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Network virtualization over WDM and flexible-grid optical networks ☆

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ABSTRACT

Network virtualization can eradicate the ossification of the Internet and stimulate innovation of new network architectures and applications. Optical networks are ideal substrates for provisioning high-bandwidth virtual-network services. In this study, we investigate the problem of network virtualization over both WDM and flexible-grid optical networks by formulating the problems as mixed integer linear programs (MILP). Two heuristics, namely *MaxMapping* and *MinMapping*, are developed for each kind of network to solve the problem quickly but suboptimally. Numerical examples show that *MinMapping* consumes fewer spectrum resources than *MaxMapping* and performs very close to the optimal results derived by the MILP in both kinds of optical networks, by exploring the opportunities of traffic grooming. Also, it is verified that flexible-grid optical networks can be more spectrum efficient than WDM networks as the substrate for network virtualization.

1. Introduction

The Internet is believed to be almost ossified [1]: today's Internet is IP-dominated, limiting innovations to simple additions (e.g., new layers, functions) to the current TCP/IP network architecture. In order to support new applications, more layers and functions are added, making the network difficult to manage and control. New applications may need totally different network architectures, and new network architectures can also stimulate the innovation of applications.

Network virtualization is a transparent abstraction of both computing and networking resources. It allows multiple virtual networks to share a single physical substrate network (Fig. 1). One virtual network is logically isolated from another and can customize its own architecture to properly support its applications, leading to heterogeneity of network architectures and technologies. Also, virtual networks can be used as testbeds for future architectures with negligible interference with the existing Internet.

A virtual network is composed of multiple virtual nodes and virtual links. Each virtual node requiring certain computing resources (e.g., CPU, storage, packet forwarding rate) is hosted on a separate substrate node (e.g., a data center or IP router). Multiple virtual nodes belonging to different virtual networks can coexist on a substrate node and share the physical resources. A virtual link is mapped to one or multiple physical paths, depending on whether traffic splitting/bifurcating is allowed by customers and supported by the infrastructure providers. Normally, certain quality of service (QoS) requirements (e.g., bandwidth, delay, availability) are imposed on each virtual link.

Network virtualization services are provided to customers (e.g., enterprises or individual users) by infrastructure providers who own computing and/or networking

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resources. Customers can establish their integrated computing and network environment without buying their own infrastructures. Also, dynamic virtualization services are promising because customers can enjoy the services as needed, which further decreases the cost and risk for customers.

Network virtualization is still in its infancy. In [1,2], the authors surveyed a wide range of recent works on network virtualization. In this section, we briefly review a few recent research works that are most related to our work. In [3], an auxiliary graph was proposed to formulate a mixed integer program (MIP), based on whose relaxation two heuristic algorithms are developed using different rounding techniques. In [4], the authors proposed a substrate network that supports path splitting (multi-path) and path migration, which achieved better resource utilization. In [5], the authors introduced the concept of optical network virtualization, but the virtual networks presented to users are still optical networks, which users may not have the expertise to operate. In contrast, we are trying to present simple computing and bandwidth resources (as virtual networks) to users. In [6], on-demand provisioning of virtual networks over a WDM substrate network was investigated, but without considering multi-hop traffic grooming and path splitting. In [7,8], another important aspect of network virtualization, namely survivability (e.g., survivability under node and link failures), was investigated.

1.1. Optical networks as substrates

Layer of virtualization refers to the layer in the network stack where virtualization is introduced. Virtualization at lower layers of the network stack provides more flexibility for virtual networks. Actually, optical networks have already been employed as the substrate for today's IP networks. A logical topology in a core network is provided by optical networks. A link viewed by IP layer is actually a circuit (e.g., a lightpath) provisioned by an optical network which may go through several fiber links and optical switches. If virtualization is realized at the optical layer, heterogeneous network architectures can be developed without interfering with today's Internet legacy: for instance, we can consider the existing Internet as a member of a collection of multiple virtual networks over optical networks.

In addition, optical networks provide huge bandwidth compared to other networking technologies and employ circuit switching which can offer better control on QoS for virtual networks. If we provision a virtual network over today's IP network, it would be difficult to guarantee certain QoS specified in the service level agreement (SLA), such as virtual link capacities and delays, because of the best-effort service provided by the IP layer.

Today, the optical spectrum of a fiber is divided using wavelength-division multiplexing (WDM) into separate channels with spectrum spacing of 50 GHz or 100 GHz, as specified by ITU-T standards (Fig. 2(a)). The optical

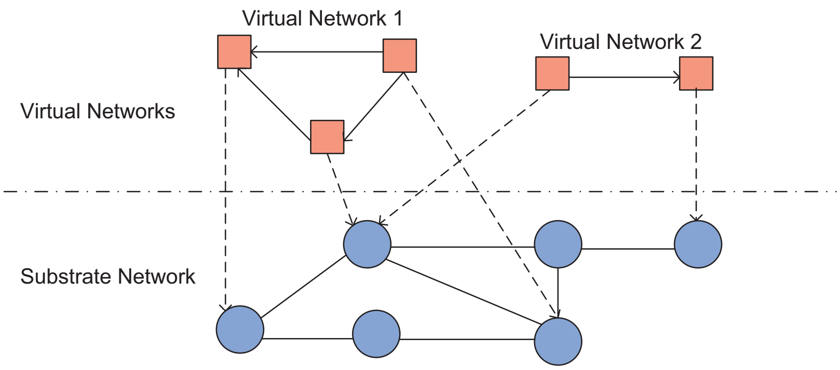

Fig. 1. Virtual networks over a substrate network.

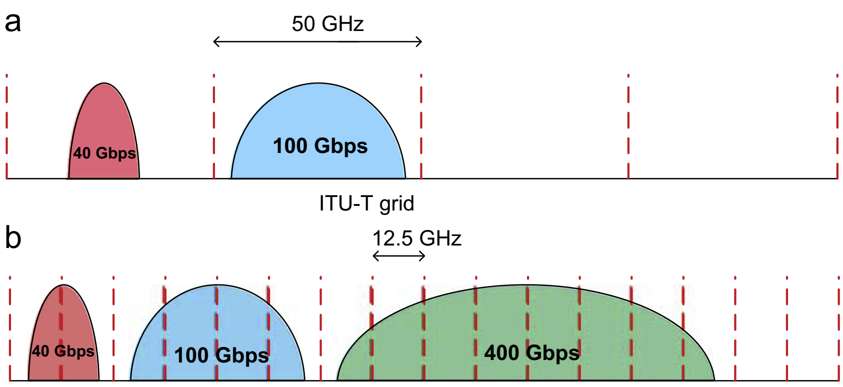

Fig. 2. The concept of flexible grid.