Efficient Load-Balanced IP Routing Scheme Based on Shortest Paths in Hose Model

Eiji Oki
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The University of Electro-Communications
Outline

- Background on IP routing
- IP routing strategy
- Traffic models
- Requirement for IP routing
- Proposed routing scheme
- Optimal routing formulations
- Performance evaluation
- Conclusions
Routing in IP networks

- What is good routing?
  - To utilize the network resources efficiently and increase the network throughput.

- Approaches
  - Route selection
    - IP packets are forwarded on the selected routes.
  - Load balancing
    - Traffic demands are split among source and destination nodes.

- Minimizing the network congestion ratio leads to increase additional admissible traffic.
  - Network congestion ratio
    - Maximum link load of all network links
  - This is a main target in this study.
Several routing strategies

- Multi-Protocol Label Switching Traffic Engineering (MPLS-TE)-based routing
- Shortest-path-based routing
  - Optimum link weight control
  - Two-Phase Routing (TPR)
  - Smart Open Shortest Path First (S-OSPF)
MPLS-TE-based routing

- Label Switch Path (LSP) tunnels are used.
- Traffic demands are explicitly routed and flexibly split among source and destination nodes.

However,
- Legacy networks mainly employ shortest-path-based routing protocols such as OSPF.
- Already deployed IP routers in the legacy networks need to be upgraded.
- Network operators need to configure and manage LSP tunnels between all edge nodes to form a mesh-like logical topology. The number of tunnels increases in proportion to \( N^2 \), where \( N \) is the number of nodes.

- It is desirable that an existing IP routing protocol still in use should be utilized.
Optimum link weight control

- Set optimum link weights in OSPF-based networks.
- Traffic is routed on shortest paths based on the computed optimum link weights.
- However,
  - When traffic demands are changed, optimum link weights are recalculated and IP routes are changed.
  - Changing routes frequently causes network instability, which leads to packet loss and the formation of loops.
Two-Phase Routing (TPR)

- Presented by Antic and Smiljanic et al. [ICC 2008]
- Performs load balancing and each flow is routed according to the existing OSPF protocol, in two stages across intermediate nodes.
- Optimum distribution ratios are obtained by solving a Linear Programming (LP) problem.
- Requires the configuration of IP tunnels, such as IP-in-IP and Generic Routing Encapsulation (GRE) tunnels, between source and destination nodes.

![Diagram of Two-Phase Routing (TPR)](image-url)
Smart OSPF (S-OSPF)

- Presented by Mishra and Sahoo. [Globecom 2007]
- Source nodes distribute traffic only to the neighbor nodes with optimum ratios, which are obtained from the LP problem.
- No tunnel configuration is required.
## Summary of four routing strategies

<table>
<thead>
<tr>
<th></th>
<th>MPLS routing</th>
<th>Shortest-path routing</th>
<th>Link weight control</th>
<th>TPR</th>
<th>S-OSPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>LSP tunnel</td>
<td>Not required</td>
<td>IP tunnel</td>
<td></td>
<td>Not required</td>
</tr>
<tr>
<td>Stability</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Routing performance</td>
<td>Ideal</td>
<td>High</td>
<td>High</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Scalability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
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</tbody>
</table>
Optimal routing for traffic models

- Pipe model
- Hose model
Pipe model

- Assumption on traffic model
  - Traffic matrix, $T=\{d_{pq}\}$, is exactly known.
    - $d_{pq}$: traffic demand from source node $p$ to destination node $q$.

- Routing scheme
  - Traffic demands are assumed to be explicitly routed and flexibly split among source and destination nodes, by using Multi-Protocol Label Switching (MPLS) technologies.

$$T = \begin{pmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{pmatrix}$$
Pipe model (cont’d)

- Under the pipe model, the most efficient routing is achieved.
- However,
  - It is difficult for network operators to get an exact traffic matrix
  - Because
    - Measurement of traffic demand for each source and destination pair is difficult when the network size is large.
    - Traffic demand is often fluctuated.

Measurement of traffic demand

\[ T = \begin{pmatrix} d_{11} & d_{12} & d_{13} \\ d_{21} & d_{22} & d_{23} \\ d_{31} & d_{32} & d_{33} \end{pmatrix} \]

Fluctuation of traffic demand

\[ d_{pq} \]
Hose model

- Easy for network operators to specify the traffic as only the total outgoing/incoming traffic from/to edge node $p$ and edge node $q$.
- The hose model is specified by:

\[
\begin{align*}
\text{Outgoing traffic:} & \quad \sum_{q} d_{pq} \leq \alpha_p \\
\text{Incoming traffic:} & \quad \sum_{p} d_{pq} \leq \beta_q
\end{align*}
\]
Requirements for IP routing

- High network utilization.
  - The routing scheme should utilize network resources efficiently and increase network throughput.

- Easy deployment.
  - Utilizing a routing protocol that is already deployed in the existing network is preferred. It should be easy to be scale in terms of network size.

- Stability against frequent traffic fluctuation.
  - The routing scheme should not allow the network to become unstable by frequently changing routes, which leads to packet losses and loops.

- Simple traffic information.
  - Complete traffic matrix information should not be required. The routing scheme should use the hose model.

**Question:** Is there any routing scheme that satisfies the above requirements?
## Routing strategies and traffic models

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<td>Pipe model</td>
<td>Solved</td>
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</tr>
<tr>
<td>Hose model</td>
<td>Solved</td>
<td></td>
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A routing scheme based on S-OSPF for the hose model is proposed.
Network model

$G(V, E)$: directed graph
$V$: set of vertexes
$Q \in V$: set of edge nodes
$E$: set of links,
$x_{ij}^{pq}$: portion of traffic from node $p \in Q$
to node $q \in Q$ through link $(i, j) \in E$
$c_{ij}$: capacity of link $(i, j) \in E$
$T = \{d_{pq}\}$: traffic demand
$r$: network congestion ratio,
  maximum value of all link utilization rates in the network
## S-OSPF routing with pipe model

<table>
<thead>
<tr>
<th>Optimization problem</th>
<th>Given parameters: $d_{pq}, c_{ij}$</th>
</tr>
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<tr>
<td>Objective: $\min r$</td>
<td>Decision variables: $r, x_{ij}^{pq}$</td>
</tr>
<tr>
<td>Constraints:</td>
<td>This is a linear programming (LP) problem.</td>
</tr>
</tbody>
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### (1a) Optimization problem

Objective: $\min r$

### (1b) Constraints:

$$x_{ij}^{pq} - \sum_{j':(j',i)\in E} x_{j'i}^{pq} = 0,$$

where $p, q \in Q, i \neq p, i \neq q, i = OSPF_{\text{next-hop}}^{pq}$.

### (1c) Constraints:

$$\sum_{j:(i,j)\in E, j\neq OSPF_{\text{ancestor}}^{pq}} x_{ij}^{pq} - \sum_{j':(j',i)\in E} x_{j'i}^{pq} = 1,$$

where $p, q \in Q, i = p$.

### (1d) Constraints:

$$\sum_{p,q\in Q} d_{pq} x_{ij}^{pq} \leq c_{ij} r, (i, j) \in E$$

### (1e) Constraints:

$$0 \leq x_{ij}^{pq} \leq 1, p, q \in Q, (i, j) \in E$$

### (1f) Constraints:

$$0 \leq r \leq 1$$
S-OSPF routing with hose model

Optimization problem

Objective: \( \min r \) \hspace{1cm} \text{(1a)}

Constraints:

\[
x_{ij}^{pq} - \sum_{j' : (j',i) \in E} x_{j'i}^{pq} = 0, \quad \text{(1b)}
\]

\[
p, q \in Q, i \neq p, i \neq q, i = OSPF_{\text{next hop}}^{pq}, \quad \text{(1c)}
\]

\[
\sum_{j : (i,j) \in E, j \neq OSPF_{\text{ancestor}}^{pq}} x_{ij}^{pq} - \sum_{j' : (j',i) \in E} x_{j'i}^{pq} = 1, \quad \text{(1c)}
\]

\[
p, q \in Q, i = p, \quad \text{(1d)}
\]

\[
0 \leq x_{ij}^{pq} \leq 1, \; p, q \in Q, (i, j) \in E, \quad \text{(1e)}
\]

\[
0 \leq r \leq 1, \quad \text{(1f)}
\]

Given parameters: \( d_{pq}, c_{ij} \)

The range of \( d_{pq} \) is given by:

\[
\sum_{q} d_{pq} \leq \alpha_p \quad \text{(1g)}
\]

\[
\sum_{p} d_{pq} \leq \beta_q \quad \text{(1h)}
\]

Decision variables: \( r, x_{ij}^{pq} \)

This optimization problem is a linear programming (LP) one. However, it is impossible to consider all possible combinations of \( d_{pq} \) specified by Eqs. (1g)-(1i).
S-OSPF routing with hose model (cont’d)

- The optimization problem is solved by the following property, which is obtained by introducing the dual theorem and extending Chu’s property for MPLS-TE to S-OSPF [ICC 07].
- Property: $x_{ij}^{pq}$ achieves congestion ratio $\leq r$ for all traffic matrices constrained by the intermediate model if and only if there exist the following non-negative parameters such that

\[
\begin{align*}
\text{i)} \quad & \sum_{p \in Q} \alpha_p \pi_{ij}(p) + \sum_{p \in Q} \beta_p \lambda_{ij}(p) \leq c_{ij} r, \text{ for each } (i, j) \in E \\
\text{ii)} \quad & x_{ij}^{pq} \leq \pi_{ij}(p) + \lambda_{ij}(q), \text{ for each } (i, j) \in E \text{ and every } p, q \in Q
\end{align*}
\]
The optimal routing problem is transformed into the following regular LP formulation.

Optimization problem
Objective: min \( r \)
Constraints:
\[
\begin{align*}
    x_{ij}^{pq} - \sum_{j' \in E} x_{j'j}^{pq} &= 0, \quad p, q \in Q, i \neq p, i \neq q, i = \text{OSPF}_{\text{nexthop}}^{pq} \\
    \sum_{j : (i, j) \in E} x_{ij}^{pq} - \sum_{j' : (j', i) \in E} x_{j'j}^{pq} &= 1, \quad p, q \in Q, i = p \\
    \sum_{p, q \in Q} d_{pq} x_{ij}^{pq} &\leq c_{ij} r, (i, j) \in E \\
    \sum_{p \in Q} \alpha_p \pi_{ij}(p) + \sum_{p \in Q} \beta_p \lambda_{ij}(p) &\leq c_{ij} r, (i, j) \in E \\
    x_{ij}^{pq} &\leq \pi_{ij}(p) + \lambda_{ij}(q), (i, j) \in E \\
    \pi_{ij}(p), \lambda_{ij}(q) &\geq 0 \\
    0 &\leq x_{ij}^{pq} \leq 1, \quad p, q \in Q, (i, j) \in E \\
    0 &\leq r \leq 1
\end{align*}
\]
Performance evaluation

- Network congestion ratios are compared
  - Proposed scheme, classical Shortest Path Finding (SPF), MPLS-TE, and TPR

- Simulation assumptions
  - Link capacities randomly generated with uniform distribution in the range of (80,120)
  - $d_{pq}$ is randomly generated with uniform distribution in the range of (0,100)

\[ \alpha_p = \sum_{q} d_{pq}, \beta_q = \sum_{p} d_{pq} \]
Network models

- Sample networks

(a) Network 1  (b) Network 2  (c) Network 3
(d) Network 4  (e) Network 5

- Random networks
  - Randomly generated under the condition that average node degree $D$ is satisfied for a given number of nodes $N$. 
Comparisons of congestion ratio in sample networks

- The proposed scheme
  - dramatically reduces the congestion ratio compared with the classical SPF.
  - provides comparable routing performance with MPLS-TE and TPR, which require functional upgrades and/or complicated configurations.
Comparisons of congestion ratio in random networks

- When a topology becomes mesh-like topology, the proposed scheme outperforms TPR.
Number of nodes dependency

- The congestion ratio characteristics of the four schemes are kept when the number of nodes is varied.

![Graph showing normalized congestion ratio vs. number of nodes]

- Proposed scheme
- MPLS-TE
- TPR

Normalized congestion ratio

Number of nodes, \( N \)
Conclusions

- The proposed scheme
  - does not need to know the traffic demand between all the source-destination edge node pairs, unlike original S-OSPF;
  - only the total amount of traffic that a node injects into the network and the total amount of traffic it receives from the network is needed.

- The optimal routing problem was transformed into a regular LP problem.

- The proposed scheme
  - reduces the network congestion ratio compared to the classical SPR scheme.
  - provides comparable routing performance with MPLS-TE and TPR, which require functional upgrades and/or complicated configurations.