Traffic Engineering

- configuring routes to traffic demands to
  - improve user performance
  - use network resources more efficiently
- operates at coarse timescales
  - not for failures, sudden traffic changes
- uses shortest path computations
  - OSPF, ISIS

Q: how to set link weights?

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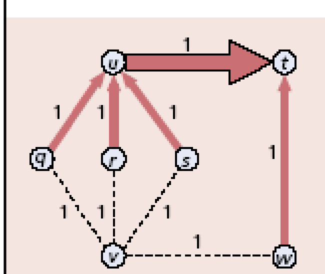
Effect of link weights

- unit link weights
- local change to congested link
- global optimization
  - to balance link utilizations



Traffic Engineering Framework

- knowledge of topology
- traffic matrix
  - K - set of origin destination flows
  - $k \in K$, d_k - demand, s_k - source, t_k - destination
- how to get traffic matrix?
  - SNMP
  - edge measurements + routing tables
  - network tomography
  - packet sampling
- optimization criteria
  - minimize maximum utilization
  - keep utilizations below 60%

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How does one set link weights?

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Linear programming problem

Primal

$$\begin{aligned} \text{minimize} \quad & c^T x \\ \text{subject to} \quad & Ax = b \\ & x \geq 0, \end{aligned}$$

Dual

$$\begin{aligned} \text{maximize} \quad & y^T b \\ \text{subject to} \quad & y^T A \leq c^T \end{aligned}$$

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Complementary slackness

Let x and y be feasible solutions. A necessary and sufficient condition for them to be optimal is that for all i

1. $x_i > 0 \Rightarrow y^T A_i = c_i$
2. $x_i = 0 \Leftarrow y^T A_i < c_i$

Here A_i is i-th column of A

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Example: primal (P-SP)

- topology $G = (V,E)$, link weights $\{w_{ij} : (i,j) \in E\}$
- K - set of origin destination flows
  - $k \in K$, d_k - demand, s_k - source, t_k - destination
- X_{ij}^k fraction of flow k going over $(i,j) \in E$
- for $k \in K$

$$\min \sum_{(i,j)\in E} w_{ij} X_{ij}^k$$

$$s.t. \quad \sum_{j:(i,j)\in E} X_{ij}^k - \sum_{j:(j,i)\in E} X_{ji}^k = 0, \quad i \neq s_k, t_k$$

$$\sum_{j:(s_k,j)\in E} X_{ij}^k - \sum_{j:(j,s_k)\in E} X_{ji}^k = 1,$$

$$\sum_{j:(t_k,j)\in E} X_{ij}^k - \sum_{j:(j,t_k)\in E} X_{ji}^k = -1,$$

$$X_{ij}^k \geq 0$$

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Interpretation

- let $\{\overline{X}_{ij}^k\}$ be optimal solutions
- if $\{\overline{X}_{ij}^k\}$ takes values 0 and 1, corresponds to shortest paths
- if $\{\overline{X}_{ij}^k\}$ takes other values, there exist multiple shortest paths.

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Example: dual (D-SP)

$$\max \sum_{k\in K} U_{t_k}^k$$

$$s.t.\quad U_j^k - U_i^k \le w_{ij},\quad \begin{matrix} k\in K \\ (i,j)\in E \end{matrix}$$

$$U_{s_k}^k = 0,\qquad k\in K$$

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Example

$$\max \sum_{k\in K} U_{t_k}^k$$

$$s.t.\quad U_j^k - U_i^k \le w_{ij},\quad \begin{matrix} k\in K \\ (i,j)\in E \end{matrix}$$

$$U_{s_k}^k = 0,\qquad k\in K$$

- $\{\overline{U}_i^k\}$ optimal solution to dual problem
- $\overline{X}_{ij}^k > 0 \Rightarrow \overline{U}_j^k - \overline{U}_i^k = w_{ij}$, $\overline{U}_j^k$ length of shortest path from s_k to j
- $\overline{U}_{t_k}^k$ length of shortest path from s_k to t_k

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Traffic engineering problem: minimize maximum link utilization

- topology $G = (V,E)$
- c_{ij} – capacity of link $(i,j) \in E$
- K – set of origin destination flows
  - $k \in K$, d_k – demand, s_k – source, t_k – destination
- α – maximum link utilization

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LP formulation

$$\min \alpha$$

$$s.t. \sum_{j:(i,j)\in E} X_{ij}^k - \sum_{j:(j,i)\in E} X_{ji}^k = \begin{cases} 0, & i \neq s_k, t_k, k \in K \\ 1, & i \neq s_k k \in K \\ -1, & i \neq t_k k \in K \end{cases}$$

$$\sum_{k\in K} d_k X_{ij}^k \leq c_{ij}\alpha, \qquad (i,j) \in E$$

$$X_{ij}^k \geq 0$$

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LP formulation

$$\min \alpha + r \sum_{k \in K} \sum_{(i,j) \in E} X_{ij}^k$$

$$s.t. \sum_{j:(i,j) \in E} X_{ij}^k - \sum_{j:(j,i) \in E} X_{ji}^k = \begin{cases} 0, & i \neq s_k, t_k, k \in K \\ 1, & i \neq s_k k \in K \\ -1, & i \neq t_k k \in K \end{cases}$$

$$\sum_{k \in K} d_k X_{ij}^k \leq c_{ij} \alpha, \qquad (i,j) \in E$$

$$X_{ij}^k \geq 0$$

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LP formulation

- can be many solutions with same α
- in case of tie, want solution with short paths

  $\Rightarrow$ add term $r \sum_{k \in K} \sum_{(i,j) \in E} X_{ij}^k$
  with small r to cost

- use standard LP algorithms (Simplex) to solve

Q: can we find link weights so that solution comes from shortest path problem?

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Duality revisited

Primal

$$\begin{aligned} \text{minimize} \quad & c^T x \\ \text{subject to} \quad & Ax = b_1 \\ & A' x \geq b_2 \\ & x \geq 0, \end{aligned}$$

Dual

$$\begin{aligned} \text{maximize} \quad & y_1^T b_1 + y_2^T b_2 \\ \text{subject to} \quad & y_1^T A + y_2^T A' \leq c^T \\ & y_2 \geq 0 \end{aligned}$$

- free variables in primal ⇒ equality constraints in dual

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Dual formulation

- decision variables $\{U_i^k\}, \quad \{W_{ij}\}$

$$\max \sum_{k \in K} d_k U_{t_k}^k$$

$$s.t. U_j^k - U_i^k \leq W_{ij} + r, \quad k \in K, (i, j) \in E$$

$$\sum_{(i,j) \in E} c_{ij} W_{ij} = 1,$$

$$W_{ij} \geq 0, U_{s_k}^k = 0$$

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Properties of primal-dual solutions

- optimal solution to primal problem $\{\overline{X}_{ij}^k\}, \overline{\alpha}$
  dual problem $\{\overline{U}_i^k\}, \{\overline{W}_{ij}\}$
- if $\overline{X}_{ij}^k > 0$, then $\overline{U}_j^k - \overline{U}_i^k = \overline{W}_{ij} + r$
- can think of $\overline{U}_j^k$ as shortest path distance from s_k to j when link weights are $\{\overline{W}_{ij} + r\}$

Therefore: solution to TE problem is also solution to shortest path problem with

$$w_{ij} = \overline{W}_{ij} + r$$

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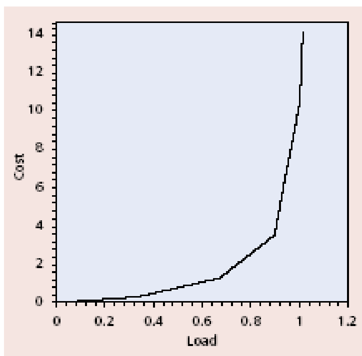
Link weight assignment

- works for rich set of cost functions
- example:

$$\Phi = \sum_{(i,j)\in E} \Phi_{ij}\left(\sum_{k\in K} d_k X_{ij}^k\right)$$

- where Φ_{ij} are piecewise linear



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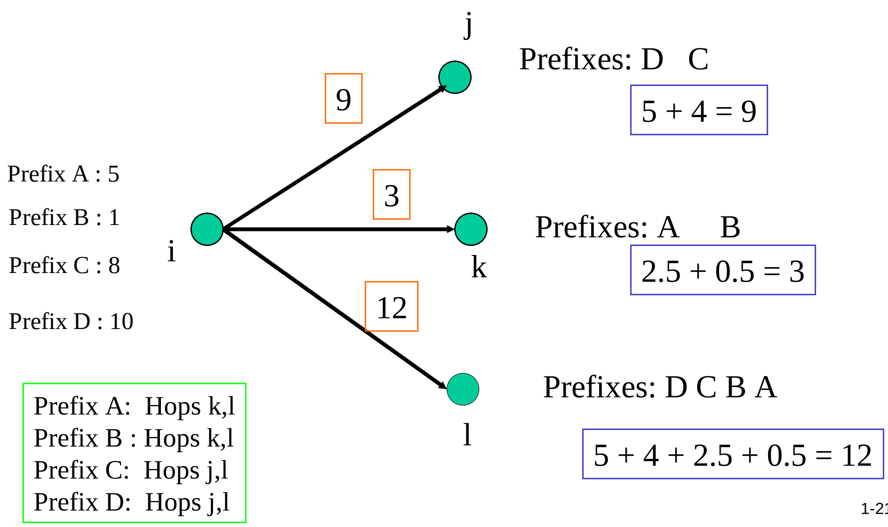
Issues

- solutions are flow specific - need destination specific solutions
  - not a big deal, can reformulate to account for this
- solutions may not support equal split rule of OSPF
  - accounting for this yields NP-hard problem
    - see heuristics in FT paper
  - modify IP routing

One approach to overcome the "splitting problem"

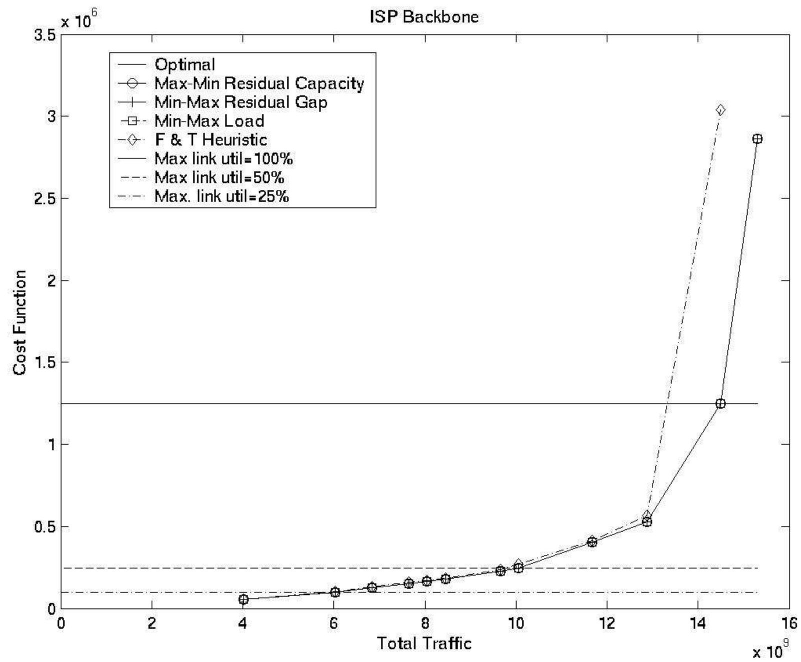
- current routing tables have thousands of routing prefixes
- instead of routing each prefix on all equal cost paths, selectively assign next hops to (each) prefix
  - i.e., remove some equal cost next hops assigned to prefixes
- goal: to approximate optimal link load

Example : EQUAL-SUBSET-SPLIT



Advantages

- requires no change in data path
- can leverage existing routing protocols
- current routers have 10,000s of routes in routing tables
  - provides large degree of flexibility in next hop allocation to match optimal allocation



Summary

- can use OSPF/ISIS to support traffic engineering objectives
- performance objectives link weights
- equal splitting rule complicates problem
  - heuristics provide good performance
  - small changes to IP routing provide in better performance
- MPLS suffers none of these problems

Recent progress on MPLS TE

- Oblivious routing
  - Goal: find a routing R that minimizes the performance ratio under worst traffic matrix
    - PR = MLU under R / MLU under optimal routing
  - Result: on realistic ISP topologies, can achieve PR of ~2
- COPE [sigcomm06]
  - Common-case Optimization with Penalty Envelope
  - Achieve close to optimal MLU with normal traffic
  - Provide worst-case PR bound with unexpected traffic
- R3: Resilient Routing Reconfiguration [ongoing]
  - Goal: avoid congestion under fast rerouting
  - Idea: convert topology uncertainty into traffic uncertainty

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