Internet Routing

Today: Intradomain Traffic Engineering

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Do IP Networks Manage Themselves?

- In some sense, yes:
  - TCP senders send less traffic during congestion
  - Routing protocols adapt to topology changes
- But, does the network run *efficiently*?
  - Congested link when idle paths exist?
  - High-delay path when a low-delay path exists?
- How should routing adapt to the traffic?
  - Avoiding congested links in the network
  - Satisfying application requirements (e.g., delay)
- … essential questions of traffic engineering

Traffic Engineering

- What is traffic engineering?
  - Control and optimization of routing, to steer traffic through the network in the most effective way
- Two fundamental approaches to adaptation
  - Adaptive routing protocols
    - Distribute traffic and performance measurements
    - Compute paths based on load, and requirements
  - Adaptive network-management system
    - Collect measurements of traffic and topology
    - Optimize the setting of the "static" parameters
- Big debates still today about the right answer

Outline: Three Alternatives

- Load-sensitive routing at *packet* level
  - Routers receive feedback on load and delay
  - Routers re-compute their forwarding tables
  - Fundamental problems with oscillation
- Load-sensitive routing at *circuit* level
  - Routers receive feedback on load and delay
  - Router compute a path for the next circuit
  - Less oscillation, as long as circuits last for a while
- Traffic engineering as a *management problem*
  - Routers compute paths based on "static" values
  - Network management system sets the parameters
  - Acting on network-wide view of traffic and topology

Load-Sensitive Routing Protocols: Pros and Cons

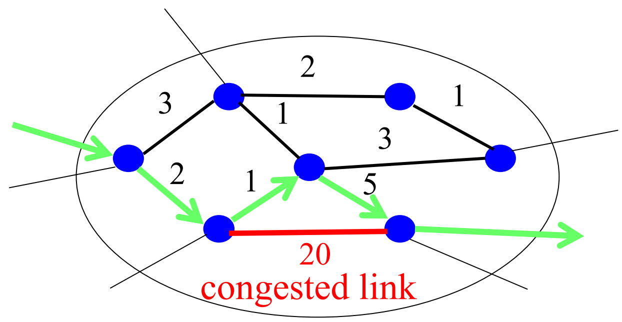
- Advantages
  - Efficient use of network resources
  - Satisfying the performance needs of end users
  - Self-managing network takes care of itself
- Disadvantages
  - Higher overhead on the routers
  - Long alternate paths consume extra resources
  - Instability from reacting to out-of-date information

Packet-Based Load-Sensitive Routing

- Packet-based routing
  - Forward packets based on forwarding table
- Load-sensitive
  - Compute table entries based on load or delay
- Questions
  - What link metrics to use?
  - How frequently to update the metrics?
  - How to propagate the metrics?
  - How to compute the paths based on metrics?

Original ARPANET Algorithm (1969)

- Routing algorithm
  - Shortest-path routing based on link metrics
  - Instantaneous queue length plus a constant
  - Distributed shortest-path algorithm (Bellman-Ford)



Performance of Original ARPANET Algorithm

- Light load
  - Delay dominated by the constant part (transmission delay and propagation delay)
- Medium load
  - Queuing delay is no longer negligible
  - Moderate traffic shifts to avoid congestion
- Heavy load
  - Very high metrics on congested links
  - Busy links look bad to all of the routers
  - All routers avoid the busy links
  - Routers may send packets on longer paths

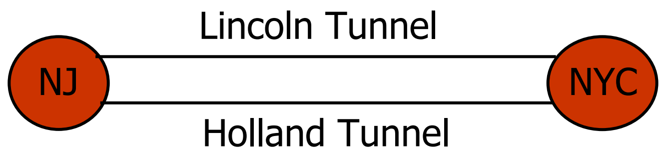
Second ARPANET Algorithm (1979)

- Averaging of the link metric over time
  - Old: Instantaneous delay fluctuates a lot
  - New: Averaging reduces the fluctuations
- Link-state protocol (more in future lecture)
  - Old: Distributed path computation leads to loops
  - New: Better to flood metrics and have each router compute the shortest paths
- Reduce frequency of updates
  - Old: Sending updates on each change is too much
  - New: Send updates if change passes a threshold

Problem of Long Alternate Paths

- Picking alternate paths
  - Long path chosen by one router consumes resource that other packets could have used
  - Leads other routers to pick other alternate paths
- Solution: limit path length
  - Bound the value of the link metric
  - "This link is busy enough to go two extra hops"
- Extreme case
  - Limit path selection to the shortest paths
  - Pick the least-loaded shortest path in the network

Problem of Out-of-Date Information



"Backup at Lincoln" on radio triggers congestion at Holland

- Routers make decisions based on old information
  - Propagation delay in flooding link metrics
  - Thresholds applied to limit number of updates
- Old information leads to bad decisions
  - All routers avoid the congested links
  - … leading to congestion on other links
  - … and the whole things repeats

Avoiding Oscillations From Out-of-Date Info

- Send link metrics more often
  - But, leads to higher overhead
  - But, propagation delay is a fundamental limit
- Make the traffic last longer
  - Circuit switching: phone network
    - Average phone call last 3 minutes
    - Plenty of time for feedback on link loads
  - Packet switching: Internet
    - Data packet is small (e.g., 1500 bytes or less)
    - But, feedback on link metrics also sent via packets
    - Better to make decisions on groups of packets

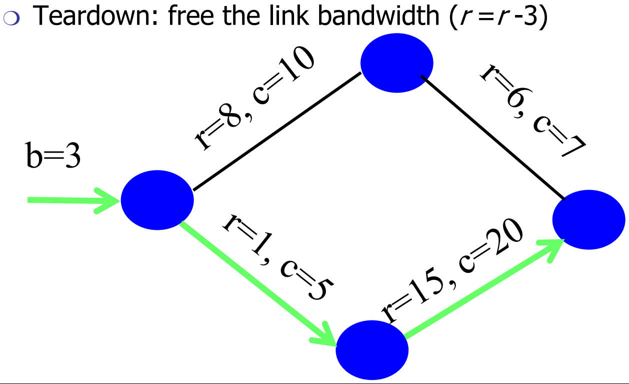
Quality-of-Service Routing on Circuits

Quality-of-Service Routing With Circuit Switching

- Traffic performance requirement
  - Guaranteed bandwidth b per connection
- Link resource reservation
  - Reserved bandwidth r_i on link I
  - Capacity c_i on link i
- Signaling: admission control on path P
  - Reserve bandwidth b on each link i on path P
  - Block: if (r_i+b>c_i) then reject (or try again)
  - Accept: else $r_i = r_i + b$
- Routing: ingress router selects the path

Source-Directed QoS Routing

- New connection with $b = 3$
  - Routing: select path with available resources
  - Signaling: reserve bandwidth along the path ($r = r + 3$)
  - Forward data packets along the selected path
  - Teardown: free the link bandwidth ($r = r - 3$)



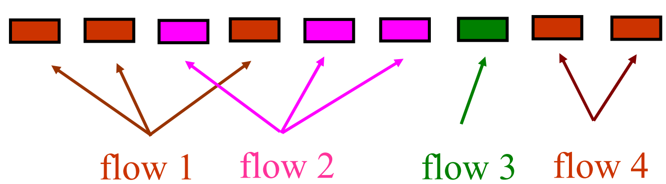
QoS Routing: Path Selection

- Link-state advertisements
  - Advertise available bandwidth ($c_i - r_i$) on link i
    - E.g., every T seconds, independent of changes
    - E.g., when metric changes beyond threshold
  - Each router constructs view of topology
- Path computation at each router
  - E.g., Shortest widest path
    - Consider paths with largest value of $min_i(c_i-r_i)$
    - Tie-break on smallest number of hops
  - E.g., Widest shortest path
    - Consider only paths with minimum hops
    - Tie-break on largest value of $min_i(c_i-r_i)$ over paths

How To Get IP Packets on to Circuits?

- Who initiates the circuit?
  - End system application or operating system?
  - Edge router?
- Edge router can infer the need for a circuit
  - Match on packet header bits
    - E.g., source, destination, port numbers, etc.
  - Apply policy for picking bandwidth parameters
    - E.g., Web connections get 10 Kbps, video gets 2 Mbps
  - Trigger establishment of circuit for the traffic
    - Select path based on load and requirements
    - Signal creation of the circuit
    - Tear down circuit after an idle period

Grouping IP Packets Into Flows



- Group packets with the "same" end points
  - Application level: single TCP connection
  - Host level: single source-destination pair
  - Subnet level: single source prefix and dest prefix
- Group packets that are close together in time
  - E.g., 60-sec spacing between consecutive packets

But, Staleness Can Still Be a Problem…

- Link state updates
  - High update rate leads to high overhead
  - Low update rate leads to oscillation
- Connections are too short
  - Average Web transfer is just 10 packets
  - Requires high update rates to ensure stability
- Idea: QoS routing only for long transfers!
  - Small fraction of transfers are very large
  - … and these few transfers carry a lot of traffic
  - Forward most transfers on static routes
  - … and compute dynamic routes for long transfers

Identifying the Long Transfers

- A nice property of transfer sizes
  - Most transfers are short, but a few are *very* long
  - Distribution of transfer sizes is "heavy tailed"
- A nice property of heavy tails
  - After you see 10 packets, it is likely a long transfer
  - Even the *remainder* of the transfer is long
- Routing policy
  - Forward initial packets on the static default route
  - After seeing 10 packets, try to signal a circuit
  - Forward the remaining packets on the circuit
- Avoids oscillation even for small update rates
  - http://www.cs.princeton.edu/~jrex/papers/sigcomm99.ps

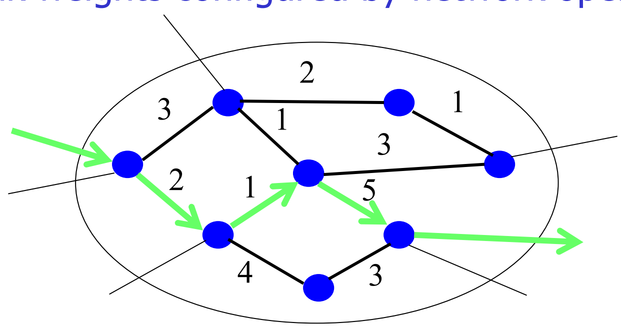
Ongoing Work on QoS Routing

- Standards activity
  - Traffic-engineering extensions to the conventional routing protocols (e.g., OSPF and IS-IS)
  - Use of MPLS to establish the circuits over the links
  - New work on Path Computation Elements that compute the load-sensitive routes for the routers
- Research activity
  - Avoid propagating dynamic link-state information
  - Based decisions based on past success or failure
  - Essentially inferring the state of the links

Traffic Engineering as a Network-Management Problem

Using Traditional Routing Protocols

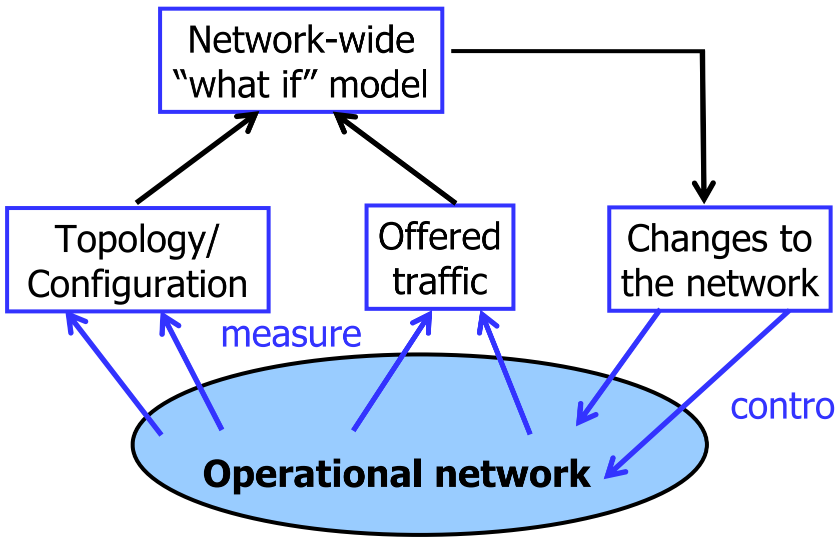
- Routers flood information to learn topology
  - Determine "next hop" to reach other routers…
  - Compute shortest paths based on link weights
- Link weights configured by network operator



Approaches for Setting the Link Weights

- Conventional static heuristics
  - Proportional to physical distance
    - Cross-country links have higher weights
    - Minimizes end-to-end propagation delay
  - Inversely proportional to link capacity
    - Smaller weights for higher-bandwidth links
    - Attracts more traffic to links with more capacity
- Tune the weights based on the offered traffic
  - Network-wide optimization of the link weights
  - Directly minimizes metrics like max link utilization

Measure, Model, and Control



Traffic Engineering in an ISP Backbone

- Topology
  - Connectivity and capacity of routers and links
- Traffic matrix
  - Offered load between points in the network
- Link weights
  - Configurable parameters for routing protocol
- Performance objective
  - Balanced load, low latency, service level agreements …
- Question: Given the *topology* and *traffic matrix*, which *link weights* should be used?

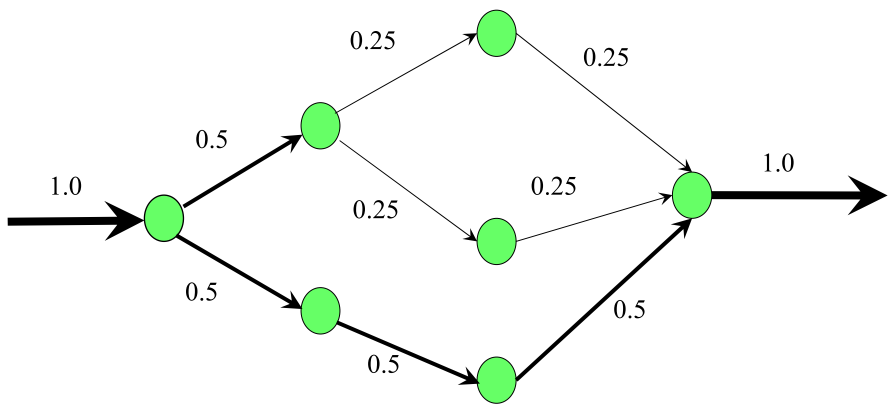
Key Ingredients of the Approach

- Instrumentation
  - Topology: monitoring of the routing protocols
  - Traffic matrix: fine-grained traffic measurement
- Network-wide models
  - Representations of topology and traffic
  - "What-if" models of shortest-path routing
- Network optimization
  - Efficient algorithms to find good configurations
  - Operational experience to identify key constraints

Formalizing the Optimization Problem

- Input: graph $G(R,L)$
  - R is the set of routers
  - L is the set of unidirectional links
  - c_l is the capacity of link l
- Input: traffic matrix
  - $M_{i,j}$ is traffic load from router i to j
- Output: setting of the link weights
  - w_l is weight on unidirectional link l
  - $P_{i,j,l}$ is fraction of traffic from i to j traversing link l

Multiple Shortest Paths With Even Splitting



Values of $P_{i,j,l}$

Complexity of the Optimization Problem

- NP-complete optimization problem
  - No efficient algorithm to find the link weights
  - Even for simple objective functions
- What are the implications?
  - Have to resort to *searching* through weight settings

Optimization Based on Local Search

- Start with an initial setting of the link weights
  - E.g., same integer weight on every link
  - E.g., weights inversely proportional to capacity
  - E.g., existing weights in the operational network
- Compute the objective function
  - Compute the all-pairs shortest paths to get $P_{i,j,l}$
  - Apply the traffic matrix $M_{i,j}$ to get link loads u_l
  - Evaluate the objective function from the u_l/c_l
- Generate a new setting of the link weights

repeat

Incorporating Operational Realities

- Minimize number of changes to the network
  - Changing just 1 or 2 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 dependence on measurement accuracy
  - Good weights remain good, despite random noise
- Limit frequency of changes to the weights
  - Joint optimization for day & night traffic matrices

Application to AT&T's Backbone Network

- Performance of the optimized weights
  - Search finds a good solution within a few minutes
  - Much better than link capacity or physical distance
  - Competitive with multi-commodity flow solution
- How AT&T changes the link weights
  - Maintenance every night from midnight to 6am
  - Predict effects of removing link(s) from network
  - Reoptimize the link weights to avoid congestion
  - Configure new weights before disabling equipment