Modeling and Optimization of Virtual Networks in Multi-AS Environment

Yong Xue, Alexander Brodsky and Daniel Menasce
George Mason University, Fairfax, Virginia, U.S.A.

Keywords: Internet Architecture, Virtual Network Optimization, Virtual Network Synthesis (VNS), Virtual Network Embedding (VNE), Multi-Domain VNE, Heuristic Approximation Algorithm.

Abstract: An evolutionary approach to the Internet Ossification problem is to adopt a pluralistic architectural paradigm by leveraging the existing Internet infrastructure and developing multiple virtual service networks on top of it to satisfy diverse and ever-demanding new service and application requirements from end users. However, optimal provisioning or mapping of virtual network requests (VNR) to shared underlay network resources across multiple autonomous network systems (i.e., Multi-AS) is still an open problem. This paper investigates issues related to the multi-domain virtual network embedding (MD-VNE) problems and proposes a novel Multi-AS Virtual Network Synthesis (VNS) paradigm that closely mimics real-world network settings. Proposed in this paper is a model-based approach to optimally solving the VNS problem through formal Multi-AS network modeling and optimization using Integer Linear Programming (ILP) with defined optimal objectives for deriving exact optimal solution. Besides, the paper also proposes a simple greedy-heuristic (GH) approximation algorithm to the optimization solution to address implementation complexity concerns. The experiment and evaluation results of the exact optimization solution and the approximation solution are presented and compared based on a number of defined evaluation metrics.

1 INTRODUCTION

Internet backbone consists of hundreds of interconnected independent networks known as autonomous systems (AS), each of which is under the control of a single technical and administrative authority from governance, routing and network management perspectives. Internet Service Provider (ISP) networks are an example of AS. The current Internet offers only best effort services and has been greatly challenged by the ever-increasing needs of emerging functions and performance capabilities to meet diverse user service and applications requirements. Due to the nature of sheer size and scale of the current Internet infrastructure and enormous investments made so far by ISPs, networking equipment vendors, and enterprise users alike, any future Internet architecture development that requires disruptive or revolutionary changes becomes extremely difficult, thus so called Internet Ossification problem (Anderson, 2005).

An evolutionary approach to the above Internet architecture dilemma is to leverage the existing Internet infrastructure and develop multiple virtual service networks on top of it to meet new network service needs, which meanwhile will also allow for different Internet architectures to be experimented and validated in an operational network environment. This pluralistic paradigm of Internet infrastructure has been widely embraced by both academia and industry communities to become a de facto choice for the next generation Internet architecture as discussed in papers (Chowdhury, 2010), (Anderson, 2005), (Duan, 2012) and (Duan, 2020). However, optimal provisioning or mapping of virtual network requests (VNR) to shared underlay network resources across multiple autonomous network systems is still an open problem.

A virtual network (VN) is a logical network designed as an overlay on top of the existing physical networks by leveraging the ritualized network link and node resources using network virtualization technologies. Network Virtualization (NV) provides an environment in which multiple logically separated virtual networks can be developed and deployed on a shared physical network infrastructure. An Overlay Service Network (OSN) is a virtual network that provides specific network services with Quality of Service (QoS) guarantee, such as Video Streaming Network, High Resiliency Network, Virtual Private Network (VPN) and software defined

Xue, Y., Brodsky, A. and Menasce, D.
Modeling and Optimization of Virtual Networks in Multi-AS Environment.
DOI: 10.5220/0011799000003396
In *Proceedings of the 12th International Conference on Operations Research and Enterprise Systems (ICORES 2023)*, pages 211-220
ISBN: 978-989-758-627-9; ISSN: 2184-4372

Wide-Area networks (SD-WAN), by leveraging the network resources in the underlay network and providing required resource and traffic control and management functions to meet the specified set of service and QoS requirements to its end users (Chowdhury, 2010), (Song, 2012), (Sitaraman 2014) and (Yang 2019). Note that modern IP-based Internet infrastructure has gone beyond terrestrial networks to encompass 5G mobile networks and high-speed SATCOM networks, which significantly extend the global reachability of the Internet with diverse network infrastructures and provides more opportunities for OSN development.

A VN can be realized using specific set of node and link resources explicitly made available by the underlay network infrastructure providers. The problem of mapping the nodes and links of a virtual network topologically to a given set of underlay network resources in an optimal way is called Virtual Network Embedding (VNE) problem (Fischer, 2013). When the underlay network is composed of multiple network domains, we call it multi-domain VNE (MD-VNE). The mapping optimization can involve multiple metrics and parameters such as QoS parameters, network cost, and network performance measures. Solutions to the VNE problems provide techniques for provisioning the virtual networks (VN) by allocating proper network resources in the underlay networks to meet VN's topology and capacity requirements. Figure 1 below illustrates the concept of mapping two virtual networks (VNET1 and VNET2) to a shared network topology from two infrastructure network providers (AS1 and AS2). For example, VNET1 can be instantiated using physical node and link resources by one provider (AS1) based on network topology and capacity constraints, while VNET2 needs resources from both AS networks (AS1 and AS2) for the mapping.

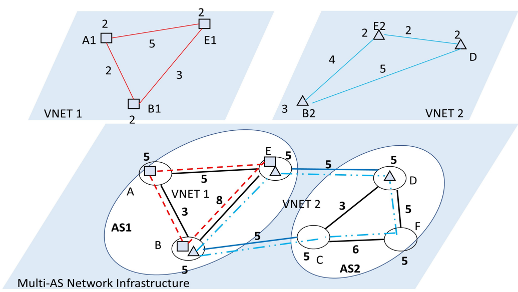

Figure 1: Multi-AS VNE Illustration.

The VNE problem requires full knowledge of underlay network topology and capacity, which is relatively straightforward in single domain environment. But the problem becomes much more challenging in a multi-AS environment due to the autonomous nature of the Internet and its distributed control and management model. Inter-AS VNE poses some special challenges in terms of resource dissemination and discovery, as well as resource allocation and network mapping. The autonomous characteristics of the multi-AS is manifested in the following adverse ways:

1. There is no visibility between adjacent AS networks because each AS, like an Internet Service Provider (ISP), normally will not reveal its internal network resources and topology information to any outside entities due to business competition. Without full-knowledge of all the underlay networks, it is hard to engineer a cross-AS virtual service network optimally.
2. There is a lack of shared control and management between adjacent AS networks, thus making it hard to provision and optimize the network resource allocation and utilization for Multi-AS VN on a global basis to meet the end-to-end cost or performance requirement.

Most existing MD-VNE solutions are top-down and faced with challenges in two fronts: 1) how to decompose a VNR into smaller VN requests to map to different underlay network domains and combine the mapped solutions thereafter; 2) how to gain full topology and resource knowledge of all network domains in a easy and salable. Note that the complexity of the current approaches can be significantly reduced if the problem is paraphrased in a bottom-up way in terms of network synthesis from a network resource pool from multiple ISPs using a distributed management and centralized control resource dissemination and management paradigm following a common network abstraction approach.

This paper proposes a model-based approach to the formal modeling and optimization of the Multi-AS VNS problem. The contributions of this research paper include the following: 1) we first developed the concept of virtual network synthesis (VNS) to simplify solving virtual network mapping problem in Multi-AS environment and proposed a dynamical resource discovery and dissemination paradigm for Multi-AS VN provisioning problem; 2) we then developed a formal network model for a gateway-based virtual network provisioning reference model in solving the Multi-AS VNS problem and formally formulate the Multi-AS VNS problem to an ILP optimization problem using a cost utility objective function, and two QoS parameters constraints: capacity and end-to-end delay; 3) finally we developed a simple greedy heuristic (GH) approximation algorithm to the Multi-AS VNS optimization problem to show a approximation method to the Multi-AS VNS optimization and conducted experimental evaluation to compare the performance of the ILP-based exact solution and GH algorithm-based approximate solution.

The rest of the paper is organized as follows. Section II provides a brief review of some related researches. After that, the paper describes the formal models and the proposed resource dissemination framework for the Multi-AS VNS problem in Section III. The formulation of the formal Mutli-AS VNS optimization problem is described in Section IV. Then Section V describes a simple GH approximation algorithm to the optimization method. Finally, in Section VI, we describe the experiment and performance evaluation results of the ILP optimization and the GH approximation algorithm. Section VII provides a brief summary of the research results and identify some potential future works.

2 RELATED WORK

VN Embedding (VNE) problems have been extensively studied in the research community and there are many different techniques, mostly based on optimization theory for solving this problem as summarized in several comprehensive survey papers, including those by (Belbekkouche, 2012), (Fischer , 2013) and (Cao, 2019). The optimization objective can be based various business or technical metrics including cost, revenue and profit, QoS, reliability and availability. The majority of the VNE research results are limited to single domain and VNE across multiple substrate network domain has gained more attention for the past decade or so in both industry and academic communities as industry has been trying to develop new networking capabilities across Internet to meet ever demanding service needs.

The solutions to the MD-VNE problem mostly use top-down approach and are explored under different restrictive assumptions as discussed in (Houidi, 2011), (Hong, 2014) and (Yang, 2019). Resource discovery and dissemination across multiple domain have been recognized as a core challenge to any practical solution for the MD-VNE problem as discussed in (Belbekkouche, 2012), (Dietrich, 2013) and (Figueria, 2015). Some examples of the proposed approaches include the policy-based framework for multi-domain VNE by (Samuel, 2013), recursive hierarchical embedding by Vaishnavi (2015), integrated approach across network and clouds in (Sonkoly, 2015), multi-domain connection stitching in (Li, 2016) and PSO meta-heuristic approach in (Hou, 2020). Note that, all the mentioned works to some degree demonstrate some ideas to address part of the gaps in the MD-VNE problems under some restrictive conditions, but they all fall short of being a complete and practical solution to the MD-VNE problem in real-world multi-AS environment.

3 NETWORK MODELS AND RESOURCE MANAGEMENT

To facilitate the development of solutions to the multi-AS VNS problem, we adopted a common layered network and service model (Fischer, 2013) and developed a robust Multi-AS VNS network reference as discussed below.

3.1 Multi-AS VNS Network Modeling

A 3-tier network and service model based on the concepts of service providers, virtual network providers and infrastructure providers as in Figure 2 can be used to model networks and services for the multi-AS VNS problem. A brief account of each layer of the network providers and their roles are as follows:

1. Service Providers (SP): A SP at top wants to build a service-specific virtual network (VN) meeting its topological, performance, budget, and QoS requirements. The SP normally submits a virtual network request (VNR) to its serving virtual network provider (VNP) for the required virtual network (VN).
2. Infrastructure Network Providers (InP): InPs at the bottom are network infrastructure service providers that can provide point-to-point network services to the VNP in the form of network segments or virtual circuits between their edge service access points. There can be zero, one or more segments between a pair of access points offered by a given InP depending upon their service offering and available resource at a given time. Associated with each segment are end points, costs, capacity and QoS parameter bonded by a service level agreement (SLA).
3. Virtual Network Provider (VNP): The VNP in the middle deploys its service gateways at locations where the VN services are expected and build needed local connections to all or a subset of InPs that are within proximity of its VNP gateways. VNP will utilize the gateways and network resource pools provided by the underlay InPs to instantiate the VNR.

Note that a VNP determines a set of strategic network hub locations to deploy virtual network gateways that are physically connected to a set of InPs

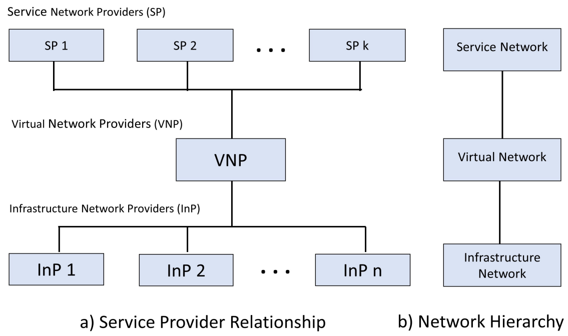

Figure 2: Tiered Network Model for Multi-AS VNS.

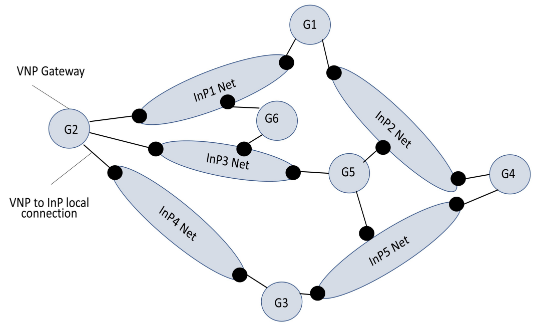

Figure 3: Multi-AS VNS Network Reference Model.

within its geographic proximity. Then the VNP will utilize the network segments between the gateway nodes to synthesize a virtual network based on VNR from SP.

Formal modeling of Multi-AS VNS optimization problem involves two level of models: 1) formal representation of networks and 2) a logical reference model for Multi-AS InP networks interconnected by VNP gateways. We formally model a network using a property graph model called an Attributed Relational Graph (ARG) that is extremely powerful in modeling networks for which its nodes and links have associated properties. Specifically, a network G can be defined by a 4-tuple $G = (N, L, A, B)$ where
$N = \{n_1, n_2, \cdots, n_m\}$ is a finite set of m nodes,
$L = \{l_{ij} | l_{ij} =< n_i, n_j > \wedge i, j = 1, 2, \cdots, n\} \subseteq N \times N$, is a set of links of the network.
$A = \{a_1, a_2, \cdots, a_k\}$ and $B = \{b_1, b_2, \cdots, b_l\}$ each is a set of defined attributes for nodes and links respectively.

We use $G^V = \left(N^V, L^V, A^V, B^V\right)$ to represent a VN in SP's VNR and $G^S = \left(N^S, L^S, A^S, B^S\right)$ to represent the combined substrate InP networks plus VNP gateway nodes as illustrated in Figure 5. Besides, the network attributes include node/link capacity (NCap/LCap), Cost and delay (D).

For formulating the Multi-AS VNS optimization problem we developed a logical network reference model shown in Figure 3, characterizing the substrate network environment in the Multi-AS problem. Note that the substrate network nodes are VNP gateways and gateway-to-gateway connections consisting of two gateway-InP connections plus one or more segments InP network in between. Together they form the network resources pool for the VNP controller to use to synthesize the VN from SP.

3.2 Resource Management

A practical Multi-AS VNS solution depends on the capability to dynamically update the network resource pool available to the VNP per contract between VNP and the InPs. This paper proposes a resource discovery and management framework in which distributed control and dissemination of network resources from InPs to VNP and central management of the resources by VNP for network resource allocation and synthesis. As shown in Figure 4, each InP has a local resource manager (LRM) responsible for available dissemination and VNP has a global resource manager (GRM) responsible for managing and allocating all the network resources provided by InP. The GRM notifies LRMs of use of a specific network segments in its VNS decision. Note that, this framework for resource management can be implemented using different technologies and methods, for example Open API for data federation.

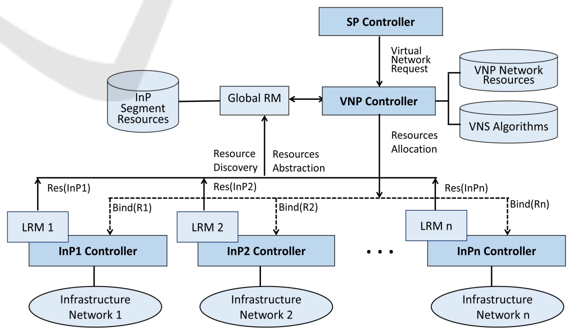

Figure 4: Multi-AS VNS Resource Management Framework.

4 VNS OPTIMIZATION

In this section, we develop a formal ILP optimization formulation for the Multi-AS VNS problem.

Table 1: Notation Description.

Notation	Description
n_i , n_j	virtual network nodes of SP
l_{ij}	virtual link between VN nodes n_i and n_j
g_k , g_l	network gateway nodes of VNP's substrate network
N_I	number of infrastructure providers InPs
L_{ku}	gateway link from gateway node g_k to InP_u
s_{klmu}	path segment m of InP_u between gateway nodes g_k and g_l
h_{klmu}	link between gateway nodes g_k and g_l via path segment s_{klmu}
S_{klu}	set of segments between gateways g_k and g_l in InP_u
β_{ku}	unit link cost for connecting gateway g_k to InP_u
α_i	unit node capacity cost for the gateway g_i
$\lvert N^V \rvert, \lvert L^V \rvert$	the number of nodes and links in the requested virtual network from SP
$\lvert N^S \rvert, \lvert L^S \rvert$	the number of nodes and links in the substrate networks formed by VNP and InP
P^S_{kl}	set of all paths between gateway nodes g_k and g_l across all InP network topology
p^S_{kln}	nth path in set P^S_{kl} between VNP nodes g_k and g_l
p^{ij}_{kl}	a mapped path in P^S_{kl} for VN link l_{ij} determined by VNP's path selection policy
C_{max}	cost budget of a virtual network request (VNR)
D_{max}	maximum delay allowed between any node pair of a virtual network request
f_{ku}	A binary parameter indicating if gateway g_k is connected to InP_u
Z_{klmu}	A binary parameter indicating if the g_k and g_l are connected via path segment s_{klmu} and gateway links
X_{ik}	A binary parameter indicating if the n_i and g_k are co-located
x_{ik}	A decision binary variable indicating if the virtual gateway node g_k is selected to host SP node n_i
z^{ij}_{klmu}	A decision binary variable indicating if a gateway hop link h_{klmu} is on the mapped path of VN link l_{ij}

4.1 Notations and VNS Mapping

Intuitively, our Multi-AS VNS problem is for VNP to find an optimal mapping between the VN and the substrate network resources such that the each node in VN is instantiated as a virtual node (in virtual machine) in a VNP gateway (node level mapping) and for each link in VN the VNS algorithm will map it to a path consisting of sequence of instantiating gateway nodes and InP segments. The objective is to minimize he total cost of the mapped virtual network that meet all the capacity, end-to-end delay and total cost constraints. Note that the VN network costs depends on the aggregated costs of the mapped gateway VMs and InP segments in the substrate network layer. The formula and equations in this section describes the mathematical formulation of the Multi-AS problem as an integer programming (ILP) problem. Figure 5 below illustrate the mapping concepts from VN to the InP segment resources and VNP gateways. Notations and variables used are defined and described in Table 1.

4.2 Optimization Formulation

In our ILP optimization formulation, the VNR's topology, node/link capacities as well as link delays are specified and provided by SP to the VNP. The goal is to select a set of gateways and path segments that

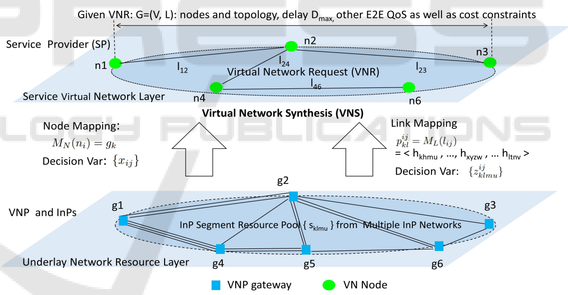

Figure 5: Multi-AS VNS Optimization Optimization.

result in a lowest cost network that satisfies the end-to-end packet delay, node/link capacity constraints and total network cost budget requirements. Figure 6 and the following equations formally define the cost, delay and capacity of the mapped path. For each VN link l_{ij}, the mapped path capacity and cost for p^{ij}_{kl} can be calculated below:

$$LCap(p^{ij}_{kl}) = min_{s \in p^{ij}_{kl}} LCap(s)$$

$$Cost(p^{ij}_{kl}) = \sum_{s \in p^{ij}_{kl}} Cost(s)$$

where $M_N(n_i) = g_k$ and $M_N(n_j) = g_l$

Input: Virtual network G^V designed by SP, Network cost budget C_{max}, and end-to-end network delay

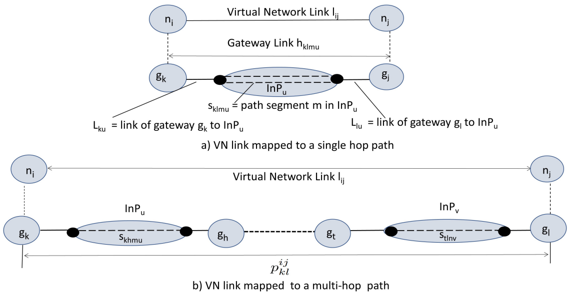

Figure 6: Multi-AS VNS Optimization Mapping.

bound

$$D_{max} = \min_{l_{ij} \in L^V, 1 \leq i < j \leq |N^V|} D(l_{ij})$$

Objective Function:

$$\textbf{Minimize } Cost(G^V) = \sum_{i=1}^{|N^V|} \sum_{k=1}^{|N^S|} K_i \alpha_k x_{ik} +$$

$$\sum_{i=1}^{|N^V|} \sum_{j<i}^{|N^V|} \sum_{k,l=1}^{|N^S|} \sum_{u=1}^{N_I} \sum_{m=1}^{|S_{klu}|} (\beta_{ku} + \beta_{lu} + Cost(s_{klmu})) z_{klmu}^{ij}$$

where $K_i = \text{NCap}(n_i)$ for $1 \leq i \leq |N^V|$

Subject to the Following Constraints:

1) Auxiliary Variables:

Z_{klmu} determines if direct connections exist between gateway nodes g_k and g_l

$$Z_{klmu} = f_{ku} f_{lu} s_{klmu} \tag{1}$$

for $1 \leq k,l \leq |N^S|$ and $1 \leq u \leq |N_I|$ and $1 \leq m \leq |S_{klu}|$

X_{ik} determines if node n_i and gateway g_k are co-located.

$$X_{ik} = 1 \text{ if } Loc(n_i) = Loc(g_k) \tag{2}$$

for $1 \leq i \leq |N^V|$ and $1 \leq k \leq |N^S|$

2) Each virtual SP node is matched to only one gateway node and each gateway node is matched to no more than one SP node.

$$\sum_{k=1}^{|N^S|} X_{ik} x_{ik} = 1 \tag{3}$$

$$\sum_{i=1}^{|N^V|} X_{ik} x_{ik} \leq 1 \tag{4}$$

(5)

for $1 \leq i \leq |N^V|$ and $1 \leq k \leq |N^S|$

3) Node and link capacity

$$(NCap(g_k) - NCap(n_i))\, x_{ik} \geq 0 \tag{6}$$

for $1 \leq i \leq |N^V|$ and $1 \leq k \leq |N^S|$

In addition, for $k,l = 1,2,\cdots,|N^S|$ and $u = 1,2,\cdots,N_I$ and $m = 1,2,\cdots,|S_{klu}|$

$$(LCap(L_{ku}) - LCap(s_{klmu}))\, Z_{klmu} \geq 0 \tag{7}$$

$$(LCap(L_{lu}) - LCap(s_{klmu}))\, Z_{klmu} \geq 0 \tag{8}$$

Then, for each gateway hop link s_{klmu}

$$\sum_{l_{ij} \in L^V} LCap(l_{ij}) z_{klmu}^{ij} \leq LCap(s_{klmu}) \tag{9}$$

4) The path preservation rules constrain the substrate network level routing for mapped path of $M_L(l_{ij})$ from the gateway node g_k to g_l. For $k \neq l$ and for $u = 1,2,\cdots,N_I$ and $m = 1,2,\cdots,|S_{klu}|$ we should have:

A. For given $l_{ij} \in L^V$ and mapped g_k and $g_l \in N^S$. There should be exact one segment starting at g_k and one ending at g_l. i.e. :

$$\sum_{h=1}^{|N^S|} \sum_{u=1}^{N_I} \sum_{m=1}^{|S_{klu}|} z_{khmu}^{ij} = 1 \tag{10}$$

$$\sum_{h=1}^{|N^S|} \sum_{u=1}^{N_I} \sum_{m=1}^{|S_{klu}|} z_{hlmu}^{ij} = 1 \tag{11}$$

B. For all intermediate gateway nodes on the path, the total number of segments coming in should equal to total number of segments coming out:

$$\sum_{h=1}^{|N^S|} \sum_{u=1}^{N_I} \sum_{m=1}^{|S_{klu}|} z_{htmu}^{ij} = \sum_{h=1}^{|N^S|} \sum_{v=1}^{N_I} \sum_{n=1}^{|S_{klu}|} z_{thnv}^{ij} \text{ for } t \neq k,l \tag{12}$$

C. For given $l_{ij} \in L^V$ and mapped g_k and $g_l \in N^S$ There should be no more than one segment used on intermediate gateway link s_{thmu} for $t \neq k, h \neq l$, i.e. :

$$\sum_{m=1}^{|S_{klu}|} z_{thmu}^{ij} \leq 1 \tag{13}$$

5) Each VN link should be mapped to a path with delay no more than the given network delay bound D_{max}, i.e.,for a mapping of $l_{ij} \in L^V$ onto the mapped path p_{kl}^{ij}

$$D(p_{kl}^{ij}) = \sum_{h_{xymu} \in p_{kl}^{ij}} (D(L_{xu}) + D(s_{xymu}) + D(L_{yu})) \leq D_{Max} \tag{14}$$

6) Variable domain constraints

$$x_{ij} \in \{0,1\} \tag{15}$$

where $i = 1,2,\cdots,|N^V|$ and $j = 1,2,\cdots,|N^S|$

$$z_{klmu}^{ij} \in \{0,1\} \tag{16}$$

where $i,j = 1,2,\cdots,|N^V|$ and $k,l = 1,2,\cdots,|N^S|, u = 1,2,\cdots,N_I$ and $m = 1,2,\cdots,|S_{klu}|$

7) Network cost constraint: total VN costs should be no more than the cost budget

$$Cost(G^V) \leq C_{max} \tag{17}$$

Decision Variables:
$\{x_{ij}\}$ and $\{z_{klmu}^{ij}\}$

5 A VNS APPROXIMATION ALGORITHM

Solving the Multi-AS VNS ILP optimization problem is expected to incur high computing costs or possibly become NP-hard because its combinatorial nature, which means the solution may not be tractable or calculated efficiently when the size of the problem is large. A viable approach to addressing this complexity is to find an approximate algorithm to the exact optimization solution. The goal is to develop a heuristic algorithm that can yield a good-enough solution close to the exact solution but with significantly lower computational cost.

This section describes an approximation algorithm using simple greedy heuristic (GH). A heuristic is a problem-domain specific knowledge that can be used to facilitate a quick and "optimal" solution development. The greedy heuristic approximation algorithm trades optimality and solvability of the problem (if an optimal solution exists) for lower computing cost (time). We assume the VN node mapping to gateway node is already determined based on the location constraint which is normally a easy step for our VNS problem.

Below is the pseudo code of our GH-based approximation algorithm that finds an approximation solution to the Multi-AS VNS optimization problem.

Greedy Heuristics (GH) Algorithm:

```
procedure GH_VNS (vnr)
  L = LinkSort (vnr) as input link list
  solution = {}
  while not NotEmpty (L) do
    l = SelectNextBestLink (L)
    map l to next feasible kth-shortest path
    if SatisfyConstraints(solution, l) then
      solution = solution U {l}
    endif
  endwhile
  return solution
end
```

Heuristics used include:

- Mapping each VN link to the lowest possible cost path between two mapped gateway nodes first tend to yield lower mapping cost for each link, thus better total cost across all the VN links.
- Map each link in VN in descending capacity order tends to generate the closest solution to the optimal one and reduce blocking probability across all the VN links.

Some of the implementation strategies and observations are in order below:

1. To save time, we pre-calculate all K-shortest paths (select K=2 or 3) between gateway nodes using segment resources across all InPs.
2. A solvable problem using optimization approach can fail to produce an approximate solution due to blocking in the GH algorithm.
3. Different sequence of VN links input could yield different blocking behavior (which one is blocked and how many), thus can lead to different approximate solutions, particularly for larger size VNS problem.

6 EXPERIMENT AND RESULTS

This section briefly describes our experiments with generating exact solution of the VNS problem using ILP and approximate solution using greedy heuristics (GH) algorithm.

6.1 Experiment Setting and Evaluation Methods

The experimental testbed uses the following hardware and software: 1) Hardware: A HP laptop with Intel Core i7 CPU, and 16 G RAM, running Window 10; 2) Software: Python 3.1 package and AMPL optimization tool and CPLEX solver are utilized.

The primary objective of the experiment is to evaluate and compare the performance of the VNS exact optimal solution and approximate solutions in terms of run-time and network cost produced by the VNS ILP optimization and approximate GH algorithm. We define the following two basic metrics plus two derived metrics for quantitative performance analysis.

1. Run time denoted by $T(alg)$: The time in seconds taken to calculate an exact or approximate solutions by the optimization or approximation algorithms,
2. Cost denoted by $C(alg)$: The total cost of the exact or approximate solutions by the optimization or approximation algorithms.

Other than these two basic metrics, we define two derived metrics to assist in the quantitative analysis. The following normalized metrics are defined where A_{opt} represents the optimization algorithm and A_{apr} represents approximation algorithm.

1. Approximation Error Rate (AER): Measure how close the cost of the solution generated by approximation algorithm is to the cost of the optimal solution.

$$AER(A_{apr}) = \frac{(C(A_{apr}) - C(A_{opt}))}{C(A_{opt})}$$

   Since $C(A_{opt})$ is always less than or equal to $C(A_{apr})$, we have $AER(A_{apr}) \geq 0$ and a larger value means a worse performance.

2. Speed-Up Factor (SF): The ratio between the time taken by optimal algorithm over the time taken by the approximate algorithm.

$$SF(A_{apr}) = \frac{T(A_{opt})}{T(A_{apr})}$$

   Since $T(A_{opt})$ is normally greater than or equal to $T(A_{apr})$, we have $SF(A_{apr}) \geq 1$ and a larger value means a better performance. This is speed up for an approximation algorithm in reference to the optimal algorithm.

6.2 Experiment Data Set

To evaluate our Multi-AS VNS algorithms, a pair of input data of SP VNR and InP networks interconnected the VNP gateways are required to run the algorithm, whether it's optimization algorithm or approximation algorithm.

The test data for each algorithm run requires the following:

1. SP network: The VNR network is specified by SP in terms of network topology, node capacity, and link QoS parameters including capacity and delay.
2. VNP network: The set of the VNP gateway nodes and associated links to the InP edge nodes within a given proximity. The links assume enough capacity.
3. InP network resource pool: The set of path segments provided by a set of InP network. Each segment includes capacity, cost and delay values.

A sample SP VNR network and InP network with aggregated path segments from multiple InPs are shown below in Figures 7 and 8.

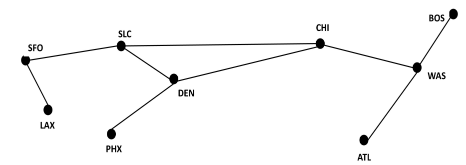

Figure 7: A Sample VNR Network Topology.

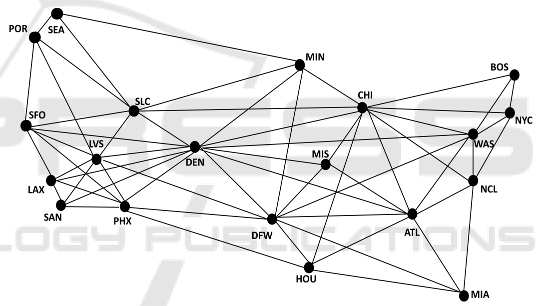

Figure 8: A Sample InP Network Topology.

The experiments use real-world like synthetic data generated using following rules:

- The test VNR network and InP network topology are from a fixed set of defined VNR and InP network topology as a base network data set, namely the building blocks.
- From the base set of the base set of the VNR and InP networks , we can combine a subset of networks from the base to generate a large number of VNR and InP test networks with with varying topological complexity and sizes.
- For this experiment, 1000 compatible VNR-InP network pair data set (i.e., matching at the node level) are generated as the population and we randomly select 50 of them as sample for the experimental evaluation.
- Each test run is for the optimization algorithm and the GH approximation algorithm to run on a select VNR-InP input data pair.

6.3 Experiment Results and Analysis

This section presents analysis results in the context of two questions we are trying to answer:

1. How does the GH approximation algorithm perform compared to the optimization algorithm in terms of basic performance metrics, namely run time and cost of the VNS algorithms for a given VNR run.
2. How well does the GH approximation algorithm perform in terms of decrease in run-time (i.e.,speed gain) vs. increase in cost of the solution (i.e., loss in optimality) for each VNR run.

The following line charts in Figures 9,10,11 and 12 show the performance comparison between the ILP based optimal algorithm and GH approximation algorithms across all the test data based on two basic metrics and two derived metrics defined in section 6.1.

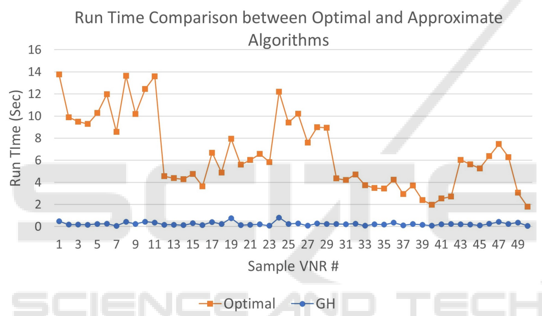

Figure 9: Run-time for Approximate GH Algorithm.

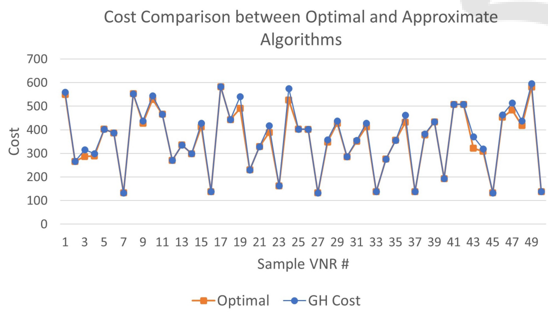

Figure 10: Cost for Approximate GH Algorithm.

From the result charts, the following observations can be made:

1. The run times for the GH approximation algorithm are fractional compared to those of the optimization algorithm for all the VNR-InP test data. It is at least one order of magnitude lower.
2. Note that the gain in speed for the approximation algorithms is at the cost of very small optimality loss for the VNS solution.

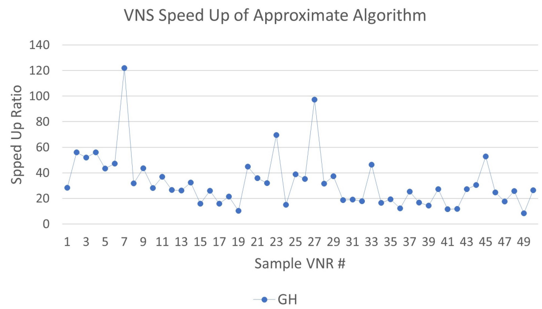

Figure 11: Speed-up for Approximate GH Algorithm.

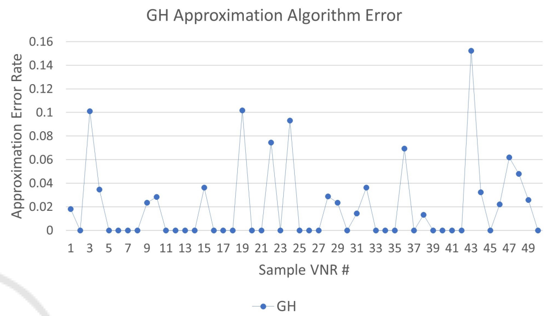

Figure 12: Error for Approximate GH Algorithm.

In summary, the GH approximation algorithm's performance seems to be pretty stable and consistent, and have a speed up of 1-2 order of magnitude compared to the optimization algorithm depending on the VNR-InP test data. However the cost increase of the GH approximate solution is practically negligible for majority of the test case. Thus GH approximation algorithm is recommended in practical system implementation.

7 CONCLUSION AND FUTURE RESEARCH

This paper addresses a challenging and open problem, called multi-AS virtual network synthesis (VNS) problem that is aimed at effectively and optimally provisioning virtual networks over shared substrate network resources across multiple ISP network infrastructure. The proposed approach is novel and tied to real-world virtual network provisioning problem across multiple ISPs, such as Over-The-Top (OTT) virtual networks, and software defined WAN (SD-WAN). The research efforts include network modeling, optimization formulation, a heuristic approximation algorithm, and the performance experiment and quantitative evaluation of the optimal and approximation algorithms based on a random set of synthetic test data. The evaluation results are promising and have demonstrated the validity and effectiveness of a GH-based approximation algorithm for practical use.

Beside the research results reported in this paper, some follow-on and extended researches can be performed, which include: 1) develop additional heuristic and meta-heuristic approximation algorithms. For example, the GRASP and ILS heuristic algorithms can be developed and evaluated; 2) Multi-objective optimization for Multi-AS VNS can be formulated to address the need to optimize generic multiple constraints and multiple objective optimization problems, e.g., combined cost and end-to-end QoS optimization.

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