

Joint Virtual Middleboxes and Application Placement with Bandwidth Guarantees in Multi-tenant Datacenter Networks

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Abstract—Hardware middleboxes are widely used in current cloud datacenter to provide network functions such as firewalls, intrusion detection system, load balancers, etc. Unfortunately, they are expensive and unable to offer customized functions for individual tenant. To overcome this issue, there is an increasing interest in deploying software middleboxes to enable flexible security, network access functionality. A key problem for cloud providers is how to efficiently deploy the software middleboxes and provide performance guarantee for both middleboxes and application while saving as many resources as possible. **Besides, to better handle the variable practical application workload, it is necessary to conduct a middlebox scaling approach when application running.** In this paper, we present vMAP, a solution that combines a tenant request model with an effective placement algorithm for middleboxes and application, while conducting a probability model based approach to addressing the middlebox scaling problem. **We first specify the model of the tenant's requirement that matches the demands for virtual machines of application and middleboxes,** as well as communication traffic. A joint virtual middleboxes and application placement algorithm is then proposed to offer predictable network performance for each tenant, and minimize datacenter bandwidth utilization. Finally, we provide an approach to solving the middlebox scaling problem through reserving additional free virtual machine (VM) resources based on a probability model. Extensive simulation results based on current large-scale datacenter networks verify that vMAP can accept more tenant requests than existing placement algorithm (e.g., Stratos) while saving $\sim 10\%$ core-level bandwidth. The middlebox scaling experiments also show that our middlebox scaling approach can accommodate the scaling requirement effectively while minimizing the waste of the reserved virtual machine resources.

I. INTRODUCTION

Large public clouds, such as Amazon EC2 and Windows Azure, provide infrastructure as a service (IaaS) for enterprises and individuals. Besides the ability to provide computing resources, public clouds are expected to support network functionality, such as load balancers (LB), firewall (FW), intrusion detection system (IDS), etc. Currently, network functions are deployed through the expensive hardware middleboxes (in short, MBs) which are placed at the point close to the data center switches. Since hardware middleboxes are shared by all tenants, it is hard to manage these expensive devices to provide customized functions for each tenant. Besides, heavy congestion may happen at links around those middleboxes. To address these issues, there is an increasing trend towards

deploying software middleboxes (or, interchangeably, virtual middleboxes, middlebox VMs) in the cloud [1], [2].

Providing virtual middleboxes with guaranteed performance is challenging for cloud service providers due to several reasons. First, we need to model various requirements of tenants, which consist of application VMs, middlebox VMs as well as the connecting network. Second, it requires an efficient algorithm to place virtual middleboxes in cloud service infrastructure to maximize the datacenter resources utilization by accepting as many requests as possible. **Last but not least, the application workload is varying in practice, and a middlebox scaling approach is then required to be considered in practice to better handle the workload.**

In this paper, we propose **vMAP** (short for **v**irtual **M**iddle**b**oxes and **A**pplication **P**lacement), a solution that combines a tenant request model with an effective placement algorithm for both middleboxes and application, while accommodating the middlebox scaling request through a probability model based approach. Tenant's requirement is represented by a weighted directed acyclic graph (DAG). The nodes consist of diverse virtual middleboxes and a set of homogeneous application VMs, both of which are dedicated for each tenant to process arrival traffic. The edge of DAG indicates the communication request of middlebox-to-middlebox, middlebox-to-application and intra-application. The weight on the edge is the minimum communication requirement between VMs of middleboxes and application [2], [3]. The inter-tenant communication [4] is also structured by a directed graph. The arrival traffic from other tenants will be forwarded to the MBs of the target tenant before arriving at its application VMs.

Existing placement algorithm like Stratos [2] seeks to partition the VMs into per-rack partitions and tries to place them with minimal inter-partition communication. **More Specifically, Stratos adopts a greedy approach that proceeds by sorting pairs of partitions in the decreasing order of the inter-partition communication. For each pair, it finds a pair of racks with the highest available bandwidth to accommodate these two partitions. However, the inter-partition communication of the partition pair may travel through several switches even the partitions can be placed under the same switch, since the algorithm only considers the bandwidth resource apart from the location of the rack pair when selecting racks.**

The location-unawareness rack selection leads to a result of bandwidth waste of core-level links which are usually the bottlenecks for most oversubscription data center networks.

In contrast, to save the core-level bandwidth, we first traverse the datacenter topology in a bottom-up manner to search for a valid lowest level subtree [3] that has enough VM slots for the tenant request, and then carefully places the required MBs and application in form of VMs under the subtree. Moreover, we consider dividing middleboxes and application VMs proportionally and putting them in the servers or racks under the same subtree to eliminate unnecessary communication cross racks or subtrees due to the mismatched assignment of traffic processing capacity. Further, we try to collocate more application VMs to reduce the intra-application communication cost through carefully exchanging the positions of middleboxes and application VMs.

The application workload is variable in practice, which necessitates scaling middleboxes when the capacity of allocated middleboxes cannot match the practical workload well. To address the middlebox scaling problem, we adopt an approach of pre-allocating a few additional free VM slots to accommodate the scaling requirement, instead of dynamically allocating resources when application running which is inefficient and may cause improper placement.

To the best of our knowledge, we are the first to model the virtual middlebox network with intra- and inter-tenant communication. Extensive simulations on large-scale datacenter topology have shown the effectiveness of our VMs placement algorithm. The accept ratio approaches to 90% with regard to a variety of tenants' requests. Compared with the existing placement algorithm, our algorithm can also greatly reduce the bandwidth utilization of core-level links while making the best of low-level links' bandwidth resource. The middlebox scaling approach can accommodate the scaling requirement effectively while minimizing the waste of the reserved VMs. Generally, the network function virtualization enables the cloud services provider to offer customized services with lower cost and our study will be helpful to build more flexible software-based cloud services to meet diverse requirements of the tenants in the datacenter network.

The rest of this paper is organized as follows. Section II reviews the background, related works and challenges of deploying tenant requests effectively in datacenter networks. Section III describes our abstraction of middlebox and the communication model. The VMs placement strategy is explained in Section IV. The scalability problem is discussed in Section V, and the simulation based performance evaluation is demonstrated in Section VI. Section VII concludes this paper.

II. BACKGROUND AND CHALLENGES

A. Background and Related Works

Multi-tenant datacenter Large-scale datacenter is the core infrastructure for cloud based services. Datacenter network is organized in a multi-level tree-like topology. See Fig. 1, each rack typically contains 40+ servers, each of which is configured with a 10Gbps network interface card (NIC)

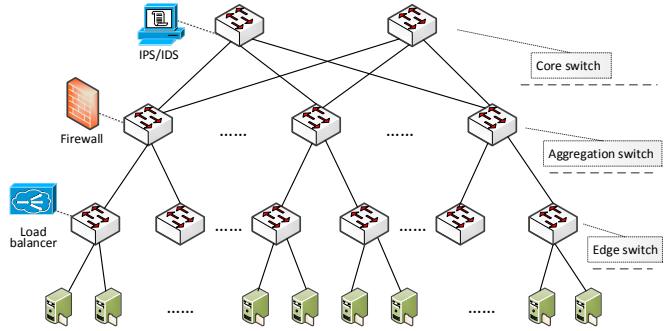


Fig. 1. Datacenter network and hardware middlebox deployment

connecting to the top-of-the-rack (ToR) switch. The ToR switch will balance the traffic to multiple aggregation switches. All aggregation switches are further connected to the core switches. Note that the communication bandwidth between adjacent layers is oversubscribed by a ratio from 2:1 to 10:1, which may vary slightly with different configurations [4], [5].

In multi-tenant datacenter environments, a tenant can rent multiple virtual machines (VMs) on physical servers. The VMs are configured with different amounts of CPUs, memories and storage resources. From the network perspective, we usually model the computation and storage resource to be the number of slots requested in physical machine. All VMs assigned to a tenant are interconnected to form a virtual network (VN) such that VMs can communicate with each other to exchange data. The traffic inside a multi-tenant datacenter carries external traffic to and from the Internet, intra-application traffic between a tenant's application VMs and inter-tenant traffic. Specifically, the inter-tenant traffic consists of flows between tenants and flow between tenant and providers [4], which can also be considered as a special tenant. Inter-tenant communication increases with the increase of services offered by cloud providers. Based on recent measurement in public cloud provider, 65% of traffic happens between VMs belonging to one tenant VN and 35% is among different VNs or tenant-provider communication [4], [6].

Middleboxes in multi-tenant datacenter Network functions are also necessary and provided in the form of hardware middleboxes in current datacenters. However, hardware middleboxes are known to have several drawbacks. For example, working as a shared resource, the hardware middleboxes can only provide common services used by all tenants instead of providing customized tenant requests. Once the middlebox failed, all the tenants will be affected. Besides, the fixed locations of hardware middleboxes result in aggregated network bandwidth consumption and cause network congestion [7], [8].

An alternative solution to hardware middleboxes is network function virtualization (NFV) [9]. Deploying software middleboxes will greatly improve the flexibility, manageability and cost-efficiency. Software middlebox is not necessary to be shared and able to provide customized services with performance guarantee for each dedicated tenant. It has been

shown that the software middleboxes are able to offer equivalent functionalities as the corresponding hardware implementation [10], [11], [1], [7]. The advance of software defined networking (SDN) further facilitates the deployment and management of software middlebox running in datacenters. Although there remains unsolved challenges before it can be integrated into the cloud ecosystem, the perspective of deploying flexible software middlebox for isolated tenants has motivated us to extend the previous works to realize predictable middlebox virtual networks through effective virtual middleboxes placement.

Placement of application VMs with performance guarantee Since the underlying network is shared by tenants, the application can be affected by variable and unpredictable network performance. A series of works have been proposed to enable traffic isolation and provide bandwidth guarantee, including Oktopus [3], FairCloud [12], etc. The above works focus only on intra-tenant communication. The inter-tenant traffic isolation is addressed by Hadrian [4]. Through hierarchical hose model, the communication dependencies can be explicitly declared. The cloud provider then allocates resources according to the specification of tenants.

Placement of middlebox VMs with performance guarantee Most of previous works considered the bandwidth guarantee for applications. As far as we know, little work addresses the bandwidth guarantee for virtual MBs in multi-tenant datacenters [13]. The NFV cloud computing platforms, like NFV OPEN LAB [14] and CloudNFV [15], provide an architecture for NFV deployment and management. Theoretically, to obtain effect use of resources, various NFV placement objectives have been studied, for example, remaining data rate, latency, number of used network nodes as well as distance and setup cost, see [16], [17] and the references therein. However, they could not provide bandwidth guarantee for tenants. Stratos [2] considered the middlebox placement in multi-tenant datacenters through a systematic way by avoiding network congestion. In contrast, we first study the bandwidth guarantee problem of both virtual middleboxes and application and then propose effective placement algorithm to make good use of network resources.

B. Design Challenges

Deploying both virtual middleboxes and application with performance guarantee is challenging for cloud service providers in datacenter networks due to several reasons following.

Model to specify the tenants' requirement In order to effectively deploy the tenant requests, we need to accurately model the tenant requirements, which consists of middlebox, application, as well as the intra- or inter-tenant communication patterns. Besides, an intuitive and descriptive abstract model benefits both tenants and providers, which is not trivial to build. To address above problems, we adopt the *Tenant Application Graph (TAG)* [18] model and extend the Hadrian [4] model to properly match the tenant requirements. We introduce the modelling details in Section III.

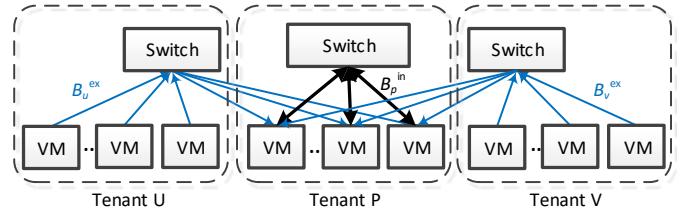


Fig. 2. Intra-tenant communication and inter-tenant communication

Strategy to place both the middleboxes and application Given tenant requests and corresponding communication models, our objective is to maximize the datacenter resources utilization by accepting as many requests as possible. This is an NP-hard problem like optimally deploying the *hose model* [19], [18]. Therefore, we search for effective heuristic solution to maximize the datacenter resources utilization. We present our placement algorithm in Section IV.

Approach to accommodating the middlebox scaling request It is a remarkable fact that the practical application workload is variable. Therefore, to better handle the practical workload, the scalability of MBs is important and need to be considered by the cloud service provider. Once the virtual network is placed in datacenter, it is hard to find a proper resource to migrate MBs and re-allocate live flows across MBs with performance guarantee [1]. We discuss the scalability issue in Section V.

III. ABSTRACTION OF VIRTUAL MIDDLEBOX NETWORK

In a multi-tenant datacenter, by leveraging the network function virtualization (NFV), cloud providers provide middlebox as a fundamental network service to tenants, like both computing and storage resources. A tenant could specify their middlebox and application (i.e., computation/storage) requirements in forms of VMs and the expected minimum bandwidth requirement for intra- and inter-tenant communication. Cloud providers will then assign VMs for middleboxes (in short, MB VMs) and applications (in short, APP VMs) according to the tenant's request. The cloud providers also enforce the middlebox policies, i.e., the sequence of middleboxes that a flow must traverse. In this section, we explain the model for APP VMs and MB VMs. We then introduce the abstraction of virtual networks associated to one tenant.

A. Model of APP VMs

To provide predictable network performance for the communication of N APP VMs in one tenant, users typically specify the minimum bisection bandwidth B^{in} for individual APP VM. Analogous to previous proposals [4], [12], the requirement of the minimum bandwidth guarantee for each APP VM belonging to the same tenant can be abstracted by the *hose model* [19]. In the hose model (see the thick black arrows in Fig. 2, tenant P), the application VMs are connected to a logical switch by a link of capability B^{in} .

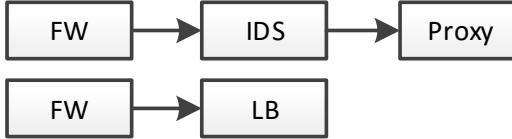


Fig. 3. Abstraction of MBs: Two MBs chains

Similarly, for the cross tenants communication, a tenant can specify the bandwidth request for a single APP VM. The minimum bandwidth guarantee for inter-tenant traffic of each APP VM is defined by B^{ex} . We extend the VN model of Hadrian [4] to support multiple external links. If the current tenant communicates to multiple tenants. The minimum bandwidth for each communication pair is guaranteed to be B^{ex} . The communication pattern between tenants can be expressed by a directed graph. We use the definition of *communication dependency* in [4] to explicitly specify the peer-to-peer traffic pattern. A tenant with a dependency of $\{*\}$ means that he could allow any other tenants' communication request. We call this kind of tenant *open tenant* while the tenant who has communication requests to the *open tenant* is called *client tenant*. When the dependency is set as $P:\{U, V\}$, it means that the communication from tenant U and tenant V to tenant P are allowed. An example is illustrated in Fig. 2, the thin blue arrows show the communication between tenant U and tenant P, as well as tenant V and tenant P.

B. Model of MB VMs

Middleboxes perform different network functions to meet traffic demand of applications. A tenant may vary network functions simultaneously to process packets of different traffic classes, as shown in Fig. 3. Each request consists of a sequence of various MBs, such as firewall (FW), intrusion detection system (IDS), redundancy elimination (RE), load balancer (LB) and NAT Proxy, etc., which provide functionality of access control and traffic engineering.

Generally, the communication between MBs can be abstracted by a directed-acyclic graph (DAG), where the vertex represents the type of middleboxes and the arc indicates the traffic flow between them. The external traffic should pass through the specified middleboxes one by one according to the DAG. The sequence can not be violated. Otherwise, the expected functionality will be ruined. In addition, we assume that the traffic still keeps the same when multiple MBs are introduced. This is reasonable because the traffic is the minimum bandwidth guaranteed for both intra- and inter-tenant communication. The normal traffic could pass all the rule checking and will not be blocked by middleboxes like FW or IDS. For those middleboxes, e.g., RE or LB, which change the traffic load, they are usually placed at the end of the DAG. The variation of traffic is specified by the proposed parameters of B^{in} and B^{ex} in the aforementioned APP VMs model.

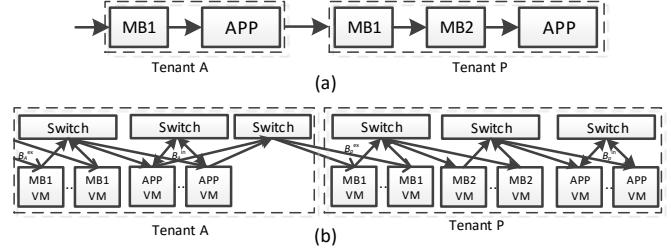


Fig. 4. Virtual Network Model. (a) the communication between two tenants; (b) cascade of TAG

Therefore, a middlebox chain model can be defined by a tuple $\langle T, M \rangle$, where the type of MBs is denoted by a vector T , and the number of required MB VMs is denoted by a vector M . The direction of traffic flow is implicitly expressed by the sequence of items in the vector T . For instance, the first MB chain in Fig. 3 can be expressed as $\langle T, M \rangle$, where $T = \{\text{FW}, \text{IDS}, \text{Proxy}\}$, $M = \{2, 4, 2\}$ (we will present the computing process in detail to obtain a more accurate value of M in Sec. IV). It means that the tenant request for 2, 4 and 2 VMs of FW, IDS, and Proxy respectively. Specifically, the sequence of middleboxes shows that the traffic will arrive at FW first, and then go to IDS and pass Proxy before reaching the application VMs. Besides, the tenant request can be classified into multiple MB chains associated with different applications [2], [16], [13] since a tenant may need to apply different middlebox policies to different traffic classes. See Fig. 3 as an example. The Internet traffic will pass Firewall, Intrusion Detection System and then NAT proxy, while the traffic from other tenants may only pass Firewall and Load Balancer. In this situation, the tenant's request can be specified by multiple middlebox chains' tuples of $\langle T, M \rangle$.

C. Virtual Network Model for MB VMs and APP VMs

We combine the MB model and APP model together to form the virtual network (VN) model to represent the tenant's request. The interaction between VMs of the same tenant is expressed by the *hose model* [19]. The middlebox chain should be attached to the ingress path of the external link of the VN. Such that, all external traffic coming into APP VMs must traverse through these specified middlebox chains which provide access control and other network functions. CloudMirror [18] provided a new network abstraction that allows the applications to specify their directional and specific communication patterns. We adopt a cascade of *Tenant Application Graph (TAG)* proposed in [18] to specify the VN model.

Fig. 4(a) shows an example, where a sequence of MBs is attached at the external link of APP VMs of tenants. The arrow shows the traffic flow. Arrival traffic of tenant A will pass through all these middleboxes before being distributed to the application services. Similarly, the departure traffic of tenant A is forwarded to its destination (tenant P) which needs to

pass through the middleboxes of tenant P first¹. Fig. 4(b) uses the cascade of TAG model to abstract the communication dependency of VNs. The external traffic passing through each type of middleboxes in sequence are expressed by the dedicated directional arrows. The internal traffic of APP VMs is expressed by bi-directional arrows, each of which has a capacity of B_A^{in} (tenant A) or B_P^{in} (tenant P). The external traffic of each VM of tenant A (resp. tenant P) is bounded by B_A^{ex} (resp. B_P^{ex}).

In general, two kinds of traffic may go through the MBs before coming to the application VMs: 1) the Internet traffic; 2) the traffic from other tenants. When declaring a connectivity relationship, this external link can only communicate with those specified virtual networks (VNs). The unauthorized traffic will be blocked by MBs. Based on the models of APP VMs and MB VMs, a tenant can specify the connectivity of an external link which receives (or sends) traffic from any VN. In summary, a tenant's request can be specified by multiple virtual networks (or VNs) and each VN can be specified by a tuple $\langle N, B^{in}, B^{ex}, dependencies, T, M \rangle$.

IV. VIRTUAL MIDDLEBOX NETWORK (VMN) DEPLOYMENT

Based on the tenant's request, the cloud provider allocates enough resources for MBs and APPs. The VMs request will be satisfied by providing enough free slots on physical machines (PMs). The network function demand consists of not only the bandwidth request but also the capability to process a specific class of traffic in order. We present a VM placement algorithm that bridges the gap between the high-level virtual middlebox network model to the low-level physical network. The placement strategy is realized by a logically centralized controller, which manages datacenter operations through a global view of the network topology. SDN based traffic engineering manipulates the underlying network routers to explicitly direct the traffic through each middlebox sequentially. If there are not sufficient slot or network resources, the request will be rejected.

In this section, we first show the main idea of our placement algorithm. Next we analyze the bandwidth requirement (or bandwidth composition) for the tenant request. And then, we design a bandwidth saving placement strategy based on the bandwidth requirement analyzing. Finally, we present our placement algorithm to efficiently deploy the VMN model.

A. Overview of the Placement Algorithm

For each placement of the tenant request, we aim to minimize the bandwidth consumption and save as much network resources as possible for future tenants. Instead of solving the placement problem as a graph partitioning problem [2], we seek to analyze the original composition of bandwidth consumption and then plan to place the middleboxes and application carefully to reduce the amount of bandwidth composition pertinently. Further, we find that: 1) placing different types of

¹Some corporations may have the requirement to detect the departure traffic through additional middleboxes. We leave this for future work.

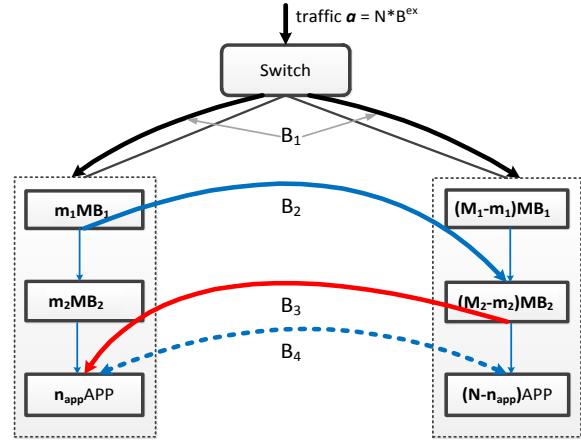


Fig. 5. Bandwidth requirement

middleboxes with application VMs together or closely is an effective approach to reducing the bandwidth consumption of middlebox-to-middlebox and middlebox-to-application; And 2) colocating application VMs is much beneficial for saving bandwidth of intra application. However, giving consideration to both beneficial placement principles above at once is not trivial when deploying the tenant request due to limited VM slot resources in practice. Therefore, we seek to firstly consider enforcing one placement principle and then try to improve another principle's benefit by carefully breaking the enforced principle before. The break of enforced principle is worthy when the achieved benefit exceeds the break loss.

In the remaining part of this section, we will first analyze the composition of bandwidth consumption, and then obtain the key conditions for beneficial break based on the analysis of bandwidth consumption. The placement algorithm is finally showed according to the conditions of the beneficial break.

B. Bandwidth Required by VMN

Given a tenant request, the cloud provider need to allocate sufficient bandwidth on the physical links to meet the bandwidth guarantees requirement specified in the VMN model. We then analyze the bandwidth consumption to achieve a better understanding of the MBs placement problem.

Consider a tenant request with a simple middlebox chain $\{MB_1, MB_2\}$ and assume that we have found two candidate subtrees that have enough slot resources to hold the request as shown in Fig. 5. The total number of instances required by middlebox k (MB_k) is indicated by M_k ². And m_k denotes the number of instances placed for MB_k in the left subtree. Correspondingly, the number of instances for MB_k in the right subtree is $M_k - m_k$. The numbers of APP VMs in the left and right subtrees are denoted by n_{app} and $N - n_{app}$ respectively.

²We assume each instance of MB_k has a maximal traffic processing capacity c_k , so the minimum required number of MB_k is defined as $M_k = \lceil \frac{N \cdot B^{ex}}{c_k} \rceil$, where $N \cdot B^{ex}$ is the total incoming traffic.

As shown in Fig. 5, the incoming traffic will pass the MB_1 and MB_2 successively and arrive at the tenant application finally. The traffic flows across and inside the subtrees are illustrated in thick and fine arrows respectively. Specifically, the middlebox prefer to send the traffic to its downstream middlebox or application inside the same subtree (see the *fine arrows*). In the case that the traffic cannot be fully handled by the downstream middlebox or application inside the same subtree, it will be partly sent to the downstream middlebox or application outside the subtree (see the *thick arrows*). Further, we find that the bandwidth consumption across the subtrees consists of four parts indicated by B_1, B_2, B_3 and B_4 . The B_1 is the external traffic (represented by the black arrows) from the switch to MB_1 which is equal to $N \cdot B^{ex}$. The traffic that cannot be fully processed by MB_2 in the left will be partly sent to the instances of MB_2 in the right subtree as shown in the blue arrow labeled by B_2 . Similarly, the traffic from MB_2 in the right to APP will be partly sent to the APP VMs in the left subtree (red arrow labeled by B_3) if the capacity of APP VMs in the right cannot serve the whole traffic from MB_2 in the same side. Besides, the bandwidth requirement (dotted arrow labeled by B_4) for intra-application communication is $2 \min(n_{app}, N - n_{app}) \cdot B^{in}$. For simplicity, we only consider the downlink bandwidth consumption since the uplink bandwidth has the similar characteristics. Then, by summing up the four parts of the bandwidth consumption, we can get the total downlink bandwidth requirement across the subtrees:

$$\begin{aligned} B_{total} &= B_1 + B_2 + B_3 + B_4 \\ &= N \cdot B^{ex} + (m_1 \cdot b_1 - m_2 \cdot b_2) \\ &\quad + ((M_2 - m_2) \cdot b_2 - (N - n_{app}) \cdot B^{ex}) \\ &\quad + 2 \min(n_{app}, N - n_{app}) \cdot B^{in}, \end{aligned} \quad (1)$$

where b_k^3 is the practical required bandwidth for each instance of MB_k .

For the general situation (i.e., the MBs and application VMs are randomly placed in the two subtrees), by adding all the inter-middlebox traffic going across the subtrees, we have the following equation:

$$\begin{aligned} B_{total} &= B_{switch,mb_1} + B_{mb_k,mb_{k+1}} + B_{mb,app} + B_{app} \\ &= N \cdot B^{ex} + \sum_{k=1}^{n-1} |m_k \cdot b_k - m_{k+1} \cdot b_{k+1}| \\ &\quad + |m_n \cdot b_n - n_{app} \cdot B^{ex}| \\ &\quad + 2 \min(n_{app}, N - n_{app}) \cdot B^{in}. \end{aligned} \quad (2)$$

B_{switch,mb_1} is the incoming traffic for MB_1 from the switch which is a constant. $B_{mb_k,mb_{k+1}}$ and $B_{mb,app}$ are the incoming traffic for MB_{k+1} and APP VMs across the subtrees from MB_k respectively. B_{app} represents the intra-application communication bandwidth requirement.

³For each VMN model, the total incoming traffic is equally assigned to each instance of MB_k . And the practical required bandwidth b_k for each instance of MB_k can be calculated by $b_k = \frac{N \cdot B^{ex}}{M_k}$.

C. Bandwidth Saving Analysis

Finding beneficial placement principles We try to save the total bandwidth requirement B_{total} by reducing the bandwidth consumption of the original four compositions of B_{total} . As illustrated above, the bandwidth composition B_{switch,mb_1} is a constant and cannot be saved. Thus, we consider to achieve bandwidth saving by reducing the bandwidth consumption of the remaining three compositions, i.e., $B_{mb_k,mb_{k+1}}$, $B_{mb,app}$, and B_{app} . More specifically, to reduce the traffic $B_{mb_k,mb_{k+1}}$ and $B_{mb,app}$ crossing the subtrees caused by the mismatched capacities between the upstream and downstream MBs or APPs, we can place the MBs and APPs proportionally in the subtree according to their traffic processing capacity. In addition, with the increase of n_{app} , the intra-application bandwidth B_{app} increases from zero to $2 \cdot (N/2) \cdot B^{in}$ when $n_{app} = N/2$ and then decrease to zero. Thus, we can greatly save the intra-application bandwidth B_{app} through colocating as many APP VMs as possible in one subtree. To sum up: 1) placing different types of MBs with APP VMs together proportionally⁴ is an effective approach to reducing the bandwidth consumption of $B_{mb_k,mb_{k+1}}$ and $B_{mb,app}$, and 2) colocating APP VMs in one subtree is much beneficial to save the intra-application bandwidth requirement B_{app} .

The problem of enforcing the beneficial placement principles However, the two beneficial placement principles cannot be always enforced simultaneously due to the limited available VM slot resources in one subtree. As illustrated in Fig. 5, the VMs for middleboxes and application of the tenant request have to be distributed among the two subtrees since one subtree cannot accommodate the full request. Specifically, the APP VMs have to be placed in both two subtrees when enforcing the first principle, which will conflict with the second principle. When colocating all APP VMs in one subtree, the remaining available slots in the same subtree will be unable to hold the MB VMs and we have to place the MB VMs in another subtree, which will break the first principle. While the conflict or break is worthy when the achieved benefit of break exceeds the break loss.

Combining the placement principles Guided by the observations above, we seek to firstly consider enforcing the principle 1 and then try to improve the benefit of principle 2 by carefully breaking the enforced principle 1. Further, we can exchange the positions of MB and APP in two subtrees to increase the degree of APP colocation in one subtree when principle 1 is already enforced. The position exchanging may lead to mismatched capacities between the upstream and downstream MBs or APPs and produce extra traffic across subtrees. The bandwidth requirement $B_{mb_k,mb_{k+1}}$ or $B_{mb,app}$ then has an increment. On the contrary, we have a reduction

⁴Assume the total free VM slots in the left subtree is N_{slot} , then the number of MB_k needed to be placed in the left can be calculated by $m_k = \left\lfloor \frac{M_k}{\sum_{i=1}^n M_i + N} \cdot N_{slot} \right\rfloor$. The number of APPs needed to be placed in the left is computed as $n_{app} = \left\lfloor \frac{N}{\sum_{i=1}^n M_i + N} \cdot N_{slot} \right\rfloor$. Correspondingly, the numbers of MB_k and APP placed in the right are given as $M_k - m_k$ and $N - n_{app}$ respectively.

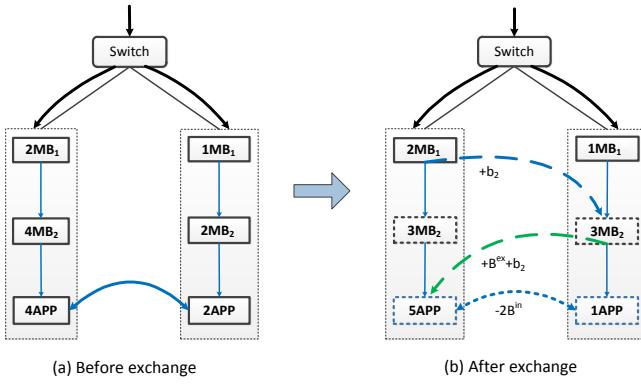


Fig. 6. Illustration of the bandwidth variation after exchange

of intra-application bandwidth requirement B_{app} because of more APP VMs colocated. Therefore, we need to carefully select MB to exchange with APP to achieve the benefit of exchanging.

Selecting proper middleboxes to exchange We then analyze the change of the total bandwidth requirement before and after the position exchanging to help to select the proper MB to exchange. The exchange can break the proportion relation of the numbers of MB and APP VMs in the same subtree, which will cause extra flows from one side to the other side and increase the bandwidth demands across the subtrees. On the other hand, we can increase the colocated APPs by exchanging, which will greatly reduce the intra-application bandwidth requirement. We let C_1 represent the increased portion of bandwidth due to the proportion relation breaking or capacities mismatching, and C_2 denote the decreased portion of bandwidth caused by increasing the number of colocated APPs. If $C_1 > C_2$, we say the portion of bandwidth reduction by colocating APPs is not able to make up for the cost of increased portion. The total bandwidth requirement then have an increase of $C_1 - C_2$. However, if $C_1 < C_2$, there will be much benefits to exchange since the total bandwidth cost will have a reduction of $C_2 - C_1$. Therefore, the total bandwidth consumption may have an increase or decrease after the exchange.

For a more intuitive understanding of above results, consider a simple example as shown in Fig. 6. The tenant request has been placed in two subtrees proportionally according to the placement principle 1 showed in Fig. 6(a). So the bandwidth requirements $B_{mb_k, mb_{k+1}}$ and $B_{mb, app}$ are reduced to zero since the traffic from MB_k can be fully processed by MB_{k+1} s or APPs in the same subtree. Note that the number of APPs in the left subtree is larger than the number in the right side. We then try to exchange the MB_2 in the left side and APP in the right side to reduce the traffic across the subtrees between APPs.

The result of exchange is shown in Fig. 6(b). The dashed arrows show the change of traffic after exchange. The label

associated with each arrow is the value of traffic change. The long-dashed arrows show the increased portion of the bandwidth in the two links. While the short-dashed arrow represents the decreased portion of bandwidth across the subtrees. After the exchange, the MB_2 in the left side cannot totally handle the traffic from MB_1 in the same side. This leads to an extra flow from MB_1 in the left to MB_2 in the right side expressed in the blue long-dashed arrow. Similarly, the APPs in the left side get additional capacity to process the extra flow from MB_2 in the right side due to the exchange showed by the green long-dashed arrow. For the intra-application communication, we get a decrease of bandwidth represented by the short-dashed arrow through increasing the number of colocated APPs in one side. Clearly, in this example, C_1 is equal to the sum of the two extra flows' bandwidth requirements computed as $b_2 + (b_2 + B^{ex}) = 2b_2 + B^{ex}$, where b_2 is the practical required capacity of MB_2 mentioned before. And C_2 is equal to $2B^{in}$ which is the bandwidth saving of intra-application communication.

Thus, if $C_2 > C_1$ or $2B^{in} > 2b_2 + B^{ex}$, it is a better choice to exchange, i.e., the total bandwidth consumption in the two links will be reduced if the decreased portion is larger than the increased portion of the bandwidth after the exchange. And, we can easily obtain the following exchange conditions for any MB_k using the same analyzing method as shown above:

$$\begin{aligned} 2B^{in} &> b_k + B^{ex}, k = 1; \\ 2B^{in} &> 2b_k + B^{ex}, k > 1. \end{aligned} \quad (3)$$

Bandwidth saving for the single link We further analyze the bandwidth variation of the single link based on the exchanging strategy above. For the single link, there may be a different result, i.e., the total decrease of the bandwidth cannot ensure that both of the links have a reduction of bandwidth. For a better understanding, we assume $b_2 = 200$, $B^{ex} = 600$, and $B^{in} = 502$ (in Mbps). It is clear that MB_2 satisfies the exchange condition mentioned above. Consider the simple example shown in Fig. 6. The right link get a bandwidth reduction computed as $B^{in} - b_2 = 502 - 200 = 302$ Mbps after exchange. While the left link have a bandwidth increase of $(B^{ex} + b_2) - B^{in} = 600 + 200 - 502 = 298$ Mbps. So the total bandwidth has been reduced. But the exchange may lead to an unbalanced utilization of the two links. And the tenant request will be rejected if the remain bandwidth is smaller than 298 Mbps in the left link before the exchange. To avoid this situation, we reconsider the condition of exchange to ensure that both links have bandwidth savings.

As shown in Fig. 6, the two links both get an extra traffic flow which causes a bandwidth increase (b_2 and $B^{ex} + b_2$ respectively) from the opposite side, respectively. In addition, there is a bandwidth reduction of B^{in} for intra-application communication in both of the links. Further, for the left link, there is a bandwidth variation $C_l = B^{ex} + b_2 - B^{in}$. While for the right link, the bandwidth variation is $C_r = b_2 - B^{in}$. If $C_l < 0$ (or $C_r < 0$), the bandwidth demand will be reduced in the left link (or right link).

Hence, the condition to have bandwidth savings for both links is given as

$$C_l < 0 \quad \text{and} \quad C_r < 0 \quad (4)$$

i.e, if $B^{in} > (B^{ex} + b_2)$, the bandwidth will be saved for both of the links. Similarly, we can obtain the following improved conditions to get a more appropriate exchanging for any middlebox MB_k .

$$\begin{aligned} B^{in} &> b_k \quad \text{and} \quad B^{in} > B^{ex}, k = 1; \\ B^{in} &> b_k + B^{ex}, k > 1. \end{aligned} \quad (5)$$

Further, using the improved exchangeable conditions to select the proper type of middleboxes for exchanging⁵, we cannot achieve a total bandwidth saving but ensuring a bandwidth reduction for each of the links when placing the tenant request.

Algorithm 1 VM Placement Algorithm

```

1: function PLACETENANT(Tenant t)
2:   st = FindlowestSubtree(t, null);
3:   while st do
4:     AllocateVM(t, t.mb, t.app, st);
5:     if ReserveBw(t) then
6:       return true;
7:     DeAllocate(t);
8:     st = FindLowestSubtree(t, st);
9:   return false;
10: function ALLOCATEVM(t, Nmb_app, st)
11: /* Nmb_app stores the numbers of instances for
12:   each type of middleboxes, and application VMs */
13: if level(st)==0 then /*st is a server*/
14:   PlaceMBAPP(t, Nmb_app, st);
15: else
16:   for each subtree v of st do
17:     if freeVM(v)>0 then
18:       if freeVM(v)<TotalVM(Nmb_app) then
19:         place MBs and APPs
20:         proportionally under v;
21:         /* Nv_mb_app stores the numbers of
22:           MBs and APPs placed under v */
23:         Nmb_app = Nmb_app - Nv_mb_app;
24:         ExchangeMbApp(t,Nmb_app,Nv_mb_app);
25:         AllocateVM(t, Nv_mb_app, v);
26:       else
27:         AllocateVM(t, Nmb_app, v);

```

D. VM Placement Algorithm

Based on above placement principles and exchangeable conditions, we design an effective heuristic VM placement algorithm that achieves bandwidth savings while providing guarantees. The basic idea behind the algorithm is to place

⁵Eq. 5 is a sufficient but not necessary condition for bandwidth saving through exchanging, and we can also have bandwidth saving even the VMs are placed randomly initially by exchanging using Eq. 5.

MBs and APPs proportionally initially to minimize the bandwidth consumption due to the unbalanced capacity assignment between middleboxes and application VMs; and then try to colocate more APPs to reduce the bandwidth cost of intra-application communication through exchanging MBs and APPs.

Algorithm 1 depicts the process to handle a tenant request. The algorithm starts with *PlaceTenant* (line 1), which takes a tenant request t as an input. To save the precious core level bandwidth, we traverse the datacenter topology in a bottom-up manner to search for a valid lowest level subtree that has enough VM slots for t (line 2). For the candidate subtree, we place t in it with *AllocateVM* (line 4) and then check whether the bandwidth requirement can be satisfied (line 5). If the trial fails due to the lack of bandwidth, *DeAllocate* (line 7) is invoked to release the resources reserved for the tenant request. And the algorithm continues to find another subtree in the same level or upper level if there is no subtree in the same level (line 8).

AllocateVM (line 10) is a recursive function, which takes a tenant request t , its APP and MB VMs number and a subtree st as inputs. The function first checks if the st is the lowest level subtree or physical server: if so, it allocates corresponding number of slots for t according to the parameters of N_{mb_app} in the server and then returns. If st is a higher level switch, we then invoke *AllocateVM* recursively for each subtree v of st which has free VM slots. For the subtree v that cannot provide enough slots for the unallocated MB and APP VMs, we first attempt to place appropriate number of MBs and APPs according to the placement principle 1 to fill the subtree v and then colocate as many APPs as possible by exchanging MBs and APPs using the exchangeable conditions of Eq. 5. After that, we invoke the function *AllocateVM* (line 25) for the adjusted MB and APPs. While for the subtree of st that has sufficient slot resource, *AllocateVm* is invoked directly (line 27).

In Algorithm 2, *ExchangeMbApp* (line 1) is invoked to exchange the positions of MBs and APPs. The function first identifies the types of middleboxes that can achieve bandwidth saving through exchanging their and APPs' positions by using the exchangeable conditions of Eq. 5 (line 2). If the exchangeable middleboxes exist, we then check the number of APPs in the two subtrees and exchange the smaller one with the MBs to increase the degree of colocation for APPs. We execute the exchanging until all exchangeable MBs or APPs have been exchanged. If current exchangeable MBs have been exchanged completely, we then select the next exchangeable type of MBs to exchange (line 9). After each exchanging, we update the numbers of MBs and APPs in the two sides.

V. MIDDLEBOX SCALING APPROACH

To address the middlebox scaling problem, instead of allocating new resources of VMs and network after MBs are placed in datacenters, we introduce a probability model to represent the variable resource requirement of individual tenant. Through statistically multiplexing on VMs, we are able

Algorithm 2 Exchange Algorithm

```

1: function EXCHANGEMBAPP( $t, N_{mb\_app}, N_{v\_mb\_app}$ )
2:    $mb = \text{GetExchangeableMB}(t);$ 
3:   if  $mb \neq \text{null}$  then
4:      $num$  is assigned as the number of types
5:       of the exchangeable MBs;
6:      $k = 0;$ 
7:     if  $N_{mb\_app}[app] > N_{v\_mb\_app}[app]$  then
8:       while  $k < num$  and  $N_{v\_mb\_app}! = 0$  do
9:         if  $N_{mb\_app}[mb[k]] == 0$  then
10:           $k++; continue;$ 
11:          /* update the numbers of MBs
12:           and APPs in both sides */
13:           $N_{mb\_app}[mb[k]]-; N_{mb\_app}[app]++;$ 
14:           $N_{v\_mb\_app}[mb[k]]++; N_{v\_mb\_app}[app]-;$ 
15:        else
16:          while  $k < num$  and  $N_{mb\_app}! = 0$  do
17:            if  $N_{v\_mb\_app}[mb[k]] == 0$  then
18:               $k++; continue;$ 
19:              /* update the numbers of MBs
20:               and APPs in both sides */
21:               $N_{v\_mb\_app}[mb[k]]-; N_{v\_mb\_app}[app]++;$ 
22:               $N_{mb\_app}[mb[k]]++; N_{mb\_app}[app]-;$ 

```

to balance the physical resources consumption and scalability requirement of software MBs.

We re-examine the MBs request and take the time-varying resource requirements of MBs into consideration. Specifically, the MBs' requirement is composed of a basic requirement and a scaling requirement with probability. Based on this model, we replace the $\langle T, M \rangle$ in Section III-B with tuples $\langle T, M, m, P \rangle$, where T and M denote the type of MBs and the corresponding number of VMs in the basic requirement, and m denotes the number of VMs in the scaling requirement with probability P . For example, given $T = \{\text{FW, IDS, LB}\}$, $M = \{2, 4, 2\}$, $m = \{1, 2, 1\}$, $P = \{0.3, 0.2, 0.3\}$, we then know that the tenant requests 2 firewall MBs and the request may increase to $2 + 1 = 3$ MBs with probability of 0.2. Similarly, 4 IDS MBs (resp. 2 LB MBs) are needed with probability 0.8 (resp. 0.7) and 6 IDS MBs (resp. 3 LB MBs) with a probability of 0.2 (resp. 0.3). In summary, a tenant's request can be specified by multiple virtual networks (VNs) and each VN can be specified by an eight-tuple $\langle N, B^{in}, B^{ex}, dependencies, T, M, m, P \rangle$. It allows elasticity by having a probability model for the number of MBs needed in each VN.

If multiple units of the scaling requirement do not occur simultaneously, we can provide few redundancy to tradeoff between utilization and availability. By sharing free VMs between variable subrequirements, a specific MB can be soon deployed on the free VM once the scale up/out requirement comes. Although the subrequirement occurs with a probability less than 1, the collision may happen if there is not enough VM provided. To guarantee the performance, we apply the probabilistic model to solve this problem.

For simplicity, we reuse the notation T to indicate how many types of MBs are required by tenant. Let X represent the practical scaled number of VMs and X_i taking values in $\{0, 1\}$ indicates whether the i -th scaling subrequirement occurs. Clearly, $X = \sum_{i=1}^T X_i \cdot m_i$. Assuming the resource requirement of different middleboxes are independent and v free VMs are reserved for multiplexing, the probability of the collision happening is

$$\begin{aligned}
Pr[X > v] &= Pr\left[\sum_{i=1}^T X_i \cdot m_i > v\right] \\
&= Pr[X = v+1] + Pr[X = v+2] \\
&\quad + \dots + Pr[X = m] \\
&= \sum_{i=v+1}^m Pr[X = i],
\end{aligned} \tag{6}$$

where m_i is the i -th scaling subrequirement and m is the max number of possible scaled VMs and equal to the sum of all number of VMs in the variable subrequirement, i.e., $m = \sum_{i=1}^T m_i$. By providing enough number of free VMs during virtual middleboxes network deployment, the probability of collision can be guaranteed less than a collision threshold ρ when the system is on board. The number of v reserved for sharing can be determined by solving the following function:

$$Pr[X > v] \leq \rho \quad \text{or} \quad Pr\left[\sum_{i=1}^T X_i \cdot m_i > v\right] \leq \rho. \tag{7}$$

The upper bound of collision probability $Pr[X > v]$ can be achieved based on the Markov's inequality, i.e.,

$$Pr[X > v] \leq \frac{E(X)}{v}. \tag{8}$$

$E(X)$ is the expectation of X and can be calculated by $E(X) = E(\sum_{i=1}^T X_i \cdot m_i) = \sum_{i=1}^T E(X_i) \cdot m_i$. Generally, let $\frac{E(X)}{v} = \rho$, we can obtain a rough evaluation for v . However, for a higher utilization of reserved VMs, a preciser value of v is required. Considering the numbers of MB types and possible scaled VMs are small, we can easily compute the probabilities $Pr[X = i]$ related to the possible numbers of scaled VMs according to the tuple $\langle m, P \rangle$. Further, we can get the minimum number of extra VMs needed to be reserved by solving:

$$\min_{v \geq 0}(v) \quad \text{s.t.} \quad \sum_{i=v+1}^m Pr[X = i] \leq \rho. \tag{9}$$

Therefore, the total number of MB VMs to be allocated for one tenant is $|M| + v$, where $|M|$ is the number of basic MBs requirement and v is the minimum additional free VMs to be allocated as backup resources.

Fig. 7(b) uses the cascade of TAG model to abstract the communication dependency of VNs given in Fig. 7(a). In comparison with Fig. 4, the VMs inside the blue dotted line are pre-allocated VMs for middleboxes subrequirement, which are shared by both types of middleboxes requests. Specifically, the

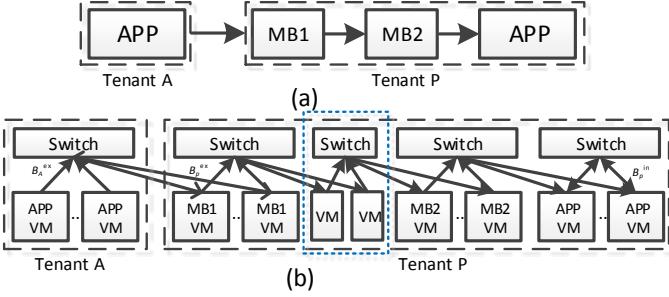


Fig. 7. Virtual Network Model. (a) the communication between two tenants; (b) cascade of TAG

reserved free VMs are pre-allocated under the same subtree as normal allocated VMs, which can greatly reduce unnecessary bandwidth consumption crossing racks or subtrees. If there are scale-out or failover request, specified MBs will be placed on these VMs to provide performance guarantee.

VI. EVALUATION

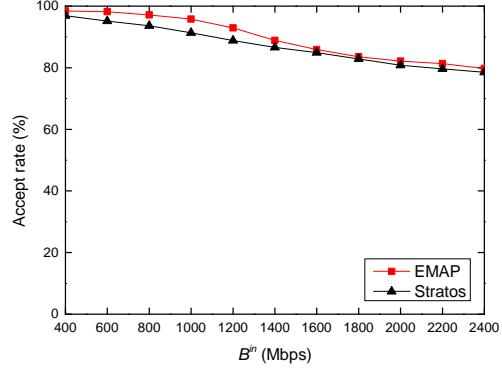
In this section, we first evaluate the benefits of our VMM model with exchanging placement algorithm. Then we simulate the tenants' scaling requirements and verify the effectiveness of our probability model based scaling approach.

A. Simulation Setup

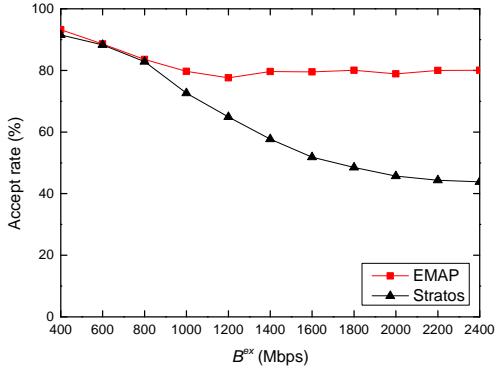
We build a tree-like three-layer network topology, which is inspired by a real cloud datacenter with 30000+ VMs. Each ToR switch is connected to 40 physical servers with 10Gbps NICs. And every PM is divided into 8 slots. The oversubscription ration are 4:1 at the leaf level and 10:1 at the spine layer.

Tenant To simulate the tenant request, we model the intra-application bandwidth B^{in} and inter-tenant bandwidth B^{ex} to follow normal distribution. The maximal capacity b_k of each type of middleboxes also follows the normal distribution with average value as 1000. For simplicity, we assume that each tenant request only contains one middlebox chain. The length of the middlebox chain is randomly selected in [1,5]. And the number of APP VMs required corresponding to a middlebox chain is equally distributed between 3 to 10. The fraction of open tenants is set to be 10% while the fraction of client tenants is defined as 25%. Furthermore, there are also some tenants that have communication request with each other. We set the fraction of these tenants to be 15%.

VM placement We consider two placement algorithms: 1) a VM placement strategy (without scaling requirement) described in Stratos [2] which logically partitions the VMs into per-rack partitions and places them with minimal inter-partition communication; 2) our placement algorithm (vMAP) that places the MB and APP VMs carefully given in Algorithm 1. To compare the two placement algorithms, we create tenant requests continuously until the datacenter could not accept tenant request any more.



(a) Accept rates under different B^{in}



(b) Accept rates under different B^{ex}

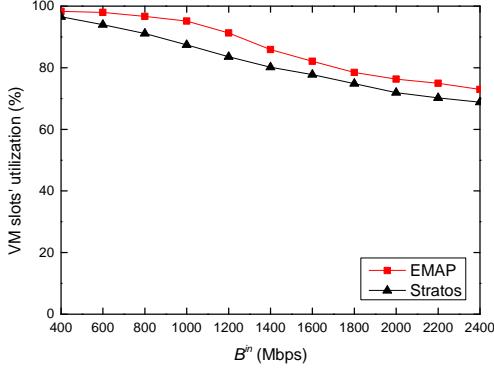
Fig. 8. Accept rates under different B^{in} and B^{ex}

Scaling requirement For each tuple $\langle m, P \rangle$ of the scaling requirement, the scaling number m_i of each MB is equally distributed in [1,8] and the scaling probability P_i follows normal distribution with a mean value of 0.5.

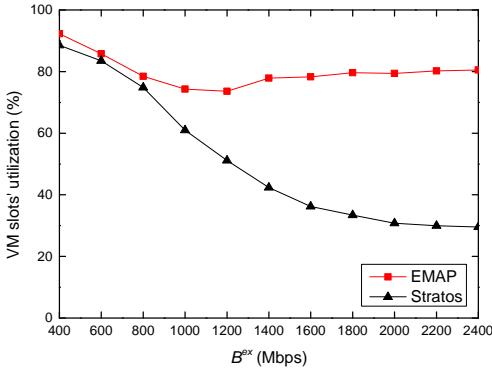
B. Simulation Results

Placement of middleboxes and application We first evaluate the tenant accept rates under different B^{in} and B^{ex} in Fig. 8. In Fig. 8(a), we consider the accept rate of tenant requests with various intra-application communication demands (B^{in}). $B^{in}=1200$ means that the tenants B^{in} follows the normal distribution with average value as 1200 and variation equal to $B^{in}/3=400$. In Fig. 8(a), we find that both algorithms have similar accept rates with varying B^{in} .

The result of accept rate with varying external bandwidth (B^{ex}) is shown in Fig. 8(b). Similarly, $B^{ex}=1200$ means that B^{ex} follows the normal distribution with average value of 1200 and variation as $B^{ex}/3=400$. We find that vMAP can always accept tenant requests repositively. And even with large B^{ex} , vMAP can keep a relatively high accept rate. While the accept rate of Stratos drops quickly when B^{ex} is greater than 800Mbps. This is because Stratos occupies more bandwidth



(a) VM slot utilizations under different B^{in}

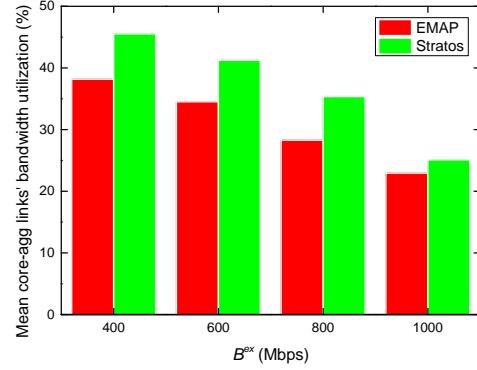


(b) VM slot utilizations under different B^{ex}

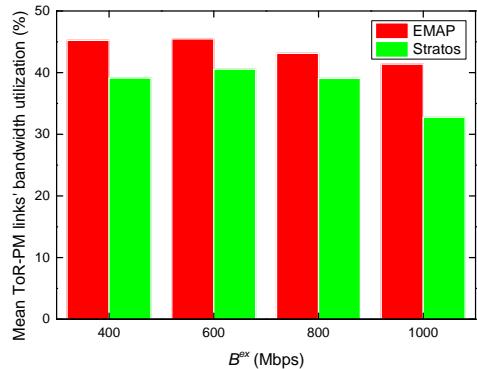
Fig. 9. VM slot utilizations under different B^{in} and B^{ex}

resource in core-level links. More specifically, the number of total VMs required for tenant requests increases as B^{ex} increases since we need more middlebox instances to process a larger external traffic. This leads to an increased demand for VM slots resource in the data center, and the tenant requests are forced to spread their VMs across more racks. The placement strategy used in Stratos is more likely to select the racks that reside across several subtrees to accommodate the tenant request, which may cause a big waste of bandwidth in the core-level links. While our placement algorithm always tries to select the lowest-level subtree that has sufficient VM slots for the tenant, which can save the precious bandwidth resource of the core-level links effectively. Thus, vMAP is helpful to allow the provider to accommodate more tenant requests while reducing the bandwidth utilization of core-level links which allows more future tenant requests to be accepted.

Fig. 9 plots the VM slots utilization of the datacenter under different B^{in} and B^{ex} . We can see that the results of VM slots utilization have similar changing trends compared to the accept rates shown in Fig. 8. This is reasonable since higher accept rates represent that there are more requests accepted and more VM slots resources allocated.



(a) Core-aggregation links' bandwidth utilizations



(b) ToR-PM links' bandwidth utilizations

Fig. 10. Bandwidth utilizations under different B^{ex}

For a better understanding of above results, we further evaluate the downlink bandwidth utilization of core-aggregation and ToR-PM links. Note that the servers are on the same layer of the three-level network topology, if there is one download bandwidth consumption, there must be another upload bandwidth consumption correspondingly. This leads to the result that the download and upload results are similar to each other. Hence, we just show the results of the download bandwidth here. The results are shown in Fig. 10, where the x-coordinate shows the intra-application bandwidth (B^{in}) consumption, and the y-coordinate shows the average bandwidth utilization of the core-aggregation and ToR-PM download links in the two subfigures respectively. In Fig. 10(a), we can see that vMAP has lower bandwidth utilization than Stratos in the core-aggregation links. On the other side, vMAP has a higher utilization of the PM-ToR links shown in Fig. 10(b) which, in turn, proves the effect of lowest-level subtrees locality placement of our algorithm. To sum up, vMAP can save the bandwidth efficiently of core-level links which are usually the bottlenecks for most oversubscription data center networks while making the best of low-level links bandwidth.

Middlebox scaling approach We then evaluate the ef-

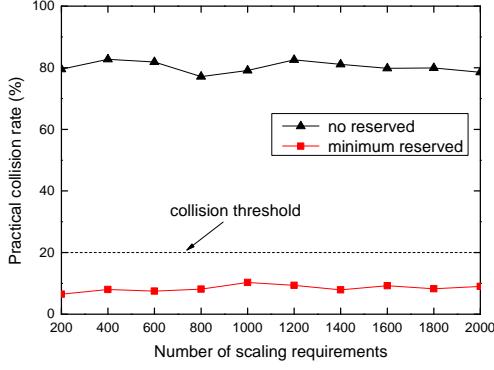


Fig. 11. Practical collision rates

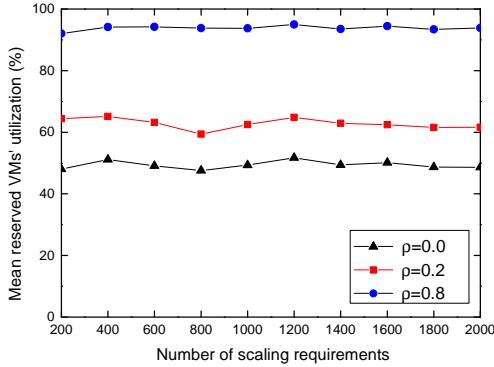


Fig. 12. Reserved VMs' utilizations

fectiveness of our probability model based scaling approach. Fig. 11 plots the practical collision rates as the number of scaling requirements increases. Specifically, we consider the practical collision rates of two different situations: 1) no free VMs reserved 2) and minimum number of free VMs needed to be reserved given a collision threshold $\rho = 0.2$. We can find that the collision rates can be controlled under the threshold stably by reserving a few free VMs for the scaling requirement, while the collision rates are comparatively high if no free VMs are reserved.

In Fig. 12, we further evaluate the reserved VMs' utilizations with different collision thresholds as the number of scaling requirements increases. As we can see that a higher reserved VMs' utilization relates to a larger collision threshold. In particular, we can guarantee that each scaling requirement is satisfied by setting threshold $\rho = 0.0$ at the cost of wasting almost a half of reserved VMs resources, which is not economic. We can also improve the reserved VMs' utilizations by setting a large value of ρ (such as 0.8) while having to tolerate a high collision rates resultantly. To further illustrate the relations of reserved VMs utilizations, collision rates and collision thresholds, we plot the simulation results of the

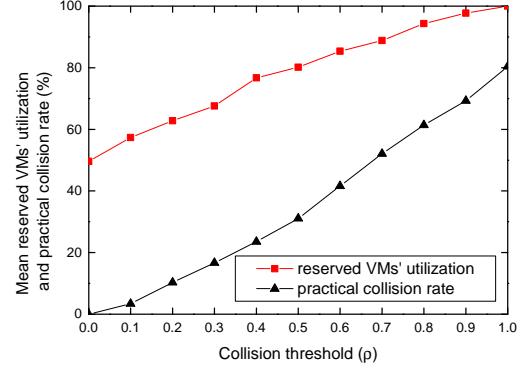


Fig. 13. Reserved VMs' utilizations and practical collision rates under different collision thresholds

relations in Fig. 13. As shown by the two lines, the reserved VMs' utilizations and practical collision rates grow linearly in terms of the collision thresholds. When the collision threshold is equal to 0.4, we can have a higher reserved VMs utilizations (almost 80%) with a lower practical collision rates (23%).

Summary The proposed exchanging algorithm for middleboxes and application can save the core-level bandwidth efficiently while making best use of the low-level bandwidth, which leads to a high accept rate of the tenant requests. And through VM resources reserving and multiplexing based on a probability model, we can accommodate the scaling requirement effectively while minimizing unnecessary resource waste.

VII. CONCLUSION

Since middleboxes are widely used in current networks, it is essential to consider middleboxes when deploying the tenant request with performance guarantees. In this paper, we introduced vMAP, a joint virtual middlebox and application deployment solution. We first models the tenant's requirement of software middleboxes and applications. By augmenting software middleboxes as VMs in the Tenant Application Graph, a VMs placement algorithm is then proposed to place these VMs (including both normal application VMs and virtual middleboxes) in the underlying infrastructure. To address the middlebox scaling problem, we propose a probability model based approach to accommodating the middlebox scaling requirement by reserving a few additional free VMs, which is beneficial for fast deployment and saving precious network resources. The evaluation results have shown that the proposed joint virtual middleboxes and application placement algorithm can efficiently use the resource of multi-tenant datacenters and provide performance guarantee for tenants while the probability model based middlebox scaling approach can accommodate the variable requirements effectively.

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