Towards Fine-Grained Billing For Cloud Networking

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**Abstract**

We revisit multi-tenant network virtualization in data centers, and make the case for *tenant-specific* virtual switches. In particular, tenant-specific virtual switches allow cloud providers to extend fine-grained billing (known, e.g., from serverless architectures) to the network, accounting not only for IO, but also CPU or energy. We sketch an architecture and present economical motivation and recent technological enablers. We also find that virtual switches today do not offer sufficient multi-tenancy and can introduce artificial performance bottlenecks, e.g., in load balancers. We conclude by discussing additional use cases for tenant-specific switches.

**1 Introduction**

Network virtualization in data center networks has come a long way since the initial days of using Linux bridge to interconnect virtual network interfaces of different (tenant) virtual machines (VMs) [18]. The state-of-the-art uses sophisticated software switches called virtual switches [19] (vswitch) that enforce isolation between the different VMs on the server as well as across servers using e.g., a tunnelling protocol like VXLAN.

This general design of co-locating the vswitch with the Host, has been adapted and tailored to the specific needs, workloads and goals of various cloud providers. For example, Azure’s VFP [13] and AccelNet [14] uses a hybrid solution of a software switch accelerated by a hardware network card (NIC); Google Cloud Platform [11], uses a software-only solution for their virtual switch, with additional network services either offloaded to Hoverboards or Coprocessors running in dedicated servers or co-located VMs respectively.

This fate-sharing model scales linearly with the number of servers and is somewhat manageable. However, it comes with restrictions, performance limitations and security weaknesses, e.g.:

- If all tenants share the underlying vswitch, they are restricted to the functionality of that particular switch:

![Figure 1: Comparison of the state-of-the-art billing for virtual networking and tenant-specific vswitches. In the latter, the cloud operator can charge the tenant for CPU cycles consumed by the vswitch and the tenant only pays for the vswitch she uses, which was previously not possible.](image)

- High-performance software network functions that outperform the vswitch are limited to the performance of the vswitch, e.g., software load-balancers can process packets at rates higher than the virtual switch, however, they are limited to the performance of the virtual switch [6]. Software load-balancer vendors (e.g., Avi Networks) have suggested a workaround for this by using dedicated servers for tenant-specific load balancing.

- From a security perspective co-locating the vswitch with the Host compounded by its monolithic code and configuration is vulnerable to compromise [10, 15, 22, 24, 25].

In this paper, we make the case for deploying *tenant-specific* vswitches in the cloud, which can overcome the
aforementioned issues. Our approach is enabled by recent developments [23] showing promising tradeoffs between security, performance and resources of multi-tenant vswitches (Section 3).

In particular, we argue that tenant-specific virtual switches enable cloud providers to amortize the costs of virtual networking by fine-grained accounting and pricing (as illustrated in Figure 1), e.g., by accounting for the CPU cycles used by tenant-specific vswitches; also IO and energy can be factored in. Such mechanisms are particularly well-suited for the serverless architecture [16], where billing is naturally fine-grained, i.e., by the second rather than by the hour or usage-based. The main challenge we believe cloud providers currently face in achieving such fine-grained pricing is the lack of a method to perform such accounting.

For example, the cloud provider Snowflake recently mentioned the need to rethink and redesign their cloud systems to perform fine-grained billing [27]. Furthermore, Singhvi et al. [20] describe the lack of fine-graining billing for the networking in Serverless architectures such as AWS Lambda. Indeed, the pricing for networking for AWS Lambda merely adopts the hourly billing rates [5]. In NFV, the programs are naturally network and CPU intensive hence, SNF [21] proposed by Singhvi et al., uses a per-packet granularity for billing serverless NFV applications. However, in SNF, the cloud operator still pays for CPU cycles used by the single vswitch on the server.

The remainder of this paper is organized as follows. In Section 2 we make our case for tenant-specific virtual networking by first describing the concept of tenant-specific virtual networking and then estimating the cost savings of such an architecture for the cloud operator and tenants. Next, in Section 3 we discuss the technical aspects of our proposal. Finally, we highlight additional use cases in Section 4.

2 The Case for Tenant-Specific Switches

The concept of tenant-specific virtual networking can be discerned via the illustration in Figure 2. Virtual switches dedicated to tenants run as compartments (e.g., processes, VMs, containers, etc.). Through a communication medium (e.g., shared memory, PCIe bus) and mechanism, the vswitch and its tenants can exchange network packets. Via a logically centralized controller, the cloud provider controls (and monitors) the communication channel between the vswitch compartments and their tenants, as tenant isolation is critical. The cloud provider also configures the tenant-specific virtual switch. Resources, in particular, CPU cores for the vswitches can be allocated in several ways: all vswitches are pinned to a dedicated core; each vswitch gets a dedicated core; the vswitch and the respective tenant VMs share the same core; or a combination of vswitches and cores.

The ability to (flexibly) allocate cores to tenant-specific vswitches, now enables the cloud provider to precisely measure, e.g., the number of CPU cycles, cache lines, pages in memory or energy consumed whenever a vswitch compartment is scheduled as illustrated in Figure 1 where CPU cycles from the tenant-specific vswitch are billed. In this way, the resources consumed by the vswitch compartment can be amortized by charging the customer accordingly. Note that, this also benefits the tenant as she does not have to pay for network communication processing she does not use, hence, a potential win-win for the operator and tenants.

2.1 Economic Motivation

To illustrate the potential economic benefits of a tenant-specific vswitch design, we discuss a back-on-the-envelope calculation for the cloud operator and cloud tenants.

2.1.1 Cloud Operator

We compare the state-of-the-art with three options:

- **Option 1**: one dedicated core for all tenant vswitches.
- **Option 2**: the vswitch shares the resp. tenant’s cores.
- **Option 3**: one dedicated core for each tenant’s vswitch.

We make the following simplifying assumptions as we do not have access to the operational costs and pricing models of cloud providers. Nonetheless, we use the publicly available prices from Amazon EC2 [4] for the pricing of VMs.

**Without tenant-specific switches.** A compute instance (VM) costs 1 cent/hour (or .01 cent/second) and we consider 100 servers, each with 12 cores. Each server can host 10 VMs (2 cores for the Host) and hosts a maximum of 5 tenants (i.e., a max of 2 tenant VMs per server). Thus, in 24 hours (1 day), the total income can amount to 1*24*10*100 = 24,000 cents/day = 87,600 dollars/year. The money spent in 24 hours is 2*24*100 = 4800 cents/day = 17,520 dollars/year. The total revenue is hence the difference, 70,080 dollars/year.

**Tenant-specific switches: Option 1.** In this case we have the following. Each server continues to host 10 VMs, however, only 1 core is allocated to the Host and the other core is shared by all the tenant-specific vswitches. We assume the

Figure 2: Conceptual illustration of tenant-specific vswitches (bottom) along with three different approaches (top).
vswitch VMs are used only 50% of the time compared to the workloads. Thus, in 1 day, the total income from the vswitch VMs can amount to $1\times12\times1\times100 = 1,200 \text{ cents/day} = 4,380 \text{ dollars/year}$. The money spent reduces by half compared to the previous calculation as the Host has only 1 core now, which is now 8,760 dollars/year. The net revenue is hence, 4,380+87,600-8,760 = 83,220 dollars/year. This is a net revenue of 18.75% more compared to co-locating the virtual switch with the Host and bearing the cost for 2 cores.

**Tenant-specific switches: Option 2.** In this scenario, the vswitch VM does not need any extra core as it is shared with the tenant’s VMs. This allows us to take 1 core from the Host and run an extra tenant with a single VM on each server. Hence, we have the following income, $1\times24\times11\times100 = 26,400 \text{ cents/day} = 96,360 \text{ dollars/year}$. The money spent is similar to Option 1, which results in a net revenue of 96,360-8,760 = 87,600 dollars/year which is 25% more to the state-of-the-art.

**Tenant-specific switches: Option 3.** Here, the situation is a little more complicated as each virtual switch VM gets a dedicated core. This results in tenants being displaced which requires purchasing new servers to host the displaced tenants. Based on that, we have the following. Similar to the previous two options, with the Host being allocated 1 core, we have an extra core. Therefore, each server can now host 3 tenants, each tenant consumes 3 cores: 2 for the workload and 1 for the vswitch VM. The remaining 2 cores can be allocated for a tenant with a single VM. Hence, we have 4 tenants per server: 7 (workload) VMs and 4 vswitch VMs. This generates $1\times24\times7\times100 = 16,800 \text{ cents/day} = 61,320 \text{ dollars/year}$ from the tenant VMs. In addition, the vswitch VMs (running at 50%) generate $1\times12\times4\times100 = 4,800 \text{ cents/day} = 17,520 \text{ dollars/year}$. The total money earned from the 100 servers = 78,840 dollars/year. However, as mentioned earlier, by dedicating cores for the vswitch VMs, we have 1.5 tenants displaced per server, or $1.5\times100 = 150$ tenants displaced in total. Since, each server can host 3.5 tenants, we will need 43 new servers, where each server costs 2,000 dollars. From the 43 new servers, we have the following earned, $1\times24\times7\times43 + 1\times12\times4\times43 = 7,224+2,064 = 9,288 \text{ cents/day} = 33,901.2 \text{ dollars/year}$. The total income is 112,741.2 dollars/year. The money spent from the 143 servers = 78,840 dollars/year. The money spent reduces by half compared to the previous calculation as the Host has only 1 core now, which is now 8,760 dollars/year. The net revenue is hence, 112,741.2-8,760 = 100,214.4 dollars/year without considering the capital/sunk cost of the 43 servers which is 43\times2,000 = 86,000 dollars. For simplicity we do not consider a return on investment calculation here. This is 43% more than the state-of-the-art.

**Key takeaway.** Based on our back of the envelope calculations we find that dedicating tenant-specific vswitch VMs/compartment with billable CPU resources introduces potential savings for the cloud provider from 10% upto 40%. Usage-based billing or pricing per millisecond could offer more savings.

### 2.1.2 Cloud Tenant

As we just saw the potential savings for the cloud operator, we now cast light on the savings for cloud tenants based on the three options described for the cloud operator. In particular, we assume the 5 tenants co-located per server use their vswitch VM as follows: 1%, 2%, 2%, 5%, 10% and 30%. This adds up to the 50% usage as stated previously for the cloud operator.

**Tenant-specific switches: Option 1, 2 and 3.** In Options 1 and 3, the savings per tenant are directly proportional to her time usage. For example, the tenant who consumes 10% pays two thirds less than the tenant who consumes 30% of the CPU for the vswitch VM. In Option 2, savings manifest if billed by CPU cycles used rather than time slices.

### 2.2 Technological Enablers

Having cast light on the economic benefits of a tenant-specific vswitch, we now point out key technologies currently available in the market that enable such a system.

Compartments can trivially be realized via virtual machines, containers or processes as operating systems and hardware already support these primitives with security and performance guarantees. The main challenge lies in connecting the tenant-specific vswitch compartment with the tenant VMs and then enforcing isolation between the different tenant vswitch and VMs.

Broadly speaking, there are two potential solutions: software or hardware. A software based approach has been proposed by Jin et al. [15], as well as Stecklina [22]. The former design places the vswitch in a VM (compartment) and then plumbs together the vswitch with all the tenants using shared memory. This requires modification to the hypervisor/virtual machine monitor as well as fine tuning, e.g., polling frequency, buffer sizes, message lengths, etc. Furthermore, polling is expensive as the CPU is constantly being used even when there are no packets. The latter approach can allow vswitch processes to be pinned to dedicated cores and hence billed appropriately. Other possibilities include a language-centric approach, e.g., using RUST.

A hardware based approach recently proposed by Thimmaraju et al. [23] uses off-the-shelf hardware and software for network virtualization. In particular, the design proposes Single Root IO Virtualization (SR-IOV) [23] as most CPUs and NICs used in the cloud already offer these features. Isolation is enforced at the NIC via a simple layer 2 Ethernet switch using VLAN tags. Virtual functions (VFs) on the NIC can be allocated to the vswitch VM and tenant VMs as desired. The vswitch and the tenants are then appropriately configured for...
connectivity and isolation.

3 Technical Aspects and Realization

We now discuss the benefits and challenges we foresee in realizing and operating a multi-tenant vswitches in the cloud. To aid our discussion, we use MTS [23] as a case study.

Security, Performance & Resources First is the point of the tradeoffs between security, performance and resources. As we can see in Figure 3, a multi-tenant architecture using SR-IOV improves the packet processing throughput and latency for Options 1 and 3 (recall Section 2.1). Furthermore, we can see that workloads in the tenant VMs, e.g., Apache and Memcached, also receive a performance improvement. It is obvious that Option 3 consumes more cores than Option 1 as each vswitch VM is dedicated a core. However, the performance and economic benefits (Section 2.1.1) are also proportional. Indeed, only Option 1 and 3 were evaluated, however, it goes to show that by running the vswitch in a dedicated VM, we can dynamically scale the security, performance and resources for virtual networking.

Configuration Virtual networking configuration and management is highly complex even if it has been wrapped around a programmatic framework. A misconfiguration in one virtual switch could end up leaking traffic and violating network isolation guarantees and policies [23]. One solution to reduce the complexity is to move away from a monolithic configuration model to a tenant-specific model. Tenant specific network configuration is restricted to the tenant’s vswitch. The tradeoff here lies in duplicating the necessary configuration across the tenant-specific vswitches which costs memory. Controllers would need to be modified to operate on tenant-specific vswitches in addition to configuring the communication medium (e.g., SR-IOV NIC), as well as flexibly allocate resources to the vswitch compartments/VMs.

Management With respect to management, indeed introducing tenant-specific vswitches will increase the number of vswitches that have to be managed by the controller. Furthermore, this will also introduce more network traffic along the links between the switches and controller. From a security perspective, this would also mean managing more keys and certificates, e.g., for TLS sessions between the switch and controller.

Routing Indeed, the way switching and routing operate will have to be adapted as tenant vswitches and their workloads (VMs) will need to be reachable via the server and network fabric. In the context of MTS, this is achieved by identifying each tenant vswitch by its MAC address and the workloads by its IP address. This is currently not the way, e.g., NSX-T [26] and OVN [17], are designed. Furthermore, if the servers are not aware they are on the same Ethernet network, then classification and reachability based on tunnels IDs would be necessary. With programmable NICs [12] and P4 [9], this issue could be overcome.

Scaling Being able to scale the number of vswitches is a high priority for cloud operators. To that end a combination of VMs and containers can be used. In particular, we evaluated the packet processing throughput of running OvS in containers in VMs and compared that with the measurements shown in Figure 3. We found the overhead introduced by the container mechanisms to be less than 2%, hence, we do not show the plot here. Instead, in the bottom right of Figure 3 we show the packet processing throughput for 16 tenants using 4 and 8 vswitch containers spread across 1, 2 and 4 VMs using Option 1. We can see that doubling the vswitch containers reduces the throughput by nearly 25%. This is due to an increased number of ports per VM and pushing packets across memory intense sk_buff buffers coupled with just a single core shared by all the vswitch VMs. Hence, Option 2 or 3 would be able to offer better performance.

Network Virtualization Interference By scheduling vswitches in dedicated VMs, we can reduce interference problems that arise by having a single vswitch shared by multiple tenants. However, interference can now surface at the communication medium, e.g., NIC level. This can be circumvented by used dedicated resources and rate-limiting mechanisms. For example, SR-IOV NICs have dedicated registers for the VFs and also implement rate-limiters for VFs [3]. The PCIe bus could also be a source of interference or even packet loss, hence, using more lanes or newer versions [2] can alleviate this problem.

NIC Resource Limitations Indeed the resources on the NIC will prove to be a limitation when using SR-IOV. However, this is really problematic only when the degree of co-located tenants on the same server is very high. Microsoft azure has a limit of 60 VMs/server and a total of 700 VMs across their cloud [1]. If we assume cloud providers use high-end Intel xeonPhi-based servers which have 72 cores per processor, then we are likely to hit a VF limit before the core limit: MTS offers 21 unique tenant vswitch VMs per Physical Function (port). To reach 72, we need at least 4 PFs. Over 70 ports communicating over the PCIe bus and NIC switch would introduce an overhead to the performance and resources of the server. One workaround is to limit the number of co-located tenants per server. For example, spread them across servers and avoid the worst case VF limitation. Note that this is really problematic only when the degree of co-located tenants on the same server is very high. Microsoft azure has a limit of 60 VMs/server and a total of 700 VMs across their cloud [1]. If we assume cloud providers use high-end Intel xeonPhi-based servers which have 72 cores per processor, then we are likely to hit a VF limit before the core limit: MTS offers 21 unique tenant vswitch VMs per Physical Function (port). To reach 72, we need at least 4 PFs. Over 70 ports communicating over the PCIe bus and NIC switch would introduce an overhead to the performance and resources of the server. One workaround is to limit the number of co-located tenants per server. For example, spread them across servers and avoid the worst case VF limitation. Note that the limitation we are talking about here is where we have 21 unique tenant vswitch VMs per server. Indeed, this raises our next point which is an increase in the number of servers to host tenants.

Workload Displacement If the number of tenants per server are to be capped, then more physical servers are necessary to host the tenants that are displaced. This would incur additional capital costs: new servers, ports on switches, cabling, energy cooling and power, etc. However, as mentioned in Section 2.1, these costs could be amortized by fine-grained billing of tenant-specific vswitches. Furthermore, when workloads are displaced, some tenants could have to pay for more
vswitch VMs than others: if there is only 1 vswitch VM and 1 workload VM on a server. Hence, placing tenants in a fair and efficient manner across the servers would need to be devised.

4 Additional Use Cases

The possibility to run a vswitch on a per-tenant basis has additional aspects and opportunities.

**Bring Your Own Switch** Using tenant-specific switches, cloud operators and the tenants do not have to wait for a feature to be introduced into the vswitch before they can use it. Furthermore, a bug in one vswitch should not impact other tenants. Hence, being able to support tenant-specific network virtualization features by either having tenants bring in their own vswitch or using vswitches tailored to a tenant’s needs, can make the overall system more robust and potentially even offer better performance.

**Snapshots And Migration** Being able to make snapshots of the vswitch state and configuration enables backup and migration. For example, if there is maintenance on a particular server or a set of servers, the cloud provider can simply take a snapshot of the vswitch VMs and then migrate the VMs to another server. This could prove to be faster and perhaps more reliable than having a sudden peak in traffic to the controller to update the vswitch state and configuration.

**Co-locate Network Functions** Spinning up tenant-specific vswitch VMs could lead to a simplified way to deploy tenant specific service function chains. For example, running the different network functions including the vswitch as containers co-located in the VM reduces the amount of traffic that has to pass through the Host for switching. This also reduces the latency between the vswitch and network functions and potentially avoids any interference from other tenants.
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