12. Traffic engineering
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Contents

- Topology
  - Traffic matrix
  - Traffic engineering
  - Load balancing
Topography

- A telecommunication network consists of nodes and links
  - Let $\mathcal{N}$ denote the set of nodes indexed with $n$
  - Let $\mathcal{J}$ denote the set of nodes indexed with $n$
- Example:
  - $\mathcal{N} = \{a,b,c,d,e\}$
  - $\mathcal{J} = \{1,2,3,...,12\}$
  - Link 1 from node a to node b
  - Link 2 from node b to node a
- Let $c_j$ denote the capacity of link $j$ (bps)
We define a path (= route) as a
- set of consecutive links connecting two nodes
- Let \( P \) denote the set of paths indexed with \( p \)

Example:
- three paths from node a to node c:
  - red path consisting of links 1 and 3
  - green path consisting of links 11 and 6
  - blue path consisting of links 10, 8 and 6
Path matrix

- Each path consists of a set of links
- This connection is described by the **path matrix** $A$, for which
  - element $a_{jp} = 1$ if $j \in p$, that is, link $j$ belongs to path $p$
  - otherwise $a_{jp} = 0$
- Example:
  - three columns of a path matrix

<table>
<thead>
<tr>
<th></th>
<th>ac1</th>
<th>ac2</th>
<th>ac3</th>
</tr>
</thead>
<tbody>
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<td>11</td>
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<tr>
<td>12</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>
Shortest paths

- If each link $j$ is associated with a corresponding weight $w_j$, the length $l_p$ of path $p$ is given by

$$l_p = \sum_{j \in p} w_j$$

  - With unit link weights $w_j = 1$, path length = hop count

- Example:
  - two shortest paths (with length 2) from node $a$ to node $c$
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Traffic characterisation

Traffic

- Circuit-switched
  - e.g. telephone traffic
  - Link
  - Network

- Packet-switched
  - e.g. data traffic
  - Link
  - Network
Traffic matrix (1)

- Traffic in a network is described by the **traffic matrix** $T$, for which
  - element $t_{nm}$ tells the **traffic demand** (bps) from origin node $n$ to destination node $m$
  - Aggregated traffic of all flows with the same origin and destination
  - Aggregated traffic during a time interval, e.g. busy hour or "typical 5-minute interval"

- Example:
  - Traffic demand from origin $a$ to destination $c$ is $t_{ac}$ (bps)
Traffic matrix (2)

- Below we present the traffic demands in a vector form
  - Let $K$ denote the set of origin-destination pairs (OD-pairs) indexed with $k$
- Traffic demands constitute a vector $x$, for which
  - element $x_k$ tells the traffic demand of OD-pair $k$
- Example:
  - if OD-pair (a,c) is indexed with $k$, then $x_k = t_{ac}$
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Traffic engineering and network design

- **Traffic engineering** = ”Engineer the traffic to fit the topology”
  - Given a fixed topology and a traffic matrix, how to **route** these traffic demands?

- **Network design** = ”Engineer the topology to fit the traffic”
Effect of routing on load distribution

• Routing algorithm determines how the traffic load is distributed to the links
  – Internet routing protocols (RIP, OSPF, BGP) apply the shortest path algorithms (Bellman-Ford, Dijkstra)
  – In MPLS networks, other algorithms are also possible
• More precisely: routing algorithm determines the proportions (splitting ratios) $\phi_{pk}$ of traffic demands $x_k$ allocated to paths $p$,

$$\sum_{p \in P} \phi_{pk} = 1 \quad \text{for all } k$$
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**Link counts**

- Traffic on a path $p$ between OD-pair $k$ is thus

$$\phi_{pk} x_k$$

- **Link counts** $y_j$ are determined by traffic demands $x_k$ and splitting ratios $\phi_{pk}$:

$$y_j = \sum_{p \in P} \sum_{k \in K} a_{jp} \phi_{pk} x_k$$

- The same in matrix form:

$$y = A \phi x$$
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**MPLS**

- **MPLS** (Multiprotocol Label Switching) supports traffic load distribution to parallel paths between OD-pairs
  - In MPLS networks, there can be any number of parallel Label Switched Paths (LSP) between OD-pairs
  - These paths do not need to belong to the set of shortest paths
  - Each LSP is associated with a label and each MPLS packet is tagged with such a label
- MPLS packets are routed through the network via these LSP’s (according to their label)
- Traffic load distribution can be affected **directly** by changing the splitting ratios $\phi_{pk}$ at the origin nodes
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**OSPF (1)**

- **OSPF** (Open Shortest Path First) is an intradomain routing protocol in IP networks.
- **Link State Protocol**
  - each node tells the other nodes the distance to its neighbouring nodes
  - these distances are the link weights for the shortest path algorithm
  - based on this information, each node is aware of the whole topology of the domain
  - the shortest paths are derived from this topology using Dijkstra’s algorithm
- **IP packets are routed through the network via these shortest paths**
Routers in OSPF networks typically apply **ECMP** (Equal Cost Multipath)

- If there are multiple shortest paths from node $n$ to node $m$, then node $n$ tries to split the traffic uniformly to those outgoing links that belong to at least one of these shortest paths
- However, this does **not** imply that the traffic load is distributed uniformly to all shortest paths! See the example on next slide.

Traffic load distribution can be affected only **indirectly** by changing the link weights

- splitting ratios $\phi_{pk}$ can not directly be changed
- due to ECMP, the desired splitting ratios $\phi_{pk}$ may be out of reach
ECMP

\[ y = \frac{x}{2} \]
\[ y = \frac{x}{4} \]
\[ \phi = \frac{1}{4} \]
\[ \phi = \frac{1}{2} \]
Effect of link weights on load distribution (1)
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Effect of link weights on load distribution (2)

![Diagram showing effect of link weights on load distribution.]

- Link weight increased
- Maximum link load

\[ w = 1, w = 1, w = 1, w = 2, w = 1 \]

\[ \phi = \frac{1}{2} \]
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Load balancing problem (1)

- Given a fixed topology and a traffic matrix, how to optimally route these traffic demands?
- One approach is to equalize the relative load of different links, $\rho_j = y_j/c_j$
  - Sometimes this can be done in multiple ways (upper figure)
  - Sometimes it is not possible at all (lower figure)
  - In this case, we may, however, try to get as close as possible, e.g. by minimizing the maximum relative link load (called: load balancing problem)
• **Load Balancing Problem:**
  - Consider a network with topology \((N,J)\), link capacities \(c_j\), and traffic demands \(x_k\). Determine the splitting ratios \(\phi_{pk}\) so that the maximum relative link load is minimized.

Minimize

\[
\max_{j \in J} \frac{y_j}{c_j}
\]

subject to

\[
\begin{align*}
y_j &= \sum_{p \in P} \sum_{k \in K} A_{jp} \phi_{pk} x_k & \forall j \in J \\
\sum_{p \in P} \phi_{pk} &= 1 & \forall k \in K \\
\phi_{pk} &\geq 0 & \forall p \in P, k \in K
\end{align*}
\]
Load balancing problem (3)

- Load Balancing Problem has always a solution but this might not be unique
- Example:
  - the same maximum link load is achieved with routes of different length
  - the upper routes are better due to smaller capacity consumption
- A reasonable unique solution is achieved by associating a negligible cost with all the hops along the paths used
Load balancing problem (4)

- **Load Balancing Problem** with a reasonable and unique solution:
  - Consider a network with topology \((N,J)\), link capacities \(c_j\), and traffic demands \(x_k\). Determine the splitting ratios \(\phi_{pk}\) so that the maximum relative link load is minimized with the smallest amount of required capacity.

Minimize: \[
\max_{j \in J} \frac{y_j}{c_j} + \varepsilon \sum_{j \in J} y_j
\]

subject to:
\[
\begin{align*}
y_j &= \sum_{p \in P} \sum_{k \in K} A_{jp} \phi_{pk} x_k \quad \forall j \in J \\
\sum_{p \in P} \phi_{pk} &= 1 \quad \forall k \in K \\
\phi_{pk} &\geq 0 \quad \forall p \in P, k \in K
\end{align*}
\]
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Example (1): optimal solution

\[
\begin{align*}
\phi &= 1/2 \\
\rho &= x/4 \\
\rho &= x \cdot \frac{1}{8}
\end{align*}
\]
Example (2): link weights $w = 1$
Example (3): optimal link weights
THE END