Achieving Near-Optimal Traffic Engineering in Hybrid Software Defined Networks

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Outline

• Introduction on hybrid SDN
• System model
  – Barrier mode and hybrid mode
  – TE problem formulations
• Proposed fast algorithms
• Simulation results
• Conclusions
Introduction

• Hybrid SDN
  - Due to unresolved challenges, deployment cost, and stability concerns, SDN will be incrementally deployed to co-work with conventional networking elements, resulting in transitional hybrid SDN
  - SDN tends to integrate virtualized sourcing servers for better control of requests for large objects, which are dominating network utilization
Hybrid SDN
Hybrid SDN: A Tale of Two Networks

• SDN
  – Provide fine-grained traffic control
  – Integrate virtualized data sources (caches, CDNs or clouds)
  – Jointly solve source redirection and flow routing

• CN
  – No global view or (logically) centralized controller
  – Separate sourcing selection from other network functionalities
Traffic Engineering in H-SDN

• In H-SDN, CN traffic and SDN traffic co-exist and share the link capacities in certain manner.

• Coexistence of SDN traffic and CN traffic may defeat the benefits of deploying SDN, if the TE solution is not carefully designed for the SDN controller.
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Link-Sharing Modes in H-SDN

• **Barrier mode**
  – Reserve a certain portion of capacity on each link for SDN requests
  – Result in two logically isolated overlay networks
  – More conservative and feasible for short term

• **Hybrid mode**
  – Link capacities are fully dynamically shared by the two forms of traffic
  – More efficient utilization, better network performance, but also more complex
Graph Formulation

• A directed graph $G(V,E)$, where $V$ is the set of nodes, including SDN nodes, sourcing nodes and CN nodes, and $E$ is the set of shared links.

• $L_i \in E$ has a capacity $c(e)$, accommodating both SDN traffic and background CN traffic.

• $R$ denotes the set of SDN requests, each defined by a tuple $(i, k)$, $i \in V, k \in O$, representing node $i$ requesting object $k$. 
$\min \lambda$

\[
f(P) \leq \lambda \eta c(e), \ \forall e \in E
\]

\[
\sum_{P: e \in P} f(P) \geq d_i^k, \ \forall (i, k) \in R
\]

\[
f(P) \geq 0, \ \forall P \in \mathcal{P}
\]

– $f(P)$ is the amount of flow to be loaded among respective admissible path set
– Potentially involves an exponential number of variables $f(P)$ due to the combinatorial explosion in path enumeration
TE Problem in Hybrid Mode

\[ \min \lambda \]
\[ f(P) \]
\[ \sum_{P:e \in P} f(P) + b(e) \leq \lambda c(e), \ \forall e \in E \]
\[ \sum_{P \in P_i^k} f(P) \geq d_i^k, \ \forall (i, k) \in R \]
\[ f(P) \geq 0, \ \forall P \in \mathcal{P}. \]  

- \( b(e) \): uncontrollable CN traffic on each link \( e \)
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Algorithm 1 for Barrier Mode

- Reformulate problem (1) to problem (3), by setting 
  \( f(P) = g(P)/\rho, \lambda = 1/\rho \):

\[
\begin{align*}
\max_{\rho} & \quad \rho \\
\text{s. t.} & \quad \sum_{P: e \in P} g(P) \leq c'(e), \quad \forall e \in E \\
& \quad \sum_{P \in \mathcal{P}_i^k} g(P) \geq \rho d^k_i, \quad \forall (i, k) \in \mathcal{R} \\
& \quad g(P) \geq 0, \quad \forall P \in \mathcal{P}.
\end{align*}
\]

- \( c'(e) \) is the reserved capacity for SDN requests on link \( e \)
- Different from maximum concurrent multi-commodity flow (MCMF) problem, where source-destination pairs are fixed
- Here, sourcing nodes remain to be selected
Reformulation of Problem (3)

• Consider a dual formulation of problem (3):

\[
\min_{l(e)} \Gamma(l) \triangleq \sum_{e \in E} c'(e)l(e)
\]

s. t. \[
\sum_{e \in P} l(e) \geq x_i^k, \quad \forall (i, k) \in R, \forall P \in P_i^k
\]

\[
\sum_{(i, k) \in R} x_i^k d_i^k \geq 1
\]

\[
l(e), x_i^k \geq 0, \quad \forall (i, k) \in R, \forall e \in E
\]

– \(x_i^k\) is a dual variable w.r.t. each request \((i, k) \in R\)
– \(l(e)\) is the length function assigned to each edge (link) \(e\)
Reformulation of Problem (3) Cont.

• Rewrite $x_i^k$ as a function of $l$:

$$x_i^k(l) \triangleq \min_{j \in S_k} x_{ji}(l), \quad \forall (i, k) \in R$$  \hspace{1cm} (5)

- Length of the “shortest” path from the “nearest” admissible node in $S_k$ to node $i$, given the length function $l$

• Define aggregate shipping cost for all requests via such “shortest” paths

$$\beta(l) \triangleq \sum_{(i, k) \in R} d_i^k x_i^k(l)$$  \hspace{1cm} (6)

• Rewrite optimal value of problem (4) as:

$$\gamma \triangleq \min_l \Gamma(l) / \beta(l)$$  \hspace{1cm} (7)
Algorithm 1: Algorithm for problem (3).

Input: Network graph $G = (V, E)$, network object set $O$, overlay link capacities $c'(e)$, source set 
\{\(S_k\), \(k \in O\), SDN requests set $R$, request demands \(d_j^k\), accuracy $\varepsilon$

Output: Primal solution $y$ and $\rho$

1: Initialize $l(e) \leftarrow \phi/c'(e)$, $\forall e$, $g(P) \leftarrow 0$, $\forall P$
2: while $\Gamma(l) < 1$ do
3:   for $j = 1$ to $n$ do
4:     For all requests $(j, k) \in R_j$, initialize $d_j^k = d_j^k$.
5:       while $k \in \{k | (j, k) \in R_j, d_j^k > 0\}$ do
6:         $\rho \leftarrow \max \left\{1, \max_{e \in \bigcup_{k \in K} P_j^k} \frac{\sum_{k: e \in P_j^k} d_j^k}{c'(e)} \right\}$
7:         for $k \in K$ do
8:           $f_j^k \leftarrow d_j^k / \rho$
9:           $d_j^k \leftarrow d_j^k - f_j^k$
10:          $g(P_j^k) \leftarrow g(P_j^k) + f_j^k$
11:        end for
12:      $l(e) \leftarrow l(e) \left(1 + \varepsilon \sum_{k: e \in P_j^k} f_j^k \right)$, $\forall e \in \bigcup_{k \in K} P_j^k$
13:   end while
14: end for
15: $\rho \leftarrow \min_{\{(j, k) \in R\}} \frac{\sum_{P_j^k \in P_j^k} g(P)}{d_j^k}$
16: end while
17: $g(P) \leftarrow g(P) / \log_{1+\varepsilon} \frac{1+\varepsilon}{\phi}$, $\forall P$

Phase
Iteration
Step
Analysis of Algorithm 1

• Correctness
• Approximation ratio
• Running time
Algorithm for Hybrid Mode

- A binary-search algorithm based on Algorithm 1
  - Suppose up to \( \lambda_0 \) fraction of link capacity can be used for all data traffic \( \rightarrow \) Upper bound
  - Maximum link utilization before scheduling SDN requests,
    \[
    f_{te} = \max_{e \in E} \frac{b(e)}{c(e)}
    \]
    \( \rightarrow \) Lower bound
  - Strategically find a near-optimal solution to problem (2) based on Algorithm 1 via a binary search

Details available in the long version at: [http://cs.unb.ca/~wsong/conference_papers.html](http://cs.unb.ca/~wsong/conference_papers.html)
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Simulation Setup

- Random topologies with a mean degree of 4; SDN nodes and sourcing nodes are randomly placed among the generated nodes.
- All links are bi-directional with a capacity of 1Gbps for each direction.
- SDN requests are randomly initiated with traffic demands uniformly selected between 512kbps and 3Mbps with discrete step of 128kbps.
- Traffic density: avg. number of requests collected at SDN nodes in each cycle, to vary SDN traffic load.
- Barrier mode: reserve 40% of link capacity for SDN traffic.
Barrier Mode: Approximation

\[ \lambda \]

\[ \lambda^* \text{ (OPT)} \]

\[ \frac{\lambda}{1+\omega} \]

Figure 5. Maximum link util. with different approx ratios \( \omega \).
Barrier Mode: Running Time

Figure 6. Number of phases in Alg. 1.
Barrier Mode: Multi-Source Gain

Figure 7. TE performance and multi-source gain.
Hybrid Mode

We use a hybrid network with 50 nodes and 20 SDN nodes, with link utilization upper bounded by $\lambda_0 = 0.95$. 

Figure 8. TE performance in hybrid mode.
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• Investigated and formulated TE problems for hybrid SDN in two transitional modes
• Proposed fast algorithms to obtain near-optimal solutions with approximation guarantee
• Simulation results confirmed our analysis and showed good TE performance in terms of minimizing max link utilization
Thanks!
Questions or Comments?