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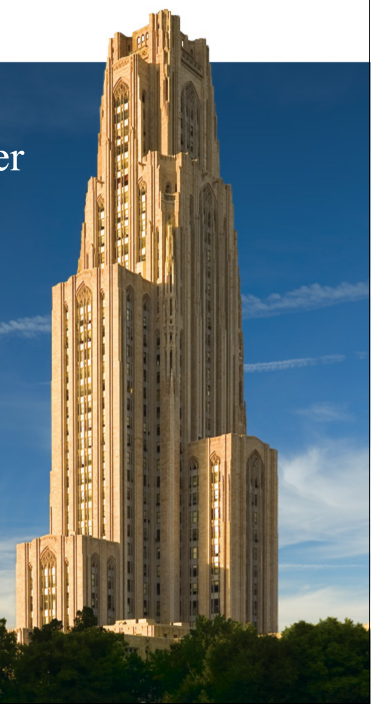

Supporting Differentiated Resilience Classes in Multilayer Networks

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Motivation

- Customers have a range of availability requirements
  - Consumer Internet access (.93 - .95) ➔ customers happy
  - Most businesses subscribe to .999 or less type service
  - Emerging applications: Smart Grid, Emergency Communications, Telemedicine -- need .99999 or greater end to end.
  - *ONLY a SMALL Fraction of Users/Traffic* need high levels of availability and are willing to PAY for it!
  - However high availability traffic derives the design ➔ free rider scenario

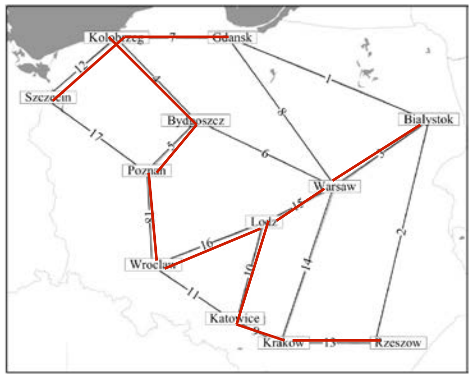
- Network Operators provide differentiated Quality of Resilience (QoR) classes
  - Categorize services into QoR classes (Bronze, Silver, Gold)
  - Each QoR class different levels of protection and routing
    - Gold : 1 +1 dedicated path protection
    - Silver : Shared backup path protection
    - Bronze: No Protection
  - If not reliable enough – additional protection, redundant protection across layers

Highly Available Spine

- Spine Concept
  - High availability must begin at physical layer and work it's way up
  - Spine: embed a higher availability subnetwork into the physical layer providing a basis for QoR
  - Highest class of QoR WP or BP routed on SPINE

Nodes, link interfaces and links on Spine have higher availability

Other links and nodes lower availability



Highly Available Spine

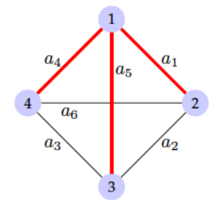
- How to provide availability differentiation for components on spine versus those off spine?
- Equipment differentiation
  - Vendors claim can get a range of availabilities by equipment arrangement/configuration and cost (e.g. hot standby line card, redundant fans, redundant backplane, etc) (.99 - .999997)
- Equipment Site differentiation
  - Situate Spine equipment to increase MTTF - longer back up power supplies, better heating/cooling, stronger outside cabinets, etc
  - Underground links versus above ground, etc.
- Reduce MTTR along Spine (5% - 25% in other industries)
  - Follow best practices and training procedures (NRIC, FCC)
  - Pre-position spare parts/equipment
  - *Assign most experienced staff to OAM Spine portion of network*
  - Ex. WDM OXC 99.994% → (99.9943% - 99.9955%)

Spine Concept

- Improve overall availability by making strong stronger in parallel systems
- Example
  - Let all the links have the same availability a
  - Spine in red

    spine links $a_S = a + \Delta$

    off spine links $a_o = a - \Delta$
  - A_S average end to end flow availability
    - One hop working path, two hop backup path



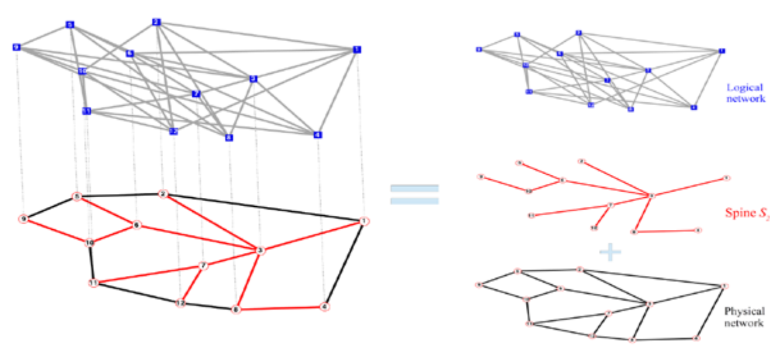
Case	A_S	Downtime (hours/year)
$a = .9,\ \Delta = 0$	.981	166.44
$a = .9,\ \Delta = 0.09$	.99712	25.23756
$a = .9,\ \Delta = 0.099$	.999701	2.61749

Case		1Hop ‖ 2Hop	1Hop ‖ 3Hop	2Hop ‖ 2Hop
$a = .9, \Delta = 0$	All $s-d$ pairs the same	0.981	0.9729	0.9639
$a = .9, \Delta = 0.09$	6 $s-d$ pairs with 1Hop WP ON spine	0.998	0.99645	0.960756
–	6 $s-d$ pairs with 1Hop WP OFF spine	0.996219 or 0.934659	0.96084	0.993156

A. Alashaikh, T. Gomes and D. Tipper, "The Spine Concept for Improving Network Availability," *Computer Networks,* Vol. 82, pp. 4-19, May, 2015

Multi-layer Network Model

- Two layer network: physical $G_P = (V_P, E_P)$, logical $G_L = (V_L, E_L)$
- Logical links E_L are mapped to paths of physical links E_P .
- The spine, G_S is defined as $V_S \subseteq V_P$ and $E_S \subset E_P$
  - For full connectivity → spine is min spanning tree (MST) i.e., $|E_S| = |V_P| - 1$.
- Demands, D_ϕ, routed at the logical layer

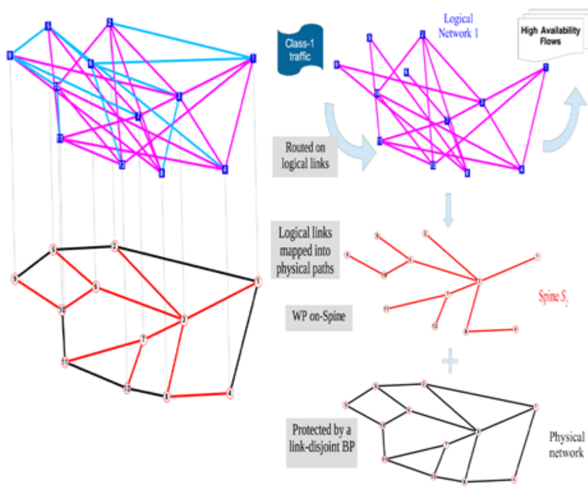


Multi-layer Network Model

- Logical routing should isolate traffic of different QoR classes
  – Results in multiple logical networks, one for each class.

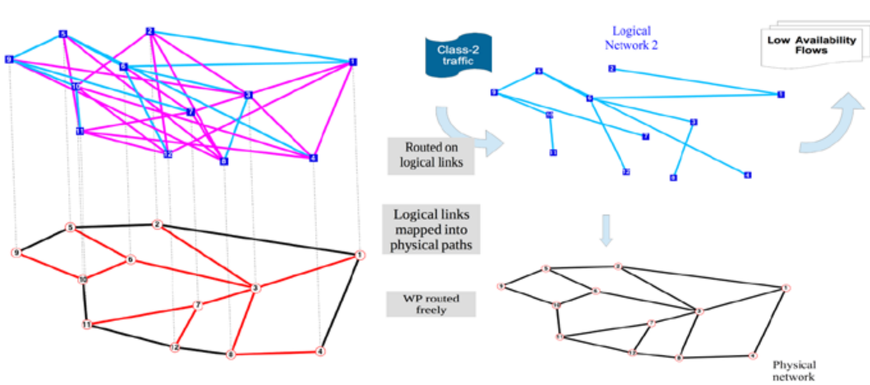
- class-1 (ϕ= 1) requires high availability levels

- Flows are routed on logical links mapped to a fully disjoint working and backup path-pair in physical network, one of which is restricted to be on the spine.



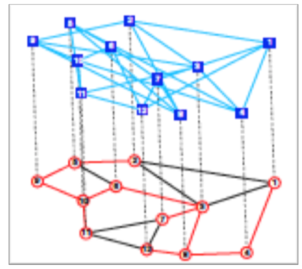
Multi-layer Network Model

- class-2 (ϕ= 2) has no strict availability requirements.
  - flows of class-2 are routed freely on the network with no protection

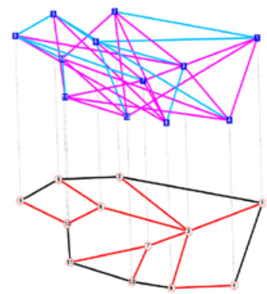


Multi-Layer Design Problems

- Two optimization models developed
- Model I: Duplicate logical links
  - Assume each class has the same set of logical links that are duplicated for exclusive use of each class.



- Model II: Partitioned logical network
  - Classes do not necessarily have identical logical networks.
  - Logical network is partitioned into two sub-networks, each network must be capable of carrying all demands of the it's class.



Multi-Layer Network Design

- Model I: Duplicate Logical Link model

OBJECTIVE

Minimize total resources

$$\underset{X_{ij}^{st,\phi},Y_{ij}^{st,\phi}}{\text{minimize}} \quad \sum_{\phi}\sum_{ij\in E_p}\sum_{st\in E_L}(X_{ij}^{st,\phi}+Y_{ij}^{st,\phi}) \tag{5}$$

s.t.

Class-1 logical links mapping on-the-spine with aggregate BW

$$\sum_{kt\in EL} Z_{kt}^{d_\phi^{mn}} - \sum_{sk\in EL} Z_{sk}^{d_\phi^{mn}} = \begin{cases} d_\phi^{mn} & \text{if } k=m \\ -d_\phi^{mn} & \text{if } k=n \\ 0 & \text{otherwise} \end{cases} \quad ,\forall k\in V_L, d_\phi^{mn} \tag{6}$$

$$\sum_{ik\in E_S} X_{ik}^{st,\phi} - \sum_{kj\in E_S} X_{kj}^{st,\phi} = \begin{cases} w_\phi^{st} & \text{if } k=s \\ -w_\phi^{st} & \text{if } k=t \\ 0 & \text{otherwise} \end{cases} \quad ,\forall k\in V_S, \phi=1 \tag{7}$$

Class-1 logical links mapping to BP

$$\sum_{ik\in E_P} X_{ik}^{st,\phi} - \sum_{kj\in E_P} X_{kj}^{st,\phi} = \begin{cases} w_\phi^{st} & \text{if } k=s \\ -w_\phi^{st} & \text{if } k=t \\ 0 & \text{otherwise} \end{cases} \quad ,\forall k\in V_P, \phi\neq 1 \tag{8}$$

$$\sum_{ik\in E_P} Y_{ik}^{st,\phi} - \sum_{kj\in E_P} Y_{kj}^{st,\phi} = \begin{cases} w_\phi^{st} & \text{if } k=s \\ -w_\phi^{st} & \text{if } k=t \\ 0 & \text{otherwise} \end{cases} \quad ,\forall k\in V_P, \phi=1 \tag{9}$$

Class-1 mapped to disjoint path-pair

$$X_{ij}^{st,\phi}+Y_{ij}^{st,\phi}\leq w_\phi^{st} \quad ,\forall (i,j)\in E_P, (s,t)\in E_L, \phi \tag{10}$$

Physical link capacity

$$\sum_{st\in E_L}\sum_{\phi}(X_{ij}^{st,\phi}+Y_{ij}^{st,\phi})\leq c_{ij} \quad ,\forall (i,j)\in E_P \tag{11}$$

Logical link capacity

$$\sum_{mn}\sum_{\phi} Z_{st}^{d_\phi^{mn}} \leq W_{st} \quad ,\forall (s,t)\in E_L \tag{12}$$

$$\sum_{mn} Z_{st}^{d_\phi^{mn}} = w_\phi^{st} \quad ,\forall (s,t)\in E_L, \phi \tag{13}$$

$$X_{ij}^{st,\phi}\geq 0 \quad ,Y_{ij}^{st,\phi}\geq 0, \quad Z_{st}^{d_\phi^{mn}}\geq 0 \tag{14}$$

Multi-Layer Network Design

- Model II : Partitioned Logical Link model
- Modify Model I by adding the constraints below
  - ➔ ILP problem - problems solved in CPLEX

- $\xi_{st} = 1$: logical link *st* can be used by class-1 demands only.
- $\xi_{st} = 0$: logical link *st* can be used by class-2 demands.

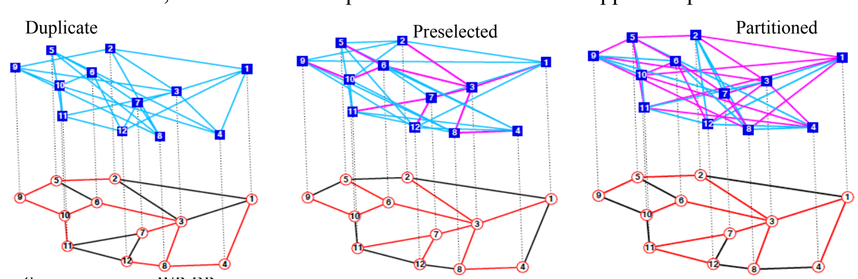
$$\sum_{mn} Z_{st}^{d_\phi^{mn}} - M\xi_{st} \le 0 \qquad ,\forall (s,t) \in E_L, \phi = 1 \qquad (15)$$

$$\sum_{mn} Z_{st}^{d_\phi^{mn}} - M(1-\xi_{st}) \le 0 \qquad ,\forall (s,t) \in E_L, \phi = 2 \qquad (16)$$

$$\xi_{st} \in (0,1) \text{ is binary} \qquad (s,t) \in E_L \qquad (17)$$

Numerical Results

- Evaluate Multi-Layer Network Design Models
  - Consider Polska network as physical network: 12 nodes – 18 links
  - Three different spines given in A. Alashaikh, T. Gomes and D. Tipper, “The Spine Concept for Improving Network Availability,” *Computer Networks,* Vol. 82, pp. 4-19, May, 2015.
  - Logical layer
    - generate a number of k–regular random graphs using k = 3, 4, 5, 6, and 7.
    - random, or random with a preselected set of links mapped to spine



S_1 = max average WP-BP disjoint path-pair availability

S_2 , maximizes the average WP path availability on the spine.

S_3 , a compromise solution

Numerical Results

- For each spine, we ran 14 scenarios
  - Duplicate logical network: 6 scenarios
  - Partitioned logical network: 8 scenarios
  - Each scenario repeated 7 times – results averaged
- Full mesh of upper layer flows with single unit demand for each class (d_ϕ^{mn} = 1; for all *mn*) 50/50 traffic split
- Averaged results compared in terms of
  - *resource use*: amount of reserved physical capacity required to realize the logical links
  - *logical link downtime per class*
  - *end-to-end flow downtime per class*

Scenario	Problem type	regular graph degree *k*	total no. of logical links	preselected logical links
1	duplicated logical network	3	36	no
2		3	36	yes
3		4	48	no
4		4	48	yes
5		5	60	no
6		5	60	yes
7	partitioned logical network	4	24	no
8		4	24	yes
9		5	30	no
10		5	30	yes
11		6	36	no
12		6	36	yes
13		7	42	no
14		7	42	yes

Numerical Results

- Availability/Downtime Logical Link results:
  - Links on the spine a_S = .999, links off spine a_O = .99
  - Large difference between class 1 and 2!
  - Slight difference in class 1 results for spine – larger impact on class 2
  - Preselection of logical links to spine improves class 1

Scenario	Problem type	regular graph degree *k*	total no. of logical links	preselected logical links	Average logical link expected downtime Class-1 (hrs/yr)			Average logical link expected downtime Class-2 (hrs/yr)			Maximum logical link expected downtime class-1 (hrs/yr)			Maximum logical link expected downtime Class-2 (hrs/yr)		
					S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
1	duplicated logical network	3	36	no	0.42	0.47	0.45	62	65	69	1.0	1.3	1.1	142.1	250.2	173.0
2		3	36	yes	0.34	0.35	0.33	40	56	40	1.2	1.5	1.1	138.4	320.9	182.7
3		4	48	no	0.43	0.48	0.46	63	69	64	1.1	1.4	1.2	142.1	250.2	174.2
4		4	48	yes	0.36	0.41	0.41	49	69	48	1.2	1.6	1.4	161.9	322.1	182.9
5		5	60	no	0.41	0.45	0.44	64	76	64	1.1	1.5	1.2	134.6	275.9	207.4
6		5	60	yes	0.39	0.46	0.41	59	76	58	1.2	1.7	1.1	161.9	333.0	203.7
7	partitioned logical network	4	24	no	0.37	0.40	0.41	73	86	84	0.8	1.0	1.0	143.3	251.5	171.8
8		4	24	yes	0.27	0.39	0.33	63	68	62	0.8	1.5	1.1	128.5	226.8	192.6
9		5	30	no	0.36	0.44	0.33	72	71	62	1.0	1.3	1.1	116.1	202.4	192.6
10		5	30	yes	0.39	0.53	0.41	58	55	70	1.2	1.7	1.5	118.5	191.5	181.6
11		6	36	no	0.39	0.44	0.47	68	76	66	1.1	1.3	1.4	150	224	158
12		6	36	yes	0.41	0.49	0.48	50	56	57	1.3	1.5	1.4	104	178	168
13		7	42	no	0.40	0.47	0.47	70	77	73	1.1	1.5	1.4	142	228	173
14		7	42	yes	0.42	0.52	0.46	63	61	69	1.2	1.6	1.3	153	182	168

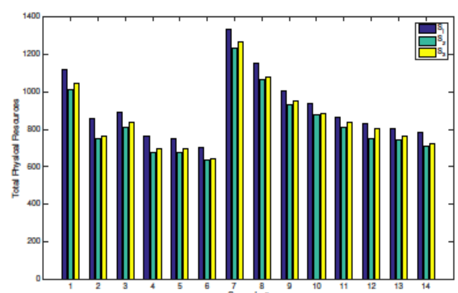
Numerical Results

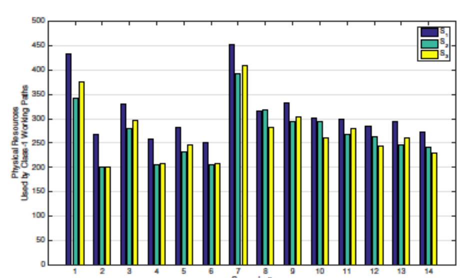
- Availability/Downtime Logical End-to-End Flows results:
  - Links on the spine $a_S = .999$, links off spine $a_O = .99$
  - Large difference between class 1 and 2!

Scenario	Problem type	regular graph degree *k*	total no. of logical links	preselected logical links	Average flow expected downtime Class-1 (hrs/yr)			Average flow expected downtime Class-2 (hrs/yr)			Maximum expected flow downtime Class-1 (hrs/yr)			Maximum expected flow downtime Class-2 (hrs/yr)		
					S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3	S_1	S_2	S_3
1	duplicated logical network	3	36	no	0.78	0.87	0.85	118	123	133	1.9	2.3	2.0	287	432	385
2		3	36	yes	0.53	0.43	0.44	54	42	42	1.5	1.7	1.4	177	333	215
3		4	48	no	0.62	0.68	0.67	102	102	94	1.6	1.7	1.6	260	352	286
4		4	48	yes	0.49	0.46	0.48	62	53	53	1.5	1.8	1.7	185	334	215
5		5	60	no	0.50	0.53	0.52	89	99	85	1.3	1.5	1.4	230	372	260
6		5	60	yes	0.46	0.47	0.46	71	67	66	1.3	1.7	1.3	200	333	264
7	partitioned logical network	4	24	no	0.83	0.92	0.98	216	239	239	2.0	2.3	2.5	467	645	527
8		4	24	yes	0.59	0.73	0.63	178	188	170	1.6	2.2	1.9	389	491	442
9		5	30	no	0.59	0.68	0.66	180	174	161	1.5	1.7	1.7	403	421	388
10		5	30	yes	0.56	0.71	0.57	150	117	151	1.6	2.0	1.8	341	368	409
11		6	36	no	0.53	0.58	0.60	154	130	134	1.3	1.6	1.6	388	451	332
12		6	36	yes	0.52	0.59	0.55	111	87	109	1.4	1.7	1.5	277	343	309
13		7	42	no	0.50	0.53	0.54	122	116	135	1.3	1.6	1.6	283	385	343
14		7	42	yes	0.48	0.56	0.49	114	90	122	1.2	1.7	1.5	276	306	355

Numerical Results

- Slight differences in total resource efficiency across the spines.
- Some what larger differences on class-1 WP depends heavily on the spine topology.
- Preselected logical Links scenarios requires less resources - affected by the logical topology layout.





Numerical Results

- Results compared against no-spine baseline model
- Downtime
  - Class-2
    - Links/flows have same results
  - Class-1
    - Downtimes for class-1➔ 10X orders more than the spine model.

Scenario	Average Class-1 logical link expected downtime (hrs/yr)	Average Class-1 flow expected downtime (hrs/yr)	Maximum Class-1 logical link expected downtime (hrs/yr)	Maximum Class-1 expected flow downtime (hrs/yr)
1	6.1	**11.7**	14	**25**
3	6.3	**9.9**	14	**25**
5	5.9	**7.3**	15	**16**
7	3.0	**13.1**	12	**30**
9	3.7	**10.1**	15	**23**
11	3.9	**8.5**	15	**18**

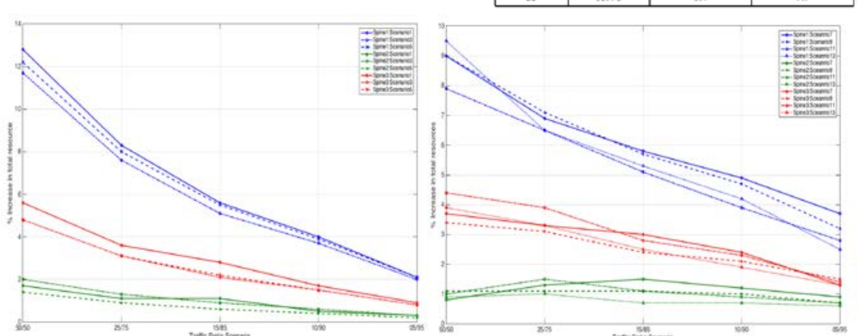
- Resources
  - Spine approach can use non-shortest path routing ➔ more resources
  - Percentage of increase in resources when using the spine can be as low as 0.8% depending on spine and logical topology

Scenario	Average total resources	% Percentage of increase in total resource usage when using the Spine		
	No Spine	S_1	S_2	S_3
1	**994**	12.6	1.4	5.3
3	**800**	11.3	1.7	4.4
5	**667**	12.1	1.2	4.6
7	**1222**	9	0.8	3.7
9	**919**	9	1.1	3.4
11	**803**	7.9	1	4.4

Numerical Results

- Resources
  - Additional resources of spine approach depends on ratio of highest QoR class to lower classes
  - *Would expect highest QoR class traffic to be small percentage of traffic*
  - Vary ratio of QoR1/QoR2
  - Decrease in additional spine resources

# scenario	Traffic ratio	Class-1 demand	Class-2 demand
d1	50/50	1	1
d2	25/75	0.5	1.5
d3	20/80	0.3	1.7
d4	10/90	0.2	1.8
d5	05/95	0.1	1.9



(a) Duplicate scenarios. (b) Partitioned scenarios.

Summary

- Quality of Resilience Classes in multi-layer networks
  - Deploy high available spine to create heterogeneous availability subnetworks at the physical layer to lay a basis for differentiation.
    - Spine created by component MTTF and MTTR differentiation
  - Cross layer mapping schemes to transfer differentiation capability to upper layers providing multiple logical networks with diverse QoR
- Two Network Design Models Developed
  - Duplicate links, Partitioned Networks
  - Numerical results show it widens the range of availability levels compared to existing techniques.
  - Effectiveness depends on
    - the layout of the logical layer
    - the spine used
    - the percentage of highest QoR class traffic

- Future work: restoration at top layer, optimum spine selection for multilayer network