EL736 Communications Networks II: Design and Algorithms

Class10: Restoration and Protection Design of Resilient Networks

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11/28/2007

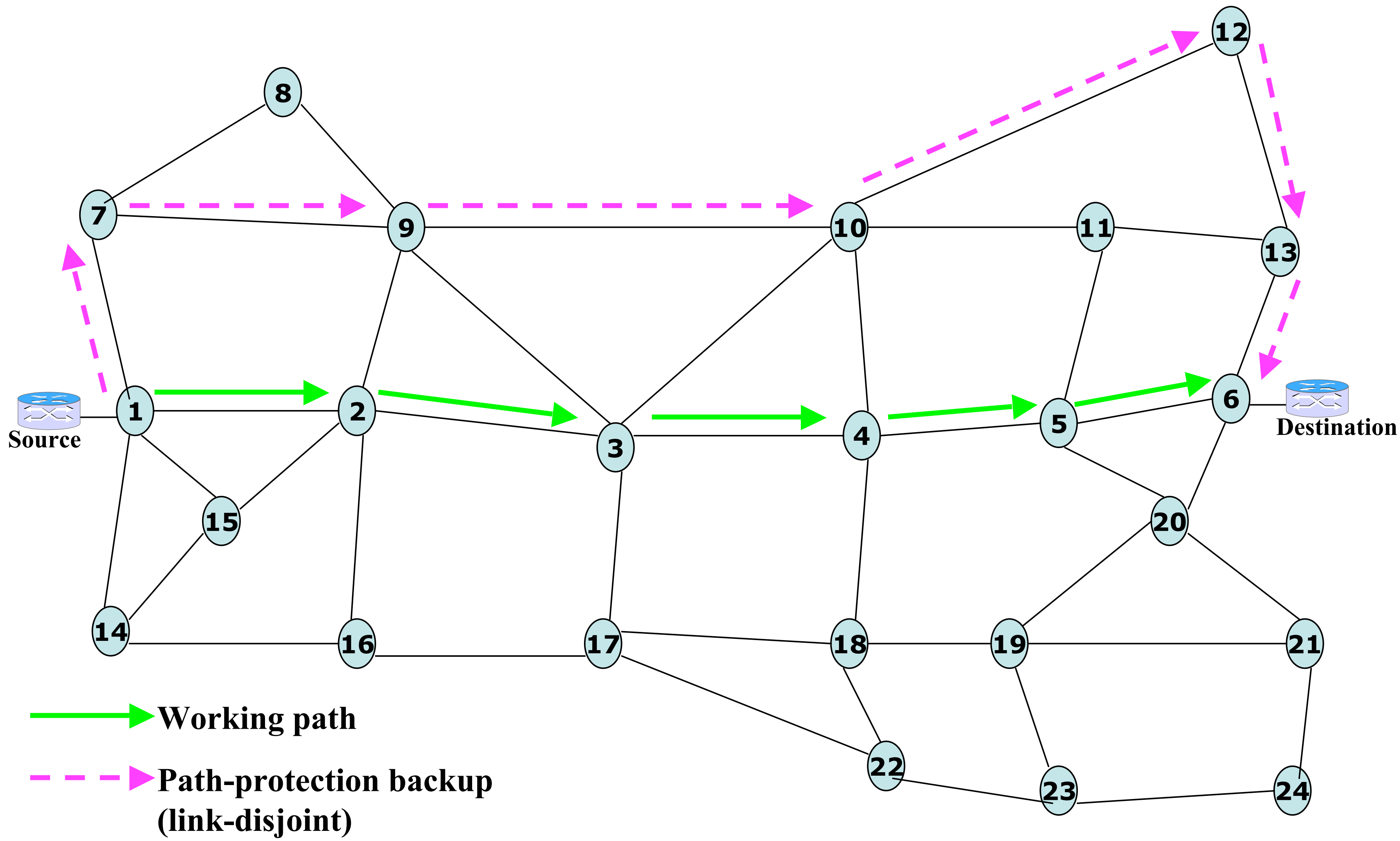
Outline

- Resilient Network Design
- Link Capacity Re-establishment
- Demand Flow Re-establishment
- Separated Normal and Protection Design

Resilient Network Design

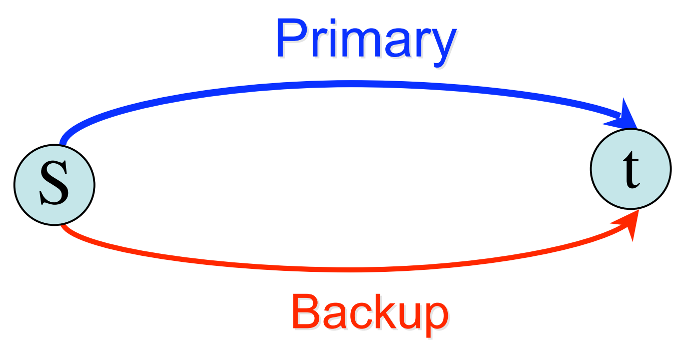
- Objective: design networks to be resilient (robust) against failure situations such that all demands can be carried when portion of network resources are temporally failed
- Recovery Mechanisms:
  - Protection (Pre-provisioned): to resolve a conflict due to a failure prior to the failure occurring
  - Restoration (Post-provisioned): to resolve a failure only once the failure has occurred

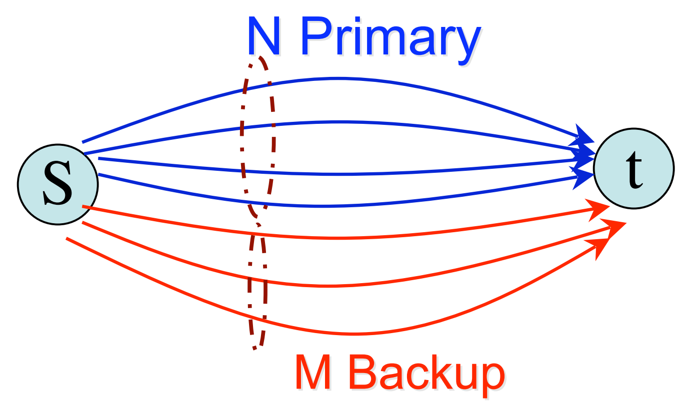
Protection Illustration



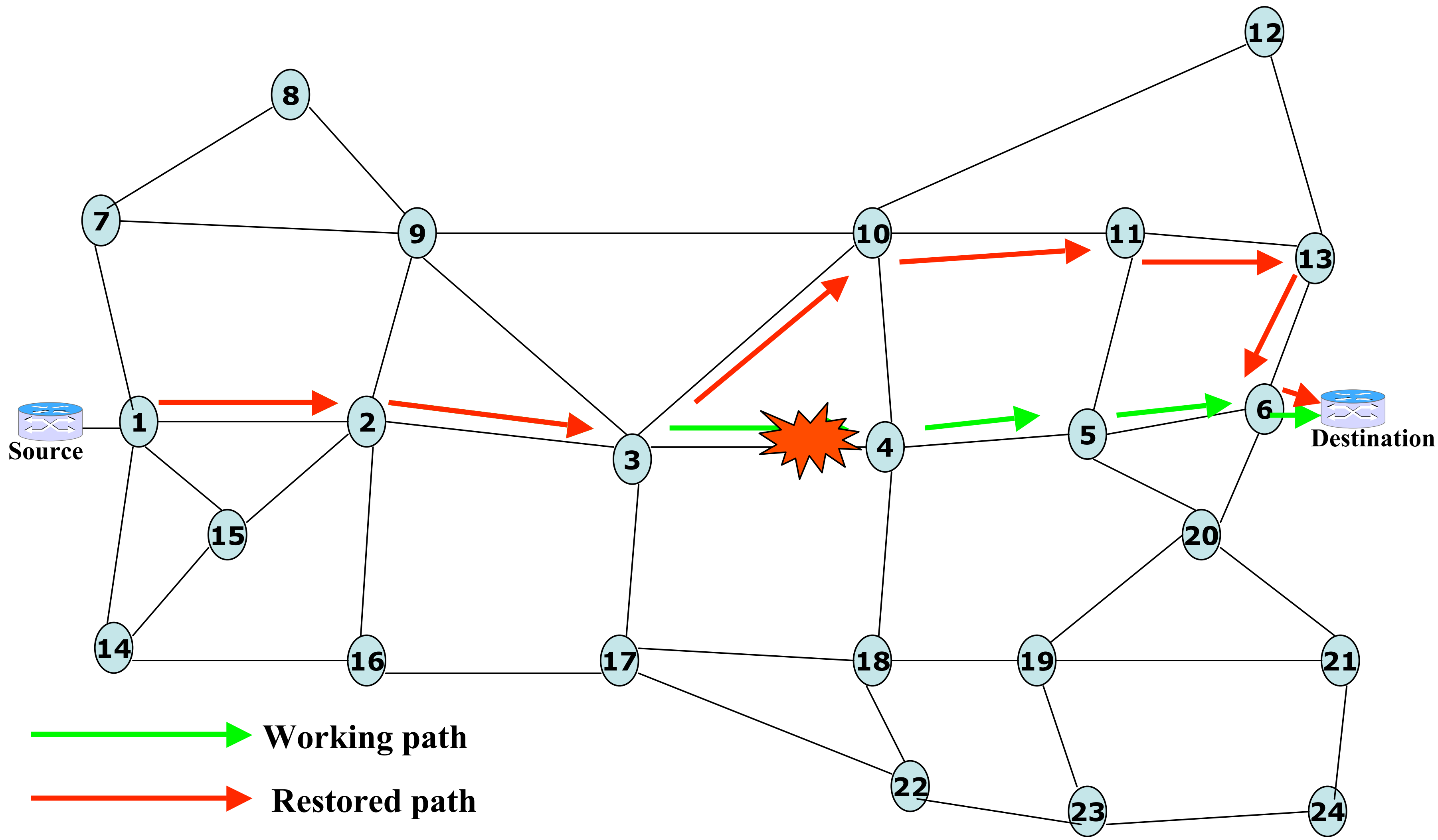
Classification of Protection

- 1+1 (Full) Protection: data transmitted simultaneously on a primary path and a dedicated backup path; switch to backup path in case the primary path fails. [hot-standby]
- 1:1 Protection: data transmitted only on primary path; switch to backup path in case the primary path fails.
- M:N Protection: M back-up paths protect N primary paths (recover from up to M failures out of N paths)





Restoration Illustration

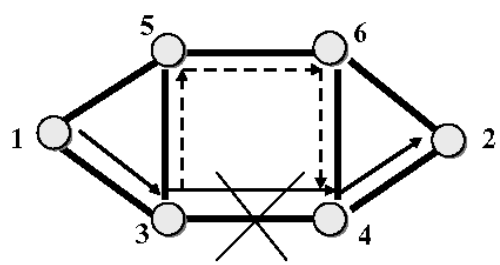


Recovery in Traffic & Transport Networks

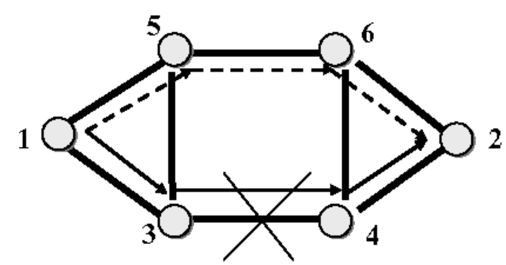
- Traffic Network: packets/calls traversing failed links re-route on surviving links (link capacity can be used for normal and recovery traffic)
- Transport Network: reserved recovery capacity for automated switch over
- Resilient Network Design: how much recovery capacity needed to accommodate packets/calls re-routing?
- Recovery Capacity
  - reserved vs. existing
    - Can it be used for normal traffic?
  - dedicated vs. shared
    - Only used for recovery of specific links/demands?
  - integrated vs. incremental design
    - Recovery considered when build the normal topology?

Link/Path Re-establishment

- Link Re-establishment
  - traffic on a failed link rerouted
  - different flows follow same route
- Path Re-establishment
  - end-end flows on a failed link re-established
  - different flows might have different routes



Link-based re-estalishment



Path-based re-estalishment

Protection Priorities

- Mission Critical Traffic -- Predetermined restoration path with pre-allocated capacity

- Premium Traffic -- Predetermined restoration path without pre-allocated capacity

- Public Traffic -- Restoration path calculated in the fly

- Low Priority Traffic -- Preemptable working paths, may be unprotected

Characterization of Failure States

- link availability coefficients
- path availability coefficients
- demand volume

Simplest Protection: path diversity

Normal Design With PD

- **indices**

  $d = 1, 2, ..., D$ demands

  $p = 1, 2, ..., P_d$ link or node disjoint candidate paths for demand d

  $e = 1, 2, ..., E$ links

- **constants**

  δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise

  h_d volume of demand d

  n_d diversity factor for demand d

  ξ_e marginal (unit) cost of link e

- **variables**

  x_{dp} (non-negative) flow allocated to path p of demand d

  y_e (non-negative) capacity of link e

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y_e$

- **constraints**

  $\sum_p x_{dp} = h_d, \quad d = 1, 2, ..., D$

  $x_{dp} \le h_d / n_d, \quad d = 1, 2, ..., D \quad p = 1, 2, ..., P_d$

  $\sum_d \sum_p \delta_{edp} x_{dp} \le y_e, \quad e = 1, 2, ..., E.$

- Pro.s: zero reconfiguration
- Con.s: low efficiency, doesn't explore bandwidth on alternate paths

Generalized Path Diversity

- surviving paths realize surviving demands

Restoration Design With Generalized Diversity

- **indices**
  - $d = 1, 2, ..., D$ demands
  - $p = 1, 2, ..., P_d$ candidate paths for demand d
  - $e = 1, 2, ..., E$ links
  - $s = 0, 1, ..., S$ situations ($s = 0$ denotes the normal state)
- **constants**
  - δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise
  - h_d volume of demand d
  - χ_{ds} demand coefficient of demand d in state s, $h_{ds} = \chi_{ds} h_d$
  - ξ_e unit cost of link e
  - α_{es} binary availability coefficient of link e in situation s ($\alpha_{es} \in \{0, 1\}$)
  - θ_{dps} binary availability coefficient of path (d, j) in situation s, $\theta_{dps} = \Pi_{\{e:\delta_{edp}=1\}} \alpha_{es}$
- **variables**
  - x_{dp0} flow allocated to path p of demand d in normal state
  - y_e capacity of link e
- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y_e$
- **constraints**

  $\sum_p \theta_{dps} x_{dp0} \geq h_{ds}, \quad d = 1, 2, ..., D \quad s = 0, 1, ..., S$

  $\sum_d \sum_p \delta_{edp} x_{dp0} \leq y_e, \quad e = 1, 2, ..., E.$

Link Capacity Re-establishment

- failure assumption: total failure on a single link,
- recover from any single link
- recovery capacity reserved, shared among all possible link failures

Design with Link Restoration

- **indices**

$d = 1, 2, ..., D$	demands
$p = 1, 2, ..., P_d$	candidate paths for demand d
$e, \ell = 1, 2, ..., E$	links
$q = 1, 2, ..., Q_e$	candidate restoration paths for link e

- **constants**

δ_{edp}	= 1 if link e belongs to path p realizing demand d; 0, otherwise
h_d	volume of demand d
ξ_e	unit cost of link e
$\beta_{\ell eq}$	= 1 if link ℓ belongs to path q restoring link e; 0, otherwise

- **variables**

x_{dp0}	(non-negative) normal flow allocated to path p of demand d
y_e	(non-negative) normal capacity of link e
z_{eq}	(non-negative) flow restoring normal capacity of link e on restoration path q
y'_e	(non-negative) spare, protection capacity of link e (not used in the normal network operating state)

Link Capacity Re-establishment

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e (y_e + y'_e)$

- **constraints**

$$\sum_p x_{dp0} = h_d \quad d = 1, 2, ..., D$$
$$\sum_d \sum_p \delta_{edp}\, x_{dp0} \leq y_e, \quad e = 1, 2, ..., E$$
$$\sum_q z_{eq} = y_e, \quad e = 1, 2, ..., E$$
$$\sum_q \beta_{\ell eq} z_{eq} \leq y'_\ell, \quad \ell = 1, 2, ..., E \quad e = 1, 2, ..., E \quad \ell \neq e.$$

Hot-Standby Link Protection

- recovery capacity: reserved, dedicated to each specific link
- single restoration path for each link

Link Protection With Hot-Standby

- **indices**

$d = 1, 2, ..., D$	demands
$p = 1, 2, ..., P_d$	candidate paths for demand d
$e, \ell = 1, 2, ..., E$	links
$q = 1, 2, ..., Q_e$	candidate restoration paths for link e

- **constants**

δ_{edp}	= 1 if link e belongs to path p realizing demand d; 0, otherwise
h_d	volume of demand d
ξ_e	unit cost of link e
$\beta_{\ell eq}$	= 1 if link ℓ belongs to path q restoring link e; 0, otherwise
K_e	upper bound on the normal capacity y_e of link e

- **variables**

x_{dp0}	(non-negative) normal flow allocated to path p of demand d
y_e	(non-negative) normal capacity of link e
z_{eq}	(non-negative) flow restoring normal capacity of link e on restoration path q
u_{eq}	binary flow variable associated with z_{eq}
y'_e	(non-negative) protection capacity of link e

Hot-Standby Link Protection

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e (y_e + y'_e)$

- **constraints**

$$\sum_p x_{dp0} = h_d, \quad d = 1, 2, ..., D$$

$$\sum_d \sum_p \delta_{edp} \, x_{dp0} \le y_e, \quad e = 1, 2, ..., E$$
$$\sum_q z_{eq} = y_e, \quad e = 1, 2, ..., E$$
$$\sum_q u_{eq} = 1, \quad e = 1, 2, ..., E$$
$$z_{eq} \le K_e u_{eq}, \quad e = 1, 2, ..., E \quad q = 1, 2, ..., Q_e$$
$$\sum_{e \ne \ell} \sum_q \beta_{\ell eq} z_{eq} \le y'_\ell, \quad \ell = 1, 2, ..., E.$$

Demand Flow Re-establishment

- restore individual flows instead of link capacities
- not restricted to single link failure
- recovery capacity unreserved, can also be used for normal traffic,.
- more efficient solution

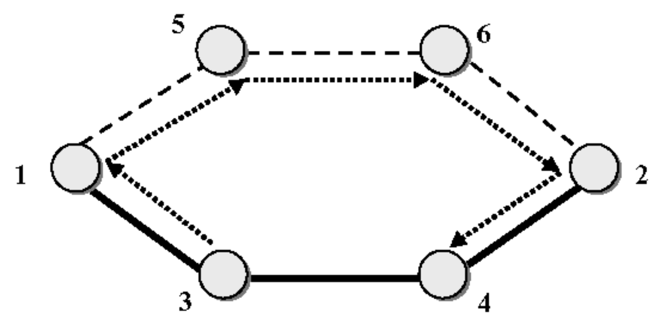


FIGURE 9.5 LR Versus FR

Unrestricted Reconfiguration

- flows can reconfigured arbitrarily for each failure state
- reconfiguration before/after failures

- **indices**

  $d = 1, 2, ..., D$ demands
  $p = 1, 2, ..., P_d$ candidate paths for demand d
  $e = 1, 2, ..., E$ links
  $s = 0, 1, ..., S$ situations

- **constants**

  δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise
  h_d volume of demand d
  χ_{ds} demand coefficient of demand d in state s, $h_{ds} = \chi_{ds} h_d$
  ξ_e unit cost of link e
  α_{es} fractional availability coefficient of link e in state s ($0 \leq \alpha_{es} \leq 1$)

- **variables**

  x_{dps} flow allocated to path p of demand d in state s
  y_e capacity of link e

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y_e$

- **constraints**

  $\sum_p x_{dps} = h_{ds}, \quad d = 1, 2, ..., D \quad s = 0, 1, ..., S$
  $\sum_d \sum_p \delta_{edp} x_{dps} \leq \alpha_{es} y_e, \quad e = 1, 2, ..., E \quad s = 0, 1, ..., S.$

Restricted Reconfiguration

- global reconfiguration incurs large overhead
- restriction: don't touch flows not on failed links
- potentially less efficient solution

- **indices**

  $d = 1, 2, ..., D$ demands
  $p = 1, 2, ..., P_d$ candidate paths for demand d
  $e = 1, 2, ..., E$ links
  $s = 0, 1, ..., S$ situations

- **constants**

  δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise
  h_d volume of demand d
  χ_{ds} demand coefficient of demand d in state s, $h_{ds} = \chi_{ds} h_d$
  ξ_e unit cost of link e
  α_{es} binary availability coefficient of link e in state s ($\alpha_{es} \in \{0, 1\}$)
  θ_{dps} binary availability coefficient of path (d, p) in state s, $\theta_{dps} = \prod_{\{e:\delta_{edp}=1\}} \alpha_{es}$

- **variables**

  x_{dps} flow allocated to path p of demand d in state s
  y_e capacity of link e

Restricted Reconfiguration

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y_e$

- **constraints**

  $\sum_p x_{dps} \geq h_{ds}, \quad d = 1, 2, ..., D \quad s = 0, 1, ..., S$

  $\sum_d \sum_p \delta_{edp} x_{dps} \leq \alpha_{es} y_e \quad e = 1, 2, ..., E \quad s = 0, 1, ..., S$

  $x_{dps} \geq \theta_{dps} x_{dp0}, \quad d = 1, 2, ..., D \quad p = 1, 2, ..., P_d \quad s = 1, 2, ..., S.$

Path Restoration under Budget Constraint

- Budget lower than lowest cost to fully recover all demand under all failure states
- recover portions of demands
- maximize the lowest portion among all demands under all failure states
  - **indices**
    - $d = 1, 2, ..., D$ demands
    - $p = 1, 2, ..., P_d$ candidate paths for demand d
    - $e = 1, 2, ..., E$ links
    - $s = 0, 1, ..., S$ states
  - **constants**
    - δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise
    - h_d volume of demand d
    - χ_{ds} demand coefficient of demand d in state s, $h_{ds} = \chi_{ds} h_d$
    - ξ_e unit cost of link e
    - α_{es} fractional availability coefficient of link e in state s ($0 \leq \alpha_{es} \leq 1$)
    - B assumed maximal budget
  - **variables**
    - x_{dps} flow allocated to path p of demand d in state s
    - y_e capacity of link e
    - r minimal proportion of the realized demand volumes

Path Restoration under Budget Constraint

- **objective**

  maximize r

- **constraints**

  $\sum_p x_{dps} \geq h_{ds} r, \quad d = 1, 2, ..., D \quad s = 0, 1, ..., S$

  $\sum_d \sum_p \delta_{edp} x_{dps} \leq \alpha_{es} y_e, \quad e = 1, 2, ..., E \quad s = 0, 1, ..., S$

  $\sum_e \xi_e y_e \leq B.$

Separated Normal and Protection Design

- Cheapest Solution: design normal and protection capacity and flow simultaneously in a coordinated way.
- In practice:
  - Phase I: design normal capacity/flow;
  - Phase II: design protection capacity/flow for phase I solution

Phase I

- **indices**

  $d = 1, 2, ..., D$ demands

  $p = 1, 2, ..., P_d$ candidate normal paths for demand d

  $e, \ell = 1, 2, ..., E$ links

  $q = 1, 2, ..., Q_e$ candidate restoration paths for link e

- **constants**

  δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise

  h_d volume of demand d

  ξ_e unit cost of link e

- **variables**

  x_{dp0} normal flow allocated to path p of demand d

  y_e normal capacity of link e

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y_e$

- **constraints**

  $\sum_p x_{dp0} = h_d \quad d = 1, 2, ..., D$

  $\sum_d \sum_p \delta_{edp} x_{dp0} \leq y_e \quad e = 1, 2, ..., E$

Phase II

Phase 2

- **additional constants**

  $\beta_{\ell eq}$ = 1 if link ℓ belongs to path q restoring link e; 0, otherwise

  c_e normal capacity of link e, i.e., $c_e = y_e$ from Phase 1 for use in Phase 2

- **variables**

  z_{ep} flow restoring normal capacity of link e on restoration path p

  y'_e protection capacity of link e

- **objective**

  minimize $\boldsymbol{F} = \sum_e \xi_e y'_e$

- **constraints**

  $\sum_q z_{eq} = c_e, \quad e = 1, 2, ..., E$

  $\sum_q \beta_{\ell eq} z_{eq} \le y'_\ell, \quad \ell = 1, 2, ..., E \quad e = 1, 2, ..., E \quad \ell \ne e.$

Protection Design with Given Capacity

- link capacities given
- reserve a portion of capacity to recover from any possible single link failure [reserved, shared]
- to guarantee full recovery, what is the maximal portion of demand can be carried?
  - **indices**

    $d = 1, 2, ..., D$ demands

    $p = 1, 2, ..., P_d$ candidate path p for demand d

    $e, \ell = 1, 2, ..., E$ links

    $q = 1, 2, ..., Q_e$ candidate restoration paths for link e
  - **constants**

    h_d "reference" volume of demand d

    δ_{edp} = 1 if link e belongs to path p realizing demand d; 0, otherwise

    c_e total capacity of link e

    $\beta_{\ell eq}$ = 1 if link ℓ belongs to path q restoring link e; 0, otherwise
  - **variables**

    y_e resulting normal capacity of link e

    x_{dp} normal flow realizing demand d on path p

    w_e protection capacity of link e

    z_{eq} flow restoring capacity of link e on path q

    r proportion of the realized demand volumes

Protection Design with Given Capacity

- **objective**

  maximize r

- **constraints**

  $r \leq \sum_p x_{dp}/h_d, \quad d = 1, 2, ..., D$

  $w_e + y_e \leq c_e, \quad e = 1, 2, ..., E$

  $\sum_d \sum_p \delta_{edp} x_{dp} \leq y_e, \quad e = 1, 2, ..., E$

  $y_e \leq \sum_q z_{eq}, \quad e = 1, 2, ..., E$

  $\sum_q \beta_{\ell eq} z_{eq} \leq w_\ell, \quad \ell = 1, 2, ..., E \quad e = 1, 2, ..., E \quad \ell \neq e.$

Extensions

- what if recovery capacity on each link is not reserved ?
- solution tells lowest ratio for all demands, what about other demands with potential higher ratios?
  - Max-min allocation?