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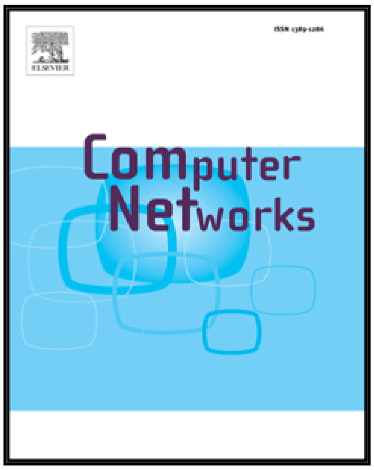

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Auction-based Resource Allocation in OpenFlow Multi-tenant Networks

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***Abstract*—In this paper, we investigate the allocation of network resources (such as Flow Table entries and bandwidth) in *multi-tenant* Software-Defined Networks (SDNs) that are managed by a FlowVisor. This resource allocation problem is modeled as an auction where the FlowVisor acts as the *auctioneer* and the network Controllers act as the *bidders*. The problem is analyzed by means of *non-cooperative* game theory, and it is shown that the auction admits a unique Nash Equilibrium (NE) under suitable conditions. Furthermore, a novel distributed learning procedure is provided that allows each Controller to reach the game's unique NE in a few iterations by exploiting only locally available information. An implementation in OpenFlow-compliant SDNs is also proposed in a way that exploits native procedures already offered by OpenFlow. Finally, simulation results show that the proposed auction-based resource management scheme leads to significant improvements in network performance (for instance, achieving gains of up to 5× reduction in transmission delays).**

***Index Terms*—Software Defined Networking, OpenFlow, auction, resource allocation.**

I. Introduction

Multitenancy is a concept referring to the possibility for several customers to share certain resources such as physical network elements and links and use them as they were the sole users of those resources. In the last years, increased attention has been paid to the application of the multitenancy concept in the networking domain. Even if most efforts have been focused on the application of multitenancy concepts to the datacenter domain [1, 2], in many other scenarios such concepts can be exploited beneficially. Two relevant scenarios, for example, are that of *virtual network operators* in which several companies sell network access services using the network infrastructure owned by a third party [3], and that of *virtualized network functions* where hardware network elements, such as switches and firewalls, are substituted by software middleboxes that execute networking procedures on one or more virtual machines (VMs) deployed on the cloud [4].

In multi-tenant scenarios, the owner of the network infrastructure has two major needs:

- Maximize the quality of service experienced by its customers, that is, render its customers *satisfied*;
- Maximize its revenue.

In order to meet both of them, efficient resource management mechanisms should be considered. Recently, thanks to their capability to provide dynamic network management [5–8], software-defined networks (SDNs) have attracted much interest in the literature as a reliable framework to provide support for multitenancy [9–13] and energy-efficiency [14, 15]. In SDNs, control and data planes are decoupled. Network control and management are centralized and implemented in software, while the data/forwarding plane consists of an underlying physical network composed by several SDN-compliant switches and links. Although there are several ways to implement SDNs, in this paper we consider OpenFlow [16] as the most popular implementation thereof. In fact, as we show later, OpenFlow specifications already provide procedures to support dynamic resource allocation in multi-tenant networks.

In a SDN, multiple networks can coexist; thus, to properly manage their interactions, OpenFlow provides a FlowVisor [17], which is a high-level controller that is designed to act as a proxy between the physical network and multiple customers. By exploiting FlowVisor protocols, OpenFlow fully supports the multitenancy principle. In fact, FlowVisor and OpenFlow together allow the network owner to divide the network resources into *slices* and give full control of each slice to one customer that, to this purpose, runs a software program referred to as *Controller*. OpenFlow and FlowVisor ensure isolation between slices and therefore, each Controller can use its share of the network resources as if it were the sole controller doing so. In the following, we will identify the network owner with the FlowVisor and its customers with the corresponding Controllers.

In this paper we address the case where the FlowVisor reserves a portion of the network resources and divides it among the Controllers that compete with each other to obtain such resources. Our problem formulation is general and can be applied to several resource allocation problems in SDN scenarios. However, for illustration purposes we focus on two relevant resource allocation problems where each Controller competes to obtain either additional space in OpenFlow routing tables, i.e., Flow Tables, to store its routing policies, or bandwidth on a certain network link to improve its achievable throughput. It is worth noting that both Flow Tables and bandwidth are scarse resources in many OpenFlow applications. On the one hand, Flow Tables are implemented in finite capacity memories. On the other hand, bandwidth is well-known to be limited on the network links. Accordingly, efficient assignment of such resources is of extreme importance.

To this end, in line with a large body of literature on the design of distributed resource management techniques we consider *auctions* as the allocation instrument.

In this perspective, the FlowVisor acts as the *auctioneer* while the Controllers act as the *bidders*. Periodically the

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