Markov Chains Based Dynamic Bandwidth Allocation in DiffServ Network

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***Abstract*—This letter proposes a Markov chain based model for dynamic bandwidth allocation in DiffServ networks. At a time-slot, the proposed Markov chain is used to predict the bandwidth requirement at the next time-slot, and resource is then allocated accordingly. Such a pre-allocation scheme can effectively reduce the operation overhead in bandwidth allocation and further reduce the connection blocking probability. We present numerical results showing that our dynamic bandwidth allocation mechanism can reduce the network blocking probability by one order of magnitude, compared with the existing bandwidth borrowing mechanism.**

***Index Terms*—DiffServ, bandwidth allocation, Markov chains, blocking probability.**

I. INTRODUCTION

WITH simplicity and extendibility, the Differentiated Services (DiffServ) model [1]-[2] has been considered as the promising Quality of Service (QoS) model for the next generation Internet. Efficient bandwidth allocation to satisfy the Service Level Agreements (SLAs) is an important issue in DiffServ networks [3]-[6]. The virtual partitioning (VP) mechanism has been shown to be an effective and fair approach to efficient bandwidth utilization and SLA guarantee [3]. Compared with the complete sharing (CS) mechanism, the VP mechanism can better protect the lightly loaded users from being overwhelmed by the highly loaded users. In [5], Cheng and Zhuang propose a bandwidth borrowing mechanism for dynamic resource sharing in DiffServ networks. Computer simulations show that their mechanism exploits the spare bandwidth to reduce the blocking probability of call service requests, thus improving resource utilization while guaranteeing the QoS. In [5], they further propose a bandwidth pushing mechanism. Simulation results show that the combination of bandwidth borrowing and bandwidth pushing mechanism will further enhance resource utilization.

However, the bandwidth allocation mechanisms in [5] are based on current network load situations and reallocate bandwidth by relevant algorithms. The algorithms there are somewhat complex and may result in long operation overhead, which can then, increase the network blocking probability due to the lag in resource allocation. This paper discusses dynamic bandwidth allocation of SLA in a DiffServ domain, for the main purpose of reducing the network blocking probability. We propose a Markov chains based dynamic bandwidth allocation mechanism, which can predict the network load of the next time-slot and allocate the bandwidth accordingly. That is to say the mechanism proposed in this letter is a pre-allocation scheme which can avoid the delay of bandwidth allocation. Compared with existing bandwidth allocation mechanisms in [5] and [11], numerical results show that our approach effectively reduces the connection blocking probability by one order of magnitude.

The rest of this letter is organized as follows: Section II establishes the Markov chain model for bandwidth prediction; Section III presents the dynamic bandwidth allocation mechanism based on the bandwidth prediction; Section IV presents the numerical results; and Section V gives a conclusion of this letter

II. THE MARKOV CHAIN MODEL

A DiffServ domain means an aggregation made of some linked DiffServ nodes (computers, switchboards, routers, etc.), which follows the uniform service strategies and implement consistent per-hop behaviors (PHB) [7]. These nodes can be categorized into boundary nodes and core nodes. Boundary nodes include ingress nodes and egress nodes, connecting the DiffServ domain and non-DiffServ domain [8]. The main function is to realize classification and adjustment mechanism of transmission, store status information of flows and adjust flows entering (or leaving) the DiffServ domain according to flow specifications. When in operation, core nodes simply dispatch and transmit while storage and monitoring of status information of flow will all be conducted on boundary nodes. To sum up, a DiffServ domain is a network structure with complicated boundary but simple inner structures.

The issue that we are dealing with is the dynamic bandwidth allocation in a DiffServ domain, in which the PHB implementation mechanism is the same. Therefore, we will not consider the PHB implementation mechanism within the domain, for example, PHB is implemented by a priority queue [9]. As a result, dynamic allocation of bandwidth recourse within a DiffServ domain will be concentrated on measurement, marking and prediction of per-flow as well as adjustment and allocation of bandwidth on boundary nodes.

We abstract nodes in a DiffServ domain, such as switchboard and router as nodes of network, directed link from ingress node to egress node in the DiffServ domain as trunk of network, and flow of each trunk as weight of network. To

Manuscript received June 5, 2012. The associate editor coordinating the review of this letter and approving it for publication was V. Vokkarane.

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This work was supported by the National Natural Science Foundation of China (No.51175264).

Digital Object Identifier 10.1109/LCOMM.2012.082012.121218

better describe the DiffServ domain, we define the following notations:

$V = \{v_1, v_2, \cdots, v_n\}$, V represents differentiable boundary or core nodes set in number n, where v_i means the ith network node in the DiffServ domain, $i = 1, 2, \cdots, n$.

$R = \{r_1, r_2, \cdots, r_m\}$, R means m multiprotocol label switching (MPLS) trunks set, where an MPLS trunk is defined as a logic pipeline within a virtual path, which is allocated a certain amount of capacity to serve a class of traffic [5]. Therefore, a virtual path between an ingress/egress pair may include multiple trunks for different service classes. We give all trunks in the DiffServ domain different labels with $r_1, r_2, \cdots, r_m$ respectively.

$W(t) = \{w_1(t), w_2(t), \cdots, w_m(t)\}$, $W(t)$ refers to weight set of m trunks at time-slot t, where $w_j(t)$ refers to the jth trunk flow at time-slot t and the value should be non-negative integer, $j = 1, 2, \cdots, m,\ \ t \in T = \{0, 1, \cdots\}$.

For a specific DiffServ domain, we make it simpler: (i) The DiffServ domain at initial time-slot t_0 contains N_0 nodes, M_0 trunks, accordingly weight set of trunks at initial time-slot is $W(0) = \{w_1(0), w_2(0), \cdots, w_{M_0}(0)\}$. (ii) Starting from t_0, the DiffServ domain measures flow of each trunk at intervals T_0, and reallocates bandwidth resource. (iii) During the whole process of bandwidth allocation, network topological structure remains unchanged. In other words, during the whole process of dynamic bandwidth allocation, the nodes, boundary and trunks of network do not change. Only weights on trunk will update along with time-slot, which correspond to the change of per-flow in the DiffServ domain along with time-slot. (iv) When trunk flow of next time-slot is less than that of current time-slot, the bandwidth allocation value of next time-slot will at least not increase and the trunk is surely not to be blocked if the bandwidth allocation value remains unchanged. In this letter, we only consider situations in which per-flow of next time-slot equals or is more than that of current time-slot. (v) Compared with current time-slot, the maximum increment of the ith trunk flow at next time-slot should not exceed C_i, where $C_i = \min\{$the corresponding SLA-defined maximum flow of the ith trunk $- k_i$, the maximum increment flow of the entire network at any time-slot$\}$, and k_i is the ith trunk flow at current time-slot, $i = 1, 2, \cdots, M_0$. (vi) Since weights in the DiffServ network display the scale-free property, that is, their weight distribution follows a power-law [12]. In addition, growth and preferential attachment mechanism are inspired the scale-free property [10]. In our model, for each increased flow, we consider the following selection mechanism: with probability p, it chooses the ith trunk with preferential probability $\frac{k_i}{A(t)}$; or with probability $1-p$, it randomly chooses the ith trunk with probability $\frac{1}{M_0}$, where p is a constant between 0 and 1, k_i is the ith trunk flow at current time-slot, $A(t)$ is the total flow of all trunks at current time-slot, and M_0 is the total number of trunks, $i = 1, 2, \cdots, M_0$.

From the simplified model, it is easy to know that the weight of each trunk is a random variable when time-slot is fixed. Besides, flow of each trunk of next time-slot is only related to the flow of current time-slot. If flow through certain trunk at current time-slot is large, then the trunk flow at next time-slot will possibly be large. Therefore, considering changes of trunk flow, weight of each trunk $w_i(t)$ $(i = 1, 2, \cdots, M_0)$ can be taken as a Markov chain with state space $E = \{0, 1, 2, \cdots\}$. Furthermore, $w_i(t+1)$ only transit from state k_i to state l_i for given present state $w_i(t) = k_i$ according to (iv) and (v), where $l_i \in E' = \{k_i, k_i + 1, \cdots, k_i + C_i\}$.

III. The Markov Chains Based Dynamic Bandwidth Allocation Mechanism

The Markov chains based dynamic bandwidth allocation mechanism refers to the one that first measures flow of each trunk at current time-slot, then predicts possible flow of each trunk at next time-slot by Markov chains theory; on such basis, take expectation flow of each trunk as bandwidth allocation value of each trunk for the next time-slot. Since the analytical procedure of each trunk is the same, we randomly select a trunk denoted by the ith trunk to analyze. Here is the detailed derivation.

Network boundary nodes measure actual flow of each trunk at current time-slot and update bandwidth resource allocation for the next time-slot. For the measurement results, let k_i be the ith trunk flow at time-slot t, namely, $w_i(t) = k_i$, $A(t)$ be the total flow of all trunks at time-slot t, namely, $A(t) = \sum_{j=1}^{M_0} w_j(t)$.

At time-slot t, $w_i(t+1)$ refers to predicted flow of the ith trunk at time-slot $t+1$. If at time-slot $t+1$ a unit flow selects the ith trunk, it means $w_i(t+1)$ will add 1. The increase process of $w_i(t+1)$ shows each increased flow's preference or uniform selection of trunk in a real network.

Let

$$B_i = p \cdot \frac{k_i}{A(t)} + (1-p) \cdot \frac{1}{M_0}, \tag{1}$$

where $i = 1, 2, \cdots, M_0$. B_i is the probability of each increased trunk flow at time-slot $t+1$ through preferentially or uniformly chooses the ith trunk, under the condition that the ith trunk flow at time-slot t is k_i.

In (1), the first term $p \cdot \frac{k_i}{A(t)}$ means that probability of each increased flow at time-slot $t+1$ passes preferred selection trunk is p, and in this case, probability of selecting the ith trunk is $\frac{k_i}{A(t)}$; the second term $(1-p) \cdot \frac{1}{M_0}$ means that probability of each increased flow at time-slot $t+1$ through random selection trunk is $1-p$, and in this case, probability of selecting the ith trunk is $\frac{1}{M_0}$, where p is a constant between 0 and 1, k_i is the ith trunk flow at current time-slot, $A(t)$ is the total flow of all trunks at current time-slot, $i = 1, 2, \cdots, M_0$.

In a real network, as long as the total number of trunks and total flow are big enough, flow of each trunk will become relatively small. We can know from (1) that probability of selecting the ith trunk by each increased flow through mixed preferred and random selection mechanism is relatively small, namely, the value of B_i is relatively small, $i = 1, 2, \cdots, M_0$. But in all trunks, the larger flow of a certain trunk at current time-slot, the bigger probability of selecting that trunk by each increased flow at next time-slot, namely, it shows the probability of selecting that trunk by each increased flow at next time-slot.

Let C_{ik_i} denote the probability of the ith trunk flow remaining unchanged or increasing at time-slot $t+1$, then

$$\begin{aligned} C_{ik_i} &= \sum_{l=0}^{C_i} (p \cdot \tfrac{k_i}{A(t)} + (1-p) \cdot \tfrac{1}{M_0})^l \\ &= \sum_{l=0}^{C_i} {B_i}^l \\ &= \tfrac{1-{B_i}^{C_i+1}}{1-B_i}, \end{aligned} \tag{2}$$

where $i = 1, 2, \cdots, M_0$.

Below we will calculate one-step transition probability of per-flow. Let $P(w_i(t+1) = k_i + l | w_i(t) = k_i)$ $(i = 1, 2, \cdots, M_0, l = 0, 1, \cdots, C_i)$ denote at time-slot t, given the condition that the ith trunk flow is k_i, the probability of trunk flow increment of l at time-slot $t+1$.

For each increased flow adopts preferred or random selection mechanism in selecting the ith trunk, so when $l \geq 1$, we get,

$$\begin{aligned} &P(w_i(t+1) = k_i + l | w_i(t) = k_i) \\ &= \tfrac{1}{C_{ik_i}} \cdot (p \cdot \tfrac{k_i}{A(t)} + (1-p) \cdot \tfrac{1}{M_0})^l \\ &= \tfrac{(1-B_i) \cdot {B_i}^l}{1-{B_i}^{C_i+1}}, \end{aligned} \tag{3}$$

where $l = 1, 2, \cdots, C_i, \;\; i = 1, 2, \cdots, M_0$.

When $l = 0$, from (2) and (3), we get

$$\begin{aligned} &P(w_i(t+1) = k_i | w_i(t) = k_i) \\ &= 1 - \sum_{l=1}^{C_i} P(w_i(t+1) = k_i + l | w_i(t) = k_i) \\ &= \tfrac{1-B_i}{1-{B_i}^{C_i+1}}, \end{aligned} \tag{4}$$

where $i = 1, 2, \cdots, M_0$.

From (3), we know that, per-flow of trunk shows the greatest probability of increasing by one unit at time-slot $t+1$, and the more flows increase, the smaller the probability. From (1) and (3), the probability of increasing by two or more units for trunk flow at time-slot $t+1$ is rather small. In other words, the increase of flow of each trunk is slow on the average.

Now, we calculate the expectation flow of each trunk. Let $e_i(t, k_i)$ be at time-slot t, given the condition that the ith trunk flow is k_i, the expectation flow of the ith trunk at time-slot $t+1$. Then we get,

$$\begin{aligned} e_i(t, k_i) &= \sum_{l=0}^{C_i} ((k_i + l) \cdot P(w_i(t+1) = k_i + l | w_i(t) = k_i)) \\ &= k_i + \frac{1}{C_{ik_i}} \cdot \sum_{l=1}^{C_i} l \cdot {B_i}^l, \end{aligned} \tag{5}$$

where $C_{ik_i} = \frac{1-{B_i}^{C_i+1}}{1-B_i}, \;\; i = 1, 2, \cdots, M_0$.

Here we use $\sum_{l=0}^{C_i} P(w_i(t+1) = k_i + l | w_i(t) = k_i) = 1$, which means the increment of each trunk flow must be one of $0, 1, \cdots, C_i$. In addition, the second equation uses (3).

Set $S = \sum_{l=1}^{C_i} l \cdot {B_i}^l = B_i + \sum_{l=2}^{C_i} l \cdot {B_i}^l$, then $B_i \cdot S = \sum_{l=1}^{C_i} l \cdot {B_i}^{l+1} = \sum_{l=2}^{C_i} (l-1) \cdot {B_i}^l + C_i \cdot {B_i}^{C_i+1}$. Subtraction of two equations, we get $(1-B_i) \cdot S = B_i + \sum_{l=2}^{C_i} {B_i}^l - C_i \cdot {B_i}^{C_i+1}$, namely, $S = \frac{B_i - C_i \cdot {B_i}^{C_i+1}}{1-B_i} + \frac{{B_i}^2 - {B_i}^{C_i+1}}{(1-B_i)^2}$. Substitute it into (5), then we get,

$$\begin{aligned} e_i(t, k_i) &= k_i + \tfrac{1}{C_{ik_i}} \cdot \sum_{l=1}^{C_i} l \cdot {B_i}^l = k_i + \tfrac{S}{C_{ik_i}} \\ &= k_i + \tfrac{B_i - C_i \cdot {B_i}^{C_i+1}}{1-{B_i}^{C_i+1}} + \tfrac{{B_i}^2 - {B_i}^{C_i+1}}{(1-B_i)(1-{B_i}^{C_i+1})}, \end{aligned} \tag{6}$$

where $B_i = p \cdot \frac{k_i}{A(t)} + (1-p) \cdot \frac{1}{M_0}, i = 1, 2, \cdots, M_0$.

In a real network, as long as the total number of trunks M_0 and total flow $A(t)$ are large enough, based on (1), we know that the value of $B_i (i = 1, 2, \cdots, M_0)$ can be relative small. Hence, we consider situations when $B_i < 0.5 (i = 1, 2, \cdots, M_0)$, then the latter two terms of (6) can be scaled into

$$e_i(t, k_i) = k_i + \tfrac{B_i - C_i \cdot {B_i}^{C_i+1}}{1-{B_i}^{C_i+1}} + \tfrac{{B_i}^2 - {B_i}^{C_i+1}}{(1-B_i)(1-{B_i}^{C_i+1})} < k_i + 2, \tag{7}$$

where $B_i = p \cdot \frac{k_i}{A(t)} + (1-p) \cdot \frac{1}{M_0}, i = 1, 2, \cdots, M_0$.

Eq. (7) refers to the number of increased flow of each trunk, which is no more than two on the average. It accords with the above analysis that the increase of each trunk flow is slow on the average. Slow increase of flow is conducive not only to dynamic adjustment of bandwidth, but also to reducing network blocking probability.

We let the bandwidth allocation value of the ith trunk at time-slot $t+1$ be $e_i(t, k)$. Then dynamic bandwidth allocation for the whole DiffServ domain can be finished by repeating the above steps. From the above analysis, our mechanism predicts possible trunk flow by Markov chains theory at current time-slot and takes expectation of prediction trunk flow as bandwidth allocation value of each trunk for the next time-slot. In other words, our mechanism is a pre-allocation scheme which can avoid the delay of bandwidth allocation.

Following consider the blocking probability of each trunk at time-slot $t+1$ under such mechanism. If the trunk blocks, $w_i(t+1)$ at time-slot $t+1$ will be larger than the value of bandwidth allocation $e_i(t, k)$. That is to say, based on our mechanism, $P(w_i(t+1) > e_i(t, k_i) | w_i(t) = k_i)$ represents the blocking probability of each trunk at time-slot $t+1$.

From (5) and (7), it is easy to know $k_i < e_i(t, k_i) < k_i + 2$, thus $1 < e_i(t, k_i) - k_i + 1 < 3$, namely, when certain trunk blocks, flow of that trunk will increase by at least one unit. In fact, it is obvious.

When $C_i < e_i(t, k_i) - k_i + 1$, it means the number of flow that needs to be increased is bigger than C_i. Such situation is impossible according to definition of C_i, namely,

$$P(w_i(t+1) > e_i(t, k_i) | w_i(t) = k_i) = 0, \tag{8}$$

where $i = 1, 2, \cdots, M_0$.

When $C_i \geq e_i(t, k_i) - k_i + 1$, combining (3), we get,

$$\begin{aligned} &P(w_i(t+1) > e_i(t, k_i) | w_i(t) = k_i) \\ &= \sum_{l = e_i(t,k_i) - k_i + 1}^{C_i} P(w_i(t+1) = k_i + l | w_i(t) = k_i) \\ &= \sum_{l = e_i(t,k_i) - k_i + 1}^{C_i} \tfrac{1}{C_{ik_i}} \cdot {B_i}^l \\ &= \tfrac{{B_i}^{e_i(t,k_i) - k_i + 1} - {B_i}^{C_i+1}}{1-{B_i}^{C_i+1}}, \end{aligned} \tag{9}$$

where $i = 1, 2, \cdots, M_0$.

TABLE I
THE CALCULATION OF THE 3RD AND 10TH TRUNK

	the 3rd path	**the 10th path**
B_i	0.0130	0.0285
$P(w_i(201) = k_i \mid w_i(200) = k_i)$	0.9870	0.9715
$P(w_i(201) = k_i + 1 \mid w_i(200) = k_i)$	0.0128	0.0277
$P(w_i(201) = k_i + 2 \mid w_i(200) = k_i)$	0.0002	0.0008
$P(w_i(201) = k_i + 3 \mid w_i(200) = k_i)$	0.0000	0.0000
$e_i(201, k_i)$	84	227
$P(w_i(201) > e_i(200, k_i) \mid w_i(200) = k_i)$	2×10^{-4}	8×10^{-4}

Here, M_0=50, $p = 0.8$, $N = 300$, $C = 30$, $k_3 = w_3(200)$= 83, $k_{10} = w_{10}(200)$= 226

TABLE II
PERFORMANCE OF THE BLOCKING PROBABILITY

	the blocking probability
the 3rd path	2×10^{-4}
the 10th path	8×10^{-4}
SLA-2	1.4×10^{-3}
SLA-3	1.04×10^{-2}
SLA-4	9.7×10^{-3}

Here, the first two data are the results of the previous example and the last three data are the call blocking probability (see Table III in [5]) of the bandwidth borrowing mechanism with virtual partitioning scheme.

IV. NUMERICAL RESULTS

In this section, we will give an numerical example and compare the blocking probability of our mechanism with the bandwidth borrowing mechanism in [5]. First, we take bandwidth allocation at $t = 200$ for example. Set total number of trunks in DiffServ domain M_0=50, probability of preferred selection of trunks by each increased flow $p = 0.8$, every maximum flow defined by SLA $N = 300$, the maximum increment of flow $C = 30$, and values of per-flow of trunk $W(200) = (w_1(200), w_2(200), \cdots, w_{M_0}(200))$ where $w_i(200)$ $(i = 1, 2, \cdots, M_0)$ take randomly in $\{1, 2, \cdots, N\}$, and the sum of separate values of $W(200)$ is $A(200) = \sum_{j=1}^{M_0} w_j(200)$= 7372. For instance, $k_3 = w_3(200)$= 83 and $k_{10} = w_{10}(200)$= 226, meaning that the 3rd and 10th trunk flow are 83 and 226 respectively.

Here, we only give the calculation of bandwidth allocation and the blocking probability of the 3rd and 10th trunk (see Table I), and the calculation of other trunks are similar. We can conclude that as long as the total number of trunks and total flow are large enough, the blocking probability of trunks will be as extremely small as at the order of magnitude of 10^{-4}.

Table II compare the blocking probability of our mechanism with the bandwidth borrowing mechanism in [5], where due to space limitations, our mechanism does not consider a trunk flow decrease for the calculation of the blocking probability is similar to that of a trunk flow increase. Additionally, the average blocking probability of dynamic bandwidth allocation mechanism in [11] is between 1×10^{-3} and 1×10^{-2}, which is higher than our results. The comparative results indicate that the mechanism proposed effectively reduces network blocking probability by one order of magnitude.

V. CONCLUSION

A Markov chain based model has been presented to predict dynamically bandwidth allocation in DiffServ networks. At a time-slot, the proposed Markov chain is used to predict the bandwidth requirement at the next time-slot, and resource is then allocated accordingly. The proposed pre-allocation scheme can effectively reduce the operation overhead in bandwidth allocation and further reduce the connection blocking probability. Numerical results show that our dynamic bandwidth allocation mechanism can reduce the network blocking probability by one order of magnitude, compared with the existing bandwidth borrowing mechanism. Furthermore, for the entire network, it is more reasonable to consider prediction flow of every trunk including increase and decrease, which requires future work.

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