Effective Bandwidth of Multiclass Markovian Traffic Sources and Admission Control With Dynamic Buffer Partitioning

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***Abstract*—We investigate the statistical multiplexing and admission control for a partitioned buffer, where the traffic is generated by multiclass Markov-modulated fluid sources. Each of the sources has $J(>1)$ classes at each state. The quality of service (QoS) is described by the packet loss probability for each class. The buffer is partitioned with $J-1$ thresholds to provide the J loss priorities. Extending the effective bandwidth concept to such a buffer system is a challenging topic. In this paper, we find the minimal effective bandwidth in the asymptotic regime of large buffers and small loss probabilities by optimally setting the partition thresholds. The minimal effective bandwidth achieves efficient resource utilization and can be used to do admission control for heterogeneous multiclass Markovian sources in an additive way. The buffer partition thresholds are dynamically adjusted according to the input traffic load to guarantee QoS. Numerical analysis and simulation results verify the QoS satisfaction and the obvious improvement of resource utilization compared with previously published results, when the minimal effective bandwidth is used for resource allocation with the proposed dynamic buffer partitioning techniques.**

***Index Terms*—Differentiated services (DiffServ), dynamic buffer partitioning, effective bandwidth, loss priorities, multiclass Markovian traffic sources.**

I. Introduction

THE classic best-effort Internet is evolving into a versatile network that can provide various multimedia real-time services in addition to the traditional data services, and can provision a certain quality of service (QoS) guarantee to different Internet applications. The differentiated services (DiffServ) model [1] has been proposed as a scalable traffic management mechanism to ensure Internet QoS without using per-flow resource reservation and per-flow signaling. In DiffServ, traffic flows having similar QoS requirements are aggregated into a common service class and experience the same queuing behavior at each hop. A simple and efficient approach to differentiate services is to use a set of buffers served with priorities. There are two levels of priority. One is the *interbuffer priority* (or priority queueing), where each class of traffic with a certain QoS requirement enters a separate buffer granted a certain priority, and the traffic in a buffer of higher priority is served before that of lower priority. Typically in a DiffServ core router, three buffers are used to achieve the *premium service* [2], the *assured service* [3], and the *best-effort service*, which are served with high, medium, and low priority, respectively. The other level of priority, *intrabuffer priority*, is to serve traffic with a *partitioned* buffer [4], which provides different loss priorities while keeping the order of packets from the same microflow. The buffer for the assured service is usually a partitioned buffer. In the performance analysis and capacity planning of such a multiclass multipriority DiffServ network, the priority structure should be considered.

Recently, it has been an active research subject to examine the impact of priority structures on bandwidth allocation and admission control in high-speed networks. For the case of interbuffer priority, Elwalid and Mitra [5] analyzed a two-priority queueing system with input traffic from Markov-modulated fluid sources. Kulkarni and Gautam [6] analyzed a multipriority queueing system by using the results on the effective bandwidth of output processes [7]. Berger and Whitt [8] formulated a notion of effective bandwidth for the multipriority queueing system supplied with general source models, and they concluded that a given connection is associated with multiple effective bandwidths: one for the priority level of the given connection, and one for each lower priority level. For the case of intrabuffer priority, Elwalid and Mitra [9] developed fluid models for the analysis of an asynchronous transfer mode (ATM) loss-priority system, where each ATM connection has some cells designated the high priority and others designated the low priority, and all cells are buffered in a single first-in–first-out (FIFO) queue, with the low priority cells being discarded when the queue length exceeds a predefined threshold. A generalization of this model with two or more loss priorities per connection was analyzed by Kulkarni *et al.* [4]. They showed that the effective bandwidth concept can be extended to effective bandwidth vectors and used for admission control. To the best of our knowledge, this is the only work addressing the effective bandwidth in a partitioned buffer. However, the derived effective bandwidth is over-conservative, and the calculation is quite complex. Kulkarni *et al.*'s earlier study in [10] gave valuable insights into the buffer partitioning problem. They obtained the optimal threshold that minimized the channel capacity required to satisfy the loss criterion of a two-priority traffic source. However, the optimal partitioning

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technique to a buffer providing multiple (larger than two) loss priorities and its application in effective bandwidth calculation have not been addressed so far in the open literature.

Our research presented in [11] extended the technique in [10] to determine the optimal buffer thresholds for a partitioned queue providing multiple loss priorities. Based on the theoretical study in [4], this paper elaborates on the work in [11]. The minimal channel capacity obtained from the buffer partitioning optimization is defined as the effective bandwidth of the multiclass Markov-modulated fluid source. The effective bandwidth is referred to as the *minimal effective bandwidth* for convenience. We demonstrate that the minimal effective bandwidth can be used in an additive way for the admission control when traffic flows from heterogeneous Markov-modulated sources enter the partitioned buffer, while it is required to dynamically adjust the *buffer partition vector* according to the accepted traffic load in order to guarantee the QoS. The system model is described in Section II. Section III presents the fluid model analysis of a large partitioned buffer providing J loss priorities. Section IV presents the optimal buffer partitioning concept, and derives a very simple algorithm to calculate the minimal effective bandwidth and the optimal partition vector. Section V discusses the application of the minimal effective bandwidth in admission control and proposes the dynamic buffer partitioning techniques to guarantee the QoS of the admitted traffic. Section VI discusses implementations of the admission control in the presence of both inter- and intrabuffer priorities. Section VII presents numerical results to illustrate that the minimal effective bandwidth can be used for efficient resource allocation and QoS guarantee, which is further verified by the simulation results given in Section VIII. Section IX draws conclusions of this research and discusses its application in a practical system.

II. System Model

Consider a partitioned buffer of size B served by a channel of constant capacity c. The input traffic is from a Markov-modulated fluid source which generates traffic having $J(\geq 2)$ QoS classes. The QoS requirement is specified by a packet loss probability (PLP) ϵ_j for class j, $j \in \{1, 2, \ldots, J\}$. Let $\mathcal{S}$ be the state space and $\boldsymbol{M}$ the generator matrix of the underlying Markov chain of the source. At state i ($i \in \mathcal{S}$), the source generates traffic of class j fluid at rate λ_i^j. The admission policy is based upon a space reservation scheme, using the buffer partition vector $\boldsymbol{B}_t = (B_1, B_2, \cdots, B_{J-1})$ to provide J loss priorities, where $0 < B_1 \leq B_2 \leq \cdots \leq B_{J-1} \leq B$.[1] For convenience, let $B_0 = 0$ and $B_J = B$. Let $X(t)$ be the amount of fluid of all classes in the buffer at time t. When $B_{j-1} \leq X(t) < B_j (1 \leq j \leq J)$, only fluid of classes $\{j, j+1, \cdots, J\}$ is admitted into the buffer. In this case, the diagonal rate matrix is denoted by $\boldsymbol{\Lambda}^j$, where $\Lambda_{ii}^j = \sum_{r=j}^{J} \lambda_i^r$. Now let $G(B_j)$ be the long-run probability that the buffer occupancy is above the threshold B_j, that is, $G(B_j) \triangleq \Pr(X > B_j)$. $G(B_j)$ usually provides an upper bound to the loss rate of class j fluid. We use this probability as an approximation of the loss rate. The QoS is satisfied for all the traffic classes if

$$G(B_j) \leq \epsilon_j, \quad \forall j \in \{1, 2, \ldots, J\} \tag{1}$$

where $\epsilon_1 > \epsilon_2 > \cdots > \epsilon_J > 0$.

The Markov-modulated fluid source can be a single source or the aggregate of $K(>1)$ statistically independent Markov-modulated fluid sources. In the latter case, the generator matrix and the rate matrix of the aggregate source can be obtained by Kronecker products of the K independent sources [12]. For simplicity of discussion, we consider the case of a single source; however, the results also apply to the aggregate of the K sources.

III. Fluid Model Analysis

Let Σ and X denote the stationary state of the Markovian source and the buffer occupancy, respectively. Let $\boldsymbol{\pi}(x)$ denote the steady-state distribution of the buffer occupancy, where $\boldsymbol{\pi}(x) = \{\pi_s(x) | s \in \mathcal{S}\}$ and $\pi_s(x) \triangleq \Pr(X \leq x, \Sigma = s)(x \geq 0)$. For $1 \leq j \leq J$, let $\boldsymbol{\pi}^j(x) \triangleq \boldsymbol{\pi}(x)(B_{j-1} \leq x \leq B_j)$.[2] According to [4] and [9], the governing differential equations of the buffer sharing system is

$$\frac{d}{dx}\boldsymbol{\pi}^j(x)\boldsymbol{D}^j = \boldsymbol{\pi}^j(x)\boldsymbol{M} \quad (B_{j-1} \leq x \leq B_j, 1 \leq j \leq J) \tag{2}$$

where $\boldsymbol{D}^j \triangleq \boldsymbol{\Lambda}^j - c\boldsymbol{I}$, and $\boldsymbol{I}$ is the identity matrix. The spectral solution to (2) is given by

$$\boldsymbol{\pi}^j(x) = \sum_r a_r^j \boldsymbol{\phi}_r^j e^{z_r^j x} \quad (1 \leq j \leq J) \tag{3}$$

where $(z_r^j, \boldsymbol{\phi}_r^j)$ is an eigenvalue/eigenvector pair. Such pairs are solutions to the eigenvalue problem

$$z\boldsymbol{\phi}\boldsymbol{D}^j = \boldsymbol{\phi}\boldsymbol{M} \quad (1 \leq j \leq J). \tag{4}$$

After solving all the coefficients $\{a_r^j\}$ in (3) from boundary conditions [4], [9], the loss rate of class j fluid can be calculated by

$$\begin{aligned} G(B_j) &= 1 - \sum_{s \in S} \pi_s^j(B_j) \\ &= 1 - \sum_r a_r^j \left\langle \boldsymbol{\phi}_r^j, \mathbf{1} \right\rangle e^{z_r^j B_j} \quad (1 \leq j \leq J) \end{aligned} \tag{5}$$

where the symbol $\langle \cdot, \cdot \rangle$ denotes the inner product of the vectors and $\mathbf{1}$ is the vector in which all elements are unity.

A. The Asymptotic Solution

When the size of the state space $\mathcal{S}$ is large and $J > 2$, the calculation of coefficients $\{a_r^j\}$ from boundary conditions becomes quite complex. If we have

$$B_j \to \infty \text{ and } \epsilon_j \to 0 \quad (1 \leq j \leq J) \tag{6}$$

[1]In the fluid model analysis, if the input peak rate of the Markov-modulated sources is less than the channel capacity, overload states do not exist and the traffic can be served bufferless and lossless.

[2]In the fluid model analysis, we assume for simplicity that $\pi_s(x) (s \in \mathcal{S})$ is continuous in the interval $[0, +\infty)$. That is, we ignore the probability mass accumulation at boundary $B_j (1 \leq j \leq J-1)$ considered in [9]. Therefore, $\boldsymbol{\pi}^j(x)$ can be defined over the close interval $[B_{j-1}, B_j]$ $(1 \leq j \leq J)$, and $\boldsymbol{\pi}^j(B_j) = \boldsymbol{\pi}^{j+1}(B_j)$ $(1 \leq j \leq J-1)$.

we can use only the *dominant eigenvalue* items to approximate the loss function $G(\cdot)$ [12].

Proposition 1: Assume that overload states exist in all the J regions of the buffer and let $z_1^j, 1 \le j \le J$, denote the dominant eigenvalues solved from (4). In the asymptotic case described by (6), we have

$$\begin{aligned} G(B_j) &\approx G(0) \prod_{r=1}^{j} \exp\left[z_1^r (B_r - B_{r-1})\right] \\ &\approx L \prod_{r=1}^{j} \exp\left[z_1^r (B_r - B_{r-1})\right] \end{aligned} \tag{7}$$

where L is the loss probability in the bufferless multiplexing system.

Proof: When we consider only the dominant eigenvalues, the loss function can be approximately represented by

$$\begin{aligned} G(x) &\approx -a_1^j \left\langle \boldsymbol{\phi}_1^j, \mathbf{1} \right\rangle e^{z_1^j x} \\ &= A_j e^{z_1^j x} \quad (B_{j-1} \le x \le B_j, 1 \le j \le J) \end{aligned} \tag{8}$$

where $A_j = -a_1^j \langle \boldsymbol{\phi}_1^j, \mathbf{1} \rangle$. For $j = 1$, (8) is $G(x) \approx A_1 e^{z_1^1 x} = G(0) e^{z_1^1 x}$ $(0 \le x \le B_1 \to \infty)$, just in the form of a classic dominant eigenvalue problem. In [5] and [13], it is shown that $G(0)$ can be approximated by L, the loss probability in a bufferless system (i.e., the stationary probability that the instantaneous rate of fluid generation from the Markovian source exceeds the channel rate). After A_1 is solved, other A_j's can be calculated easily by

$$A_j = A_1 \exp\left(-z_1^j B_{j-1}\right) \prod_{r=1}^{j-1} \exp[z_1^r (B_r - B_{r-1})] \quad (2 \le j \le J) \tag{9}$$

based on the condition that $G(x)$ is continuous at boundaries, that is, $G(B_j^-) = G(B_j^+)$ $(1 \le j \le J-1)$. Substituting (9) into (8) and calculating $G(B_j)$ for all the J classes with $A_1 = G(0) \approx L$, we obtain (7). ■

Equation (7) is, in fact, the same as [4, Th. 4.1], where the theorem is derived by tedious matrix algebra and its physical meaning is not obvious.

B. Example of a Two-Class On-Off Source

Consider a single on-off voice source, which has exponentially distributed talkspurt and silence durations with the expectations $1/\beta$ and $1/\alpha$, respectively. When the source is on, it produces two classes of fluids at rates λ^1 and λ^2 with the target loss probabilities of ϵ_1 and ϵ_2 $(\epsilon_1 > \epsilon_2)$, respectively. A buffer of size B is partitioned by a threshold B_1 $(0 < B_1 < B)$. Traffic enters the buffer with rate $\lambda^1 + \lambda^2$ when $0 \le X(t) < B_1$ and with rate λ^2 when $B_1 \le X(t) < B$. Assume that the channel capacity c satisfies the condition

$$\frac{\alpha}{\alpha+\beta}(\lambda^1 + \lambda^2) < c < \lambda^2. \tag{10}$$

The assumption assures that the negative eigenvalues exist in both parts of the buffer. This system is solved in [10], and the steady state distribution, $\boldsymbol{\pi}(x) = [\pi_0(x), \pi_1(x)]$, is given by

$$\boldsymbol{\pi}(x) = \begin{cases} a_1[\beta,\alpha] + b_1\left[(\lambda^1+\lambda^2-c)\beta, c\beta\right] e^{z_1^1 x}, & 0 \le x < B_1 \\ a_2[\beta,\alpha] + b_2\left[(\lambda^2-c)\beta, c\beta\right] e^{z_1^2 x}, & B_1 \le x < \infty \end{cases} \tag{11}$$

where

$$\begin{aligned} a_1 &= \frac{1}{\alpha+\beta} \frac{c - \lambda^2 \frac{\alpha}{\alpha+\beta}}{c - \left(\lambda^2 + \lambda^1 e^{z_1^1 B_1}\right) \frac{\alpha}{\alpha+\beta}} \\ b_1 &= -\frac{\alpha}{c\beta} a_1 \\ a_2 &= \frac{1}{\alpha+\beta} \\ b_2 &= \frac{-e^{z_1^1 B_1}}{c\beta e^{z_1^2 B_1}} \frac{\alpha}{\alpha+\beta} \frac{c - (\lambda^2 + \lambda^1)\frac{\alpha}{\alpha+\beta}}{c - \left(\lambda^2 + \lambda^1 e^{z_1^1 B_1}\right) \frac{\alpha}{\alpha+\beta}}. \end{aligned}$$

From (11), we can calculate the loss probability for both classes by

$$\begin{aligned} G(B_1) &= 1 - [\pi_0(B_1) + \pi_1(B_1)] = G(0) \exp\left(z_1^1 B_1\right) \\ G(B) &= 1 - [\pi_0(B) + \pi_1(B)] \\ &= G(0) \exp\left(z_1^1 B_1\right) \exp\left[z_1^2 (B - B_1)\right] \end{aligned}$$

where

$$G(0) = \frac{\lambda^2}{c} \frac{\alpha}{\alpha+\beta} \frac{c - (\lambda^2 + \lambda^1)\frac{\alpha}{\alpha+\beta}}{c - \left(\lambda^2 + \lambda^1 e^{z_1^1 B_1}\right) \frac{\alpha}{\alpha+\beta}}.$$

The above results show that, for a two-class on-off source, the solution for $G(B_j)$ is exactly in the form of (7).

Equation (7) can be used directly for admission control in a partitioned buffer, where z_1^r is calculated according to the aggregate of the input Markovian fluid sources. It is also the theoretical basis for the effective bandwidth analysis in the following two sections, where $G(0)$ or L is ignored for simplicity. Note that taking $L = 1$ effectively eliminates the statistical multiplexing advantage of aggregating multiple traffic flows into one buffer [14], and leads to a conservative bandwidth requirement. We will exploit the resource utilization improvement brought by L in Section VII, where L is referred to as statistical multiplexing factor for convenience.

IV. Optimal Buffer Partitioning

From (7), when a Markov-modulated source which generates J-class fluid is served by a space-sharing buffer partitioned by the $J-1$ thresholds, the fluid loss rate of each class is approximately given by

$$G(B_j) = \prod_{r=1}^{j} \exp\left[z_1^r(c)(B_r - B_{r-1})\right] \quad (1 \le j \le J) \tag{12}$$

where L is set as 1 and the "=" sign is used for simplicity. The expression $z_1^r(c)$ emphasizes that QoS is directly affected by the channel capacity c. Equation (12) indicates that when other parameters are fixed, the choice of $\boldsymbol{B}_t$ determines the channel capacity required to guarantee the QoS for all the J classes. Our objective in this section is to find the optimal partition vector $\boldsymbol{B}_t^* = (B_1^*, B_2^*, \cdots, B_{J-1}^*)$ that minimizes the required capacity c. Now let c_j be the solution to $G(B_j) = \epsilon_j$ $(1 \le j \le J)$, i.e.,

$$\prod_{r=1}^{j} \exp\left[z_1^r(c_j)(B_r - B_{r-1})\right] = \epsilon_j \quad (1 \le j \le J). \tag{13}$$

For the QoS satisfaction, it is required that

$$c \ge \max\{c_1, c_2, \cdots, c_J\}. \tag{14}$$

Proposition 2: Under the QoS constraint, the required channel capacity c achieves its minimal value c^*, if $\boldsymbol{B}_t$ is adjusted to $\boldsymbol{B}_t^*$ such that

$$c_1 = c_2 = \cdots = c_J \triangleq c^*. \tag{15}$$

Proof: If $\boldsymbol{B}_t \ne \boldsymbol{B}_t^*$, then the channel capacity c is chosen according to (14), and there exists at least one fluid class j $(1 \le j \le J)$, for which $c_j < c$. Thus, we have

$$\prod_{r=1}^{j} \exp[z_1^r(c)(B_r - B_{r-1})] < \prod_{r=1}^{j} \exp[z_1^r(c_j)(B_r - B_{r-1})] = \epsilon_j$$

as $z_1^r(c)$ has a negative value and is a monotonic, strictly decreasing function of the channel capacity c [12]. The above result means that the channel capacity c is more than enough for the class j traffic to guarantee the QoS. When $\boldsymbol{B}_t = \boldsymbol{B}_t^*$ such that $c_j = c^*(1 \le j \le J)$, each class fills the channel capacity exactly and achieves its specified QoS. No bandwidth is wasted. Thus, in this case, the capacity to guarantee QoS of all the J classes is minimized and is defined to be c^*. ■

The capacity c^* is referred to as the minimal effective bandwidth of the Markov-modulated source. At $\boldsymbol{B}_t = \boldsymbol{B}_t^*$, all the J equations in (13) are satisfied simultaneously with the solution pair (c^*, $\boldsymbol{B}_t^*$). Substituting c^* and $\boldsymbol{B}_t^*$ into (13) and simplifying the expression, we have

$$\exp\left[z_1^j(c^*)\left(B_j^* - B_{j-1}^*\right)\right] = \frac{\epsilon_j}{\epsilon_j - 1} \quad (1 \le j \le J) \tag{16}$$

where $B_0^* = 0$, $B_J^* = B$, and $\epsilon_0 = 1$ for convenience. After a simple manipulation to (16), the following equation of c^* can be obtained:

$$\sum_{j=1}^{J} \frac{\ln \frac{\epsilon_j}{\epsilon_j - 1}}{z_1^j(c^*)} - B = 0. \tag{17}$$

Again due to the monotonicity of the dominant eigenvalue $z_1^j(c)$, the left side of (17) is a strictly decreasing function of c^*. We can solve (17) for c^* by using a standard iterative root-finding technique (such as Newton's method). One thing to note is that in each run of the iterative root-finding algorithm to check a candidate solution point c^*, the calculation of $z_1^j(c)$ and its inclusion in the sum in the left side of (17) need to be done only for those regions with overload states. With the c^* value, $\boldsymbol{B}_t^*$ can be easily solved from (16). If the input peak rate decreases below the channel capacity c^* when buffer content exceeds B_j^* $(1 \le j \le J-1)$, the algorithm gives $B_j = \cdots = B_{J-1} = B$, and there is no packet loss for the traffic of classes $\{j+1, j+2, \ldots, J\}$.

The work in [4] considers the effective bandwidth only for a buffer with arbitrarily preconfigured partition thresholds. The effective bandwidth to guarantee the QoS of all classes is calculated according to (14), and a complex binary search and maximization procedure is used to calculate each c_i. When the thresholds are not set properly, the above algorithm leads to a conservative effective bandwidth, which can be much larger than the peak rates in the high-end partition regions. Compared to the work in [4], our techniques have the following advantages: 1) according to *Proposition 2*, the optimal partition vector and the effective bandwidth can be solved in a combined way. The previously proposed complex binary search and maximization procedure is replaced by solving the simple equation given in (17); 2) the minimal effective bandwidth achieves much more efficient resource utilization. No bandwidth is wasted to oversatisfy the QoS. The algorithm adaptively decreases the partition to zero for those regions where the input rate decreases below the capacity. All the buffer size is used to absorb the overload traffic, leading to a smaller bandwidth requirement for guaranteeing QoS. The resource utilization improvement is verified by numerical analysis and simulation results to be presented.

V. Minimal Effective Bandwidth

A. Admission Control

In a partitioned buffer, admission control is necessary to provision QoS. The admission control can be done in the following manner. Consider that there are $K-1$ admitted sources in the system and that there is a new service request from a Markovian source. The admission control for the Kth source is based on the aggregate traffic, including the new arrival and the already admitted ones. With the given K sources (considered as one Markovian source via Kronecker products) and a selected partition vector, the loss probability for each class is calculated by (12). The new request is accepted only if (1) is satisfied for all the J classes. The above procedure is referred to as *aggregate admission control*, and the corresponding admission region is referred to as the *aggregate admission region*. In the asymptotic regime of large buffers and small loss probabilities, the aggregate admission control gives the accurate admission region for a given buffer partition vector $\boldsymbol{B}_t$.

Furthermore, the aggregate admission control can be combined with the optimal buffer partitioning technique to improve resource utilization. In such a case, first the buffer partitioning optimization problem is solved for the aggregate traffic according to (17).[3] The minimal effective bandwidth required to serve the aggregate traffic, with the loss requirements for all classes guaranteed, is denoted as c^*_{agg}. Then, the new request is accepted only if $c^*_{\text{agg}} \le c$. This procedure is referred to as *ideal admission control* and the corresponding admission region is referred to as the *ideal admission region*, under the assumptions that the admission overhead time and hardware memory required for the buffer partitioning optimization are acceptable. The ideal admission control may not be practical,

[3]When solving (17), the calculation of the dominant eigenvalue $z_1^j(c)$ of the K-fold aggregate Markovian traffic can follow the approach presented in [12].

but it gives the maximal utilization of the system capacity and can serve as a benchmark to evaluate admission control techniques based on the minimal effective bandwidth, which is to be discussed in the following.

B. Minimal Effective Bandwidth

In order for the admission control based on the optimal buffer partitioning to be practical, we want to approximate the optimization result for the aggregate traffic by the summation of single-source optimization results. In other words, we want to check whether the new Markovian source can be admitted given that

$$\sum_{i=1}^{K} c_i^* \leq c \tag{18}$$

where c_i^* is the minimal effective bandwidth of source i. As the left-hand side of (18) is a linear operation of the effective bandwidths, the admission control based on (18) is referred to as *linear admission control* and the corresponding admission region is referred to as the *linear admission region*.

In a homogeneous multiplexing system, the optimal vector $\boldsymbol{B}_t^*$ can be found by analyzing the corresponding single-source system. Given the buffer size B, the channel capacity c, and the QoS vector $(\epsilon_1, \cdots, \epsilon_J)$, the optimal vector is determined by the dominant eigenvalue vector $(z_1^1(c), z_1^2(c), \cdots, z_1^J(c))$. When $K(> 1)$ homogeneous Markov sources enters the system independently, the eigenvalue vector can be calculated by considering one of the sources in isolation with the capacity decreased by a factor of K [12], as $(z_1^1(c/K), z_1^2(c/K), \cdots, z_1^J(c/K))$. Thus, when the optimal vector $\boldsymbol{B}_t^*$ minimizes the capacity required to guarantee the QoS of a single source as c^*/K, it also minimizes the total capacity required for the multiplexing system as c^* at the same time. This means that (18) can be used for admission control of homogeneous multiclass Markovian traffic.

In a heterogeneous multiplexing system, with a given buffer of size B, different Markovian sources usually have different generator matrices and rate vectors, hence, different minimal effective bandwidths and partition vectors. In this situation, can we use the minimal effective bandwidths to get the linear admission region? At present, no mathematical analysis can answer the question. However, numerical analysis in Section VII demonstrates that (18) indeed gives a linear admission region that is conservative as compared with the ideal admission region. Furthermore, in Section VIII, we present the PLPs based on computer simulations, which verify that the QoS is guaranteed with linear admission control.

C. Dynamic Buffer Partitioning

The ideal admission control requires dynamic buffer partitioning. To guarantee the QoS of the admitted traffic sources, the buffer partition vector should be optimized dynamically with the traffic variation. Here we propose heuristic approaches to approximate the optimal partition vector to avoid the heavy calculation and memory burdens in the optimization for the aggregate traffic. Once a new admission request arrives, the traffic source is classified into a traffic type (not a QoS class) m according to its statistical parameters (generator matrix and rate matrix), and the number of sources in each traffic type is recorded and denoted by N_m. An optimal partition vector $\boldsymbol{B}_{t,m}^*$ is calculated for traffic type m. The optimal vector $\boldsymbol{B}_t^*$ is approximated by averaging over the vectors for different traffic types. The following are three possible schemes:

(a) *call level average* (CLA), using

$$\boldsymbol{B}_t^* = \sum_m \frac{N_m}{N} \boldsymbol{B}_{t,m}^* \tag{19}$$

where $N = \sum_m N_m$ is the total number of accepted sources;

(b) *packet level average* (PLA), using

$$\boldsymbol{B}_t^* = \sum_m \frac{N_m c_m^*}{C_N} \boldsymbol{B}_{t,m}^* \tag{20}$$

where c_m^* is the minimal effective bandwidth of a type m source, and $C_N = \sum_m N_m c_m^*$;

(c) *bursty-weighted call level average* (BWCLA), using

$$\boldsymbol{B}_t^* = \sum_m \frac{N_m u_m}{U_N} \boldsymbol{B}_{t,m}^* \tag{21}$$

where $u_m =$ (peak rate/average rate) for a type-m source, referred to as bursty coefficient, and $U_N = \sum_m N_m u_m$.

The CLA scheme is based on the intuition that the overall optimal partition vector should be a compromise among the optimal partition vectors for different traffic types. As for the PLA scheme and the BWCLA scheme, we take into account that the burstier a source is, the more the buffer partition vector affects the QoS. The optimal partition vectors with respect to the burstier sources should be given higher weights. The above three schemes have similar and very low complexity for implementation. Under the assumption that the Markovian traffic models, the QoS requirements, and the buffer size are known in advance by the admission controller, the minimal effective bandwidth and the optimal partition vector of each traffic type can be precalculated. In the on-line admission control, only simple weighted average calculation is needed, and very little memory space is required to store the optimal partition vector and the number of flows for each traffic type. Even in the situations that the buffer optimization needs to be recalculated on-line due to the addition of a new traffic type or due to traffic parameter reconfiguration, the solution of an equation using a standard iterative root-finding technique does not bring much extra calculation load. Performance of the CLA, PLA, and BWCLA schemes to guarantee QoS in the admission control is to be verified by numerical analysis and simulations.

VI. Admission Control With Priorities

The preceding sections discuss the effective bandwidth and admission control in a partitioned buffer, which provides intrabuffer priorities. In a DiffServ router, usually both the inter- and intrabuffer priority structures are utilized to differentiate services. In this case, the admission control technique developed in [8] can be combined with the technique proposed here to address the admission control in such a multilevel priority environment.

TABLE I
EFFECTIVE BANDWIDTH AND OPTIMAL BUFFER PARTITION VECTOR

Traffic Configuration			Results of [4]		Our Results	
type	rate vector	target QoS vector	$\boldsymbol{B}_t$	c	$\boldsymbol{B}_t^*$	c^*
$\mathcal{A}$	R_p	10^{-10}	$(0, 100)$	158.30	$(0, 100)$	158.30
$\mathcal{B}$	$(\frac{R_p}{2}, \frac{R_p}{2})$	$(10^{-1}, 10^{-10})$	$(0, 55, 100)$	157.17	$(0, 100, 100)$	96.80
$\mathcal{C}$	$(\frac{R_p}{4}, \frac{R_p}{2}, \frac{R_p}{4})$	$(10^{-1}, 10^{-7}, 10^{-10})$	$(0, 55, 91, 100)$	151.97	$(0, 54, 100, 100)$	118.68
$\mathcal{D}$	$(\frac{R_p}{4}, \frac{R_p}{4}, \frac{R_p}{4}, \frac{R_p}{4})$	$(10^{-1}, 10^{-4}, 10^{-7}, 10^{-10})$	$(0, 55, 60, 91, 100)$	145.42	$(0, 63, 100, 100, 100)$	113.31

Consider a DiffServ router providing three classes of services, with total capacity c of the output link. Three separate buffers, the priority-1 (the highest priority), priority-2 (a partitioned buffer providing J loss priorities), and priority-3 buffer (the lowest priority), are used to support the premium, assured, and best-effort services, respectively. The effective bandwidth approach is used for admission control of the premium and the assured traffic. The best-effort traffic picks up the leftover capacity, served without admission control. Let M_i denote the number of the Markovian source types entering the priority-i buffer. According to [8], a conservative approximation of the admission set is in the linear form

$$\sum_{m=1}^{M_1} e_{1m} n_{1m} \leq c \tag{22}$$

$$\sum_{m=1}^{M_1} e_{1m}^2 n_{1m} + \sum_{m=1}^{M_2} c_{2m}^* n_{2m} \leq c. \tag{23}$$

In the above equations, n_{im} $(i = 1, 2)$ is the number of acceptable type-m prority-i traffic sources, which forms the admission set. e_{1m} is the effective bandwidth of a type-m priority-1 source, which equals the peak rate of the traffic flow to achieve the premium service. c_{2m}^* is the minimal effective bandwidth of a type-m priority-2 source obtained from optimal buffer partitioning, and e_{1m}^2 is the effective bandwidth of a type-m priority-1 source as seen in the priority-2 buffer.

The proposed dynamic buffer partitioning schemes make it simple to set the thresholds of the priority-2 buffer. Assume that the buffer size is known and is the same at different routers. The optimal buffer partition vector of a type-m assured service source can be calculated off-line in advance. The partition vector is provided to the admission controller at the time that the source requests service. If the new request is accepted, its partition vector can be used to adjust the buffer partitioning according to the BWCLA (CLA, or PLA) heuristics.

Based on [8], e_{1m}^2 can be calculated as if each type-m priority-1 source is served by the priority-2 buffer with the highest priority (i.e., class J) in a FIFO manner, with the guaranteed loss probability specified by ϵ_J.[4] Furthermore, the priority-1 traffic does not affect the buffer partitioning for the admitted priority-2 traffic. This can be explained as follows. The addition of priority-1 traffic to the priority-2 buffer is an equivalent representation of the capacity consumption due to the premium service. As the capacity reduction has the same impact on packet serving in all partition regions of the priority-2 buffer, the equivalent input rate does not change with buffer partitions. In other words, the equivalent input is served by the priority-2 buffer with the full size. No matter what partition thresholds are used, the equivalent traffic will achieve the same QoS, ϵ_J, if the bandwidth e_{1m}^2 is provided. Thus, the BWCLA buffer partitioning only needs to consider the priority-2 traffic to guarantee its QoS. In the next section, a numerical example will be presented to illustrate the application of the effective bandwidth and BWCLA dynamic partitioning for admission control in the above multilevel priority system.

[4]Effective bandwidth calculation in a FIFO buffer is discussed in detail in [14].

VII. NUMERICAL RESULTS

This section presents three numerical examples to demonstrate the performance of the proposed techniques. In the first example, the minimal effective bandwidths of multiclass on-off sources are calculated and compared to the effective bandwidths presented in [4], showing that the channel capacity can be used more efficiently by the optimal buffer partitioning proposed here. In the second example, admission control for heterogeneous multiclass on-off sources is evaluated. The results show that, by dynamic buffer partitioning (especially by the BWCLA), the minimal effective bandwidth can be used for admission control with QoS guarantee. The third example illustrates the application of the effective bandwidth for resource allocation in a multilevel priority environment (i.e., a DiffServ router). In the next section, we estimate the PLPs via computer simulations. The results verify the QoS satisfaction with bandwidth allocation based on the minimal effective bandwidth.

Example 1: Minimal Effective Bandwidth: We use the same system parameters as those given in [4]. Consider $B = 100$ packets and homogeneous on-off voice sources. Each voice source at the "on" state generates traffic with a constant rate $R_p = 72\,170$ b/s (170.21 packets/s, each packet having 53 bytes). The average talkspurt duration is 0.35 s, and the average silence duration is 0.65 s. Four different loss-priority configurations are considered, for $J = 1$, 2, 3, and 4, respectively. For each configuration, the on-off source generates J classes of traffic at the "on" state with the rate vector and the target loss probability vector (each having J elements) given in Table I (the traffic configuration column). For convenience, the traffic source is tagged as type $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$, respectively, for the four configurations (referred to as configuration $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$, accordingly). The optimal buffer partition vector (in packets) and the effective bandwidth (in packets/s) of the on-off

TABLE II
TRAFFIC CHARACTERISTICS, QOS REQUIREMENTS, THE OPTIMAL BUFFER PARTITION VECTORS, AND THE MINIMAL EFFECTIVE BANDWIDTHS FOR THE HETEROGENEOUS SOURCES

traffic type	$1/\alpha$	$1/\beta$	R_p	u	rate vector	QoS vector	B	B_t^*	c^*
1	0.65	0.35	170.21	2.86	$(\frac{R_p}{4}, \frac{3R_p}{4})$	$(10^{-1}, 10^{-10})$	100	$(0, 51, 100)$	121.10
2	1.20	0.35	353.77	4.43	$(\frac{R_p}{4}, \frac{3R_p}{4})$	$(10^{-1}, 10^{-10})$	100	$(0, 82, 100)$	262.86
3	0.65	0.35	170.21	2.86	$(\frac{R_p}{8}, \frac{R_p}{8}, \frac{3R_p}{4})$	$(10^{-1}, 10^{-4}, 10^{-10})$	250	$(0, 63, 170, 250)$	113.23
4	1.50	0.35	424.53	5.29	$(\frac{R_p}{8}, \frac{R_p}{8}, \frac{3R_p}{4})$	$(10^{-1}, 10^{-4}, 10^{-10})$	250	$(0, 95, 236, 250)$	316.09
5	0.65	0.35	170.21	2.86	$(\frac{R_p}{4}, \frac{3R_p}{4})$	$(10^{-2}, 10^{-4})$	1000	$(0, 821, 1000)$	68.46
6	1.20	0.35	361.84	4.43	$(\frac{R_p}{4}, \frac{3R_p}{4})$	$(10^{-2}, 10^{-4})$	1000	$(0, 696, 1000)$	136.92

source for the above four configurations are determined and compared with the results given in [4], as shown in Table I. The basic discrete unit of the buffer occupancy is one packet and the rounding error of the channel capacity is up to 0.5 packet/s.

From Table I, we have the following observations: 1) with the optimal buffer partitioning, the required channel capacity is much less than that reported in [4] in all the multiple-loss-priority cases, achieving more efficient resource utilization; 2) the optimal results show that, at most, a two-region buffer is enough to guarantee the QoS requirements for all the configurations considered, due to the relatively low rate of high-priority traffic. For example, in configuration $\mathcal{C}$, with capacity 118.68 packets/s, the QoS for class 1 and class 2 can be guaranteed as $G(54) = 0.10$ and $G(100) = 0.8 \times 10^{-7}$. The highest priority traffic only has a peak rate of $(R_p/4) = 42.56$ packets/s, less than the capacity required for low-priority class. As a result, the highest priority traffic can be served without buffering and suffers no loss, based on the fluid model. The approach proposed in [4] gives very conservative results when high priority traffic constitutes only a small portion of the total traffic; 3) the optimal results also show that the required minimal channel capacity increases as the traffic proportion of high priority (low loss probability) classes increases. It is intuitively understandable that more bandwidth is required to provision more stringent QoS. For example, in configuration $\mathcal{B}$, 50% of the total traffic has a very loose PLP requirement of 10^{-1}, while in configurations $\mathcal{C}$ and $\mathcal{D}$, this part of traffic decreases to 25% (the high-priority part increases). Therefore, these two configurations have a larger effective bandwidth allocated than configuration $\mathcal{B}$. Note that in this case, the result given in [4] does not reflect such a relationship between bandwidth allocation and QoS provision, due to the improper selection of the partition thresholds.

Example 2: Admission Control for Heterogeneous Traffic: In the following, we numerically evaluate: 1) the aggregate admission region where the buffer partition vector is chosen to be the optimal vector for one traffic type or the arithmetic average of the optimal vectors of all the traffic types (referred to as static buffer partitioning) or is obtained using the three proposed heuristic dynamic buffer partitioning schemes; 2) the linear admission region; and 3) the ideal admission region. To check whether the QoS of the admitted traffic flows in the linear admission control can be guaranteed, we compare the linear admission region with the aggregate admission region with both

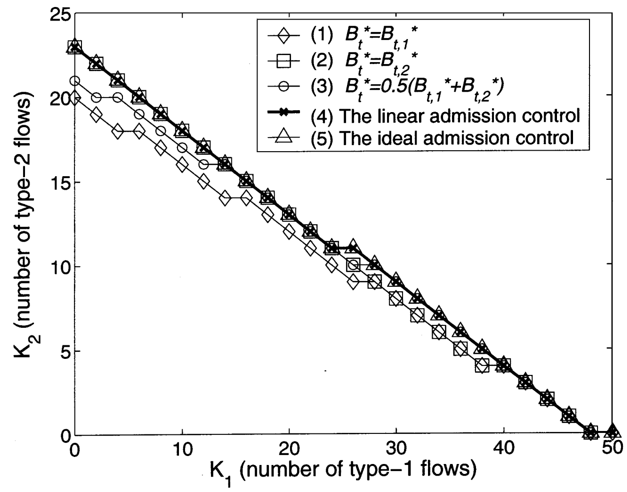

Fig. 1. Admission regions of two types of on-off sources under configuration 1: static buffer partitioning, $B = 100$.

static (for a given buffer partition vector) and dynamic buffer partitioning (by the average approximation). In particular, we consider the multiplexing of two heterogeneous traffic types of on-off sources in a partitioned buffer, with two configurations. In configuration 1, type-1 and type-2 sources are multiplexed in a buffer of size 100 packets. A type-2 flow is burstier than a type-1 flow. In configuration 2, type-3 and type-4 sources are multiplexed in a larger buffer of size 250 packets for better statistical multiplexing. A type-4 flow is burstier than a type-3 flow. The traffic characteristics, QoS requirements and the optimal buffer partitioning vector of all the four traffic types are presented in Table II. The units of time, buffer size, and rate are second, packet, and packet/second, respectively. To further differentiate the statistical multiplexing gain between the two configurations, the channel capacity is set as $50c_1^*$ in configuration 1 and $150c_3^*$ in configuration 2. The admission regions in different situations are calculated and plotted in Figs. 1–4 as $K_y \sim K_x$ curves, where K_y and K_x are the numbers of admitted type-y (=2 or 4) and type-x (=1 or 3) flows, respectively. For quantitative comparison, we calculate the area of each admission region by $\sum_{K_x=0}^{\max(K_x)} K_y(K_x)$ and the results are given in Table III.

The aggregate admission regions with the static buffer partitioning (curves 1, 2, and 3) are plotted and compared with the linear admission region (curve 4) and the ideal admission re-

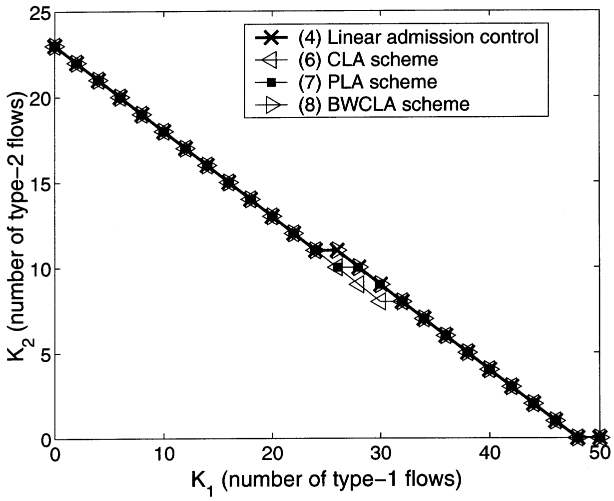

Fig. 2. Admission regions of two types of on-off sources under configuration 1: dynamic buffer partitioning, $B = 100$.

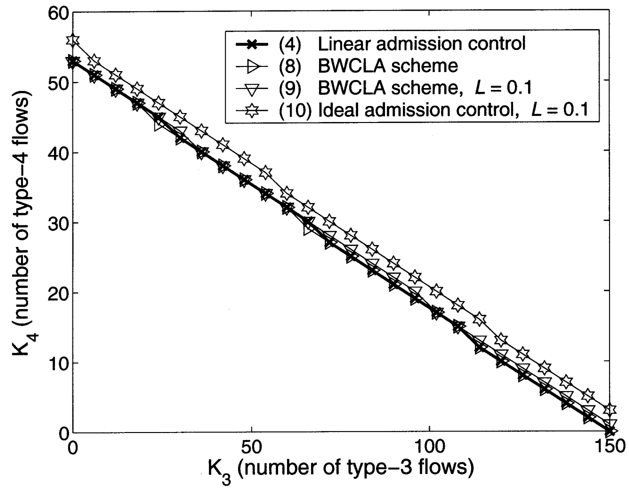

Fig. 4. Admission regions of two types of on-off sources under configuration 2: dynamic buffer partitioning, $B = 250$.

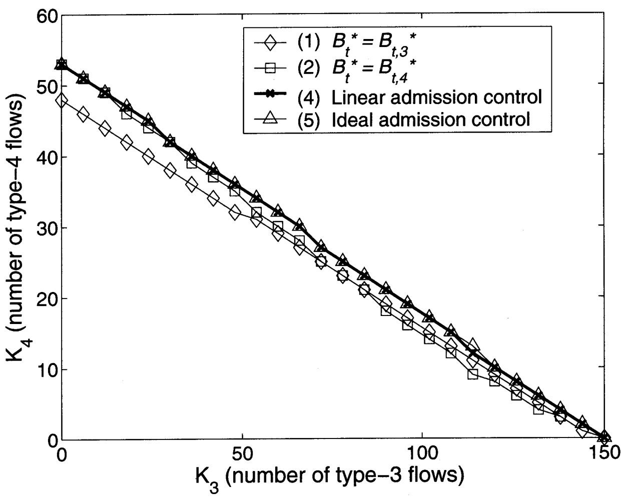

Fig. 3. Admission regions of two types of on-off sources under configuration 2: static buffer partitioning, $B = 250$.

TABLE III
AREAS OF THE ADMISSION REGIONS: HETEROGENEOUS MULTIPLEXING

admission control and buffer partitioning	configuration 1	configuration 2
Aggregate admission control: static buffer partitioning		
(1) $B_t^* = B_{t,x}^*$	501	3585
(2) $B_t^* = B_{t,y}^*$	547	3726
(3) $B_t^* = \frac{B_{t,x}^* + B_{t,y}^*}{2}$	542	3832
Aggregate admission control: dynamic buffer partitioning		
(6) CLA	554	3876
(7) PLA	560	3954
(8) BWCLA	562	3969
(9) BWCLA, $L = 0.1$	565	4063
(4) linear admission control	562	3983
(5) ideal admission control	562	3995
(10) ideal admission, $L = 0.1$	622	4419

gion (curve 5), in Fig. 1 for configuration 1 and in Fig. 3 for configuration 2. The aggregate admission regions with the dynamic buffer partitioning (curves 6, 7, and 8) are plotted and compared with the linear admission region, in Fig. 2 for configuration 1 and in Fig. 4 for configuration 2. From Figs. 1–4 and Table III, we have the following observations.

(1) In both configurations, the $K_y \sim K_x$ curves bounding all the admission regions are approximately linear. The linear admission regions are almost exactly the same as the corresponding ideal ones. In configuration 1, the linear admission region (curve 4) is exactly the same as the ideal admission region (curve 5). In configuration 2, as the type-4 flows are burstier than the type-2 flows multiplexed in configuration 1 and the buffer size increases to 250, the larger statistical multiplexing gain (than that in configuration 1) results in a larger ideal admission region than the linear one. The closeness of the linear admission region to the ideal one shows that the bandwidth allocation based on the minimal effective bandwidth can achieve an efficient resource utilization.

(2) In both configurations, curves 1, 2, and 3 have obviously smaller admission regions than the linear admission region. It means that the linear admission control with the static buffer partitioning may admit traffic sources too aggressively and, therefore, may result in that the QoS of the accepted traffic sources can not be guaranteed.

(3) The buffer partition vector affects the burstier source more than the less bursty source. In configuration 1, with the partition vector $\boldsymbol{B}_t^*$ switching from $\boldsymbol{B}_{t,1}^*$ to $\boldsymbol{B}_{t,2}^*$, the impact on the less bursty type 1 source is reflected by a bandwidth utilization decrease of $(50 -$

$48) \times 121.10 = 242.20$ packets/s, while a larger impact on the burstier type 2 source is reflected by a larger bandwidth utilization increase of $(23-20) \times 262.86 = 788.58$ packets/s. The relation between burstiness and bandwidth utilization also applies to the type-3 and type-4 traffic in configuration 2, when the partition vector $\boldsymbol{B}_t^*$ switching from $\boldsymbol{B}_{t,3}^*$ to $\boldsymbol{B}_{t,4}^*$. This observation justifies that a burstier source should be given a heavier weight in determining the optimal vectors for different sources.

(4) Simply using arithmetic average in determining the buffer partition vector for the heterogeneous sources does not give an admission region larger than the linear admission region. Curve 3 is not plotted for configuration 2 for the clarity of the figure.

(5) With dynamic buffer partitioning, the aggregate admission regions achieved by CLA, PLA, and BWCLA are very close to the linear admission region in both configurations. The three dynamic buffer partitioning schemes show very similar performance, which indicates that the traffic load is the determinant factor, when weighted average approaches are used to approximate the optimal partition vector. All the three schemes consider this factor when dynamically adjusting the partition thresholds as given in (19)–(21). In the middle of the curves where the two types of traffic have a similar load, the impact of bursty coefficients becomes more prominent. In this region, CLA performs the worst, because this scheme does not give a higher weight to a burstier source when determining the optimal partition vector, while PLA and BWCLA schemes take into account traffic burstiness. BWCLA performs slightly better than PLA.

(6) In the aggregate admission control, the loss probabilities are calculated by (12), which is a conservative estimation, compared with (7). Therefore, the obtained aggregate admission region is a conservative result. As a result, even though in the figures the linear admission curve is occasionally above the aggregate admission curve obtained based on (12), if they are close enough, it is reasonable to assume that the linear admission curve should still go below the admission curve from (7). For example, by setting $L = 0.1$ (this is a conservative value indicated by the simulation results presented in next section), we recalculate the BWCLA admission region (curve 9) and the ideal admission region (curve 10). It is clearly observed that curve 10 is moved up by the decrease of the L value from 1.0 to 0.1. For clarity, curve 9 and 10 are plotted only in Fig. 4. In this case, the optimal admission curve is well above the linear admission curve and the BWCLA curve falls between them.

We have also numerically evaluated the admission regions with many other parameter settings, including various traffic characteristics, buffer sizes, and channel capacities. The results are in agreement with the above observations. Although the BWCLA may not always provide the best approximation, it has very consistent performance and always achieves an admission region very close to that of the linear admission control. With $L \leq 0.5$, the BWCLA admission control always gives a larger admission region than the linear admission control in our numerical study.

Examples 3: Admission Control With Multilevel Priorities: This example illustrates resource allocation based on the effective bandwidth in a DiffServ system, where type-$\mathcal{A}$ traffic (parameters given in Table I) requires the premium service, type-1 and type-2 (parameters given in Table II) the assured service, and some other data traffic the best-effort service. The admission controller manages resource allocation for the premium and the assured services, and the leftover capacity after provisioning the two services is taken by the best-effort service. The admission controller accepts a type-$\mathcal{A}$ traffic flow with the peak rate bandwidth allocation of 170.21 packets/s, and a type-1 and type-2 traffic with the minimal effective bandwidth of 121.10 and 262.86 packets/s, respectively. The constraint on the admission set $(n_{\mathcal{A}}, n_1, n_2)$ is given in the following linear form:

$$170.21 n_{\mathcal{A}} \leq c$$
$$158.30 n_{\mathcal{A}} + 121.10 n_1 + 262.86 n_2 \leq c$$

where 158.30 is the effective bandwidth of a type-$\mathcal{A}$ flow as seen in the priority-2 buffer for the assured service, and c is the channel capacity. The partition vector of the assured buffer is given by (using BWCLA)

$$\boldsymbol{B}_t = \left\lceil \frac{2.86 n_1}{2.86 n_1 + 4.43 n_2}(0, 51, 100) + \frac{4.43 n_2}{2.86 n_1 + 4.43 n_2}(0, 82, 100) \right\rceil$$

which is not affected by the type-$\mathcal{A}$ traffic.

Note that in the dynamic buffer partitioning, it is possible that some traffic admitted based on the old partitioning, which is not acceptable with the new buffer thresholds, is not cleared in time and causes the undesirable loss under the new buffer partitioning (a logically admitted packet finds no buffer space). The dual-buffer approach proposed in [15] can be used for smooth adjustment of the buffer partition vector, without harming the QoS.

VIII. Simulation Results

Based on all the numerical results in Section VII, it is expected that in a large partitioned buffer providing small loss probabilities, the minimal effective bandwidth can be used for efficient resource allocation and QoS guarantee. This can be further verified by the simulation results presented in this section. The PLPs will be estimated by simulations for three traffic situations: the single flow, homogeneous multiplexing, and heterogeneous multiplexing, where the resources are allocated based on the minimal effective bandwidth.

To improve the simulation accuracy, we use *importance-sampling* (IS) [16] whenever applicable. The rate matrices of the on-off Markov fluid sources are adjusted according to the techniques presented in [17] to speed up the simulation. Likelihood ratios are used to recover an estimate of the loss for the original traffic parameters. The A-cycle [16], [18] method is used in the simulation to estimate the loss probability and the confidence interval, when using importance sampling. To obtain the loss probabilities of all the J classes, J runs are executed in

TABLE IV
PLPs AND RELATIVE ERRORS: A SINGLE FLOW WITH OPTIMAL AND NONOPTIMAL BUFFER PARTITIONING

traffic type		PLP of class 1	PLP of class 2	PLP of class 3	PLP of class 4
$\mathcal{A}$	nonoptimal partitioning [4]	1.58×10^{-12}; 9.92%	N/A	N/A	N/A
	optimal partitioning	1.58×10^{-12}; 9.92%	N/A	N/A	N/A
$\mathcal{B}$	nonoptimal partitioning [4]	4.66×10^{-7}; 9.97%	0	N/A	N/A
	optimal partitioning	5.55×10^{-2}; 9.96%	0	N/A	N/A
$\mathcal{C}$	nonoptimal partitioning [4]	6.18×10^{-5}; 9.94%	0	0	N/A
	optimal partitioning	8.07×10^{-2}; 9.81%	7.59×10^{-9}; 9.94%	0	N/A
$\mathcal{D}$	nonoptimal partitioning [4]	1.12×10^{-3}; 9.94%	0	0	0
	optimal partitioning	8.16×10^{-2}; 9.93%	3.31×10^{-5}; 9.98%	0	0
1	optimal partitioning	8.96×10^{-2}; 9.94%	5.23×10^{-12}; 9.98%	N/A	N/A
2	optimal partitioning	8.70×10^{-2}; 9.83%	1.59×10^{-12}; 9.97%	N/A	N/A
3	optimal partitioning	8.88×10^{-2}; 9.87%	6.74×10^{-5}; 9.95%	3.02×10^{-12}; 9.95%	N/A
4	optimal partitioning	9.29×10^{-2}; 9.70%	6.44×10^{-5}; 9.72%	3.89×10^{-14}; 9.99%	N/A

each simulation. In the simulation run for class j, the rate matrices are adjusted accordingly in each IS A-cycle to speed up the simulation until the threshold B_j is hit. The relative error, defined as the ratio of the 95% confidence interval of the loss probability to the estimated loss probability, is also calculated and presented.

A. Single Flow

For the single flow situation, the eight types of traffic studied in Section VII are simulated, respectively, where the buffer is optimally partitioned and the minimal effective bandwidth is used as the channel capacity. The PLPs of each class of traffic and the corresponding relative errors are obtained in the simulations and presented in Table IV. It can be observed that the simulated loss probabilities, except for the highest priority class, are smaller but very close to the QoS requirements used for the effective bandwidth calculation. For the highest priority classes, the simulation results are much smaller than the QoS specification because of the finite buffer effect [19].

For the traffic of types $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$, we estimate the PLPs under both buffer settings from [4] and from the optimal buffer partitioning analysis.[5] The results are compared in Table IV. We see that, with the setting from [4], the PLPs are much smaller than the specified QoS requirements. Some classes with higher priorities even achieve zero packet loss, due to the fact that the input peak rate becomes less than the channel capacity when the buffer content exceeds a certain threshold. The results show that the buffer is not configured optimally; the algorithms in [4] can not detect this impropriety and give a very conservative effective bandwidth. On the other hand, the techniques developed in this paper can partition the buffer optimally according to the QoS specifications (a zero partition is assigned for the regions where the peak rate is less than the channel capacity), and achieve the minimal bandwidth requirement. From Table IV, we can see that, with the optimal partitioning and the minimal effective bandwidth allocation, the PLPs are very close to (but smaller than) the QoS specifications, taking into account the finite buffer effect.

[5]In the simulations, extra space of one packet is added to the buffer to absorb the packet discreteness so that the bufferless effect based on the fluid model can be simulated properly. The partition vectors used in simulation are (0, 100), (0, 100, 101), (0, 54, 100, 101), (0, 63, 100, 101, 101) for traffic types $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, and $\mathcal{D}$, respectively.

B. Homogeneous and Heterogeneous Multiplexing

We also simulate the partitioned buffer with input from multiple Markovian sources. The channel capacity is set as the summation of the effective bandwidths required by the input traffic flows. In the homogeneous multiplexing case, the optimal partition vector of the traffic type is used to differentiate different classes of traffic. In the heterogeneous case, the BWCLA scheme is used to approximate the optimal partition vector for the aggregate traffic. The results are summarized in Tables V and VI.

Table V presents the results of multiplexing of a small number of Markovian sources to illustrate the effect of the statistical multiplexing factor L in (7), and the BWCLA's capability to guarantee QoS. From Table IV, we can see that for a single type-3 flow, the factor L in (7) can be conservatively set as $L = ((8.88 \times 10^{-2})/10^{-1}) = 0.888$. Table V shows that L reduces to 0.465 and to 0.084, respectively, when two and five type-3 flows are multiplexed, which means a larger statistical multiplexing gain is achieved when the number of multiplexed flows increases. Typically, there are a large number (hundreds or thousands) of traffic flows served by a buffer in a router or switch; therefore, it is reasonable to deduce that L is smaller than 0.1. In Section VII, the numerical results show that the BWCLA admission region is larger than the linear admission region when setting $L = 0.1$. The simulation results demonstrate that the setting is reasonable and conservative for a typical router or switch. It is also observed from Table V that, for type-4 traffic, L reduces from 0.929 to 0.205 when multiplexing two traffic flows. The decrease in L value is faster than that for

TABLE V
PLPs AND RELATIVE ERRORS: HOMOGENEOUS AND HETEROGENEOUS MULTIPLEXING OF MULTICLASS MARKOVIAN TRAFFIC

traffic sources		PLP of class 1	PLP of class 2	PLP of class 3
2 type-3 flows		4.65×10^{-2}; 9.92%	3.01×10^{-5}; 9.98%	1.49×10^{-12}; 9.99%
5 type-3 flows		8.42×10^{-3}; 9.95%	4.13×10^{-6}; 9.99%	1.29×10^{-13};14.95%
2 type-4 flows		2.05×10^{-2}; 9.99%	1.47×10^{-5}; 9.94%	2.06×10^{-14}; 11.69%
1 type-3 flow	$\boldsymbol{B}_t^* = \boldsymbol{B}_{t,3}^*$	6.44×10^{-2}; 9.65%	1.39×10^{-4}; 9.98%	1.79×10^{-17}; 14.89%
and	$\boldsymbol{B}_t^* = \boldsymbol{B}_{t,4}^*$	2.66×10^{-2}; 9.83%	7.85×10^{-6}; 9.98%	3.73×10^{-9}; 9.97%
1 type-4 flow	BWCLA	3.55×10^{-2}; 9.90%	2.33×10^{-5}; 9.98%	5.70×10^{-12}; 9.97%

TABLE VI
PLPs AND RELATIVE ERRORS: LINEAR ADMISSION CONTROL WITH BWCLA DYNAMIC BUFFER PARTITIONING

(K_5, K_6)	(20, 0)	(16, 2)	(12, 4)	(8, 6)	(4, 8)	(0, 10)
PLP of class 1	2.04×10^{-3} 0.22%	1.35×10^{-3} 0.27%	1.07×10^{-3} 0.30%	9.97×10^{-4} 0.31%	9.20×10^{-4} 0.32%	8.09×10^{-4} 0.34%
PLP of class 2	1.10×10^{-6} 9.34%	8.90×10^{-7} 10.39%	8.33×10^{-7} 10.74%	5.47×10^{-7} 13.25%	4.67×10^{-7} 14.34%	2.19×10^{-6} 6.62%

type-3 traffic, which means that the burstier traffic achieves a larger statistical multiplexing gain.

To verify that the buffer with BWCLA partition can serve the traffic with QoS guarantee, we simulate the multiplexing of a type-3 and a type-4 traffic flow, where the summation of the minimal effective bandwidths (113.23 + 316.09) is set as the channel capacity. We run simulations for three cases where the partition vectors $\boldsymbol{B}_{t,3}^*(= (0, 63, 170, 250))$, $\boldsymbol{B}_{t,4}^*(= (0, 95, 236, 250))$, and the BWCLA vector $(\lceil(2.86/(2.86 + 5.29))\boldsymbol{B}_{t,3}^* + (5.29/(2.86 + 5.29))\boldsymbol{B}_{t,4}^*\rceil)$, are used, respectively. Table V shows that the PLPs of classes 2 and 3 are larger than the QoS specification with partition vector $\boldsymbol{B}_{t,3}^*$ and $\boldsymbol{B}_{t,4}^*$, respectively. The QoS is not guaranteed for all classes of traffic in these two cases. Using the BWCLA partition vector, the QoS requirements of all the classes are satisfied.

To demonstrate the dynamic performance of the BWCLA scheme, we simulate the following admission control case for multiple (>2) heterogeneous on-off traffic flows. As IS simulation techniques for Markovian sources [16]–[18] are derived from large buffer analysis $(B \to \infty)$, the techniques perform poorly when the number of flows is large and the buffer size B is small [18]. Therefore, we use the conventional Monte Carlo simulation in this case. The statistical parameters and the buffer optimization results of the two types of traffic (type-5 and type-6) under consideration are listed in Table II. The channel capacity is set as $20c_5^*$ and the linear admission control is used. The buffer size and the peak rates of the traffic are chosen in such a way in order to: 1) achieve PLPs that can be simulated accurately with 4×10^8 arrivals; 2) obtain the minimal effective bandwidths with $c_6^* = 2c_5^*$ so that the channel capacity can be fully used with the linear admission control. We estimate the PLPs with simulations for different (K_5, K_6) operation points, where K_5 and K_6 are the acceptable number of type-5 and type-6 flows. The PLP results are listed in Table VI. At points (20, 0) and (0, 10), we actually have homogeneous multiplexing cases and the BWCLA gives the optimal partition vector. Table VI shows that at other operation points with different mixture of heterogeneous traffic, the QoS requirements of both classes of traffic are guaranteed and loss probabilities are quite close to that in the homogeneous cases.

IX. CONCLUSIONS AND DISCUSSIONS

In this paper, we study the effective bandwidth of a partitioned buffer system from a novel perspective. With the buffer partition thresholds being optimized, the bandwidth required to guarantee the QoS of all traffic classes is minimized. This minimal channel capacity is defined as the effective bandwidth of a multiclass Markovian traffic source. The optimal buffer partition vector and the minimal effective bandwidth are solved in a combined way with simple calculation. The minimal effective bandwidth can be used in an additive way to do admission control, achieving efficient resource utilization. In a heterogeneous multiplexing situation, to guarantee the QoS of the admitted traffic, the buffer partition vector should be optimized dynamically in response to the traffic variation. Dynamic buffer partitioning techniques are proposed to well approximate the optimal partition vector, while avoiding the heavy calculation and memory burdens being incurred in searching of the exact optimal partition vector. The low complexity makes the proposed dynamic buffer partitioning techniques convenient for practical use. The improvement of resource utilization under the QoS constraint based on the minimal effective bandwidth, is demonstrated by numerical analysis and computer simulation results, as compared with the previously published results. When combined with the interbuffer priority technique, the proposed minimal effective bandwidth can be applied to achieve the linear admission sets in a DiffServ router, which makes the capacity planning of DiffServ networks based on stochastic-loss-network model [20], [21] possible. The techniques of optimal buffer partitioning and minimal effective bandwidth should be very useful in practice, even though they are limited to the traffic from the Markovian sources, as the Markov-modulated fluid source model is extensively used for voice and video sources. Furthermore, many recent measurement studies show that the traffic over the Internet exhibits long-range dependence (LRD) and self-similarity. As the LRD traffic can be approximated by Markovian models [22], it is possible that the techniques proposed in this paper can be extended to the LRD traffic.

For simplicity and scalability, the present DiffServ model does not support explicit admission control. The admission control is applied implicitly by provisioning policing parameters at network boundaries. While such implicit admission control does protect the network to some degree, it can be quite ineffective [23]. Also, without per-flow information, the network capacity planning is very difficult. Many researchers agree on that the edge routers of a DiffServ network are capable enough to keep per-flow information [24], since flows presenting at an edge router is not so many as those at a core router. In our proposed admission control technique, we also assume that the edge router is sufficiently powerful to keep the identity information and calculate the minimal effective bandwidth and the optimal buffer partition vector for a traffic flow. The effective bandwidth and the partition vector should be provided to the resource manager, for admission control and dynamic buffer threshold adjustment.

The theoretical basis of this effective bandwidth study is established for the asymptotic regime of large buffers and small loss probabilities. In fact, the resource utilization can be further improved if the finite buffer effect can be included in the buffer optimization and effective bandwidth calculation. A possible approach is to use (7) for PLPs in the buffer partition regions except the last one, and to use the techniques presented in [19] to determine the PLP in the last region. Further research on this topic is necessary.

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