Game Based Virtual Bandwidth Allocation for Virtual Networks in Data Centers

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Abstract

In current data center, virtual machines may experience severely degraded performance due to the competing of network traffic on shared physical links. This situation is mainly caused by unreasonable and unfair allocation of the bandwidth resource. This paper presents a schema based on the idea of non-cooperative game theory in the field of microeconomics for dynamic bandwidth resource allocation between virtual networks. By modeling virtual networks as competing players and giving the pricing mechanism which decided by the physical substrate network and to guarantee efficiency, the schema can achieve optimal bandwidth allocation at the Nash equilibrium point of the game. We prove that the scheme admits a unique equilibrium point. Experimental results show that the bandwidth allocation between virtual networks is efficient and fair.

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1. Introduction

In recent years, more and more data centers are being built to provide increasingly popular online application services, such as search, e-mails, IMs, web 2.0, and gaming, etc. These data centers often host some bandwidth-intensive services such as distributed file systems (e.g., GFS [1]), structured storage (e.g., BigTable [2]). There are significant networking requirements across all these cases.

The major cause of congestion in current data center is that non-coordination of these traffic may result in the number of packets exceed the buffering capacity of the switch for output. In modern data centers, especially towards the cloud computing, not all network traffic is TCP (or TCP-friendly) and not all protocols perform self-regulation the way TCP does. In fact, a growing proportion of network traffic is not TCP-friendly such as streaming media, voice/video over IP, and peer-to-peer traffic. Although TCP is
self-regulating, even a small amount of non-TCP friendly traffic can disrupt fair-sharing of switched network resources.

Network virtualization has opened up new opportunities for explicit coordination that are simple, effective, feasible, and complementary to switch-level hardware support. Network virtualization can extenuate the ossifying forces of the current Ethernet and stimulate innovation by enabling diverse network architectures to cohabit on a shared physical substrate \[3, 4\]. In the main thought of network virtualization, virtual machines of same applications in data center are partitioned into same virtual networks by network slicing; therefore the business model can be two part: infrastructure provider who builds the data center fabric and service provider who rents the virtual machines to run their own applications and provides Internet service.

This paper makes the case for dynamic bandwidth allocation between virtual links after the creation of virtual networks in the data center Ethernet to proactively prevent network congestion and provide more agility. By leveraging the non-cooperative game theory in the field of microeconomics, virtual networks are modelled as competing players to run a game. We also present a pricing mechanism which decided by the physical substrate network to guarantee efficiency and prove that the given schema can prevent congestion and maximize the utilization of the physical substrate network.

The rest of the paper is organized as follows. The basic game model is presented in Section 2. In section 3, we describe a distributed implementation for dynamic bandwidth allocation running on programmable switches. Section 4 presents experimental evidence via a simulation implementation. Section 5 gives the conclusion.

2. Basic model

The virtual bandwidth allocation optimization model in this section is considered from the overall perspective of the system which contains virtual networks and substrate hardware resource, i.e. the bandwidth of the physical network. Consider a substrate network with a set \( L \) of links, and let \( C_j \) be the capacity of substrate link \( j \in J \). The network is shared by a set \( N \) of virtual networks and indexed by \( i \).

Define a vector \( b_{il} \) which denotes the allocated bandwidth of virtual network \( i \) in link \( j \). Let \( U_i(b_{il}) \) be the utility of virtual network \( i \) as a function of his bandwidth \( b_{il} \). Note that the utility \( U_i(b_{il}) \) should be an increasing, nonnegative, strictly concave and twice continuously differentiable function of \( b_{il} \) over the range \( b_{il} \geq 0 \). Assume further that utilities are additive. The bandwidth control problem can be formulated as the following optimal problem. The bandwidth control problem can be formulated as the following optimal problem.

\[
P1: \quad \text{MAX} \sum_{i=1}^{N} \sum_{l=1}^{L} U_i(b_{il})
\]

\[
s.t. \quad \forall i, \forall l, \quad b_{il} \geq 0,
\]

\[
\forall l \in L, \quad \sum_{i=1}^{N} b_{il} \leq C_l
\]

For each virtual network, its bandwidth must be greater than or equal to 0, the total bandwidth of all virtual networks in physical link \( l \) does not exceed the maximum bandwidth \( C_l \) allowed by the hardware. Since the utility functions are strictly concave, and hence continuous, and the feasible solution set is compact then the above optimal problem has a unique optimal solution.

\( P1 \) is an overall problem with multiple constraints. Considering the fact that virtual networks on data centers are of non-cooperative nature in terms of their demand for networks resources, leveraging non-cooperative game theory, let the network announce a rental price per unit of bandwidth, then let all virtual
networks play a non-cooperative game, the resulting bandwidth allocation at the Nash equilibrium point of the game solves the above optimal problem $P1$.

3. Distributed implementation

As mentioned above, the solution for virtual bandwidth allocation in data center is still a global problem. It’s impossible to manage vast amounts of virtual nodes in large-scale network, because a centralized solution which requires real-time access to all physical switches within the physical network to get virtual bandwidth consumption and also need a large-scale computing is obviously unrealistic. There is no gain in using the local interpretation unless we can devise a local way to solve the problem. In this section, we present a distributed framework which running on the rack switches in data centers to implement the bandwidth control game.

The overall optimization problem $P1$ can be split into several distributed problem. Recall the problem in the previous section, each $b_{il}$ in vector $b_i = (b_{il}, l \in L)$ denotes the allocated bandwidth for virtual network $i$ in link $l$. For any set of virtual network links $L$, we have $L_i \subseteq L$. Taking into account of the diversification and variability of virtual network topologies, we need to regulate all dimensions of $L_i$ and make it equal to the dimension of $L$. Let $L_i'$ be the new link set of virtual network $i$, the two under sets are equivalent.

\[
L_i' \equiv L_i', \quad \forall l \in L_i, \begin{cases} 
L_{il} = 1, & \text{if } l \in L_i; \\
L_{il} = 0, & \text{if } l \notin L_i;
\end{cases}
\]  

(1)

$L_i' = 0$ means that the bandwidth allocated for virtual network $i$ on link $l$ is 0. Then the overall optimal problem $P1$ can be rewritten as:

\[
\text{MAX } \sum_{i=1}^{N} \sum_{l=1}^{L} U_i(b_{il}) = \sum_{i=1}^{N} \sum_{l=1}^{L} U_i(b_{il})
\]  

(2)

From equation (2) we can see the $P1$ can be transformed into $L$ sub optimization problems on each network port of rack switches. When the bandwidth allocation for every virtual network on each port of the rack switches in the physical network is optimal, the overall optimization problem $P1$ can be solved simultaneously. This distributed solution in large-scale data center network was feasible, and can be easily achieved.

Then we can get the sub optimization problems on each network port of rack switches:

\[
\text{MAX } \sum_{i=1}^{n} U_i(b_i)
\]

s.t. $\forall i, \quad b_i \geq 0,$

\[
\sum_{i}^{n} b_i \leq C_i
\]  

(3)

Where $n$ is the number of virtual networks, $b_i$ denotes the allocated bandwidth for virtual network $i$. $U_i(b_i)$ is the utility function discussed in the previous section. Then we can build the non-cooperative game model for bandwidth allocation according to sub optimization problem (3). Giving the utility function of each virtual network:

\[
F_i(\omega_i, b_i) = u_i(b_i) - \omega_i
\]  

(4)
Where $\omega_i$ is a willingness-to-pay (also called a bid) announced by virtual network $i$ to the substrate network, $u_i(b_i)$ is the utility function of virtual network $i$ likes $U_i()$. After collecting each $\omega_i$, the substrate network chooses a bandwidth allocation strategy $\bar{b}(b_1, b_2, ..., b_N)$. If the substrate network always seeks to allocate the entire link capacity, then price is calculated as follows:

$$p = \sum_{i=1}^{n} \frac{\omega_i}{C_i}$$  \hspace{1cm} (5)

Assuming that all virtual networks on link $l$ are rational and do not know the bid of any other virtual networks, then equation (4) and (5) define a non-cooperative game, at the Nash equilibrium point of the game the bandwidth allocation is optimal.

We then proof there exists a unique Nash equilibrium point in the game definite by (4).

**Proof:**

From equation (5) we can calculate the allocated bandwidth for virtual network $i$: $b_i = \frac{\omega_i}{p}$. Then rewrite the utility function of each virtual network:

$$F_i(\omega_i, \omega_{-i}) = u_i(\frac{\omega_i}{\sum_{i=1}^{n} \omega_i} c) - \omega_i$$  \hspace{1cm} (6)

Where $\omega_{-i} = (\omega_1, \omega_2, ..., \omega_{i-1}, \omega_{i+1}, ... , \omega_n)$ reflects the effect to virtual network $i$ according to the demand of other virtual networks. For the game definite by equation (6), there exists a Nash equilibrium point only if for any virtual network $i$, when there is no change on the bid of other virtual networks, there is a fixed strategy $\omega^*$ meet:

$$F_i(\omega^*, \omega^*_{-i}) \geq F_i(\tilde{\omega}, \omega^*_{-i})$$  \hspace{1cm} (7)

Let $W_{-i} = \sum_{i \neq k} \omega_k$, substitute it into (6) and calculate the first order derivative:

$$F'_i = u'_i c \frac{W_{-i}}{(W_{-i} + \omega_i)^2} - 1$$  \hspace{1cm} (8)

Since $u_i()$ is a twice differentiable concave function, $u'_i c$ is strictly decreasing in $b_i \geq 0$. Obviously, $cW_{-i} / (W_{-i} + \omega_i)^2$ is strictly decreasing in $\omega_i \geq 0$. So $F'_i < 0$, i.e. $F$ is also a twice differentiable concave function, so there exists a unique $\omega^*$ maximize the function $F$, thus the game has a unique Nash equilibrium point. At the equilibrium point the profit of each virtual network is maximized, so the virtual bandwidth allocation strategy is fair and efficient.

4. Performance Evaluation

We implemented the distributed virtual bandwidth allocation schema discussed in Section 3 using OpenFlow VM\(^{[5]}\) environment. For the limitation of the current software, we made a simple but sufficiently persuasive experiment as shown in Fig. 1, where PC 1 has two ports, eth1 and eth2 and PC 2 has one port connect to the OpenFlow Switch.
In PC 1, we use two iperf clients to generate a TCP flow and a UDP flow with destination to PC 2. We test each flow’s assigned bandwidth with and without bandwidth allocation schema to verify the fairness. Note that in the experiment with the allocation schema, link 3 is sliced into two virtual links.

For non-virtualized case as shown in Fig. 2 (a), when UDP flow was sent, the bandwidth assigned to TCP flow dropped seriously. In Fig. 2 (b), for the substrate network was sliced into two virtual networks, and with the dynamic bandwidth allocation schema, both flow’s QoS is guaranteed. They fairly share the bandwidth when they oversubscribed the link simultaneously under same willingness-to-pay. This can confirm the truth of that network virtualization can provide an efficient mechanism to prevent congestion in data center network which full of virtual machines, and also a more agility way for QoS guarantee.

5. Conclusion

This paper introduced a bandwidth allocation schema base game theory to alleviate congestion problems in data center networks. We present a overall optimal problem and give a distributed implementation approach. Maybe there is a certain distance from a practical fully mature system, we believe that network virtualization and dynamic bandwidth allocation are more suitable for the future data center networks, especially in the context of multi-tenancy mechanism of cloud computing.

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