

Postprint of Adaptive Bandwidth Allocation Algorithm Based on Two-Level Controller and Linear Model

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Abstract

To address the bandwidth allocation problem in virtualized networks, we propose an adaptive bandwidth allocation algorithm based on a two-level controller system. This controller system consists of a set of SP controllers containing VN sub-controllers and an InP controller. First, the characteristics of each VN at each control interval are locally approximated using a linear model to obtain the relationship between its past and current bandwidth allocations and past packet delay performance. Then, based on the constraints of physical link capacity, the system responds to bandwidth requests from each VN and performs dynamic adjustments to achieve flexible distributed autonomous control and ensure reasonable bandwidth allocation for each VN. Simulation results demonstrate that the proposed algorithm can not only reasonably and dynamically allocate available link capacity among multiple VNs, but also improve the utilization of total bandwidth and the fairness of allocation, satisfying the QoS requirements of each VN.

Full Text

Adaptive Bandwidth Allocation Algorithm Based on Two-Stage Controller and Linear Model

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Abstract: To address bandwidth allocation challenges in virtualized networks, this paper proposes an adaptive bandwidth allocation algorithm based on a two-stage controller architecture. The controller system comprises a set of SP

controllers (each containing VN sub-controllers) and InP controllers. First, the characteristics of each virtual network (VN) at every control interval are locally approximated using a linear model to capture the relationship between its past and current bandwidth allocations and past packet delay performance. Then, based on physical link capacity constraints, the system responds to bandwidth requests from each VN and performs dynamic adjustments to achieve flexible distributed autonomous control while ensuring reasonable bandwidth allocation for each VN. Simulation results demonstrate that the proposed algorithm not only allocates available link capacity reasonably and dynamically among multiple VNs, but also improves overall bandwidth utilization and allocation fairness, thereby meeting the QoS requirements of each VN.

Keywords: controller; linear model; virtual network; bandwidth allocation; Quality of Service

0 Introduction

The exponential growth of Internet users has made it increasingly difficult to provide new services, particularly those with stringent delay requirements. Consequently, the concept of network virtualization has emerged. Network virtualization enables multiple logical networks to operate simultaneously on a shared underlying physical network, with these logical networks commonly referred to as Virtual Networks (VNs). In such environments, each physical link is partitioned into multiple virtual links, with each VN receiving a portion of the available physical link capacity. This technology allows multiple logical networks to coexist on a shared infrastructure, facilitating flexible deployment of Internet services. Simultaneously, network virtualization has transformed Internet Service Providers (ISPs) into two independent entities: Service Providers (SPs) and Infrastructure Providers (InPs), where InPs are also known as substrate physical network or physical link providers.

A critical challenge in network virtualization is Virtual Network Embedding (VNE), which addresses the allocation of physical node and link bandwidth resources to find efficient and optimal mappings of virtual nodes and links onto the underlying physical network. VNE consists of three steps: First, resource discovery, where each InP monitors its physical network and shares information about load, usage, and measurement processes with multiple SPs. Second, virtual network mapping, performed by SPs to match their bandwidth requirements with available network resources—this is the most complex step as it must consider both node and link capacity constraints. Third, bandwidth allocation, a process where InPs reserve and allocate physical resources to virtual nodes and links based on bandwidth requests received from SPs.

Bandwidth allocation constitutes a crucial component of virtual network provisioning. Current bandwidth allocation algorithms for virtual networks can be broadly categorized into static or dynamic methods, implemented as either

centralized or distributed algorithms. Some strategies solve embedding problems, while others provide hybrid solutions for resource discovery and network mapping. For bandwidth allocation among multiple VNs, the objective is to distribute physical link capacity among competing VNs—a significant challenge for both SPs and InPs, as the allocation must consider the Quality of Service (QoS) requirements of data flows traversing each VN, optimize network resource utilization, and avoid physical network congestion. This problem is generally NP-hard, prompting the development of numerous heuristic algorithms.

Existing research has proposed various approaches. Some formulations treat VN embedding as an optimization problem with effective heuristic solutions, incorporating fast rerouting strategies and pre-reserved backup bandwidth on each physical link to handle link failures and support node migration. Other architectures, such as DaVinci, support dynamic adaptive bandwidth allocation for multiple VNs using optimization theory to maximize overall VN performance. In these systems, each physical link periodically reallocates bandwidth shares based on local link load among virtual links, while each VN runs its own traffic management protocol to maximize individual performance objectives. Although such approaches converge quickly to optimal allocations, they do not address scenarios where all VNs become greedy and request excessive bandwidth.

Alternative studies have examined network virtualization mechanisms for proportional bandwidth allocation in virtual machines on SR-IOV platforms, implementing ITR and TBF control mechanisms that effectively manage VM network bandwidth. Other research has proposed dynamic bandwidth reuse algorithms to address resource underutilization caused by virtualization isolation, allowing SPs to further virtualize temporarily idle bandwidth and lease it to other SPs through auctions. Economic models and game-theoretic approaches have also been employed, including non-cooperative game models with iterative algorithms to achieve Nash equilibrium for bandwidth allocation, and two-stage non-cooperative game approaches to reduce management complexity and avoid performance issues.

This paper addresses bandwidth allocation in VN environments by proposing an adaptive algorithm based on a two-stage controller system that considers QoS requirements. The approach locally approximates each VN's characteristics at every control interval using a linear model to capture the relationship between past and current allocations and packet delay performance. The controller system aims to determine optimal bandwidth requests for each VN, enabling them to compete for physical link capacity while minimizing end-to-end delay and ensuring fair, efficient resource allocation.

1 System Design

The physical network is modeled as an undirected graph denoted by $G_v = \{N_v, L_v\}$, where N_v represents the set of physical nodes and L_v represents the

set of physical links. Each link $l_v(i, j) \in L_v$ between substrate nodes i and j is associated with a bandwidth capacity value C_l , representing the total available bandwidth. Figure 1 [Figure 1: see original paper] illustrates the proposed architecture, which comprises a set of SP controllers and InP controllers. Each SP controller consists of multiple VN sub-controllers that monitor dynamic workload changes during each control interval and calculate the required bandwidth capacity to achieve desired performance. InP controllers collect capacity requests from multiple SPs and determine allocation for each physical link based on capacity constraints.

Notation Definitions

- S : Set of all Service Providers SP_n
- I : Set of all Infrastructure Providers InP_k
- V : Set of all Virtual Networks $V_{i,j}$ deployed by an $SP \in S$
- L : Set of all physical links $l_{k,l}$ managed by an $InP_k \in I$
- $VN_{i,j}$: The j -th VN deployed by the i -th SP
- T : Control interval
- $x(T)$: Value of variable x at control interval T
- $F_r^{s,v,l}$: Bandwidth requested by VN $v \in V$ (deployed by $SP \in S$) for physical link $l \in L$
- $F_a^{s,v,l}$: Bandwidth allocated by physical link $l \in L$ to VN $v \in V$ (deployed by $SP \in S$)
- $d_{s,v,l}$: Measured packet delay for VN $v \in V$ (deployed by $SP \in S$) traversing physical link $l \in L$
- $dt_{s,v,l}$: Target packet delay for VN $v \in V$ (deployed by $SP \in S$) traversing physical link $l \in L$
- $p_{s,v,l}$: Packet loss rate for VN $v \in V$ traversing physical link $l_{k,l}$
- $y_{s,v,l} = 1/d_{s,v,l}(T)$: Measured performance metric for VN $v \in V$ at interval T traversing link $l \in L$
- $yt_{s,v,l} = 1/dt_{s,v,l}(T)$: Target performance metric for VN $v \in V$ at interval T traversing link $l \in L$
- $ym_{s,v,l} = y_{s,v,l}/yt_{s,v,l}$: Normalized delay for VN $VN_{i,j}$ traversing link $l \in L$
- $k(T)$: Characteristic parameter of the allocation algorithm at interval T

1.1 SP Controller

The SP controller connects VN sub-controllers with each VN. VN sub-controllers monitor past performance and bandwidth allocations to determine optimal requested bandwidth. The SP controller also collects bandwidth requests from all VN sub-controllers and submits the request vector to each InP. This optimal bandwidth request guarantees packet delay between two physical nodes at a fixed rate based on dynamic workload changes. Each VN sub-controller contains two modules: an estimator and a requestor, as shown in Figure 2 [Figure 2: see original paper].

The characteristics of each VN at control interval T are locally approximated by

a linear model that captures the relationship between bandwidth allocation and packet delay performance for each $VN_{i,j}$, deployed by SP_j . Each SP submits a bandwidth request vector F_r^s to each InP, representing the requested bandwidth for all VNs deployed across different physical links managed by that InP.

1) Estimator: The estimator employs a linear adaptive model to correlate allocated bandwidth on each physical link with VN packet delay, thereby updating the relationship between allocated bandwidth and each VN' s performance. Model parameters are updated at each control interval T using the recursive least squares algorithm shown in Equation (1), enabling periodic learning and adaptive parameter changes.

2) Requestor: Upon receiving estimated linear model parameters, the requestor predicts the bandwidth required for each physical link based on the estimated model to satisfy the target packet delay for $VN_{i,j}$ traversing that link. The requestor' s objective is to find the optimal bandwidth request that meets end-to-end delay requirements by minimizing the following cost function to determine $F_r^{s,v,l}(T)$:

$$\text{Cost function: } \min [a_1, a_2, b_0, b_1]$$

where a_1 , a_2 , b_0 , and b_1 are updated values obtained via recursive least squares algorithm at control interval T .

1.2 InP Controller

The InP controller first receives bandwidth requests from multiple SP controllers, collecting each VN' s bandwidth request for every physical link. It then employs an adaptive allocation algorithm based on link capacities to determine optimal allocation, establishing a mathematical relationship between allocated bandwidth and packet loss for each VN. This provides a feedback mechanism for allocating available link capacity and implements rate-based congestion control by punishing greedy VNs with reduced capacity allocation.

Consider M VNs deployed by N SPs sharing a physical link l managed by a single InP. The InP controller receives bandwidth requests from all VNs competing for available link capacity. It calculates the packet loss probability for the M -th VN based on traffic load generated by the other $M - 1$ VNs. For each physical link l , the InP computes the total bandwidth request from all VNs sharing that link as:

$$F_r^l(T) = \sum_{s=1}^N \sum_{v=1}^M F_r^{s,v,l}(T)$$

If $F_r^l \leq 1$, each VN receives its requested bandwidth. Otherwise, the InP controller calculates two parameters $\alpha(T)$ and $\beta(T)$:

$$\alpha(T) = F_r^l(T) - 1$$

$$\beta(T) = \frac{F_r^l(T)}{F_r^l(T) - 1}$$

where $k(T)$ defines the allocation algorithm's characteristics at time T , $\alpha(T)$ measures overloaded traffic on the link, and $\beta(T)$ measures total allocation load among competing VNs. Boundary conditions for $F_{r0}(T)$ and $F_{rm}(T)$ are defined as:

$$F_{r0}(T) = 0, \quad F_{rm}(T) = C_l$$

The allocation algorithm exhibits the following characteristics when assigning $p_{s,v,l}$: a) If the sum of all requested bandwidth is less than or equal to link capacity, then $p_{s,v,l} = 0$ for all VNs b) If the sum exceeds link capacity, then $p_{s,v,l} > 0$ for all contending VNs c) $p_{s,v,l}$ is a non-decreasing function of requested bandwidth

When $M - 1$ VNs request bandwidth $F_r(T)$ from link L 's capacity C_l , the packet loss rate $P(F_r(T))$ for the M -th VN at control interval T is calculated based on the allocation algorithm's behavior.

2 Algorithm Performance Simulation and Analysis

The performance of the proposed adaptive bandwidth allocation algorithm is evaluated through MATLAB simulations. To reduce complexity, we assume three VNs $\{VN_{1,1}, VN_{2,1}, VN_{3,1}\}$ deployed by three different SPs sharing a single physical link $l_{1,1}$ managed by InP_1 . The control interval is set to $T = 1s$, with target delay configured at 10ms per control interval.

Figure 3 [Figure 3: see original paper] shows the bandwidth requested by $VN_{1,1}$, $VN_{2,1}$, and $VN_{3,1}$ from physical link $l_{1,1}$, along with the actual bandwidth obtained through both the proposed adaptive algorithm and the Proportional Share Algorithm (PSA). The results demonstrate that the adaptive algorithm responds effectively to workload variations on the physical link. Each VN monitors its past packet delay and bandwidth allocation to understand their interrelationship, stabilizing the workload. When the total bandwidth request from the three VNs exceeds link capacity (i.e., when VNs become greedy), the adaptive algorithm penalizes them by allocating appropriate bandwidth to prevent congestion from large traffic bursts, thereby achieving optimal bandwidth requests on the physical link. While PSA also maintains stable allocation without causing congestion during traffic bursts, the proposed adaptive algorithm achieves higher link capacity utilization for every VN.

Figure 4 [Figure 4: see original paper] compares the measured delay against target delay for the shared link. The adaptive algorithm maintains the average packet delay around the 10ms target, thereby satisfying each VN' s QoS requirements.

To compare fairness between the proposed algorithm and PSA, we calculate the average difference δ between requested and allocated bandwidth for the three VNs across 10 control intervals. Figure 5 [Figure 5: see original paper] presents these results, showing that both algorithms exhibit similar overall average differences. Since PSA is a typical fair allocation algorithm, this confirms that the proposed adaptive algorithm also provides fair bandwidth sharing among multiple VNs on the same physical link.

The pseudocode for the adaptive bandwidth allocation algorithm is as follows:

Input: Virtual networks $v : VN_{i,j} \in V$; Service providers $SP_j \in S$; Infrastructure providers $InP_m \in I$; Physical links $l : l_{m,n} \in L$; Control interval T ; Total requested bandwidth $f_l(T - 1)$; Partial requested bandwidth $F_r^{s,v,l}$; Algorithm characteristic parameter $k(T - 1)$

Output: Partial allocated bandwidth $F_a^{s,v,l}$

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for each control interval T do
  for each physical link l_{m,n} do
    for each service provider SP_j do
      for each virtual network VN_{i,j} do
        if F_r^l(T) > 1 then
          F_a^{s,v,l}(T) = F_r^{s,v,l}(T)
        if F_r^l(T-1) > 1 then
          k(T) = 2 * k(T-1)
        k(T) = k(T-1) - 1
        end if
        (T) = F_r^l(T) - 1
        end if
      end for
    end for
  end for
end for

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3 Conclusion

This paper proposes an adaptive bandwidth allocation algorithm based on a two-stage controller system for dynamic bandwidth allocation in virtual network environments. The control system consists of SP controllers and InP controllers. SP controllers comprise a set of VN sub-controllers responsible for estimating and optimizing bandwidth requests from each VN for physical links. InP controllers allocate available link capacity among multiple VNs deployed by

different SPs, aiming to provide autonomous bandwidth allocation while ensuring fair and efficient link capacity distribution to avoid bottlenecks. Future work will investigate the algorithm under constraints where VNs require mapping to specific nodes and links to further improve bandwidth allocation outcomes in network virtualization.

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