EL736 Communications Networks II: Design and Algorithms

Class11: Multi-Hour and Multi-Layer Network Design

12/05/2007

Outline

- Multi-Hour Network Modeling & Design
  - uncapacitated
  - capacitated
  - robust routing
- Multi-Layer Networks
  - modeling
  - dimensioning
  - restoration

Time-of-Day Effect

- Traffic demand varies during hours of a day
- Variations not synchronized

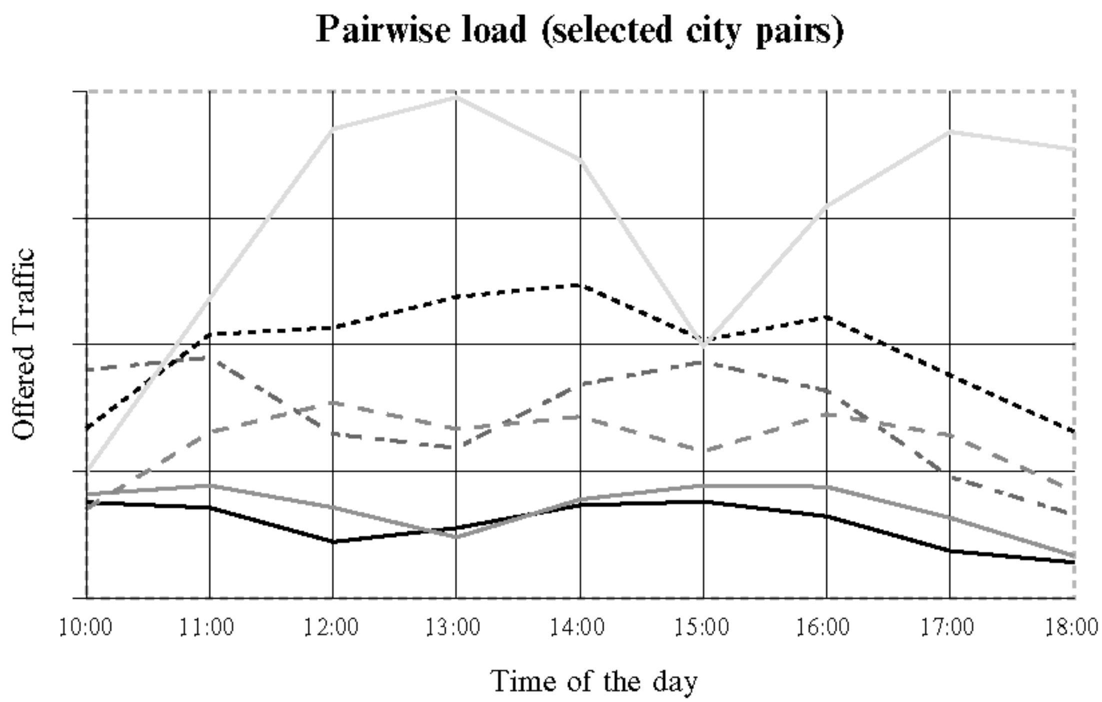


FIGURE 11.2 Traffic Variation for a Selected Set of City Pairs During the Day for a 10-Node Network Spanning Continental U.S. (Time is on Eastern Time Zone in U.S.)

Multi-Hour Dimensioning

- how much capacities needed to handle demands at all times?
- rearrange routing when demand changes
- modular link dimensioning

Modular Links, Multi-Hour, Rearrangeable

- **indices**
  - $d = 1, 2, ..., D$ demands
  - $t = 1, 2, ..., T$ traffic busy hours
  - $p = 1, 2, ..., P_d$ allowable paths for flow realizing demand d
  - $e = 1, 2, ..., E$ links
- **constants**
  - δ_{edp} = 1, if link e belongs to path p realizing demand d, 0 otherwise
  - h_{dt} volume of demand d at time t
  - ξ_e cost of one capacity module on link e
  - M size of the link capacity module
- **variables**
  - x_{dpt} (non-negative) flow allocated to path p of demand d at time t (continuous non-negative)
  - y_e capacity of link e expressed in number of modules (non-negative integer)
- **objective**
  - minimize $\boldsymbol{F} = \sum_e \xi_e y_e$
- **constraints**
  - $\sum_p x_{dpt} = h_{dt}, \quad d = 1, 2, ..., D \quad t = 1, 2, ..., T$
  - $\sum_d \sum_p \delta_{edp} x_{dpt} \le M y_e, \quad e = 1, 2, ..., E \quad t = 1, 2, ..., T.$

Multi-Hour Dimensioning

- unsplittable flows: one path each demand
- non-rearrangeable routing: don't change routes over time

Modular Links, Multi-Hour, Non-Rearrangeable, Unsplittable

- **indices**

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

  $t = 1, 2, ..., T$ traffic busy hours

  $p = 1, 2, ..., P_d$ allowable paths for flow realizing demand d

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

- **constants**

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

  h_{dt} volume of demand d at time t

  ξ_e cost of one capacity module on link e

  M size of the link capacity module

- **variables**

  u_{dp} binary variable corresponding to the flow allocated to path p of demand d

  y_e capacity of link e expressed in the number of modules (non-negative integer)

- **objective**

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

- **constraints**

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

  $\sum_d h_{dt} \sum_p \delta_{edp} u_{dp} \leq M y_e, \quad e = 1, 2, ..., E \quad t = 1, 2, ..., T.$

Multi-Hour Routing

- link capacity fixed
- recalculate routing for each time t
- problem separable, optimal routing at each t

Multi-Hour, Rearrangeable, Capacitated

- **indices**

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

  $t = 1, 2, ..., T$ time of the day index

  $p = 1, 2, ..., P_d$ allowable paths for flow realizing demand d

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

- **constants**

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

  h_{dt} volume of demand d at time t

  ζ_{dpt} unit routing cost on path p for demand d in time window t

  c_e capacity of link e

- **variables**

  x_{dpt} flow allocated to path p of demand d at time t (continuous non-negative)

- **objective**

  minimize $\boldsymbol{F} = \sum_d \sum_p \zeta_{dpt} x_{dpt}$

- **constraints**

  $\sum_p x_{dpt} = h_{dt}, \quad d = 1, 2, ..., D \quad t = 1, 2, ..., T$

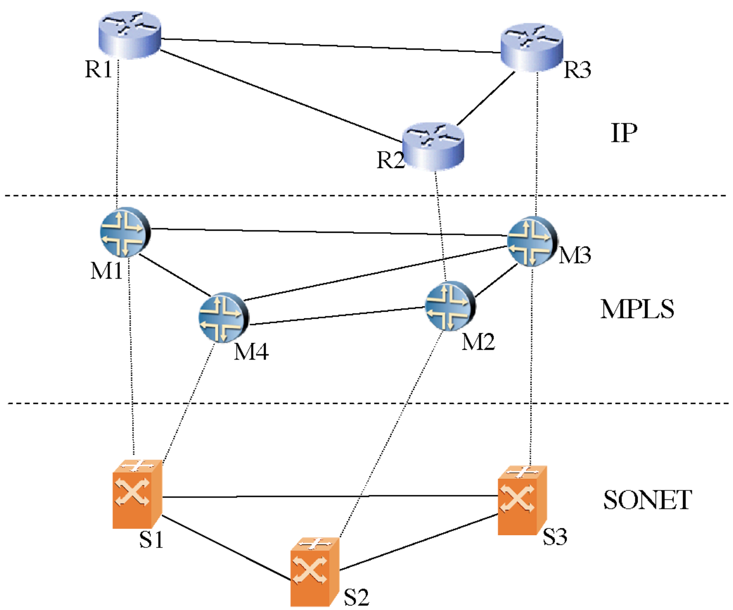
  $\sum_d \sum_p \delta_{edp} x_{dpt} \leq c_e, \quad e = 1, 2, ..., E \quad t = 1, 2, ..., T.$

Extension: robust routing under with multiple Traffic Matrices (TM)

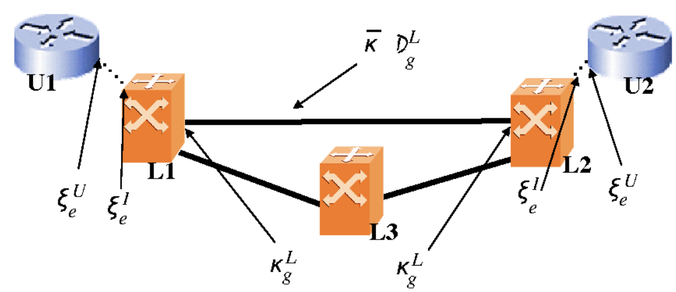
- multiple Traffic Matrices
  - dynamic traffic: demands between routing update period
  - estimation error: possible traffic demands
- Robust routing: single set of routes achieving good performance under all possible TMs
  - routing reconfiguration too expensive
  - routing: link-path, node-link, destination based, link weight based
  - performance measure
    - good average performance
    - bounded worst-case performance
    - trade-off between two
- References
  - "On Optimal Routing with Multiple Traffic Matrices", http://eeweb.poly.edu/faculty/yongliu/docs/Zhang04_OptRoutingMultiTms.pdf
  - "Optimal Routing with Multiple Traffic Matrices: Tradeoff between Average Case and Worst Case Performance", ftp://gaia.cs.umass.edu/pub/Zhang05_tradeofftr.pdf

Multi-Layer Networks

- Traffic vs. Transport Networks
- Technology Example



- Cost Component
  - cross-layer connection
  - physical connection



Dimensioning at two Resource Layers

- demand layer
  - demand between pairs of users
  - to be carried by traffic network
- traffic network layer
  - set of logical links
  - realize each demand through flow allocation
  - capacity of each link realized by transport layer
- transport network layer
  - set of physical links
  - realize each logical link capacity through flow allocation
- dimensioning: how much capacity needed on each logical/physical link?

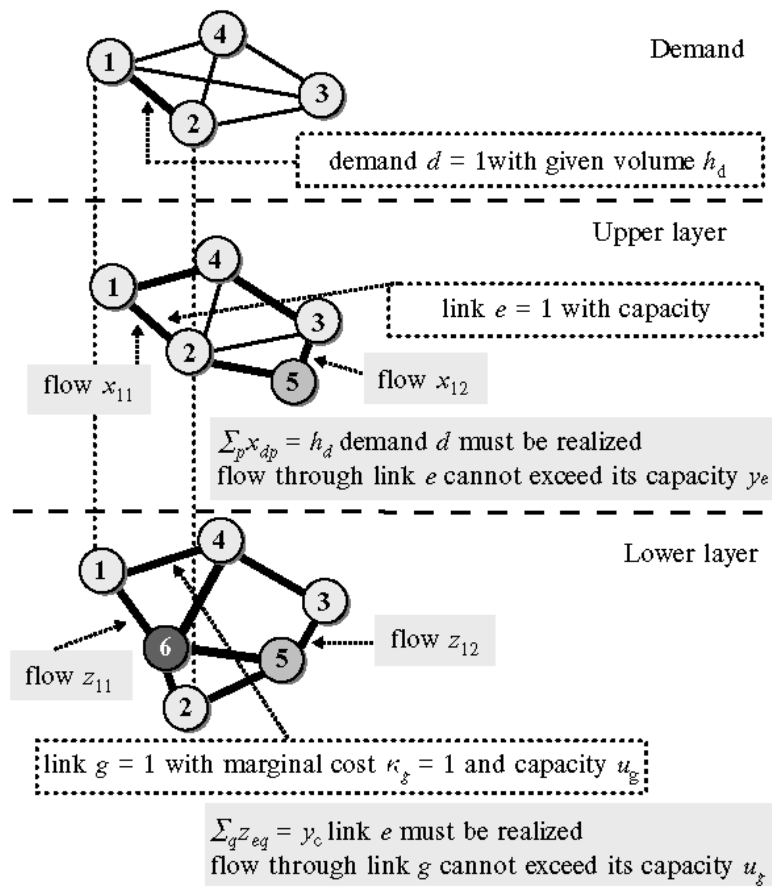


FIGURE 12.4 Two Resource Layer Network Example

Two-Layer Dimensioning (continuous case)

- **indices**

$d = 1, 2, \dots, D$	demands
$p = 1, 2, \dots, P_d$	candidate paths in upper layer for flows realizing demand d
$e = 1, 2, \dots, E$	links of upper layer
$q = 1, 2, \dots, Q_e$	candidate paths in lower layer for flows realizing link e
$g = 1, 2, \dots, G$	links of lower layer

- **constants**

h_d	volume of demand d
δ_{edp}	= 1 if link e of upper layer belongs to path p realizing demand d; 0, otherwise
ξ_e	unit cost of link e of upper layer
γ_{geq}	= 1 if link g of lower layer belongs to path q realizing link e of upper layer; 0, othe
κ_g	unit cost of link g of lower layer

- **variables**

x_{dp}	(non-negative continuous) flow allocated to path p realizing volume of demand d
y_e	(non-negative continuous) capacity of upper layer link e
z_{eq}	(non-negative continuous) flow allocated to path q realizing capacity of link e
u_g	(non-negative continuous) capacity of lower layer link g

- **objective**

minimize $\boldsymbol{F} = \sum_e \xi_e y_e + \sum_g \kappa_g u_g$

- **constraints**

$$\sum_p x_{dp} = h_d, \quad d = 1, 2, \dots, D$$
$$\sum_d \sum_p \delta_{edp} x_{dp} \le y_e, \quad e = 1, 2, \dots, E$$
$$\sum_q z_{eq} = y_e, \quad e = 1, 2, \dots, E$$
$$\sum_e \sum_q \gamma_{geq} z_{eq} \le u_g, \quad g = 1, 2, \dots, G.$$

Two-Layer Dimensioning (continuous/Integral)

- **indices**

$d = 1, 2, \ldots, D$	demands
$p = 1, 2, \ldots, P_d$	candidate paths in upper layer for flows realizing demand d
$e = 1, 2, \ldots, E$	links of upper layer
$q = 1, 2, \ldots, Q_e$	candidate paths in lower layer for flows realizing link e
$g = 1, 2, \ldots, G$	links of lower layer

- **constants**

h_d	volume of demand d
δ_{edp}	= 1 if link e of upper layer belongs to path p realizing demand d; 0, otherwise
M	size of the link capacity module in upper layer
ξ_e	cost of one (M-module) capacity unit of link e of upper layer
γ_{geq}	= 1 if link g of lower layer belongs to path q realizing link e of upper layer; 0, otherwise
N	size of link capacity module in lower layer
κ_g	cost of one (N-module) capacity unit of link g of lower layer

- **variables**

x_{dp}	(non-negative *continuous*) flow allocated to path p realizing volume of demand d
y_e	(non-negative integral) M-module capacity of upper layer link e
z_{eq}	(non-negative integral) flow allocated to path q realizing capacity of link e
u_g	(non-negative integral) capacity of lower layer link g

- **objective**

minimize $\boldsymbol{F} = \sum_e \xi_e y_e + \sum_g \kappa_g u_g$

- **constraints**

$$\sum_p x_{dp} = h_d, \quad d = 1, 2, \ldots, D$$
$$\sum_d \sum_p \delta_{edp} x_{dp} \leq M y_e, \quad e = 1, 2, \ldots, E$$
$$\sum_q z_{eq} = y_e, \quad e = 1, 2, \ldots, E$$
$$\sum_e M \sum_q \gamma_{geq} z_{eq} \leq N u_g, \quad g = 1, 2, \ldots, G.$$

Allocation with Two Layers of Resources

- lower layer capacities fixed
- upper layer capacities variable

LP: A/2L/CF/BR/CC **Link-Path Formulation**

Two-Layer Allocation Problem

indices

$d = 1, 2, \ldots, D$ demands

$p = 1, 2, \ldots, P_d$ candidate paths in upper layer for demand d

$e = 1, 2, \ldots, E$ links of upper layer

$q = 1, 2, \ldots, Q_e$ candidate paths in lower layer for flows realizing link e

$g = 1, 2, \ldots, G$ links of lower layer

constants

h_d volume of demand d

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

γ_{geq} = 1 if link g of lower layer belongs to path q realizing link e of upper layer; 0, otherwise

c_g capacity of lower layer link g

variables (all non-negative continuous)

x_{dp} flow allocated to path p realizing volume of demand d

y_e capacity of upper layer link e

z_{eq} flow allocated to path q realizing capacity of link e

constraints

$$\sum_p x_{dp} = h_d, \quad d = 1, 2, \ldots, D \tag{12.1.7a}$$

$$\sum_d \sum_p \delta_{edp} x_{dp} \leq y_e, \quad e = 1, 2, \ldots, E \tag{12.1.7b}$$

$$\sum_q z_{eq} = y_e, \quad e = 1, 2, \ldots, E \tag{12.1.7c}$$

$$\sum_e \sum_q \gamma_{geq} z_{eq} \leq c_g, \quad g = 1, 2, \ldots, G. \tag{12.1.7d}$$

Two-Layer Mixed Dimensioning Allocation Problem

- lower layer capacities fixed
- upper layer link cost, lower layer routing cost
  - **constants**

h_d	volume of demand d
δ_{edp}	= 1 if link e of upper layer belongs to path p realizing demand d; 0, otherwise
γ_{geq}	= 1 if link g of lower layer belongs to path q realizing link e of upper layer; 0, otherwise
c_g	capacity of lower layer link g
M	size of the link capacity module in upper layer
ξ_e	cost of one (M-module) capacity unit of link e of upper layer
ζ_{eq}	unit routing cost in the lower layer

  - **variables**

x_{dp}	(non-negative continuous) flow allocated to path p realizing volume of demand d
y_e	(non-negative integral) capacity of upper layer link e
z_{eq}	(non-negative integral) flow allocated to path q realizing capacity of link e

  - **objective**

minimize $\sum_e \xi_e y_e + \sum_e \sum_q \zeta_{eq} z_{eq}$

  - **constraints**

$$\sum_p x_{dp} = h_d, \quad d = 1, 2, \dots, D$$
$$\sum_d \sum_p \delta_{edp} x_{dp} \le M y_e, \quad e = 1, 2, \dots, E$$
$$\sum_q z_{eq} = y_e, \quad e = 1, 2, \dots, E$$
$$\sum_e \sum_q \gamma_{geq} z_{eq} \le c_g, \quad g = 1, 2, \dots, G.$$

Extension to More than Two Layers

- Example: IP/MPLS/SONET
- link at layer k+1 is demand for layer k
- demand considered the top layer
- joint dimensioning across all layers
- generalized shortest path allocation rule
  - at layer k, allocate a layer k+1 demand (link l^{k+1}) to its cheapest path p^k
  - set link weight at layer k+1 for l^{k+1} using length of p^k at layer k
  - repeat until find the shortest paths for all demands

Extension: joint optimal routing and capacity design in upper layer

- routing: given demands, link capacities, find the best flow allocation
- capacity allocation normally done in coarser time scale
- exception in wireless/sensor network
  - no well-defined link capacity
  - links from same node share resource: spectrum, power, timeslot
  - link capacities be adjusted along with routing
- joint optimization of rate control, routing and resource allocation
  - reference: "A Distributed Algorithm for Joint Sensing and Routing in Wireless Networks with Non-Steerable Directional Antennas", ftp://gaia.cs.umass.edu/pub/Zhang06_jointopt_tr0612.pdf

Multi-Layer Networks for Restoration Design

- Upon failures, path restorations can be done
  - in both upper and lower layers
  - low layer only
  - upper layer only
- Example: IP/SONET
  - upon failure: IP Re-routing/SONET reconfiguration
  - time-scale difference
  - transit loss of link capacity in IP layer
  - transit loss of packets for demands

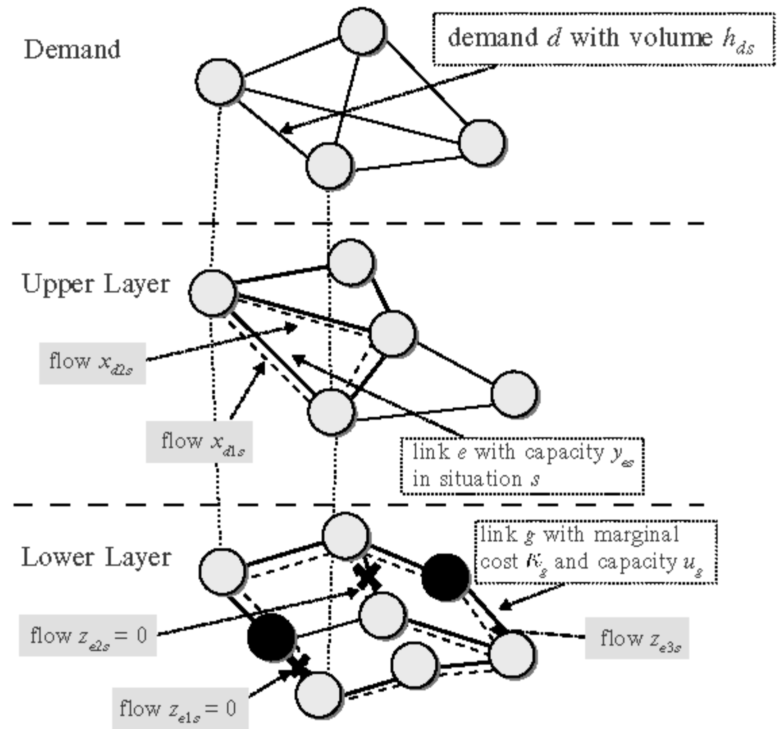


FIGURE 12.5 Two-Layer Networks with Failures

Two-Layer Restoration Dimensioning with Unrestricted Flow Reconfiguration

- capacity dimensioning to handle all possible failure states
- arbitrary flow reconfiguration at both layers

indices

$d = 1, 2, \ldots, D$	demands
$p = 1, 2, \ldots, P_d$	candidate paths in upper layer for flows realizing demand d
$e = 1, 2, \ldots, E$	links of upper layer
$q = 1, 2, \ldots, Q_e$	candidate paths in lower layer for flows realizing link e
$g = 1, 2, \ldots, G$	links of lower layer
$v = 1, 2, \ldots, V$	nodes of upper layer
$s = 1, 2, \ldots, S$	failure-demand states (situations) (including the normal state)

constants

h_d	volume of demand d
a_{ve}	= 1 if link e is incident with node v; 0, otherwise
δ_{edp}	= 1 if link e of upper layer belongs to path p realizing demand d; 0, otherwise
γ_{geq}	= 1 if link g of lower layer belongs to path q realizing link e of upper layer; 0, otherwise
ς_v	unit cost of the capacity of node v of upper layer (termination cost and switching cost)
κ_g	unit cost of link g of lower layer
χ_{ds}	demand coefficient of demand d in state s, $h_{ds} = \chi_{ds} h_d$
β_{vs}	binary availability coefficient of node v of upper layer in state s ($\beta_{vs} \in \{0, 1\}$)
α_{gs}	fractional availability coefficient of link g of lower layer in state s ($0 \leq \alpha_{gs} \leq 1$)

Two-Layer Restoration Dimensioning with Unrestricted Flow Reconfiguration

- **variables** (all variables are continuous and non-negative)

  x_{dps} flow allocated to path p of demand d in state s

  Y_v capacity of node v of upper layer (state-independent)

  y_{es} capacity of link e in state s (situation-dependent)

  z_{eqs} flow allocated to path q realizing capacity of link e in state s

  u_g capacity of link g

- **objective**

  minimize $\boldsymbol{F} = \sum_g \kappa_g u_g + \sum_v \varsigma_v Y_v$

- **constraints**

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

$$\sum_d \sum_p \delta_{edp} x_{dps} \le y_{es}, \quad e = 1, 2, \ldots, E \quad s = 1, 2, \ldots, S$$

$$\sum_e a_{ve} y_{es} \le \beta_{vs} Y_v, \quad v = 1, 2, \ldots, V \quad s = 1, 2, \ldots, S$$

$$\sum_q z_{eqs} = y_{es}, \quad e = 1, 2, \ldots, E \quad s = 1, 2, \ldots, S$$

$$\sum_e \sum_q \gamma_{geq} z_{eqs} \le \alpha_{gs} u_g, \quad g = 1, 2, \ldots, G \quad s = 1, 2, \ldots, S.$$

Restoration Dimensioning with reconfiguration only at lower layer

- upper layer link capacities and flows required to be same under any failure state (no rerouting allowed)
- lower layer flow reconfigurable

additional constants

H_d max$\{h_{ds},\ s = 1, 2, \ldots, S\}$ maximal value of demand d

variables (all variables are continuous and non-negative)

x_{dp} flow allocated to path p of demand d in all states

y_e capacity of link e in all states

z_{eqs} flow allocated to path q realizing capacity of link e in state s

u_g capacity of link g

objective

$$\text{minimize } \boldsymbol{F} = \sum_g \kappa_g u_g \tag{12.2.4a}$$

constraints

$$\sum_p x_{dp} = H_d, \quad d = 1, 2, \ldots, D \tag{12.2.4b}$$

$$\sum_d \sum_p \delta_{edp} x_{dp} \le y_e, \quad e = 1, 2, \ldots, E \tag{12.2.4c}$$

$$\sum_q z_{eqs} = y_e, \quad e = 1, 2, \ldots, E \quad s = 1, 2, \ldots, S \tag{12.2.4d}$$

$$\sum_e \sum_q \gamma_{geq} z_{eqs} \le \alpha_{gs} u_g, \quad g = 1, 2, \ldots, G \quad s = 1, 2, \ldots, S. \tag{12.2.4e}$$

Restoration Dimensioning with reconfiguration only at upper layer

- lower layer flows are not reconfigurable, lower layer path may not available after failure
- upper layer link capacities affected by failure, and flows can be reconfigured arbitrarily

variables (all variables are continuous and non-negative)

- x_{dps} flow allocated to path p of demand d in state s
- y_{es} capacity of link e in state s
- z_{eq} flow allocated to path q realizing capacity of link e in all state
- u_g capacity of link g

objective

$$\text{minimize } \boldsymbol{F} = \textstyle\sum_g \kappa_g u_g \qquad (12.2.5a)$$

constraints

$$\textstyle\sum_p x_{dp} = h_{ds}, \quad d = 1, 2, \ldots, D \quad s = 1, 2, \ldots, S \qquad (12.2.5b)$$

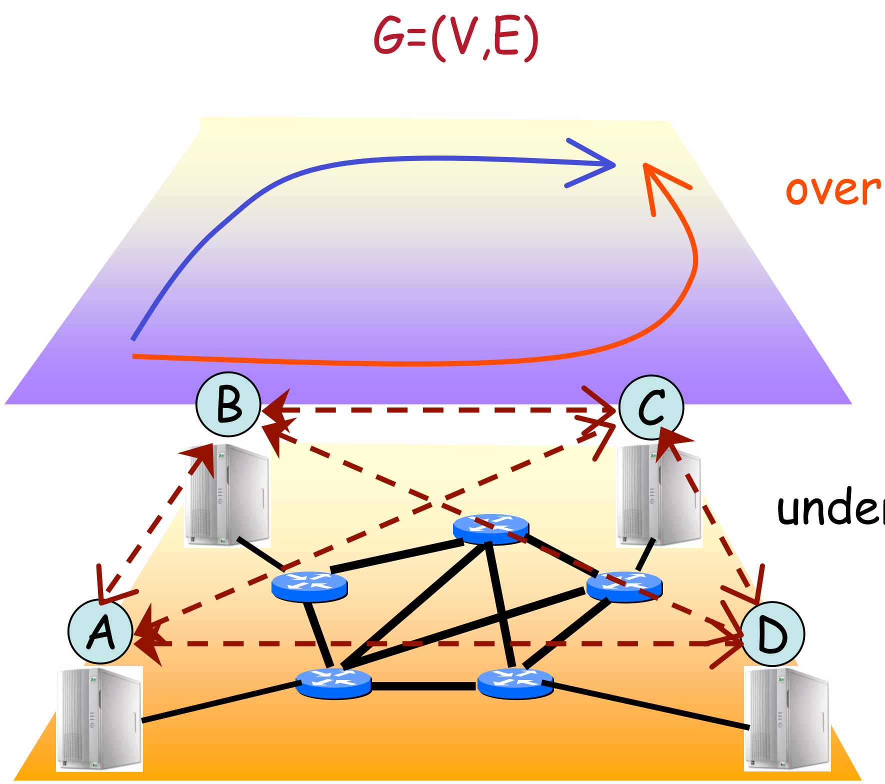
$$\textstyle\sum_d \sum_p \delta_{edp} x_{dps} \le y_{es}, \quad e = 1, 2, \ldots, E \quad s = 1, 2, \ldots, S \qquad (12.2.5c)$$

$$\textstyle\sum_q \theta_{eqs} z_{eq} \ge y_{es}, \quad e = 1, 2, \ldots, E \quad s = 1, 2, \ldots, S \qquad (12.2.5d)$$

$$\textstyle\sum_e \sum_q \gamma_{geq} z_{eq} \le u_g, \quad g = 1, 2, \ldots, G. \qquad (12.2.5e)$$

Extension: Overlay/P2P Networks

- Overlay Networks
  - logical networks on top of physical networks
  - improved end user performance
  - new services:
    - Content distribution: Akamai
    - p2p file sharing: BitTorrent, EMule
    - Streaming/multicast: Skype/IPTV



- Overlay Network Design
  - efficiency: topologies, routing, scheduling, rate control
  - interaction with native IP networks
- Reference:

"On the Interaction Between Overlay Routing and Traffic Engineering'', http://eeweb.poly.edu/faculty/yongliu/docs/info05.pdf