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

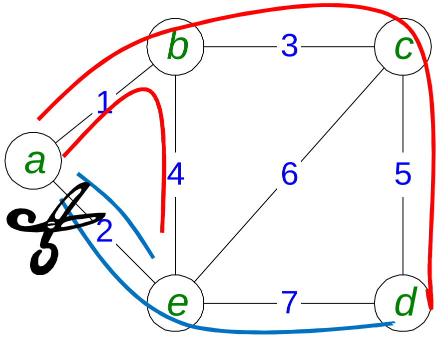
  Based on the (non)sharing between any two backup paths → *limited scalability*

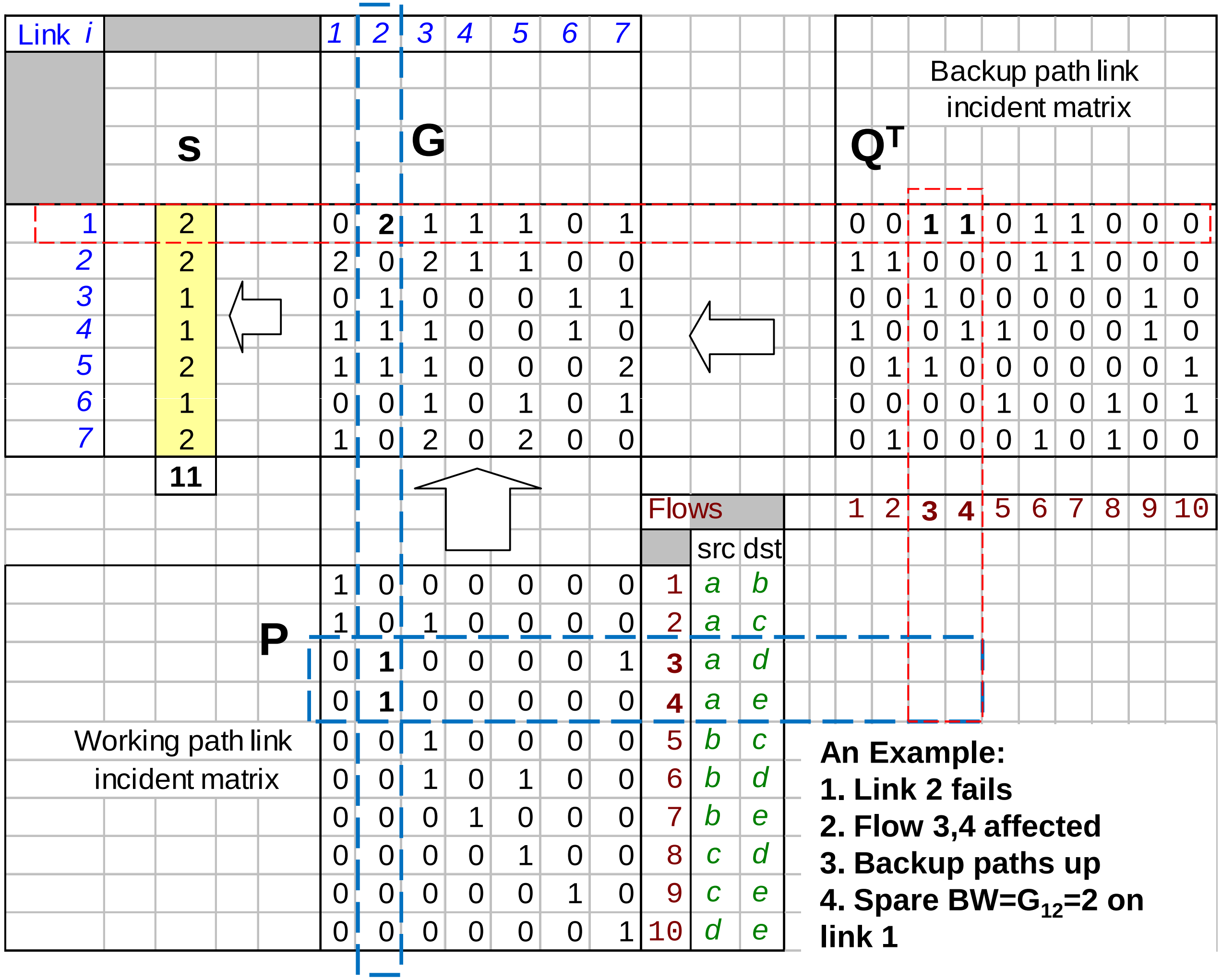
➢ **A** ***road block*** for accurate/efficient dual failure protection

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 = maxG**





Link *i*	s	*1*	**2**	*3*	*4*	*5*	*6*	*7*
1	2	0	**2**	1	1	1	0	1
2	2	2	0	2	1	1	0	0
3	1	0	1	0	0	0	1	1
4	1	1	1	1	0	0	1	0
5	2	1	1	1	0	0	0	2
6	1	0	0	1	0	1	0	1
7	2	1	0	2	0	2	0	0
	11							

G

Backup path link incident matrix

Q^T

Flows	1	2	**3**	**4**	5	6	7	8	9	10
1	0	0	**1**	**1**	0	1	1	0	0	0
2	1	1	0	0	0	1	1	0	0	0
3	0	0	1	0	0	0	0	0	1	0
4	1	0	0	1	1	0	0	0	1	0
5	0	1	1	0	0	0	0	0	0	1
6	0	0	0	0	1	0	0	1	0	1
7	0	1	0	0	0	1	0	1	0	0

P

Working path link incident matrix

1	**2**	*3*	*4*	*5*	*6*	*7*	Flows	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*
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

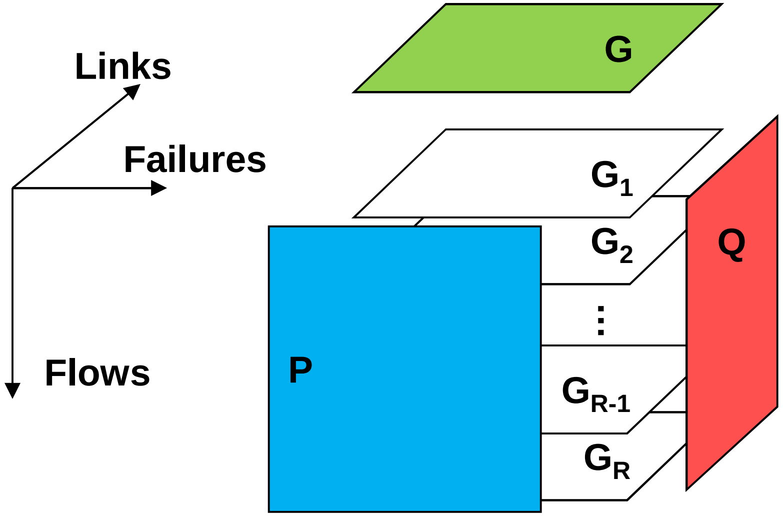
- P indicates all working paths. Each row represents a path of a flow. Each column shows a link usage on these paths.
- Q is the backup paths matrix. Same as above.
- Assume each flow has one unit demand.
- $G = Q^{\wedge T} P$, $^{\wedge T}$ is the matrix transpose operation

  → 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

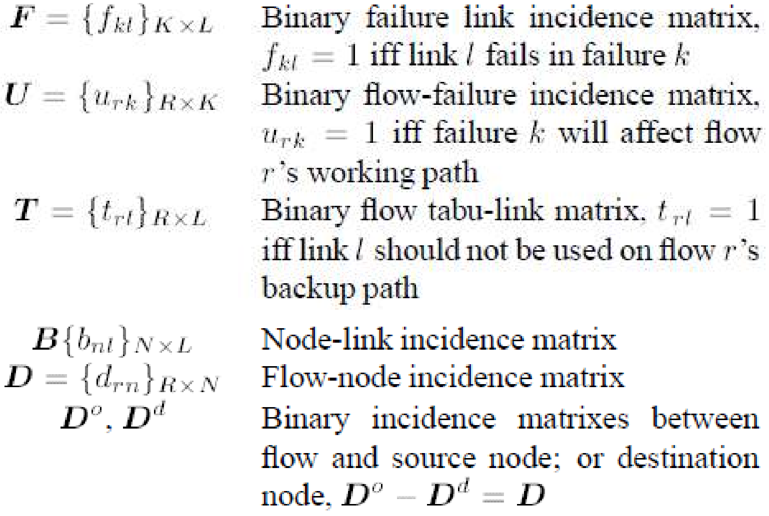
Another way to compute SPM

- $G = \Sigma_r G_r$, 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

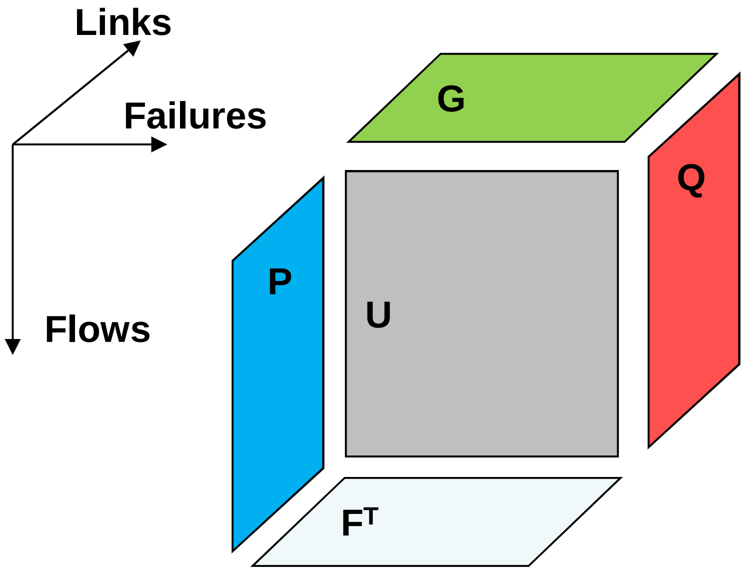


Model Node Failure or SRLG

- 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 $G = Q^{\wedge T} U$
    - 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 $$T = U \odot F \quad (2)$$



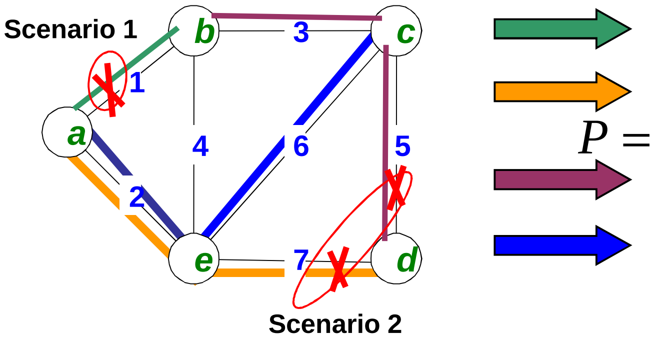
$F = \{f_{kl}\}_{K \times L}$	Binary failure link incidence matrix, $f_{kl} = 1$ iff link l fails in failure k
$U = \{u_{rk}\}_{R \times K}$	Binary flow-failure incidence matrix, $u_{rk} = 1$ iff failure k will affect flow r's working path
$T = \{t_{rl}\}_{R \times L}$	Binary flow tabu-link matrix, $t_{rl} = 1$ 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 → 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
  - $T = U \odot F$



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

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

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

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

SCA model for arbitrary failures

$$\min_{Q,s} \quad S = e^T s \tag{1}$$

Minimize total spare capacity

$$\text{s.t.} \quad s = \max G \tag{2}$$

Enough spare capacity on each link

$$G = Q^T M U \tag{3}$$

Calculation of spare provision matrix

$$T + Q \leq 1 \tag{4}$$

Failure-disjointed backup paths

$$Q B^T = D \tag{5}$$

Flow conservation of backup

$$Q : binary \tag{6}$$

$$U = P \odot F^T \tag{7}$$

Path failure incident matrix

$$T = U \odot F \tag{8}$$

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?

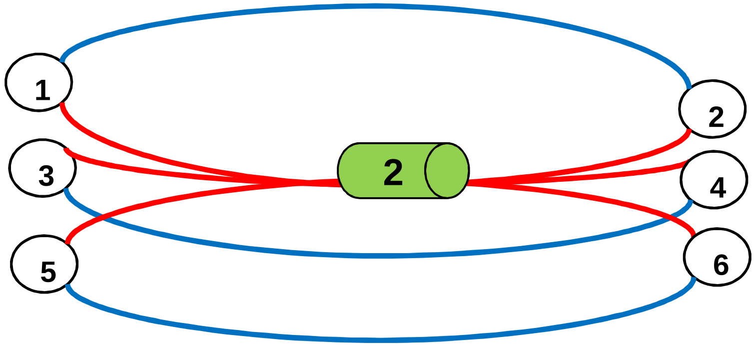
- Single failures are well studied
- Dual link failures such as dual fiber cuts did happen under
  - Scenarios where frequent network changes occur
  - Scenarios where reduced reliability on network facility & equipment
  - Scenarios where intentional sabotage cannot be avoided

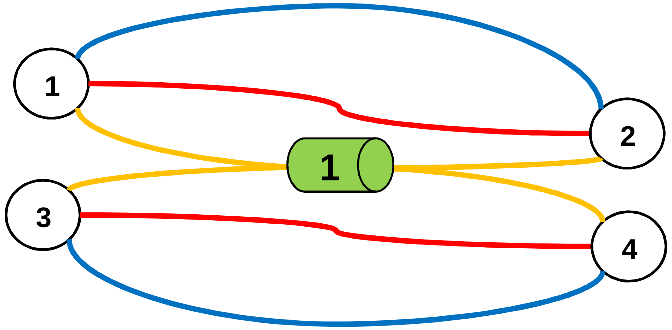
How?

- 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 **2** 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 $\boldsymbol{P} = \{\boldsymbol{p_r}\} = \{\boldsymbol{p_{ri}}\}$,

      where $\boldsymbol{p_{ri}} = \mathbf{1}$ iff working path of flow r uses link i.
    - All primary backup paths $\boldsymbol{Q} = \{\boldsymbol{q_r}\} = \{\boldsymbol{q_{ri}}\}$
    - All secondary backup Paths $\boldsymbol{Z} = \{\boldsymbol{z_r}\} = \{\boldsymbol{z_{ri}}\}$

Failure Vector $\boldsymbol{u_r}$ 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 $p_{ri} = 1 \,\&\, q_{rj} = 0 \quad or \quad p_{rj} = 1 \,\&\, q_{ri} = 0$
  - ➢ or the first failure vector for flow r, has value 1 on position k

$$u_r^1 = vec\left(p_r^T \overline{q}_r \oplus q_r^T \overline{p}_r\right) \qquad k = (i-1)L + (j-i)$$

- 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 $p_{ri} = 1 \,\&\, q_{rj} = 1 \quad or \quad p_{rj} = 1 \,\&\, q_{ri} = 1$
  - ➢ or the second failure vector for flow r, has value 1 on position k

$$u_r^2 = vec\left(p_r^T q_r \oplus q_r^T p_r\right)$$

Example of computing failure vector

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

$$p_r = [1000100]$$

$$q_r = [0011001]$$

$$u_r^2 = vec\left(\begin{pmatrix}1\\0\\0\\0\\1\\0\\0\end{pmatrix}(0011001) \oplus \begin{pmatrix}0\\0\\1\\1\\0\\0\\1\end{pmatrix}(1000100)\right) = vec(\begin{pmatrix} & & 1 & 1 & & & 1\\ & & & & & & \\ 1 & & & & 1 & & \\ 1 & & & & 1 & & \\ & & 1 & 1 & & & 1\\ & & & & & & \\ 1 & & & & 1 & & \end{pmatrix})$$

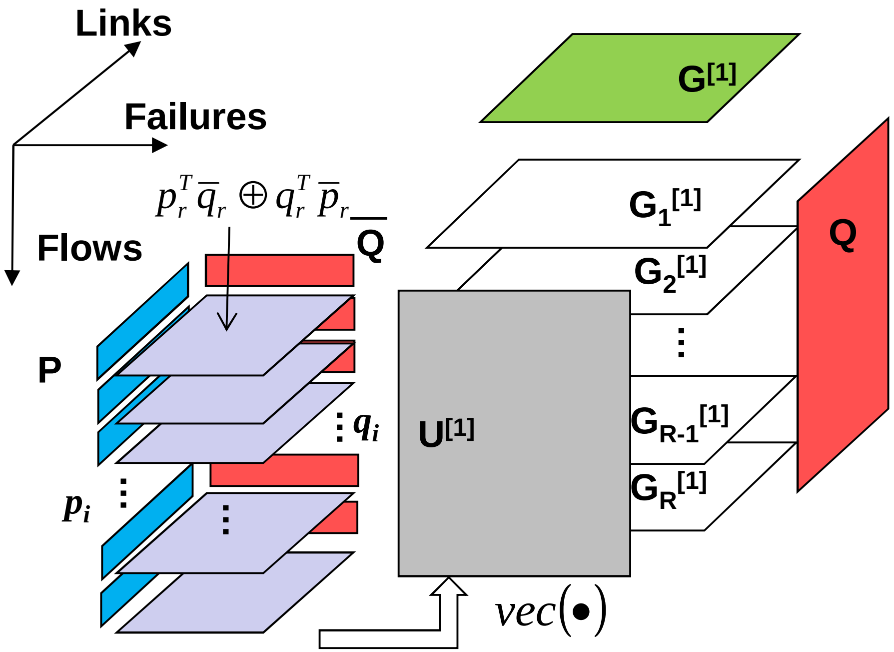
$$= (0011001 \cdots 1000100)_{49}$$

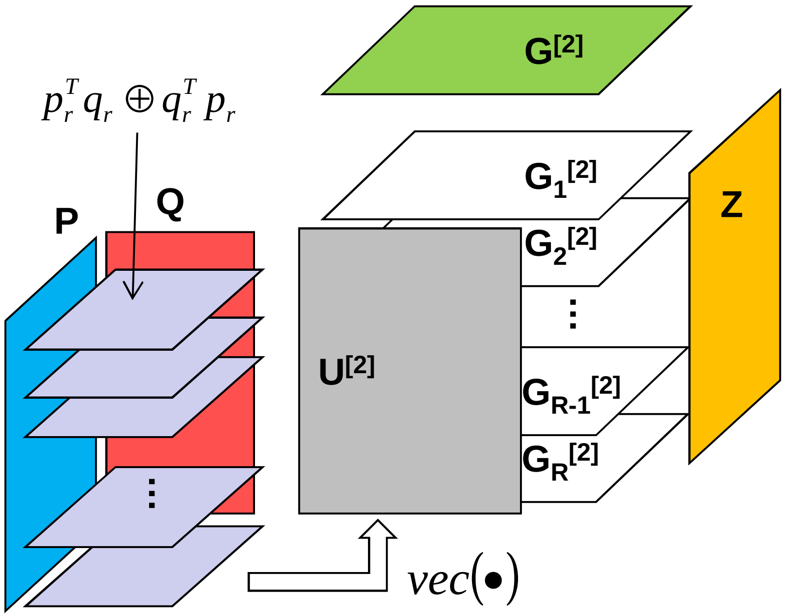
Spare Provision Matrix for Dual Link Failures

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

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

- 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
	$G = Q^T M U^1 + Z^T M U^2$	(18)	Calculation of spare provision matrix
	$P + Q + Z \le 1$	(19)	Mutually disjointed backup paths
	$QB^T = D$	(20)	Flow conservation of backup
	$ZB^T = D$	(21)	
	$Q, Z : binary$	(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)
	$G^{[1]} = Q^T M U^1$	(26)
	$P + Q \le 1$	(27)
	$QB^T = D$	(28)
	$Q : binary$	(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 $u_r^1 = vec\left(p_r^T \overline{q}_r \oplus q_r^T \overline{p}_r\right)$
    - To $u_r^1 = vec\left(p_r^T e_r \oplus e_r^T \overline{p}_r\right)$
  - 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

$$p_r = [1000100]$$

$$q_r = [0011001] \quad \overline{q}_r = [1100110]$$

$$u_r^1 = vec\left(p_r^T e \oplus e^T p_r\right)$$

$$= vec\left(\begin{pmatrix} 1&1&1&1&1&1&1 \\ 1&&&&1&& \\ 1&&&&1&& \\ 1&&&&1&& \\ 1&1&1&1&1&1&1 \\ 1&&&&1&& \\ 1&&&&1&& \end{pmatrix}\right)$$

$$= (1111111 \cdots 1000100)_{49}$$

Various Protection Schemes

- Whether backup paths use dedicated or shared resource

Scheme	*Primary Backup Path*	*Secondary Backup Path*
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

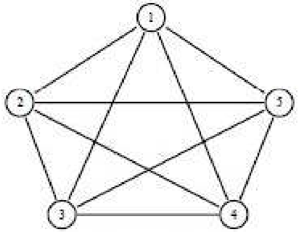
- Whether capacity sharing occur during or after routing

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

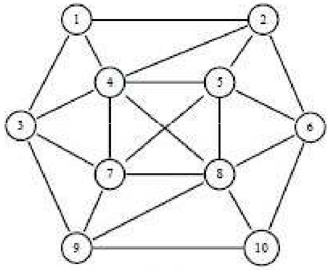
Networks for Numerical Study

Five networks

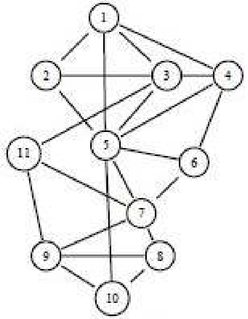
- All tri-connected
- Link capacity unlimited → Reduce interferences from capacity



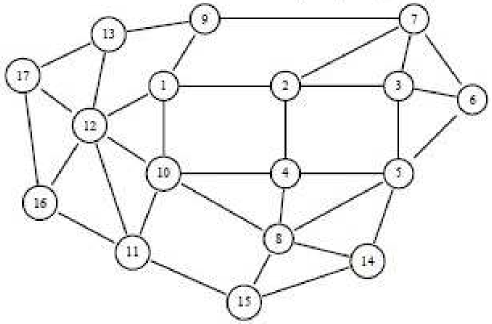
Net1: $(5, 10, 20)$



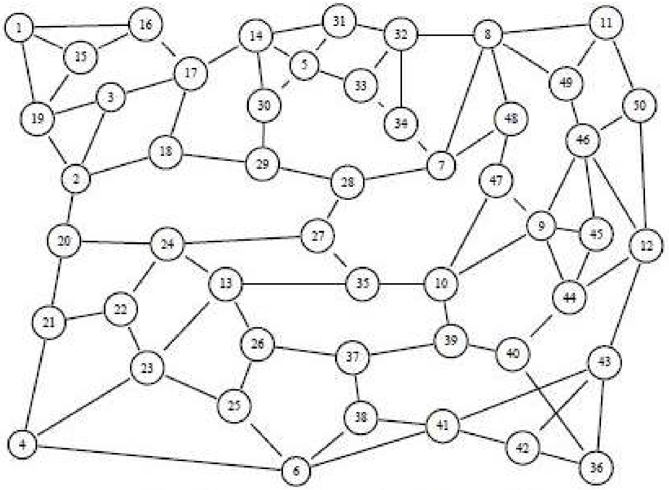
Net2: $(10, 22, 90)$



Net3: $(11, 22, 110)$

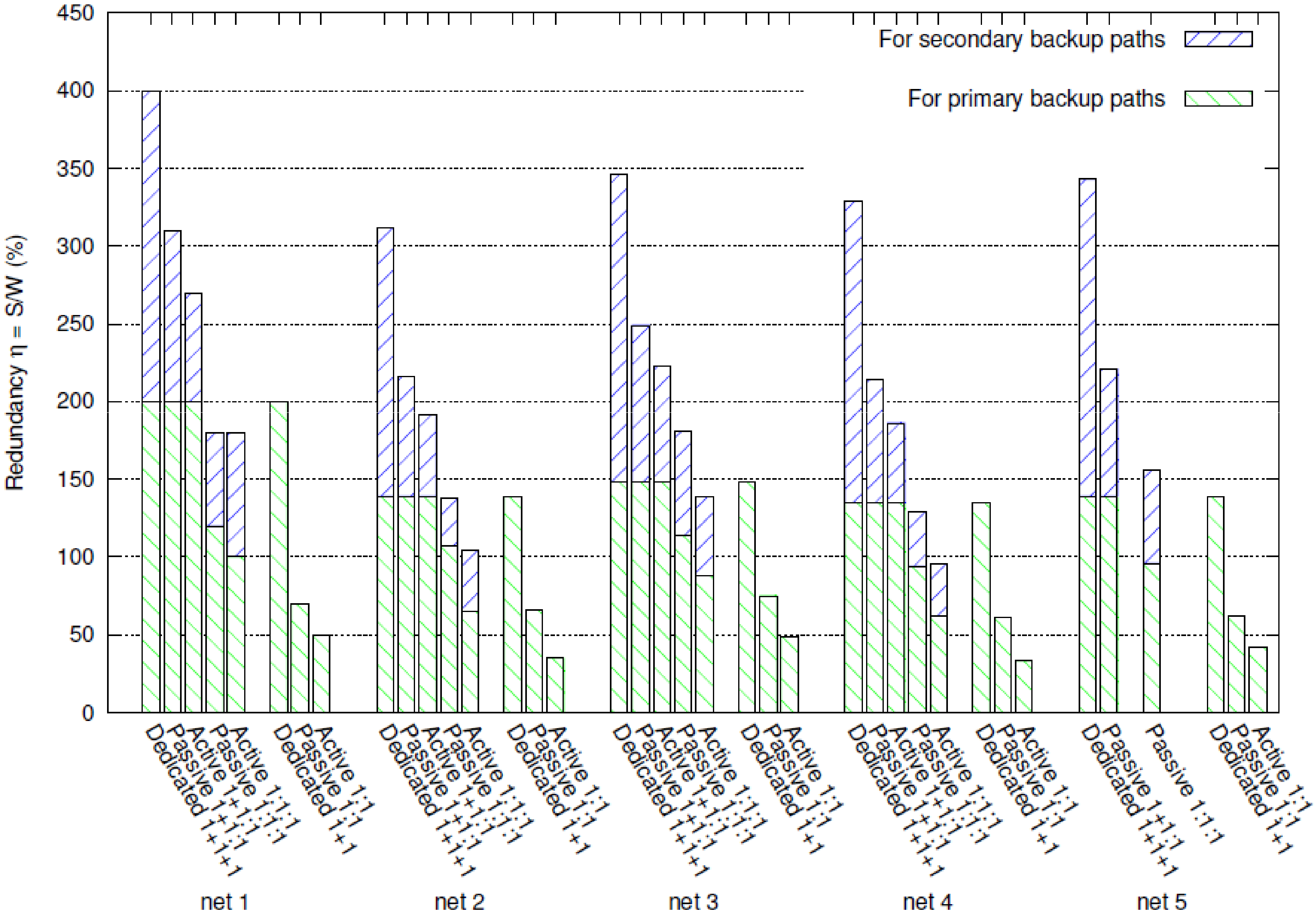


Net4: $(17, 33, 136)$

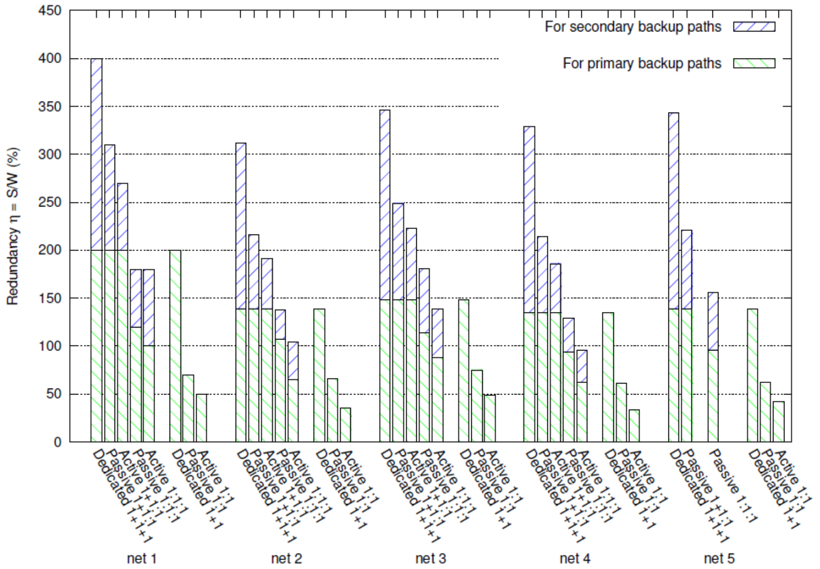


Net5: $(N, L, R) = (50, 86, 2450)$

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?