Fully-Flexible Virtual Network Embedding in Elastic Optical Networks

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Achieving a Fully-Flexible Virtual Network Embedding in Elastic Optical Networks

Outline

- Introduction
  - Elastic optical networks (EONs)
  - Virtual network (VN) embedding
  - Related work and contribution

- Proposed solutions
  - Integer Linear Program (ILP) formulation
  - Heuristic algorithm for a VN
    - Dynamic programming (DP) algorithm for single virtual link

- Evaluation

- Summary and future work
Introduction

- Internet traffic is growing at a very fast rate
  - AT&T experienced 100000% increase in traffic between 2008 and 2016\(^1\)

- Optical backbone networks are evolving to keep pace
  - Fine-grained spectrum allocation using 12.5GHz slices as opposed to fixed 50 or 100GHz wavelength grids
  - Elasticity in tuning transmission parameters (e.g., data rate, modulation, and forward error correction (FEC))

- Network virtualization improves utilization
  - Virtual network embedding (VNE) is a fundamental problem

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### Elastic optical networks (EONs)

#### Traditional optical networks

<table>
<thead>
<tr>
<th>Data Rate (Gbps)</th>
<th>Modulation</th>
<th>FEC (%)</th>
<th>Spectrum bandwidth (GHz)</th>
<th>Reach (km)</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>QPSK</td>
<td>25%</td>
<td>50</td>
<td>2000</td>
<td>T1</td>
</tr>
<tr>
<td>200</td>
<td>QPSK</td>
<td>25%</td>
<td>100</td>
<td>1000</td>
<td>T2</td>
</tr>
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</table>

#### Elastic optical networks

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<td>2000</td>
<td>T1</td>
</tr>
<tr>
<td></td>
<td>16QAM</td>
<td>20%</td>
<td>25</td>
<td>1250</td>
<td>T2</td>
</tr>
<tr>
<td>200</td>
<td>QPSK</td>
<td>25%</td>
<td>75</td>
<td>1000</td>
<td>T3</td>
</tr>
<tr>
<td></td>
<td>32QAM</td>
<td>20%</td>
<td>37.5</td>
<td>400</td>
<td>T4</td>
</tr>
</tbody>
</table>
Virtual network embedding (VNE)

- Embed a VN on an EON
  - A virtual node is hosted on a physical node
  - A virtual link is mapped to a non-empty set of lightpaths
  - Each lightpath is assigned a transmission configuration and required spectrum
  - Spectrum contiguity and continuity constraint

Achieving a Fully-Flexible Virtual Network Embedding in Elastic Optical Networks
Related work and contribution

- [1] studied route, spectrum, and modulation level assignment with demand splitting

- We allow virtual link to be mapped over multiple spectrum segments on the same path

- We consider full fledged VN as opposed to demands

Proposed solutions

- VNE problem is NP-hard in general
  - Node and link mapping are difficult even when solved independently

- A path based ILP formulation to optimally solve the VNE over EON problem inspired by the formulation of [1]
  - k-shortest paths between pairs of physical nodes are precomputed and given as input
  - ILP formulation can find solutions for small problem instances

- A heuristic algorithm to scale to large problem instances
  - A DP based optimal algorithm to solve for a single virtual link

ILP formulation

- **Objectives**
  - Minimize total spectrum resource allocation for a VN (Primary)
  - Minimize total number of splits for all the virtual links of a VN (Secondary)

- **Link mapping constraints:**
  - The number of splits for a virtual link does not exceed an upper limit, q
  - The slices assigned to each split are adjacent to each other
  - One slice on a link can be allocated to only one lightpath
  - Cannot allocate more than the available number of slices on a link

- **Node mapping constraints**
  - A physical node can host at most one virtual node of a VN
  - A virtual node is mapped to at most one physical node satisfying location constraint

- **Coordination between link and node mapping**
  - A non-linear constraint that we linearize
Solves the link mapping problem for a single virtual link with given mappings of the two virtual nodes of the link

- Path selection
- Transmission configuration selection
- Spectrum slice allocation

A path, a transmission configuration, and a slice allocation can appear more than once in a solution

- $\langle P_1, P_1, P_3, P_3 \rangle, \langle T_1, T_2, T_2, T_3 \rangle, \langle S_2, S_4, S_3, S_4 \rangle$

Each of them is a multi-set which further increases complexity
Algorithm for single virtual link

A set of shortest paths, $A$ and a set of data rates, $D$ for virtual link $E$

Generate the set of all multi-sets, $M$ from $A$ with cardinality 1 to $q$

There is an unexplored multi-set $P$ in $M$

Yes

Generate all multi-sets from $D$ with cardinality of $P$ and sum of data rates equals to demand of $E$

No

There is a multi-set of data rates, $R$ not used in $P$

Yes

Generate all permutations, $W$ of $R$

No

There is a permutation, $J$ in $W$ not used in $P$

Yes

$<T, S> = DP(P, J)$

No

Return $<P, T, S>$ minimizing spectrum

P and J

No

If $F[P, J]$ is empty

Yes

If cardinality of $P$ is 1

No

$i = 1$

Yes

$<T[i], S[i]> = DP(P[i], J[i])$

$i = i + 1$

If $i >$ cardinality of $P$

No

Yes

Find Traffic table and Slice Free

Yes

If all $P[i]$ are disjoint

No

If $n >$ best solution

Yes

Generate all permutations $W$ of the paths in $P$

No

There is a permutation, $Y$ in $W$

Yes

Update slice assignment $S$ using $T[i]$ and First-Fit to each path in the order of paths in $Y$

Yes

Valid slice assignment $S$ found

No

Store and Return $F[P, J] = <T, S>$

Store and Return $F[P, J] = <T, S>$

Return $F[P, J]$
Heuristic algorithm for a VN

- The DP based algorithm solves the problem for a virtual link
  - How to extend it for VNs with more than one virtual link?

- Let’s assume, a VN has $E$ virtual links
  - An optimal solution requires to explore $E!$ possible ordering
  - Computationally intractable for large VNs

- Our heuristic algorithm explores one of $E!$ orderings chosen according to a criteria (e.g., decreasing order of demand)
  - Apply look-ahead techniques so that selecting a solution for one virtual link does not block the spectrum for remaining links
Running time analysis

invokes Algorithm 2 \(\frac{c}{(|D_{P_k}^e| + q - 1)!} \times \frac{(|D_{P_k}^e| - 1)! \times \prod_{d_j \in D_{P_k}^e} m_4(d_j)!}{q! \prod_{p_j \in P_k^e} m_1(p_j)!}\) times to compute \(n(P_k^e)\). The most expensive step of Algorithm 2 is the exploration of all the permutations of the paths in \(P_k^e\) requiring \(q!\) possibilities in the worst case. Therefore, to find \(A_e\), Algorithm 1 enumerates \(\left(\sum_{i=1}^{q} \binom{k + i - 1}{i}\right) \times \frac{(|D_{P_k}^e| + q - 1)!}{(|D_{P_k}^e| - 1)! \times \prod_{d_j \in D_{P_k}^e} m_4(d_j)!} \times \frac{q!}{\prod_{p_j \in P_k^e} m_1(p_j)!}\) possibilities. Typical values of \(k\) and \(q\) are small, therefore, the running time is dominated by the size of \(D_{P_k}^e\).
Evaluation – compared approaches

- key questions
  - How jointly considering all the flexible transmission parameters impact VNE?
  - What is the gain of incrementally introducing flexibility?

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
<th>Fixed FEC</th>
<th>Variable FEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Modulation</td>
<td>Variable Modulation</td>
<td>Fixed Modulation</td>
</tr>
<tr>
<td>Fixed grid</td>
<td>Fixed-fixmod-fixfec (FM-FF)</td>
<td>Fixged-varmod-fixfec (VM-FF)</td>
</tr>
<tr>
<td>Flex grid</td>
<td>Flex-fixmod-fixfec (FM-FF)</td>
<td>Flex-varmod-fixfec (VM-FF)</td>
</tr>
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</table>
Evaluation – simulation settings

- Small scale
  - EON: Nobel Germany (17 nodes, 26 links)\(^1\)
  
  - Number of spectrum grids/slices per physical link
    - Flex grid: 48 slices of 12.5GHz
    - Fixed grid: 12 grids of 50GHz
  
  - VNs are generated synthetically
    - 8 virtual nodes with varying number of virtual links
    - Node mapping is given

\(^1\) http://sndlib.zib.de/
Evaluation – simulation settings

- Large scale
  - EON: Germany50 network (50 nodes, 88 links)\(^1\)
  - Number of spectrum grids/slices per physical link
    - Flex grid: 320 slices of 12.5GHz
    - Fixed grid: 80 grids of 50GHz
  - VNs are generated synthetically
    - 50 virtual nodes with varying number of virtual links
    - Node mapping is given

1. http://sndlib.zib.de/
Evaluation – spectrum saving gain

Up to 60% spectrum saving
Evaluation – impact of varying $q$
Evaluation – impact of variable node mapping
Evaluation – running time
Evaluation – optimality of the heuristic
Evaluation – large scale results

[Bar charts showing the percentage of spectrum usage for different scenarios: Fixed-FM-FF, Fixed-VM-FF, Fixed-FM-VF, Fixed-VM-VF, Flex-FM-FF, Flex-VM-FF, Flex-FM-VF, Flex-VM-VF. The x-axis represents VN LNR (Virtual Network Load Ratio) ranging from 1 to 3.]
Evaluation – large scale running time

![Graph showing execution time vs VN LNR for different network embedding strategies: Fixed-FM-FF, Flex-FM-FF, Fixed-FM-VF, Flex-FM-VF, Fixed-VM-FF, Flex-VM-FF, Fixed-VM-VF, Flex-VM-VF.](image)
Conclusion and future work

- We study the VNE over EON problem with full flexibility of all transmission parameters of an EON
  - An ILP based optimization model
  - A heuristic algorithm that obtains near optimal solutions while executing several orders of magnitude faster than ILP
  - Saves up to 60% spectrum compared to VNE with no flexibility

- What’s next?
  - Extend the heuristic algorithm to compute node mappings
  - Analyze the performance of the heuristic
  - Explore alternate objective functions (e.g., load balancing)
Thank you