Network Traffic Engineering (I)

EL 933, Class9

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Motivation

- Network is highly dynamic
  - traffic demand: time variant, flash crowd
  - network resource: add/drop/failure
- Network control
  - rate control: end-end
  - routing conf.: network operator, inter/intra domain
- Good traffic engineering
  - quality of service (QoS) of end users
  - efficient use of network resource
    - minimize network cost given traffic demand
    - maximize traffic demand given resource
  - beyond performance: security/reliability/resilience

Outline

- Overview of Internet routing
  - slides from Prof. Lixin Gao, UMass
- Paper1:
  "Traffic engineering with traditional IP routing protocols", B. Fortz, J. Rexford and M. Thorup, IEEE Communications Magazine, 40(10):118-124, 2002
  - slides modified from authors'
- Paper2:
  "Internet Traffic Engineering by Optimizing OSPF Weights", B. Fortz and M. Thorup, In Proc. of IEEE/INFOCOM 2000
  - slides modified from authors'

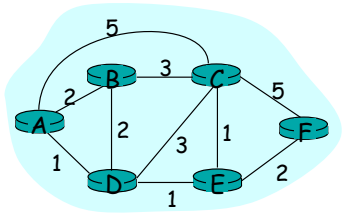
Routing

Routing protocol

Goal: determine "good" path (sequence of routers) thru network from source to dest.

Graph abstraction for routing algorithms:

- graph nodes are routers
- graph edges are physical links
  - link cost: delay, $ cost, or congestion level



- "good" path:
  - typically means minimum cost path
  - other def's possible

Route Construction

- Static Routing
  - listed manually: change route slowly
  - not robust: reachability is independent of network condition
  - stable
- Dynamic Routing
  - learn route via routing protocols
  - react to topology, traffic or configuration changes directly
  - might not converge or oscillate
  - might have loop

Dynamic Routing Algorithms

- Global or Link state algorithm
  - use global knowledge about topology and cost
- Decentralized or Distance Vector algorithm
  - use only knowledge of attached links and neighbors
  - iterative algorithm

Global or Link State Algorithm

- Dijkstra's shortest path algorithm
- Implementation:
  - each node broadcast its connectivity and link costs to all nodes

A Link-State Routing Algorithm

Dijkstra's algorithm

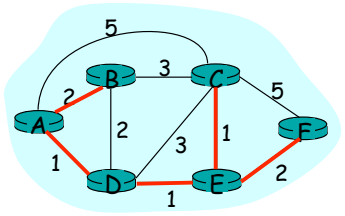
- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info
- computes least cost paths from one node ('source") to all other nodes
  - gives routing table for that node
- iterative: after k iterations, know least cost path to k dest.'s

Notation:

- c(i,j): link cost from node i to j. cost infinite if not direct neighbors
- D(v): current value of cost of path from source to dest. V
- p(v): predecessor node along path from source to v, that is next v
- N: set of nodes whose least cost path definitively known

Dijkstra's algorithm: example

Step	start N	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



Decentralized or Distance Vector Algorithm

- each node communicates *only* with directly-attached neighbors
- computes shortest path
- continues until no nodes exchange information

Distance Vector Routing Algorithm

iterative:

- continues until no nodes exchange info.
- *self-terminating*: no "signal" to stop

distributed:

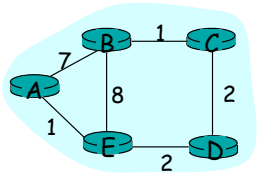
- each node communicates *only* with directly-attached neighbors

Distance Table data structure

- each node has its own
- row for each possible destination
- column for each directly-attached neighbor to node
- example: in node X, for dest. Y via neighbor Z:

$$D^{X}(Y,Z) = \text{distance } \textit{from } X \textit{ to } Y, \textit{ via } Z \text{ as next hop} = c(X,Z) + \min_w\{D^{Z}(Y,w)\}$$

Distance Table: example



$D^{E}(C,D) = c(E,D) + \min_w\{D^{D}(C,w)\}$
$= 2+2 = 4$

$D^{E}(A,D) = c(E,D) + \min_w\{D^{D}(A,w)\}$
$= 2+3 = 5$ loop!

$D^{E}(A,B) = c(E,B) + \min_w\{D^{B}(A,w)\}$
$= 8+6 = 14$ loop!

$D^{E}()$ — cost to destination via

destination	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Routing in the Internet

So far

- all routers identical
- network "flat"

… *not* true in practice

scale: with 50 million destinations:

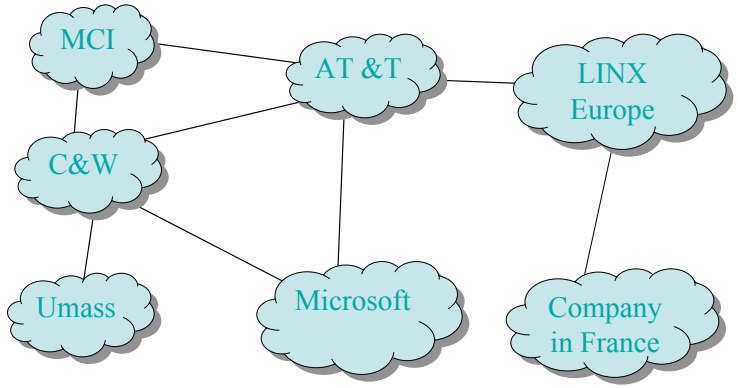
- can't store all dest's in routing tables!
- routing table exchange would swamp links!

administrative autonomy

- internet = network of networks
- each network admin may want to control routing in its own network

Internet Structure

- Thousands of Organizations
- Many many Routers
- Lots of Hosts



Routing Protocols

- Divide into Autonomous Systems (AS)
  - according to administrative domains
    - internet Service Providers (ISP)
    - cooperate networks
    - college campuses
- Two kinds of routing protocols
  - intra-Domain Routing (IGP)
    - within one domain
  - inter-Domain Routing (EGP)
    - among different domains

Intra-Domain Routing

- Goal:
  - find a "good" path (sequence of routers) through network from source to destination
    - delay, loss, bandwidth, cost or other definitions
- Static routing
- Popular dynamic routing protocols
  - RIP: Routing Information Protocol
  - IS-IS: Intermediate-System-to-Intermediate System
  - OSPF: Open Shortest Path First
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary)

Intra-Domain Routing

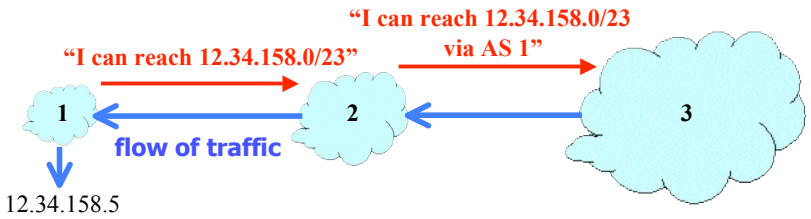
- Routing Information Protocol (RIP)
  - Distance Vector Algorithm
- Open Shortest Path First (OSPF)
  - Link State Algorithm
- IS-IS
  - Link State Algorithm

OSPF

- Link state routing
- Each router keeps a complete map of the network
  - Rather than just how to get to each of the other routers
  - All routers should have exactly the same map.
- Routing updates are "flooded" to all nodes
- Compute shortest paths between any two points
  - Dijkstra's shortest path algorithm
- Converge fast when the network topology changes
- Link weights configured by the network operator

Inter-Domain Routing

- Internet consists of ~12,000 Autonomous Systems
- ASes exchange info about who they can reach
- Local policies for selecting and propagating routes
- Policies configured by the AS's network operators



AS = Autonomous System

Inter-Domain Routing Protocols

- Use EGP in NSFNET
- Border Gateway Protocol (BGP)
  - BGP-4: de facto standard
  - Path Vector Algorithm

Traffic Engineering With Traditional IP Routing Protocols

B. Fortz, J. Rexford, and M. Thorup

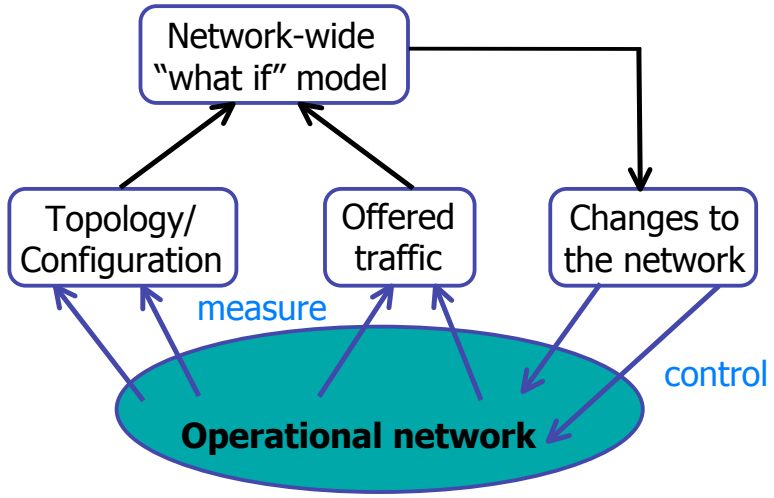
Outline

- IP network operations
  - motivation and examples
  - measure, model, and control
- Traffic engineering
  - measuring traffic and topology
  - modeling intradomain routing
  - optimization of routing weights
- Conclusions and ongoing work

IP Network Operations

- Don't IP networks manage themselves?
  - TCP adapts sending rate to network congestion
  - routing protocols adapt to changes in topology
- … not if we want to network to run *well*
  - adjust the routing of traffic to the prevailing load
  - ensure the network can accommodate failures
  - plan the outlay of new routers and links over time
- The driving goals
  - good end-to-end performance for users
  - efficient use of the network resources
  - reliable system even in the presence of failures

Our Approach: Measure, Model, and Control



Key Ingredients of Our Approach

- Instrumentation
  - offered load: widely deployed traffic measurement
  - topology: monitoring of the routing protocols
- Network-wide models
  - representations of traffic and topology
  - "What-if" models of resource allocation policies
- Network optimization
  - efficient algorithms to find good configurations
  - operational experience to identify key constraints

Example: traffic engineering by tuning routing protocols

Traffic Engineering in an ISP Backbone

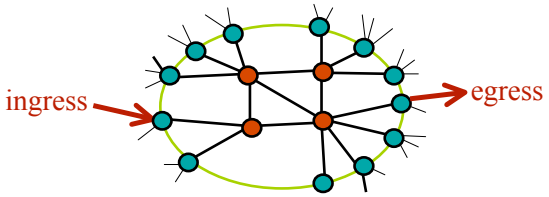
- Network topology
  - connectivity and capacity of routers and links
- Configurable policies for resource allocation
  - interdomain policies and intradomain weights
- Traffic demands
  - expected load between points in the network
- Performance objective
  - balanced load, low delay, service level agreements
- Question: Given the *topology* and *traffic*, which routing configuration should be used?

Topology/Routing

- Router configuration files
  - daily snapshot of network assets & configuration
  - software to parse the router config commands
  - network-wide view of topology & routing policies
  - also useful for detecting configuration mistakes
- Routing monitors
  - online monitoring of routing protocol messages
  - real-time view of routes via neighboring ASes
  - real-time view of paths within the AS
  - software for aggregating and querying the data
  - also useful for detecting and diagnosing anomalies

Traffic Matrix: offered Traffic

- Flow-level measurement (Cisco Netflow)
  - measurements at the level of TCP/UDP flows
  - addresses, port #s, #bytes/packets, start/finish
  - collected on links connecting AT&T to its peers
- Collection of the measurement data
  - distributed set of collection servers in the network
  - software for online aggregation of the data
  - computation of a "traffic matrix" for the network

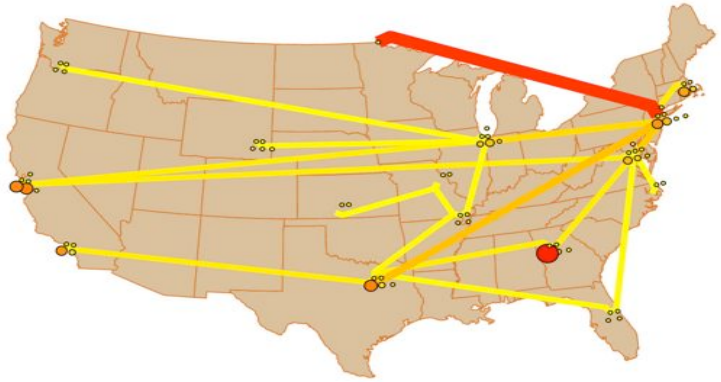


Network Model

- Data model
  - physical level, IP level, router-complex level
  - traffic demands, router attributes, link attributes
- Routing model
  - shortest-path routing, with tie-breaking
  - multi-homed customers, inter-domain routing
  - book-keeping to accumulate load on each link
- Visualization environment
  - coloring/sizing to illustrate link and node statistics
  - querying to show statistics for links and nodes
  - what-if experiments with routing configurations

Example: Traffic Through Backbone

Source node: public peering link in New York
Destination nodes: AT&T access routers



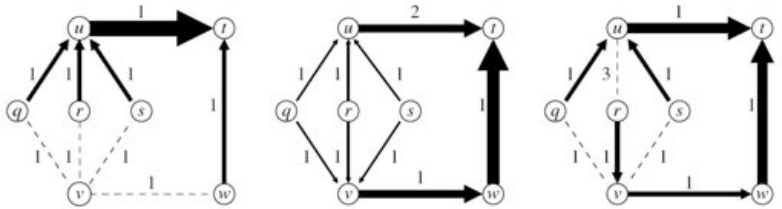
Color/size of node: proportional to traffic to this router (high to low)
Color/size of link: proportional to traffic carried (high to low)

Network Optimization: The Problem

- Intradomain traffic engineering
  - predict influence of weight changes on traffic flow
  - minimize objective function (say, of link utilization)
- Inputs
  - networks topology: capacitated, directed graph
  - routing configuration: routing weight for each link
  - traffic matrix: offered load each pair of nodes
- Outputs
  - shortest path(s) for each node pair
  - volume of traffic on each link in the graph
  - value of the objective function

Link Weights Adjustment: example

- Balance traffic by changing link weights



Network Optimization: Our Approach

- Local search
  - generate a candidate setting of the weights
  - predict the resulting load on the network links
  - compute the value of the objective function
  - repeat, and select solution with lowest objective function
- Computation
  - explore the "neighborhood" around good solutions
  - exploit efficient incremental graph algorithms
- Performance results on AT&T's network
  - much better than simple heuristics
    - weights inversely proportional to capacity
    - weights proportional to physical distance
  - competitive with multi-commodity flow solution
    - Optimal routing possible with more flexible routing protocols

Network Optimizations: Operational Realities

- Minimize changes to the network
  - changing just one or two link weights is often enough
- Tolerate failure of network equipment
  - weights settings usually remain good after failure
  - … or can be fixed by changing one or two weights
- Limit the number of distinct weight values
  - small number of integer values is sufficient
- Limit dependence on accuracy of traffic matrix
  - good weights remain good after introducing random noise
- Limit frequency of changes to the weights
  - joint optimization for day and night traffic matrices

Conclusions

- Our approach
  - measure: network-wide view of traffic and routing
  - model: data representations and "what-if" tools
  - control: intelligent changes to operational network
- Other applications
  - visualization of traffic, performance, and reliability
  - capacity planning to place new routers and links
  - estimating impact of new customers on network
  - evaluating the effects of router and link failures
  - comparing benefits of different routing protocols

Internet Traffic Engineering by Optimizing OSPF Weights

Bernard Fortz and Mikkel Thorup

Outline

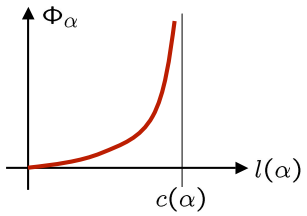
- Base-line optimal routing
- Difficulty in OSPF weights Optimization
- Local search algorithm
- Experiments on operational networks

Optimal Routing

- Design Space:
  - given source destination pairs (TM)
  - any possible paths between any two pairs
- Objective:
  - link incurs cost by carrying traffic
  - network cost is the summation of all link costs
  - find a set of routes to minimize network cost

Optimal Routing: formulation

- routing variable: $f_\alpha^{(s,t)}, \alpha \in A, (s,t) \in N \times N$
- link data rate: $l(\alpha) = \sum_{(s,t)\in N\times N} f_\alpha^{(s,t)}$
- link cost: increasing, convex function of link data rate
  - example: $\Phi_\alpha = \frac{l(\alpha)}{c(\alpha) - l(\alpha)}$ M/M/1 delay



- network cost
  - summation: $\Phi = \sum_{\alpha\in A} \Phi_\alpha$
  - normalization:

$$\Phi^* = \frac{\Phi}{\sum_{(s,t)\in N\times N}(D(s,t) \times dist_1(s,t))}$$

Optimal Routing: formulation

network cost: $\min \Phi = \sum_{\alpha\in A} \frac{l(\alpha)}{c(\alpha) - l(\alpha)}$

link rate: $l(\alpha) = \sum_{(s,t)\in N\times N} f_\alpha^{(s,t)}, \quad \alpha = (x,y) \in N \times N$

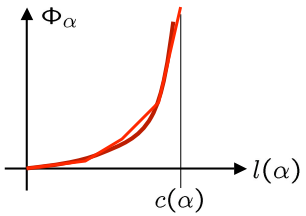
feasible flow: $\sum_{x:(x,y)\in A} f_{(x,y)}^{(s,t)} - \sum_{z:(y,z)\in A} f_{(y,z)}^{(s,t)} = \begin{cases} -D(s,t) & \text{if } y = s \\ D(s,t) & \text{if } y = t \\ 0 & \text{otherwise} \end{cases}$

$$f_{(x,y)}^{(s,t)} \geq 0, \quad \forall x, y, s, t \in N$$

can be solved by centralized and distributed algorithms

Linear Programming

- approximate link cost function with piece-wise linear function



- LP formulation

$$\min \Phi = \sum_{a \in A} \Phi_a$$

subject to

$$\sum_{x:(x,y)\in A} f^{(s,t)}_{(x,y)} - \sum_{z:(y,z)\in A} f^{(s,t)}_{(y,z)} = \begin{cases} -D(s,t) & \text{if } y=s, \\ D(s,t) & \text{if } y=t, \\ 0 & \text{otherwise,} \end{cases}$$

$$y, s, t \in N, \quad (1)$$

$$\ell(a) = \sum_{(s,t)\in N\times N} f^{(s,t)}_a \qquad a \in A, \quad (2)$$

$$\Phi_a \geq \ell(a) \qquad a \in A, \quad (3)$$

$$\Phi_a \geq 3\ell(a) - \tfrac{2}{3}c(a) \qquad a \in A, \quad (4)$$

$$\Phi_a \geq 10\ell(a) - \tfrac{16}{3}c(a) \qquad a \in A, \quad (5)$$

$$\Phi_a \geq 70\ell(a) - \tfrac{178}{3}c(a) \qquad a \in A, \quad (6)$$

$$\Phi_a \geq 500\ell(a) - \tfrac{1468}{3}c(a) \qquad a \in A, \quad (7)$$

$$\Phi_a \geq 5000\ell(a) - \tfrac{19468}{3}c(a) \qquad a \in A, \quad (8)$$

$$f^{(s,t)}_a \geq 0 \qquad a \in A;\ s,t \in N. \quad (9)$$

Limitation with OSPF routing

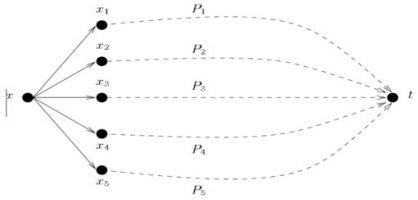
- free repartition of flow not possible using OSPF
  - traffic equally split between shortest paths
- contrived example: cost of optimal OSPF policy may be up to 5000 times the cost of the optimal routing.
- the optimization of OSPF weights is NP-hard.

Local Search Heuristics

- Local search to reduce network cost
- Neighborhoods for OSPF weight setting
- Hashing tables to escape local minima
- Diversification
- Algorithmic aspects
- Numerical results

Neighborhood of OSPF weight setting

- Change the weight of one arc.
- Change the weights of all arcs leaving a node to make paths of equal weights.



- Too big neighborhoods: random sampling.

Hash tables to avoid cycling

- A solution is completely determine by a set of weights.
- Hashing: compression of a set of weights into one hash value (storable on 16 bits).
- Record hash value of each iterate and reject solutions having a value already encountered.
- Completely avoids cycling.

Diversification

- Local search converges to local minimum
- Key tool for exploring different regions of the solution space.
- Two approaches:
  - smaller hashing table used to create collisions and reject more and more solutions;
  - random perturbations.

Cost Evaluation

- Evaluation network cost if one weight setting is implemented (algorithm perf. bottleneck)
- Shortest path tree to a destination t
  - reverse link direction
  - shortest path tree from "source t" in the reversed graph
- Each node find all outgoing links on shortest path t, and equally split traffic on those links
- Link rate is the summation of traffic between all src-dst pairs allocated on it

Routing Computation

For each destination t:

- Shortest paths to $t \rightarrow$ Backward Dijkstra.
- Build the graph $G' = (N, A^t)$ of arcs that belong to a shortest path to t.

$$A^t = \{(i,j) \in A : d(i,t) = w_{ij} + d(j,t)\}.$$

- Visit the nodes in order of decreasing distance to t. When visiting v, set

$$l = \frac{1}{|\delta_t^+(v)|}\left(D(v,t) + \sum_{(u,v)\in A^t} l^t_{(u,v)}\right)$$

and set $l^t_{(v,w)} = l$ for each $(v,w) \in A^t$.

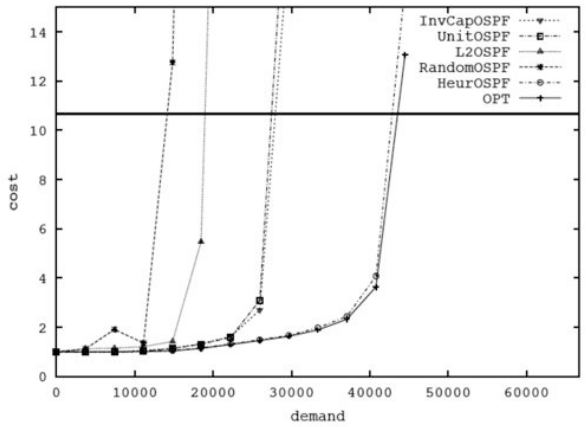
Algorithmic Aspects

- Only a few weights change when considering a neighbor of a solution.
- Dynamic updates of the cost:
  - recompute only shortest paths that really change;
  - recompute flows only from nodes for which an ingoing or outgoing arc has appeared in or disappeared from the shortest paths graph.
  - details in papers
- Computation time divided by 20 !

Numerical Experiments

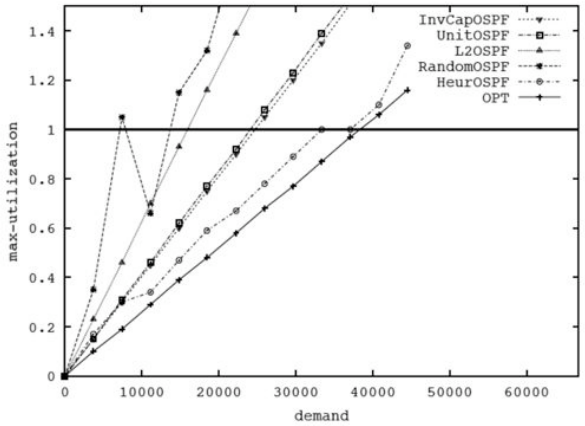
- AT&T WorldNet and synthetic networks.
- 5000 iterations of local search.
- Comparison with:
  - Optimal routing (lower bound).
  - UnitOSPF.
  - InvCapOSPF (CISCO recommendation).
  - L2OSPF
  - RandomOSPF (performs really bad).

Numerical Experiments



AT&T backbone with 90 nodes and 274 arcs

Numerical Experiments



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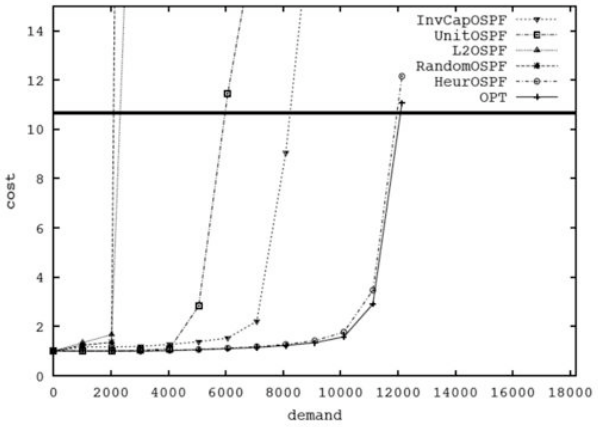
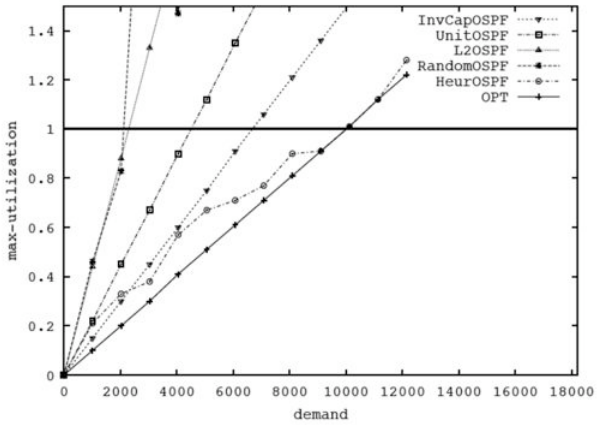


2-level graph with 100 nodes and 360 arcs

Numerical Experiments



2-level graph with 100 nodes and 360 arcs

Numerical Experiments

- Our heuristic allows to deal with an increase of demands of 55 % compared to simple OSPF strategies.
- Optimal routing can cope with a 3 % increase in demands only, so it would be preferable to increase the hardware capacity.
- For realistic network topologies, OSPF works well (with our heuristic).

Extensions

- Restoring capacity with a few weight changes.
- Robustness vs. hot spots and link failures.
- Multiple demand matrices.
- Robust optimization for link failure scenarios.

To Read More…

- Overview papers
  - "Traffic engineering for IP networks" (http://www.research.att.com/~jrex/papers/ieeenet00.ps)
- Topology and configuration
  - "IP network configuration for intradomain traffic engineering" (http://www.research.att.com/~jrex/papers/ieeenet01.ps)
  - "An OSPF topology server: Design and evaluation" (http://www.cse.ucsc.edu/~aman/jsac01-paper.pdf)
- Intradomain route optimization
  - "Optimizing OSPF/IS-IS weights in a changing world" (http://www.research.att.com/~mthorup/PAPERS/change_ospf.ps)
- Routing optimization
  - David G. Cantor and Mario Gerla, "Optimal routing in a packet-switched computer network", *IEEE Transactions on Computer*, vol. C-23, no. 10, pp. 1062-1069, 1974.
  - Robert G. Gallager, "A minimum delay routing algorithm using distributed computation", in *IEEE Transaction on Communications*, January 1977, pp. 73-85