

Availability Analysis of Span- Restorable Mesh Networks

Partly adapted from slides originally presented at TR Labs Tech Forum by,
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Outline

- Motivation
- Definition
- Theory & Analysis of Mesh Restoration
- Experiment Results
- Comparison
- Conclusion

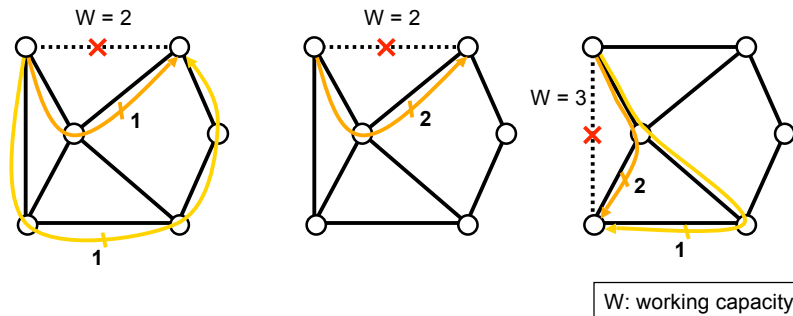
Motivation

- To study qualitatively and quantitatively the advantage of span-restorable mesh network to dual span failure situations given a 100% single span failure restorability level.

Definition

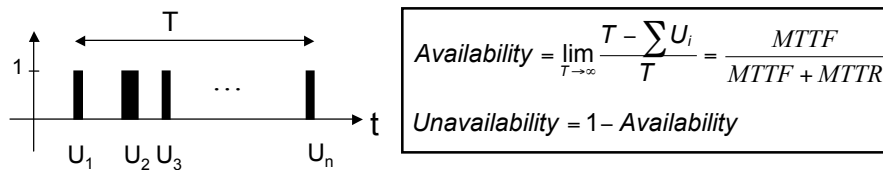
- **Reliability** of a network can be measured by several means such as, availability, throughput, delay, etc.
- **Restorability** is the average fraction of failed working span capacity that can be restored within the spare capacity provided in the network.
- **Availability** is the probability that a system (in this case a signal path) will be found in the operating state at a random time in the future (e.g., the average fraction of time that one will find the system in the operating state?)

Mesh Restoration



- The network is fully protected against single span failures

Availability



- The availability of a service over a period T is the fraction of this period during which the service is up.
- The repair rate is very much greater than the failure rate. Equivalently, the MTTR is much smaller than the MTTF (e.g. for 100 miles of optical cable, the component of highest failure rate, MTTF = 19000 hrs, whereas MTTR = 12 hrs).

Path Availability

$$A_{path}(d) \approx 1 - \sum_{i=1}^n U_{link}(i)$$

$U_{link}(i)$ is the physical unavailability of the i^{th} link in the path

Define the equivalent unavailability, $U_{link}^*(i)$ = probability that link i^{th} is down and not restored.

Non-Restorable Network, $U_{link}^*(i) = U_{link}(i)$

Restorable Network, because of restoration mechanism $U_{link}^*(i) \ll U_{link}(i)$, we will see later that $U_{link}^*(i) \sim U_{link}^2$,

Equivalent Unavailability

- U_{link}^* depends on how the network reacts to multiple failures.

$$U_{link}^* = U_{link} * \sum_{f=1,2,3,\dots} p(f-1) * \left[\underset{\text{time exposure}}{\text{restoration time}} * R_f + \underset{\text{capacity exposure}}{(1 - R_f)} \right]$$

$p(f-1)$ = probability of unavailability of other spans.

$$= \frac{(s-1)!}{(s-f-2)!(f-1)!} * (U_{link})^{f-1}$$

R_f is the fraction of the total failed working capacity that can be restored averaged over all f -order failure scenarios.

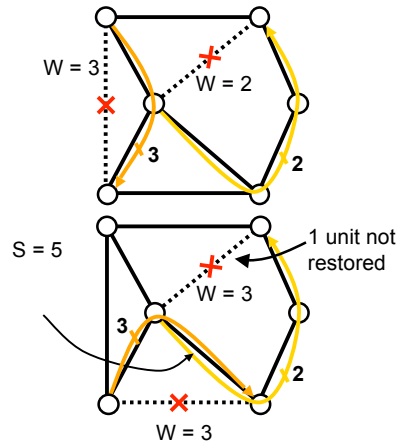
Equivalent Unavailability

- By assuming that, restoration time is insignificant compared to $MTTR$ and because higher order failure (> 2) is less likely to happen and to be restored, $p(f-1)$, $R_f \ll 1$, therefore in practice, dual failure ($f = 2$) scenarios will dominate the unavailability.
- As an example, consider a 20 span networks ($s = 20$), $U_{link} = 3 \times 10^{-4}$, $R_1 = 1$, $R_2 = 0.5$, and $R_3 = 0$. Single failure contributes 1.38×10^{-8} , dual failure = 8.55×10^{-7} and triple failure = 4.62×10^{-9} to the equivalent link unavailability U_{link}^* .

Dual Failure Restorability

- Therefore, U_{link}^* can be approximated by,
$$U_{link}^* \approx (U_{link})^2 * (s - 1)(1 - R_2)$$
- The only unknown is, Dual-Failure Restorability R_2
- Therefore, in order to find the equivalent link unavailability, we just need only estimate R_2 .

Dual Failure Restorability



- The availability of service paths mainly depends on how the network reacts to dual failures.
- R_2 : Restorability to dual failures (in % of the failed nominal working units)
- Case-by-case inspection is needed in order to determine R_2

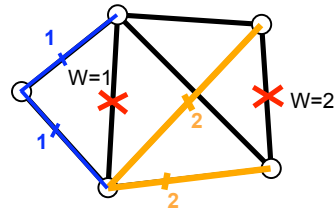
S: spare capacity

Dual Failure Restorability

- Case 0: Span failure and $w_i >$ feasible spare paths
(not possible by definition in a restorable network)
- Case 1: Two failures but no spatial interactions
→ no outage
- Case 2: Two failures and spatial interactions (competition for spare capacity) → may be outage
- Case 3: Two failures with second failure hitting the first restoration pathset → may be outage
- Case 4: Two failures isolating a degree-2 node
→ certain outage

Dual Failure Event

Example #1 of dual-failure event:

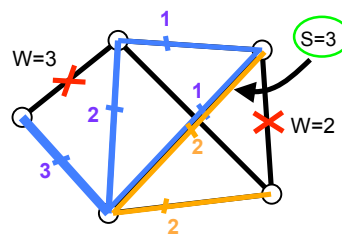


W: working capacity
S: spare capacity

No spatial interaction → **NO OUTAGE**

Dual Failure Event

Example #2 of dual-failure event:



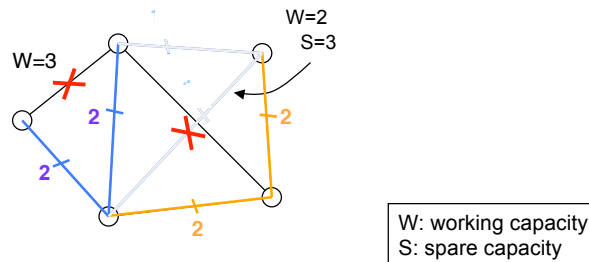
W: working capacity
S: spare capacity

There is enough spare capacity for the 2 failures

→ **NO OUTAGE**

Dual Failure Event

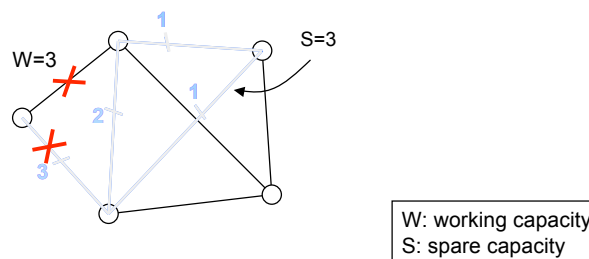
Example #3 of dual-failure event:



There is not enough spare capacity to restore both failures
→ 1 unit will suffer outage during a time on the order of MTTR

Dual Failure Event

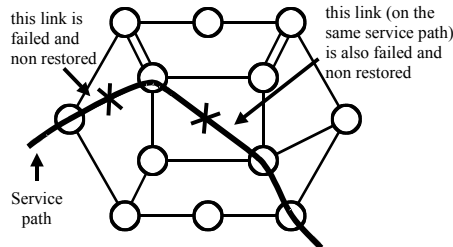
Example #4 of dual-failure event:



A degree-2 node is isolated by the two failures
→ No restoration possible
OUTAGE

Over Estimation

- Summing link unavailabilities along a service path does in fact provide a higher bound on total path unavailability:
 - The unavailability values of each link are not completely independent. The following figure shows how a span failure can be counted twice in the unavailability of a given service path:



$$U_{path} \approx \sum_{i=1}^5 U_{link}^*(i) \quad \leftarrow \text{Higher bound on path unavailability}$$

R₂ Calculation

Method for R₂ calculation:

- Simulate each dual-failure scenario for a given network. S(S-1) cases for a network with S spans (covers all f = 2 experiment trials)
- Very difficult to predict mesh availability analytically. R₂(i,j) depends in detail on the specifics of the (i,j) pair, the failure sequence, the exact working and spare capacities, the graph topology, and the assumed restoration dynamics.
- Count the number of non-restored units in each case
 - Ex: span 1 and span 2 → 5 units non restored, N_{1,2} = 5
 - span 1 and span 3 → 2 units non restored, N_{1,3} = 2

R₂ Calculation

- Compute the average dual-failure restorability:

$$R_2 = 1 - \frac{\sum_{\forall(i,j), i \neq j} N(i,j)}{\sum_{\forall(i,j), i \neq j} (w_i + w_j)}$$

- The restoration routing experiments are based on k-shortest paths (ksp) routing behavior. First taking all paths feasible on the shortest route, followed by all paths feasible on the next shortest route not reusing any already seized spare capacity and so on, until all required paths are found.
- Using three different restoration behavior model
 - Static Restoration Preplans (gives lower bound on availability)
 - First-Event Adaptive
 - Fully Adaptive Behavior (gives best availability)

Restoration Behavior

- Static behavior:
 - Based on centrally computed single-failure pre-plans.
 - The network tries to restore both failed spans as if each was an isolated failure
 - The simulation consists of identifying and counting the number of restoration paths which have to be suppressed from the restoration paths sets for the restoration to be possible. This number is $N_{i,j}$

Restoration Behavior

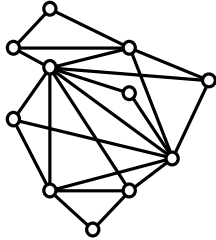
- Partly-adaptive behaviour:
 - A) The restoration mechanism for the second failed span adapts to the changes in available spare capacity
 - B) Restoration paths of the first failed span hit by the failure of the second span are lost.
- Fully-adaptive behaviour:
 - Same as A) above but B) the restoration mechanism will try to find new restoration paths to replace the initial restoration paths for the first failure that were severed by the second.

Experimental Results

- Following these trials we have everything to compute the unavailability:
 - We now know $N_{i,j}$ for each failed span combination
 - $N_{i,j} \rightarrow R_2 \rightarrow U_{link}^* \rightarrow$ Availability of any path
- The exact availability of specific path can be found by:
 - Calculating specific $R_2(i,j)$ value for each span s, which gives a specific U_{link}^* for each link i.

Experimental Results

Typical test network:

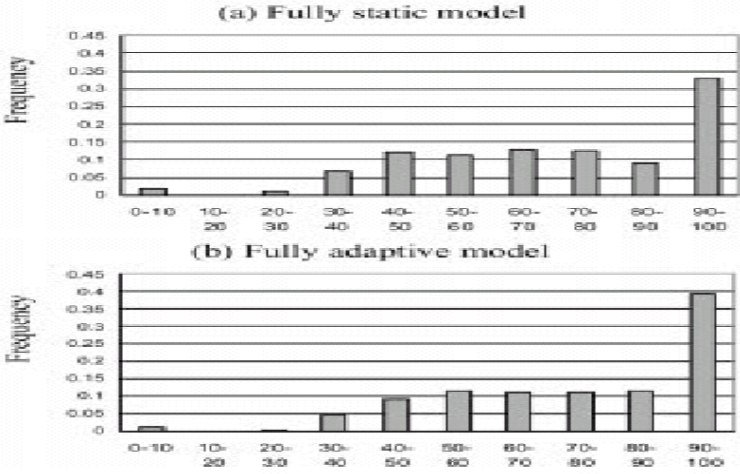


R2 Results for 5 test networks:

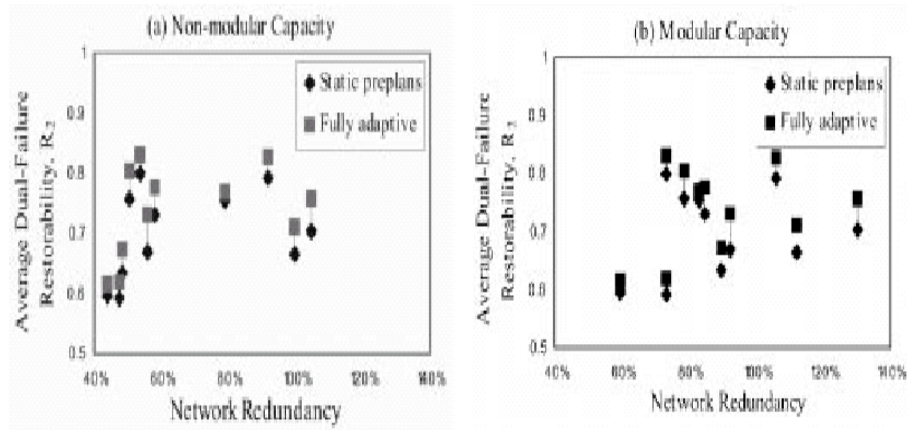
Mesh Restoration Model	Non-modular environment	Modular Environment*
Static behaviour	0.53 to 0.75	0.69 to 0.83
Partly-adaptive	0.55 to 0.79	0.87 to 0.91
Fully-adaptive	0.55 to 0.80	0.91 to 0.99

* Designed with Optimal Modular Spare Capacity Placement

Experimental Results



Experimental Results



Experimental Results

- Demand patterns were generated using the gravity based demand model. The modular capacity designs use module sizes of 12, 24, and 48 capacity units.
- With $R_1 = 1$, at least 70% of failed capacity was restored in double-failure scenarios for both non-modular and modular capacity environments.
- Under static behavior, about 70% of the time the network could support more than 60% of dual-failure restorability, and up to 95% of the time under fully adaptive behavior.
- Observed flat general nature of the scatter plot, the availability depends more on the individual network and demand pattern than on the redundancy of the network. Higher spare capacity does not always reflect in higher availability.

Experimental Results

Path availability improvement example:

Test network: EuroNet (19 nodes, 37 spans)
Reference path: 5 hops
Assumption: $U_{link} = 10^{-5}$

If the network is non-restorable: $U_{path} = 5 \times 10^{-5} = 26 \text{ min/year}$

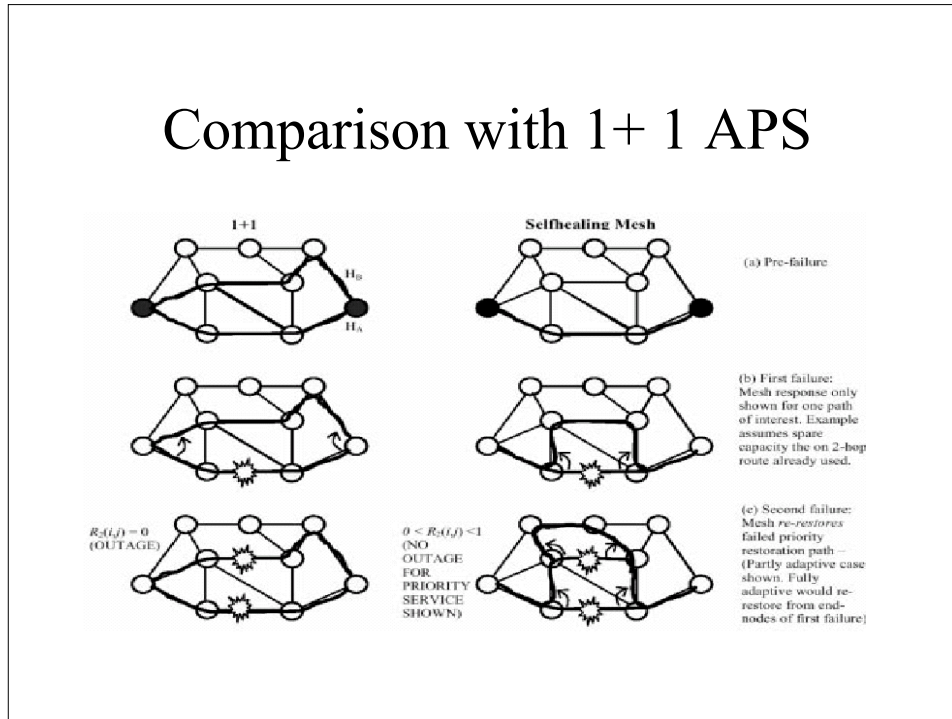
If the network is restorable, the simulation with fully adaptive behaviour gives:

$R_2 = 0.716735 \rightarrow U_{link}^* = 1.02 \times 10^{-9} \rightarrow U_{path} = 5.1 \times 10^{-9}$
 $= 0.0026 \text{ min/year}$

Comparison with 1 + 1 APS

- If any dual failure combination hits both arms of the 1 + 1 APS, an outage is inevitable.
- Even if R_2 was as low as 20%, and this minimum was allocated preferentially to priority service paths. Only a triple failure or higher would affect such premium services.
- *Given mesh minimum $R_2 > 0$, a certain of priority services in mesh can always enjoy higher availability than in a corresponding ring or 1 + 1 APS-based network.*

Comparison with 1+ 1 APS



Conclusion

- With a 100% single failure restorability level, dual failure dominates the unavailability of the mesh network.
- Under fully adaptive restoration algorithm, R_2 level is over 90%.
- Despite lower redundancy, self-healing adaptive mesh restoration network enjoys higher level of dual-failure restorability, and far superior in terms of providing high quality of premium-path service.