

Spare Capacity Allocation Using Shared Backup Path Protection for Dual Link Failures

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Content

- **Literature review**
- **Previous work on Shared Backup Path Protection (SBPP) for single failures**
- **New model for dual link failures**
- **Numerical study on**
 - **1+1+1, 1+1:1, 1:1:1;**
 - **with active/passive sharing for ‘:1’**

Literature Review

- ***Clouqueur, Doucette, & Grover/U Alberta [8-11]***

For networks resilient single failure, study their dual failure recovery probabilities, or study relationships between survivability and redundancy using local protection

- ***Choi & Subramaniam/GWU [12], Srini/U AZ[13]***

Using local protection, design link mutual exclusion for dual link failure protection

- ***Zhang et al & Mukherjee/UC Davis[14], Ruan/Iowa[15]***

Using restoration for second failure, less than 100% restorability for dual link failure

- ***Prinz, Autenrieth & Schupke [16]; Huawei's Synergetic Protection[17]***

Use protection on IP & optical together, to achieve coordinated protection

- ***He & Somani / Iowa State Univ. [2]***

Accurately modeled the spare capacity sharing, aka backup multiplexing

Based on the (non)sharing between any two backup paths → *limited scalability*

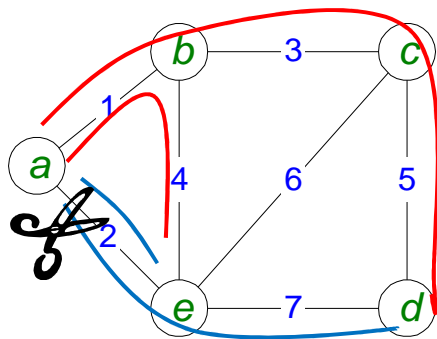
➤ **A *road block*** for accurate/efficient dual failure protection

2001: Computing Shared Spare Capacity

For single link failure:

1. Use the working and backup paths, compute $G = Q^T P$
2. From G , compute highest watermarks

$$s = \max G$$



Link i		1	2	3	4	5	6	7	Backup path link incident matrix												
	S								Q^T												
1	2	0	2	1	1	1	0	1	0	0	1	1	0	1	1	0	0	0	0	0	0
2	2	2	0	2	1	1	0	0	1	1	0	0	0	1	1	0	0	0	0	0	0
3	1	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0
4	1	1	1	1	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0
5	2	1	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0	1	0	0
6	1	0	0	1	0	1	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0
7	2	1	0	2	0	2	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
	11																				
									Flows		1	2	3	4	5	6	7	8	9	10	
									src	dst											
		1	0	0	0	0	0	0	1	a	b										
		1	0	1	0	0	0	0	2	a	c										
		0	1	0	0	0	0	1	3	a	d										
		0	1	0	0	0	0	0	4	a	e										
Working path link incident matrix		0	0	1	0	0	0	0	5	b	c										
		0	0	1	0	1	0	0	6	b	d										
		0	0	0	1	0	0	0	7	b	e										
		0	0	0	0	1	0	0	8	c	d										
		0	0	0	0	0	1	0	9	c	e										
		0	0	0	0	0	0	1	10	d	e										

- An Example:**
1. Link 2 fails
 2. Flow 3,4 affected
 3. Backup paths up
 4. Spare BW= G_{12} =2 on link 1

Computing Shared Spare Capacity 2

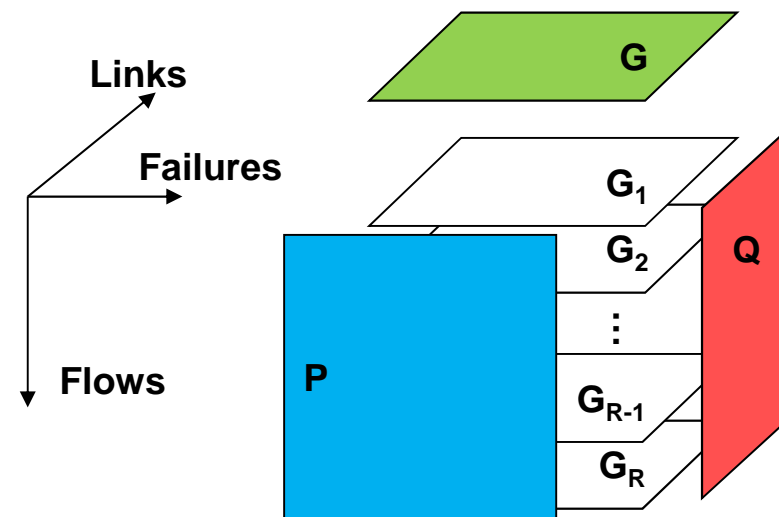
- P indicates all working paths. Each row represents a path of a flow. Each column shows a link usage on these paths.
- Q is the backup paths matrix. Same as above.
- Assume each flow has one unit demand.
- $G = Q^T P$, T is the matrix transpose operation
→ called Spare Provisioning Matrix (**SPM**)
- Elements of G , g_{ij} indicates the required spare capacity on link i when the other link j fails
- $s = \max G$ indicates element s_i takes the maximum value in the i -th row of G
- To meet 100% survivability requirement, the maximum spare capacity across all failure scenarios is needed on link i



Accumulate Single Flow Information in G

Another way to compute SPM

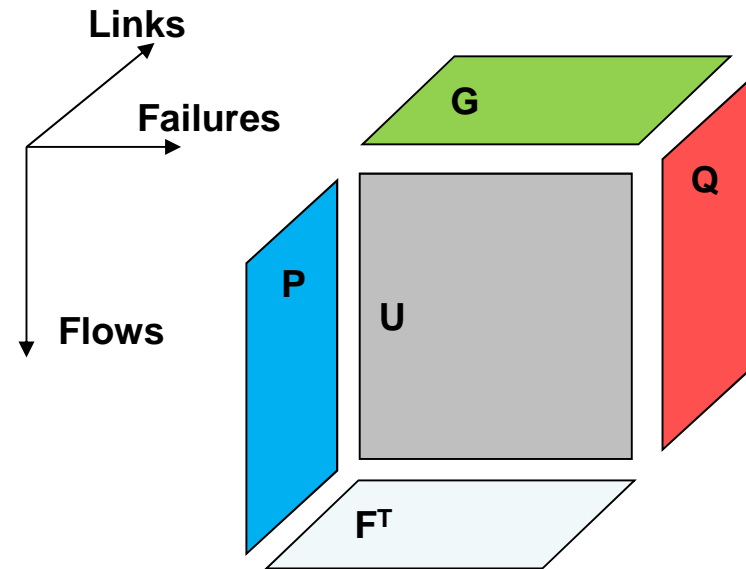
- $G = \sum_r G_r$, where $G_r = q_r^T p_r$ and p_r, q_r are the working and backup paths of flow r
- This is a scalable way to compute shared spare capacity from individual flows
 - No need to store large amount of flow paths
 - Only needs G and G_r on related nodes



Model Node Failure or SRLG

- Treat node failure as a failure of all adjacent links of the node
 - Using a failure matrix $F = B$,
 - Replace working path matrix P with failure matrix U in $G = Q^T U$
 - Elements $u_{\{r, k\}}$ indicates weather a failure k will break working path of flow i
 - The failure matrix U :
$$U = P \odot F^T - D^o - D^d \quad (1)$$
 - It derives the tabu link matrix T
$$T = U \odot F \quad (2)$$

$F = \{f_{kl}\}_{K \times L}$ Binary failure link incidence matrix, $f_{kl} = 1$ iff link l fails in failure k
 $U = \{u_{rk}\}_{R \times K}$ Binary flow-failure incidence matrix, $u_{rk} = 1$ iff failure k will affect flow r 's working path
 $T = \{t_{rl}\}_{R \times L}$ Binary flow tabu-link matrix, $t_{rl} = 1$ iff link l should not be used on flow r 's backup path
 $B = \{b_{nl}\}_{N \times L}$ Node-link incidence matrix
 $D = \{d_{rn}\}_{R \times N}$ Flow-node incidence matrix
 D^o, D^d Binary incidence matrixes between flow and source node; or destination node, $D^o - D^d = D$



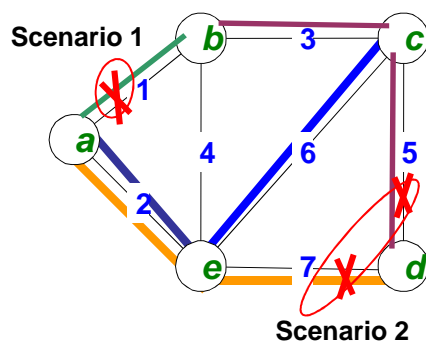
- SRLG is similarly formulated



Model Arbitrary Failures

- F : failure matrix, $f_{ik} = 1 \rightarrow$ link k fails in the i -th failure scenario
- U : flow failure incidence: how flows affect by i -th failure scenario
 - $U = P \odot F^T$, \odot binary multiply, capture logical relations
- T : flow tabu-link matrix, links to be avoided in backup

■ $T = U \odot F$



$P = \begin{bmatrix} 1000000 \\ 0100001 \\ 0010100 \\ 0100010 \end{bmatrix}$

$U = \begin{bmatrix} 1000000 \\ 0100001 \\ 0010100 \\ 0100010 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 10 \\ 01 \\ 01 \\ 00 \end{bmatrix}$

$F = \begin{bmatrix} 1000000 \\ 0000101 \end{bmatrix}$

$T = \begin{bmatrix} 10 \\ 01 \\ 01 \\ 00 \end{bmatrix} \begin{bmatrix} 1000000 \\ 0000101 \end{bmatrix} = \begin{bmatrix} 1000000 \\ 0000101 \\ 0000101 \\ 0000000 \end{bmatrix}$

SCA model for arbitrary failures

$$\begin{array}{ll} \min_{Q,s} & S = e^T s \\ \text{s.t.} & s = \max G \\ & G = Q^T M U \\ & T + Q \leq 1 \\ & Q B^T = D \\ & Q : \text{binary} \end{array}$$

- (1) **Minimize total spare capacity**
- (2) **Enough spare capacity on each link**
- (3) **Calculation of spare provision matrix**
- (4) **Failure-disjointed backup paths**
- (5) **Flow conservation of backup**
- (6)

$$U = P \odot F^T$$

- (7) **Path failure incident matrix**

$$T = U \odot F$$

- (8) **Path tabu-link incident matrix**

- Decision variable: Q, s
- Given: M – traffic demand matrix
- P : working path link incidence matrix
- B and D : node-link & flow-node incidence matrices
- Solve SCA model using Branch and Bound algorithm – NP hard → SSR



Why and How to Protect Dual Link Failures


Why?

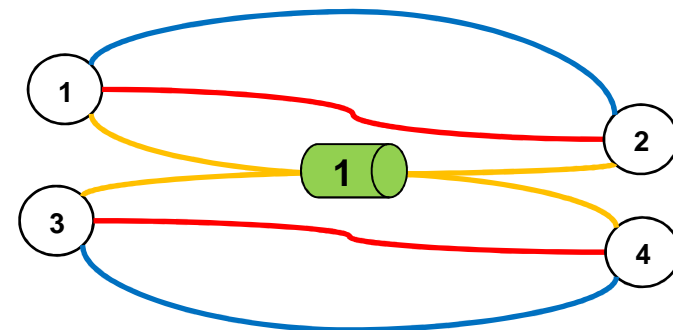
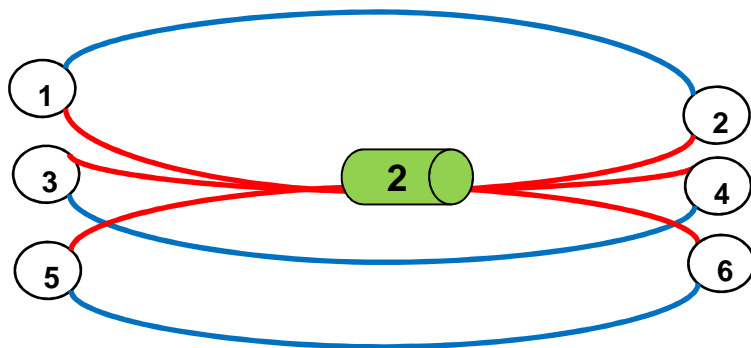
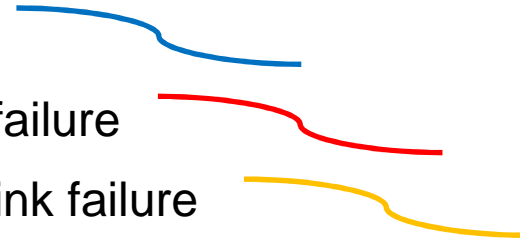
- Single failures are well studied
- Dual link failures such as dual fiber cuts did happen under
 - Scenarios where frequent network changes occur
 - Scenarios where reduced reliability on network facility & equipment
 - Scenarios where intentional sabotage cannot be avoided

How?

- Extra resource: secondary backup path, spare BW, connectivity
- Schemes to restore traffic upon dual failures
- Global and local protection schemes

Shared Backup Path Protection to Protect Dual Link Failures

- Each flow has three disjoint paths:
 - Working path: carrying traffic
 - Primary backup path: protect first link failure
 - Secondary backup path: protect dual link failure
- Sharing spare capacity among different flows, i.e.:
 - Three primary backup paths can share **2** unit of bandwidth on the overlap segment  when the working paths are mutually disjoint
 - Two secondary backup paths can share on their overlap segment when their working and primary backup paths are mutually disjoint;



How to Capture Dual Link Failures

- Each dual link failure can be identified by two links i & j
- Number of all dual link failures is $K = \binom{L}{2} = \frac{L(L-1)}{2}$ where L is number of links
- All dual link failures can be captured in a $L \times L$ matrix
- For two disjoint paths that can be disrupted by a dual failure
 - All working paths $P = \{p_r\} = \{p_{ri}\}$,
where $p_{ri} = 1$ iff working path of flow r uses link i .
 - All primary backup paths $Q = \{q_r\} = \{q_{ri}\}$
 - All secondary backup Paths $Z = \{z_r\} = \{z_{ri}\}$

Failure Vector u_r for Flow r

- The primary backup path will carry traffic when
 - One link failure i is on the working path; and
 - Another link failure j is NOT on the primary backup path
 - i.e. when $p_{ri} = 1 \& q_{rj} = 0$ or $p_{rj} = 1 \& q_{ri} = 0$
 - or the first failure vector for flow r , has value 1 on position k
- The secondary backup path will carry traffic when
 - One link failure i is on the working path; and
 - Another link failure j is on the primary backup path
 - i.e. when $p_{ri} = 1 \& q_{rj} = 1$ or $p_{rj} = 1 \& q_{ri} = 1$
 - or the second failure vector for flow r , has value 1 on position k

$$u_r^1 = \text{vec}(p_r^T \bar{q}_r \oplus q_r^T \bar{p}_r) \quad k = (i-1)L + (j-i)$$

$$u_r^2 = \text{vec}(p_r^T q_r \oplus q_r^T p_r)$$

Example of computing failure vector

- Dual link failures that disrupt two paths, p_r and q_r , can be identified by: $u_r^2 = \text{vec}(p_r^T q_r \oplus q_r^T p_r)$
- Example:

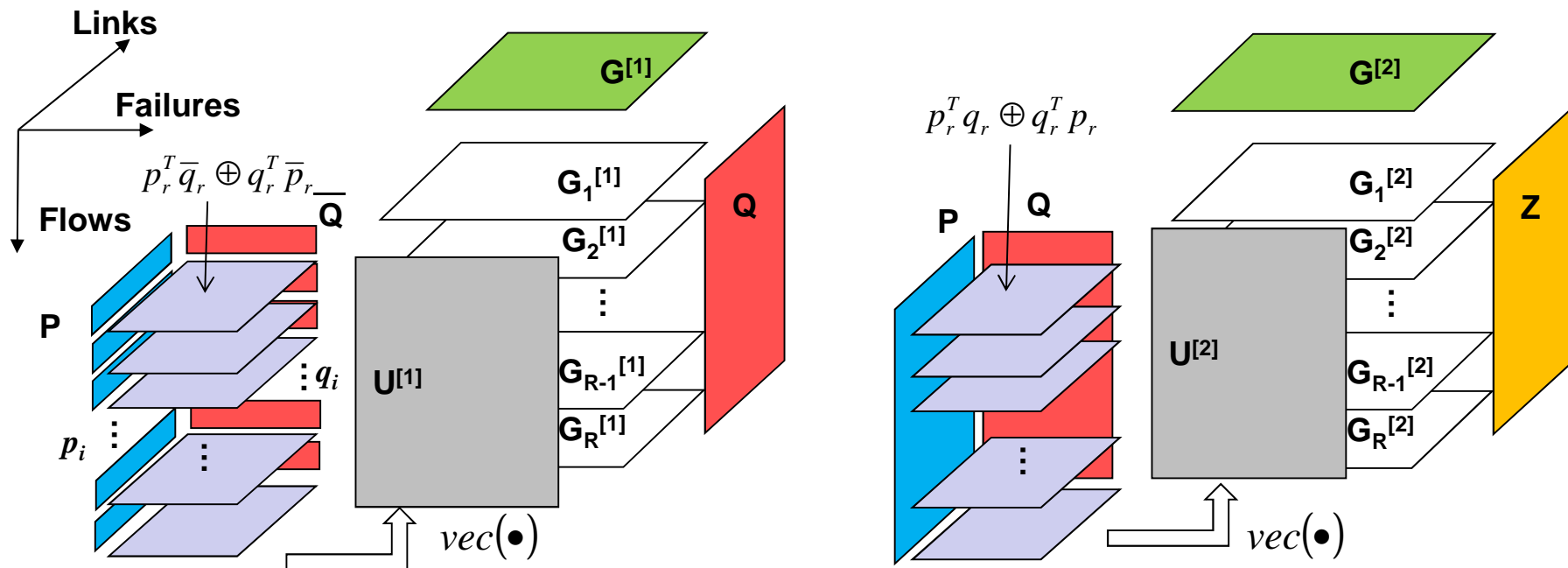
$$\begin{aligned}
 p_r &= [1000100] \\
 q_r &= [0011001] \\
 u_r^2 &= \text{vec} \left(\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} (0011001) \oplus \begin{pmatrix} 0 \\ 0 \\ 1 \\ 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} (1000100) \right) = \text{vec} \begin{pmatrix} & 11 & 1 \\ 1 & & 1 \\ 1 & & 1 \\ & 11 & 1 \\ 1 & 1 & \end{pmatrix} \\
 &= (0011001 \cdots 1000100)_{49}
 \end{aligned}$$

Spare Provision Matrix for Dual Link Failures

- For both backup paths, compute their $G^{[1]}$, $G^{[2]}$

$$G^{[1]} = \sum_{r=1}^R G^{r[1]}, \quad G^{r[1]} = m_r q_r^T u_r^1 \quad G^{[2]} = \sum_{r=1}^R G^{r[2]}, \quad G^{r[2]} = m_r z_r^T u_r^2$$

- Use $G^{[1]}$ and $G^{[2]}$ in 1:1:1; Use $G^{[2]}$ for 1+1:1



SCA model for dual link failures

$\min_{Q,Z,s}$	$S = e^T s$	(16)	Minimize total spare capacity
s.t.	$s = \max G$	(17)	Enough spare capacity on each link
	$G = Q^T MU^1 + Z^T MU^2$	(18)	Calculation of spare provision matrix
	$P + Q + Z \leq 1$	(19)	Mutually disjointed backup paths
	$QB^T = D$	(20)	Flow conservation of backup
	$ZB^T = D$	(21)	
	$Q, Z : \text{binary}$	(22)	
	$u_r^1 = \text{vec}(p_r^T \bar{q}_r \oplus \bar{q}_r^T p_r)$	(12)	Primary backup path failure incident matrix
	$u_r^2 = \text{vec}(p_r^T q_r \oplus q_r^T p_r)$	(14)	Secondary backup path failure incident matrix

- Has non-linear components → split into two sub-models
 - Find all primary backup paths first, all secondary backup paths next

\min_{Q,s_1}	$S_1 = e^T s_1$	(24)
s.t.	$s_1 = \max G^{[1]}$	(25)
	$G^{[1]} = Q^T MU^1$	(26)
	$P + Q \leq 1$	(27)
	$QB^T = D$	(28)
	$Q : \text{binary}$	(29)

Solution Approach

Original model is not linear

- Solve ILP models sequentially
 - Find all primary backup paths first
 - Find all secondary backup paths next
- Other tweaks:
 - Change the first flow failure vector
 - From $u_r^1 = \text{vec}(p_r^T \bar{q}_r \oplus q_r^T \bar{p}_r)$
 - To $u_r^1 = \text{vec}(p_r^T e_r \oplus e_r^T \bar{p}_r)$
 - Reduce the chance of capacity sharing among primary backups
 - more 1 in the final flow failure vector u_r^1
- Advantages: linear constraints; fast to get results
- Disadvantages: loss of optimality

$$\begin{aligned}
 p_r &= [1000100] \\
 q_r &= [0011001] \quad \bar{q}_r = [1100110] \\
 u_r^1 &= \text{vec}(p_r^T e \oplus e^T p_r) \\
 &= \text{vec} \begin{pmatrix} 1111111 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1111111 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} \\
 &= (1111111 \cdots 1000100)_{49}
 \end{aligned}$$

Various Protection Schemes

- Whether backup paths use dedicated or shared resource

Scheme	<i>Primary Backup Path</i>	<i>Secondary Backup Path</i>
1+1+1	Dedicated	Dedicated
1+1:1	Dedicated	Shared
1:1:1	Shared	Shared

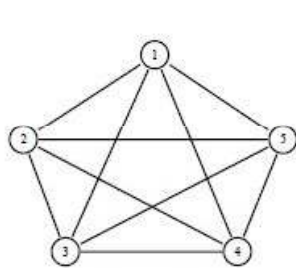
- “+1” or “1+” for dedicated resource; “:1” or “1:” for shared resource
 - **M:N** means **M** backup protects **N** working → discussion
- Whether capacity sharing occur during or after routing

Scheme	Passive	Active
Routing	First	Same time
Capacity Sharing	Second	Same time
Simplicity	Simple	Complicated
Redundancy	Low	Lowest

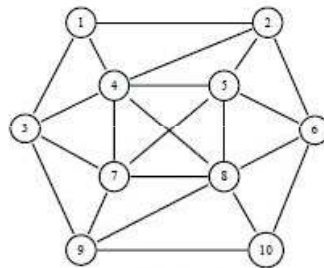
Networks for Numerical Study

Five networks

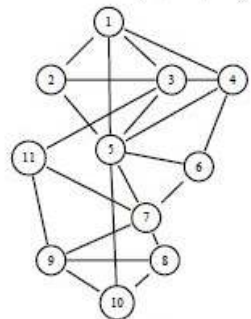
- ▣ All tri-connected
- ▣ Link capacity unlimited → Reduce interferences from capacity



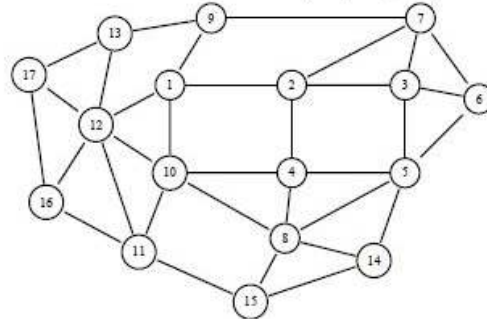
Net1: (5, 10, 20)



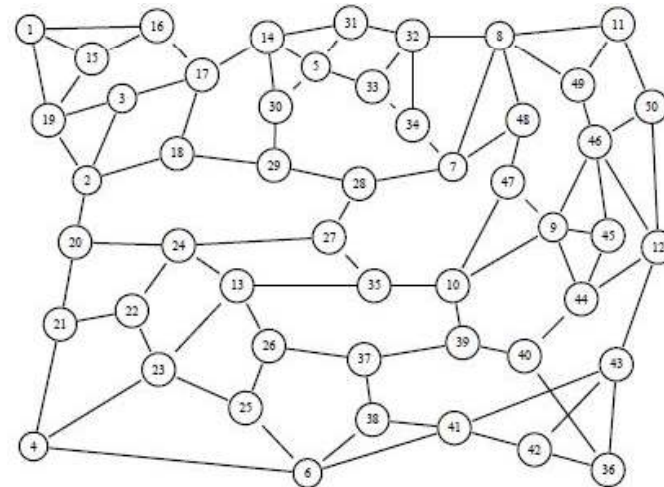
Net2: (10, 22, 90)



Net3: (11, 22, 110)



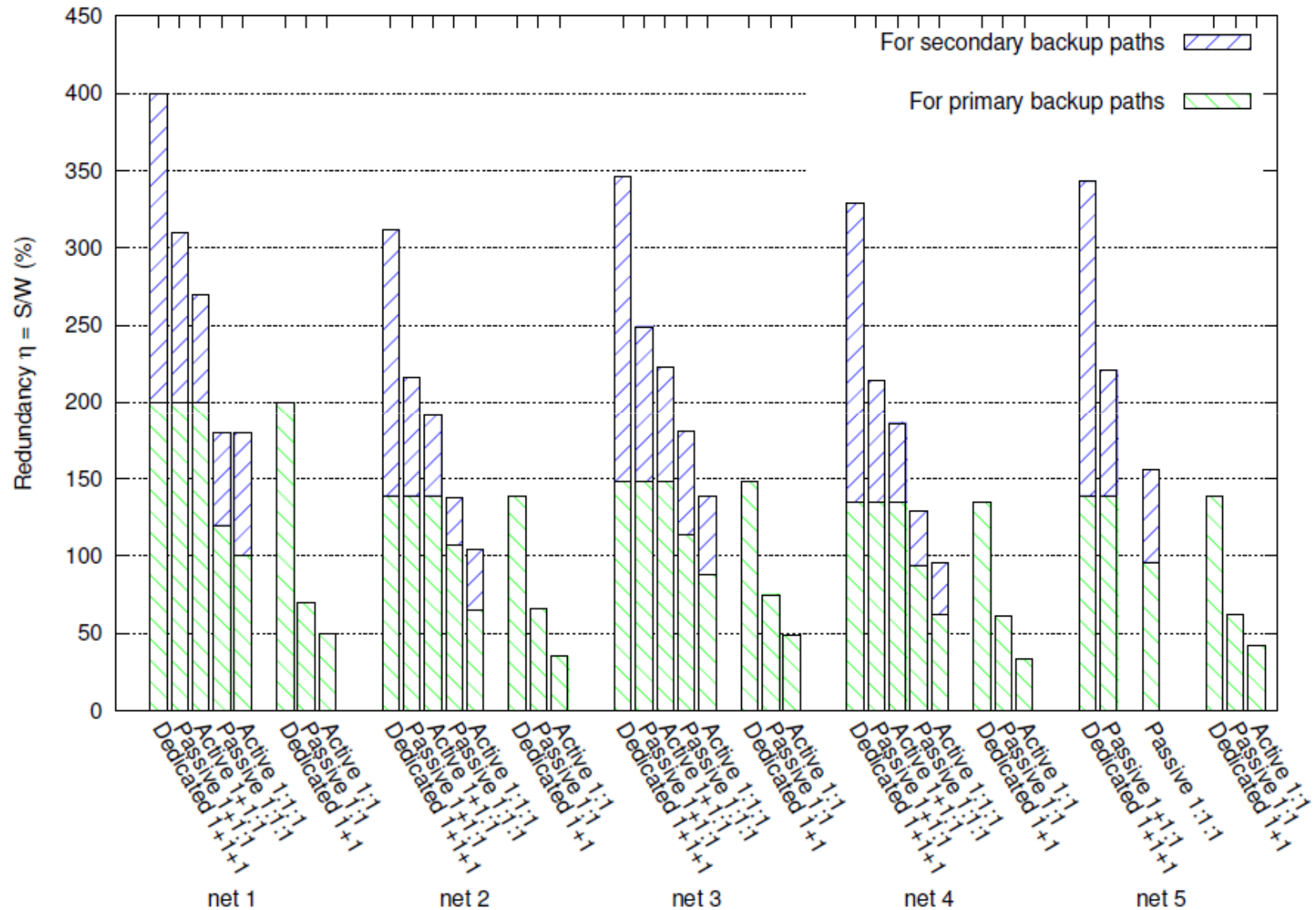
Net4: (17, 33, 136)



Net5: $(N, L, R) = (50, 86, 2450)$

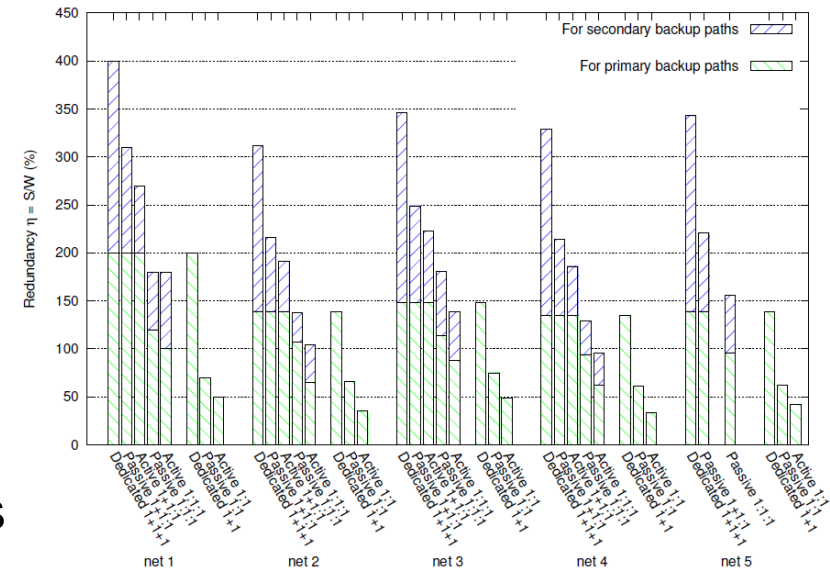


Numerical Results



Observations

- Redundancy can be reduced by increased complexity
 - From 1+1+1, 1+1:1, to 1:1:1
- The *active* approach always has lower redundancy than the *passive* approach
 - 12% reduction on Net 2-4 for 1+1:1 and
 - 25% reduction on Net 2-4 for 1:1:1
- The *secondary* backup paths use less spare capacity than the *primary* backup paths
- Much more redundancy to protect 100% dual link failure than single link failures



Conclusion

Contributions:

- A scalable method to optimize spare capacity sharing
- Removal of a roadblock on dual link failure protection

Current and future work

- Partial diverse backup paths on bi-connected networks for dual link failure protection – Ready [24]
- Improve/remove sub-optimal introduced by sequential models
 - Other research

Questions?

