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A novel paths algebra-based strategy to flexibly solve the link mapping stage of VNE problems

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ABSTRACT

One of the main challenges of network virtualization is the virtual network embedding problem (VNE) that consists of mapping virtual network demands in physical network resources. VNE can be decomposed into two stages: virtual node and virtual link mapping. In the first stage, each virtual node is mapped to a suitable node in the physical network whereas the second stage is in charge of mapping the links connecting virtual nodes to paths in the physical network that suit the virtual network demands.

In this paper we propose the utilization of a mathematical multi-constraint routing framework called "paths algebra" to solve the virtual link mapping stage. Paths algebra provides the flexibility to introduce an unlimited number of linear and non-linear constraints and metrics to the problem while finding all the eligible paths in the physical network to perform the virtual link mapping resulting in better and more flexible embeddings.

1. Introduction and problem

The deployment of new Internet services is nowadays being more and more difficult, the lack of cooperation among stakeholders does not allow radical changes to the Internet architecture (Papadimitriou et al., 2009; Anderson et al., 2005; Tutschku et al., 2009).

Network virtualization has been proposed as the building block for the future internet architecture (Feamster et al., 2007; Chowdhury and Boutaba, 2010). It allows multiple heterogeneous networks to cohabit on a shared substrate network (SN).[1] One of the main recognized challenges of network virtualization will be the efficient allocation of virtual network elements on top of SN elements, this problem is commonly known as the *virtual network embedding/mapping* (VNE) problem. It can be solved in two different stages: node and link mapping. In this paper, we tackle the virtual link mapping stage that can be seen as multiple multi-constraint routing problems.

Several implementation ways of QoS (Quality of Service) control (either by the network, directly by the application or via a mixed solution (Cui et al., 2003; Furini and Towsley, 2001; Jukan and Franzl, 2004; Quoitin et al., 2003; Su and Gellman, 2004; Xiao, 2000)) and the singular nature of each QoS parameters (availability, distance, flow, etc.) allow several network routing solutions to be proposed such as exact and approximated routing algorithms, algorithms based on backward–forward heuristics, linear composition, hybrid, random, routing computation from the origin or destination, reservation and resource allocation protocols, etc. (Bejerano et al., 2005; Fujita et al., 2001; Kuipers et al., 2002; Shen et al., 2004).

In practice however, as the multi-constraint routing is an $\mathcal{NP}$-complete problem (Mieghem and Kuipers, 2004, 2005), we verify that many of these solutions have their merits restricted to an universe whose validity is often defined either by the size of the networks or by their topology, and their intuitive portability does not work for other applications. In other words, the use of a heuristic originally designed for distance metrics such as Dijkstra does not converge with another kind of metrics such as flow (Gouda and Schneider, 2003; Lagoa et al., 2004; Miyamura et al., 2003; Pei et al., 2004; Sobrinho, 2003; Wattenhofer and Venkatachary, 2001).

Analyzing this problem under the perspective of protocols design, it has been necessary to conceive a heuristic or an algorithm to ensure the routing convergence for different types of QoS metrics or QoS metrics composition, in which this problem could be addressed from an integrated and generic manner by means of a mathematical framework which allows validating the proposed solutions independently from network topology or implementation details (Jaggard and Ramachandran, 2005).

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[1] This paper will use indifferently the terms *substrate network* and *physical network*.

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Therefore, besides establishing a homogeneous mathematical basis, the concepts of paths algebra used in this work (Herman, 2008; Herman and Amazonas, 2007) provide a guideline for developing a traffic engineering adaptive tool in which users can define their own path searching policy that can be closer to the existing traffic profile of their networks.

In addition, such mathematical framework allows for systematically comparing different mono-constraint and multi-constraint routing heuristics concerning their convergence guarantees, best path convergence and loop avoidance, and validating a generic and homogeneous solution that can be integrated into a single mathematical outline, flexible enough to be used in the validation or development of new routing protocols that can be used either inside of a single administrative domain (AS—Autonomous Systems) or across different ASs.

1.1. Network virtualization and virtual network embedding

The introduction of the Infrastructure as a Service (IaaS) paradigm (Bhardwaj et al., 2010) will change the current Infrastructure Service Providers (ISPs) based Internet business model. IaaS decouples the role of current ISPs into two new roles: the Infrastructure provider (InP) who owns, deploys and maintains the network infrastructure and the service provider (SP) responsible for deploying network protocols and offer end-to-end services. This new business model is well suited for the future dynamics in networking service requests. Customized services will be demanded by specific group of users, and provided by the SPs that will have to perform optimal allocations of them over the substrate network (SN) (composed of the networks owned by the set of InPs).

Network virtualization will be a fundamental enabler to provide end-to-end QoS guarantees in an IaaS based network architecture. It will be not just a technology to implement IaaS, but a component of the architecture itself (Feamster et al., 2007). Network virtualization basic element is the virtual network (VN). A VN is a combination of active elements called virtual nodes and passive elements called virtual links running on top of the SN. Virtual nodes are interconnected through virtual links, building a virtual topology.

One of the SP tasks is the generation of virtual network requests (VNRs), based on the analysis of the user service demands. Each VNR contains a set of demands of networking and non-networking parameters needed to provide the end-to-end QoE (Quality of Experience) required by the demanded service. After the VNR is created, an algorithm is executed to choose, over the heterogeneous resources provided by the SN, the optimal allocation of the virtual demands on top of the SN with regard to some predefined objective (VNE problem). This mapping, that defines the relationship of virtual network elements to their respective counterparts in the substrate network, can be divided into two stages. First, virtual node mapping, where each virtual node of a VNR is mapped to one substrate node with enough capacity to accomplish the virtual node resource demand. In second place, virtual link mapping, where each virtual link is mapped to a directed path in the substrate network with enough resource capacity to meet the virtual link demand. In this paper, we focus in the second stage, the virtual link mapping. Figure 1 shows the embedding of two VNR on top of one SN.

1.2. Formal VNE problem formulation

The formal description of the VNE problem is as follows. A SN is represented as a directed graph $G=(V,A)$ where vertices represent the SN nodes and arcs represent the SN links. On top of the SN, a set of virtual network requests – each described by its own digraph $G^k=(V^k,A^k)$ – are embedded by assigning a SN node for each virtual node and a SN set of paths for each virtual link.

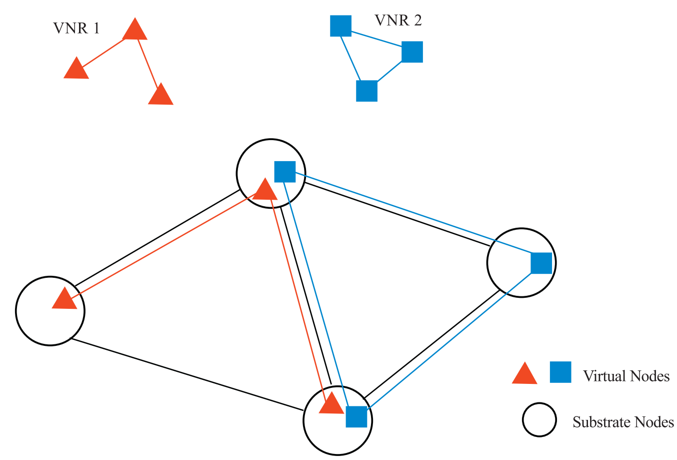

Fig. 1. Embedding of two virtual network requests.

We define a pair of functions to describe the mapping operation realized by the VNE algorithms. Node and link mapping functions. The node mapping function $X: V^k \rightarrow V$ assigns virtual nodes to substrate nodes. Likewise, the link mapping function is defined as $Y: A^k \rightarrow 2^P$ where 2^P consists of all sets of directed paths in the SN. If Y is able to assign a virtual link to a set with more than one element, the VNE problem will allow a virtual link mapping with the use of multi-path routing (i.e., one link is mapped to several SN paths). Otherwise, the result is the SN path used to allocate the virtual link. Both functions must not exceed the resources of either a node or a link in the SN. An optimal VNE is then the result of the node and link mapping functions that satisfies all the above restrictions and, additionally, reaches a given optimization objective.

To accommodate a demand between two virtual nodes inside a virtual network, in this paper, only one path is taken into account (single-path virtual link mapping). This is often a realistic restriction due to the routing protocol used, or simply because it is an explicit management requirement. However, multi-path approaches have been proposed. In Yu et al. (2008) the virtual link demand is split among the possible paths, reducing in this way the computational complexity of the problem. Although this approach is computationally better, the difficulty of its implementation in the SN is higher.

Most of the existing VNE proposals treat the single-path virtual link mapping problem as a mono-constraint problem, that is, their objective is to map the virtual link in substrate paths that minimize/maximize the usage of one resource (typically bandwidth). This paper introduces a virtual link mapping approach supporting multiple constraints thanks to the paths algebra routing framework.

1.3. Paths algebra for VNE

The virtual link mapping stage of the VNE problem may be seen as multiple multi-constraint routing problems. VNE link mapping corresponds to finding the best route(s) on the substrate network for each virtual link in the VN, where best implies the adoption of some optimization criteria.

The paths algebra is an adequate mathematical framework to explore the design space. It solves the multi-constraint problem using linear metrics as bandwidth, number of hops and delay, or non-linear metrics as availability and package loss rate. It can also use a combination of metrics as, for example, QoS taken as

$$QoS = f(THRU, PDT, PDV, PLR),$$

where:

- THRU is the throughput;
- PDT is the packet delay transfer;