This can be expensive in terms of spare capacity requirements because an SHR can have extravagant spare capacity requirements if there is a serious imbalance between working capacity on its spans.

1.2 Study Methods

Three basic transport network examples (denoted as NetA, NetB and NetC), with dimensioned working capacity were used as study vehicles. NetA and NetB are representative of metropolitan transport networks whilst NetC is an abstraction of a national long haul transport network typical for a European country. The characteristics of the 3 networks are given in Table 1. In the table, average node degree refers to average number of spans at node within the given network.

<table>
<thead>
<tr>
<th>Network</th>
<th># Nodes</th>
<th># Spans</th>
<th># Working</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>NetA</td>
<td>11</td>
<td>23</td>
<td>313</td>
<td>4.2</td>
</tr>
<tr>
<td>NetB</td>
<td>20</td>
<td>31</td>
<td>3903</td>
<td>3.1</td>
</tr>
<tr>
<td>NetC</td>
<td>33</td>
<td>63</td>
<td>371</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 1 Characteristics of the 3 original study networks

A series of study designs were developed according to the design process illustrated in Fig 2. For each of NetA, NetB and NetC two heuristically transformed networks designated Des#1 and Des#2 were constructed (using the techniques of core/access partitioning and span elimination which are described in section 3). Thus six study networks (NetA Des#1, NetA Des#2, NetB Des#1,..., etc.) were formed and 100% restorable Mesh/Arc and Mesh/Ring designs were made for each of these. In addition, a 100% restorable design for each of the original networks (NetA, NetB and NetC) was produced under the assumption that the entire network was protected by DRA technology.

Fig 2 Flow chart describing Mesh/Ring and Mesh/Arc design procedures used in the study.

These designs for the original networks are referred to as the Full Mesh case in the following. They are included to provide baseline design comparison cases against which the Des#1 and Des#2 designs may be judged. Network equipment counts were then assembled for all design cases. Comparisons between the different designs were made and conclusions drawn.

Spare capacity was allocated to each of the network designs to give 100% restorability against single span failure. In the Mesh/Ring Architecture designs the mesh-core was 'spared' using TRLabs implementation of the Sparse Link Placement Algorithm (SLPA) [4]. The sparing of the access SHRs was done according to the usual principles for spare capacity assignment in SHRs [5]. In the Mesh/Arc designs and the Full Mesh baseline designs, the entire network was spared using the SLPA. All applications of the SLPA used a restoration path length limit of 6 spans. The choice of a 6 span limit to restoration path lengths was a judicious one based on accumulated experience with using the SLPA code at TRLabs. Full details of all designs can be found in [6].
2. Network Transformation Techniques

In this section we describe in detail the (heuristic) transformation techniques of Core/Access partitioning and Span Elimination which were used to develop the study designs (see Fig 2). There is no existing design theory for Mesh/Arc networks. The techniques were developed as the study proceeded. They represent new contributions to the theoretical basis for the design of Mesh/Arc networks.

2.1 Core/Access Partitioning

The first task in the design process was to partition the original network into core and access portions. In general, we require the core to form a mesh which is at least 2-connected (i.e. each core node must be connected to no less than two other core nodes). This ensures that no core node will become isolated by a single span cut. Consequently the core nodes will have higher nodal degree than access nodes. This idea forms the basis for a heuristic method to implement core/access partitioning.

Heuristic Core/Access Partitioning: Plot a distribution chart of node degree in the network. This gives insight into the population distribution of nodal degree (symbol d) within the network. Choose some whole number threshold value of degree \( d_{th} \). All nodes whose degree exceeds \( d_{th} \) are assigned to the core. The remaining nodes become access nodes. Form the graph consisting of all spans linking the core nodes (chosen by the above \( d_{th} \) criterion) together. If this is a 2-connected graph or higher, accept this as the mesh core region. The remaining nodes and spans which are not part of this core graph are deemed to be in the access region. However if the core graph is only 0 or 1 connected it will not form a survivable mesh network. In this case some access region nodes and spans should be heuristically added to the core region. It is suggested that the network designer first considers access nodes of degree \( d_{th} - 1 \) and tries to recruit some or all of these nodes into the core region until at least a 2-connected (or higher) core mesh is formed. If recruiting \( d_{th} - 1 \) nodes does not produce a 2-connected core then \( d_{th} - 2 \) degree nodes should be examined etc.

To illustrate, Fig 3a shows the nodal degree distribution for NetA. Nodal degrees ranged from 2 to 7 in NetA. The height of each column of Fig 3a represents the number of network nodes whose degree is not less than the column label. Adopting the heuristic for core/access partitioning described above, enables us to re-interpret the horizontal axis as the minimum degree of core nodes (i.e. \( d_{th} \)) and the column height as the corresponding number of nodes within the core.

![Fig 3b](image)

Core/Access Partition for NetA corresponding to \( d_{th} = 6 \).

Fig 3b shows the core network that results from choosing \( d_{th} = 6 \). This choice defines a three node core consisting of nodes \( \{0,4,7\} \) and their interconnecting spans, shown as solid lines in Fig 3b.

![Fig 3c](image)

Core/Access Partition for NetA corresponding to \( d_{th} = 3 \).

Fig 3c
Fig 3c shows the result for selecting $d_{th} = 3$ which yields a core consisting of nodes $\{0,2,3,4,5,7,8,10\}$ and their interconnecting spans. This shows how varying $d_{th}$ in conjunction with consideration of the nodal degree distribution, systematically produces larger or smaller core networks for consideration by the network designer/planner.

2.2 Access Loop Formation by Span Elimination

After core/access partitioning has been completed, the next step is to convert the remaining access nodes and spans into loops which intersect the mesh region at two or more core nodes. By stipulating that access loops should intersect the core at two or more nodes, we ensure that no single node failure can isolate a loop from the rest of the network. Similar survivability design rules are typically used for network architectures based on overlapping SHRs.

We try to form the access region into a number of 'arcs' (i.e. chains of concatenated spans linking degree 2 nodes i.e. potential ADM sites) which terminate on the core region. In a subsequent Mesh/Ring design the access 'arcs' become parts of SHR cycles which are completed using spans of the core region. Alternatively the access 'arcs' are used directly without further transformation in a subsequent Mesh/Arc design.

The formation of access 'arcs' can be frustrated by the presence of degree 3 access nodes. (We assume that a node with degree higher than 3 should be assigned to the core rather than remain within the access network). A degree 3 node would normally become a DCS site. However the node degree can be reduced to 2 by removing a span terminating at the node and re-routing the traffic it carried on the shortest available alternative path. The degree 2 node thus formed can now be used as an ADM site. Naturally the elimination of a span must not result in a disconnected network. Various span elimination transformations can be considered to aid in the formation of access node 'arcs'.

2.3 DCS Cost-Fibre-Km Cost Trade-off

Span elimination increases the total number of working links in the network and probably thereby the total fibre-km cost of the network. However at the potential expense of increasing the fibre-km cost of the network, a degree 3 access node which typically would be a DCS site can be converted to degree 2 node where a lower cost ADM can be installed. Thus span elimination enables a trade-off between fibre-km cost and total DCS cost in the network. This trade-off is (conceptually) illustrated in Fig 4.

Such trade-offs can only really be judged if more detailed cost information than was available for this study can be used, although in general a significant cost saving is expected everytime a DCS site is converted into to an ADM site through a span elimination. It is anticipated that a software tool could be developed which would carry out alternative candidate span-eliminations and identify the most cost effective of them. Such a tool would be one component of a more general Mesh/Ring & Mesh/Arc network design suite.
2.4 An Example of a Span Elimination Transformation

Span elimination is illustrated by the example shown in Figs 5a,b: a core/access partition has already been chosen for NetB in Fig 5a.

An access loop (0,19,8,17,13,4) which intersects the core at four nodes (i.e. at nodes 17,13,4 & 0) could be formed if not for the existence of span (8-13). By removing span (8-13) and re-routing its 218 working links along (8-17-13), the desired access loop can be formed. Alternatively, we could also have re-routed via the four-span route (8-19-0-4-13) but this would have increased worker link counts more. As a general principle it is desirable to re-route around the candidate access loop in the direction which yields the shortest logical path length (number of concatenated spans). Nodes 19 and 8 now become ADM sites. If we had retained span (8-13) then node 8 would be a degree 3 node requiring a DCS at its site. There is currently a strong cost differential between DCS and ADM products which implies that the capital cost of the network can probably be reduced by installing ADMs, as in this example.

3. Results and Interpretation

To illustrate the nature of the results collected in the study, Fig 6 presents the total link count (workers + spares) for the six study designs including the Full Mesh, Mesh/Ring and Mesh/Arc cases. All results have been normalized to the total link count for the relevant baseline Full Mesh design.

Fig 5a Before elimination of span (8-13) in NetB.

Fig 5b After elimination of span (8-13) in NetB by re-routing 218 links on path (8-17-13) in preference to path (8-19-0-4-13).

Fig 6 3D column chart showing comparison of total link counts after sparing, normalised to the Full Mesh cases, for all study networks.

Similar comparisons between the total DCS count, total ADM count and the total Fibre-km requirement were made for the six study designs.

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Table 2 Use of Span Elimination

The following points emerged from consideration of Fig 6:

(i) Mesh/Arc designs always yield a lower total link count than the corresponding Mesh/Ring Designs. The difference is least marked when no span elimination transformations have been used in the design process. Referring to Table 2, Mesh Ring designs have a normalised total link count which exceeds the Mesh/Arc alternatives by more than 38% when span elimination transformations are used in the design process. In the absence of span eliminations, the Mesh/Ring designs have normalised link count which is no more than 28% larger than that of the Mesh/Arc alternative.

(ii) For cases that used span elimination, the formation of large access loops which have several spans in common with the previously chosen core, can lead to poor Mesh/Ring designs with high total link count compared to a corresponding Mesh/Arc solution. For example, NetC Des#2 used several large loops which have more than one span in common with the core. The NetC Des#2 Mesh/Ring design total link count was 204% of the Full Mesh case total link count. (See Fig 6). This compared with 141% for the Mesh/Arc variant of the same design.

Other points which emerged in the study are:

(iii) With or without span elimination, Mesh/Arc designs used significantly fewer ADMs than corresponding Mesh/Ring designs.

(iv) Mesh/Ring designs always yield higher fibre-km figures than corresponding Mesh/Arc Designs.

(v) Span elimination tended to increase the fibre-km figure in a network. This is a direct consequence of increasing the working link count. However under some circumstances span elimination can lead to a reduction in the fibre-km requirement. The total fibre-km requirement for a network can be reduced if the workers on the eliminated span can be routed onto under-utilized (i.e. low fibre fill) alternative spans.

The main findings are summarised in Table 3.

<table>
<thead>
<tr>
<th>Case</th>
<th>Total Link Count</th>
<th>Total ADM Count</th>
<th>Total Fibre Km</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh Ring</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>(i) Significantly more expensive than Mesh/Arc when span elimination is excessively used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(ii) Large imbalanced SHR's lead to expensive designs. This should be avoided.</td>
</tr>
<tr>
<td>Mesh Arc</td>
<td>Economical/May exceed Baseline but is superior to Mesh/Ring equivalent</td>
<td>Equals Baseline in most cases. Always superior to Mesh/Ring case</td>
<td>Economical. May exceed Baseline but is superior to Mesh/Ring equivalent</td>
<td>(i) Link count always lower than corresponding Mesh/Ring design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(ii) Total ADM count is always lower than corresponding Mesh/Ring design</td>
</tr>
</tbody>
</table>

Table 3 Summary of Main findings

4. Conclusions

The Mesh/Arc network architecture has proved that it is more efficient in terms of spare capacity required to achieve full survivability against single span failure than the Mesh/Ring architecture in all 6 study network designs exercises. Mesh/Arc networks also generally require fewer ADMs than equivalent Mesh/Ring designs. The total fibre requirement is also significantly less for Mesh/Arc networks. Mesh/Arc
networks allow spare capacity savings for a 100% restorable network design, which typically range from 6% when no span elimination procedures are used in the design, to 60/70% when the span transformation procedure has been applied excessively.

Significant progress has been made toward the possibility of developing a systematic Mesh/Arc network design procedure. A core/access partitioning principle has been developed which aids the network designer in specifying the mesh restorable core in the network. Span elimination has been developed to reduce network cost by eliminating degree 3 nodes in the access region, once a core region has been established. Span elimination invokes a trade-off between fibre related costs in the network and the network total DCS cost component. Span elimination is a promising means to reduce total network cost when DCS cost is a dominant component. However span elimination is not an effective cost reducing transformation of the access network region when fibre related costs dominate. Modularity effects may mean that network costs can be reduced even in a fibre cost dominated network design by span elimination if re-routing via poorly utilized spans can be exploited.

5. References


