Optimal buffer partition for provisioning QoS of wireless network

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Abstract: Next generation wireless network is evolving toward IP-based network that can various provide multimedia services. A challenge in wireless mobile Internet is support of quality of service over wireless access networks. DiffServ architecture is proposed for evolving wireless mobile Internet. In this paper we propose an algorithm for optimal buffer partitioning which requires the minimal channel capacity to satisfy the QoS requirements of input traffic. We used a partitioned buffer with size B to serve a layered traffic at each DiffServ router. We consider a traffic model with a single source generates traffic having J $(J \geq 2)$ quality of service (QoS) classes. QoS in this case is described by loss probability ε_j for QoS class j. Traffic is admitted or rejected based on the buffer occupancy and its service class. Traffic is generated by heterogeneous Markov-modulated fluid source (MMFS).

I. Introduce

Provision of various real-time multimedia services to mobile users is main object of the next-generation wireless network, which will be IP-based and interwork with the Internet backbone. The major task is provision of QoS guarantee over IP-based wireless access network. There are two main architectures for QoS provisioning in IP network, the intergrated services (IntServ) and differentiated services (DiffServ). In IntServ architecture uses Resource Reservation Protocol (RSVP) to explicitly signal and dynamically allocate resources at each intermediate node along the path for each traffic flow, which the heavy signal overhead reduces the utilization efficiency of the wireless bandwidth. DiffServ approach uses a much coarser differentiation model to obviate the above disadvantages, where packets are classified into a small number of service classes at the network edge [1]. The DiffServ services has been proposed as an efficient and scalable traffic management mechanism to ensure Internet QoS without using per-flow resource reservation and per-flow signaling.

A simple and efficient approach to differentiate services is to use the priority structure. There are two kind of priority structure. One is priority queue, each class of traffic with certain QoS requirement enters a separate queue granted a certain priority, and the traffic in buffer with higher priority is served before traffic in buffer with lower priority. Elwalid and Mitra [2] analyzed a two-priority queuing system supplied with Markov-modulated fluid source. Berger and Whitt [3] consider the case of network nodes that use a priority-service discipline to support multiple classes of service, and determine an appropriate notion of effective bandwidths. But in this structure, it has some drawbacks: the buffer utilization is inferior, the cell of different priority emanate from a single source, then having separate buffers for QoS requirement forces resequencing at the destination.

The other priority structure is to serve traffic with a partitioned buffer [4], which can provide difference loss-priorities while keeping the order of packets from the same microflow. Kulkarni, Gun and Chimento's earlier study gave valuable insights into the buffer partitioning problem. In [4] and [7], they have calculated optimal partitioned buffer. However, it is too complicated and has not been addressed in heterogeneous system. In this paper we propose a general algorithm to determine the optimal buffer thresholds for a partitioned queue, similar to [4].

The paper is organized as follows. Session II describes the system model. Session III describes fluid model analysis. Session IV presents algorithm for calculating optimal partitioned buffer. Session V shows an approach to adaptively adjust the threshold vector for a high resource utilization in a heterogeneous multiplexing system.

II. The system model

Consider a system with a partitioned buffer of size B, where input traffic is from Markov modulated fluid source and output traffic is served by a channel of constant capacity c. Let S be the state space and M the generator matrix of the Markov chain. At state $i(i \in S)$, the source generates traffic of class $j(1 \leq j \leq J)$ fluid at rate λ_i^j. Admission policy is based on a space reservation scheme, using threshold $\{B_j, 1 \leq j \leq J\}$. 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 $\{j, j+1, ..., J\}$ is admitted into the buffer. In this case the diagonal rate matrix is termed as Λ^j, where $\Lambda_{ii}^j = \sum_{r=j}^{J} \lambda_i^r$. Let $G(B_j)$ be the long-run probability that the buffer content is equal to or above the threshold B_j, i.e., $G(B_j) \triangleq \Pr(X \geq B_j)$. We consider this probability to be the loss rate of class j fluid. The QoS is satisfied for all the traffic class if $G(B_j) \leq \varepsilon_j \quad \forall j \in \{1,2,\ldots,J\}$ where $\varepsilon_1 > \varepsilon_2 > \ldots > \varepsilon_J > 0$

The Markov-modulated fluid source can be a single source or the aggregate K (K>1) statistically independently Markov-modulated fluid sources. For simplicity of discussion, we consider the case of single Markov-modulated fluid source, however the results also apply to the aggregate of K independent sources.

III. Fluid model analysis

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

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

where the drift matrix $D \triangleq \Lambda^j - cI$ and I is identity matrix. The spectral solution to (1) is given by $\pi^j(x) = \sum_r a_r^j \phi_r^j e^{z_r^j x} \quad (1 \leq j \leq J)$, where (z_r^j, ϕ_r^j) is an eigenvalue/eigenvector pair. Such pairs are solutions to the eigenvalue problem

$$z\phi D^j = \phi M \quad (1 \leq j \leq J) \quad (2)$$

After solving all the coefficients a_r^j, the loss rate of class j fluid can be calculated by

$$\begin{aligned} G(B_j) &= 1 - \sum_{s \in S} \pi_s(B_j^-) \\ &= 1 - \sum_r a_r^j \langle \phi_r^j, 1 \rangle e^{z_r^j x} \quad (1 \leq j \leq J) \end{aligned} \quad (3)$$

The symbol $\langle .,. \rangle$ denotes the inner product of vectors and 1 is vector in which all elements are unity.

Where the size of the state space S is large and the number of loss priorities is more than 2 (J>2), the calculation of coefficients $\{a_r^j\}$ from boundary conditions becomes quite complex. If we have

$$B_j \to \infty, \text{ and } \varepsilon_j \to 0 \quad (1 \leq j \leq J) \quad (4)$$

we can use only the dominant eigenvalue item to approximate the loss function G(.) [5]. Let z_1^j denote the main eigenvalue solved from (2). In [4] proves that in case of (4) we have

$$G(B_j) \approx \prod_{r=1}^{j} \exp[z_1^r (B_r - B_{r-1})] \quad (1 \leq j \leq J) \quad (5)$$

IV. Optimal buffer partitioning

For simplicity, when a Markov-modulated source generates J class fluids and is served by a buffer partition by J-1 thresholds, the fluid loss rate of each class can be approximately calculated by:

$$G(B_j) = \prod_{r=1}^{j} \exp[z_1^r(c)(B_r - B_{r-1})] \quad (1 \leq j \leq J) \quad (6)$$

$z_1^r(c)$ emphasizes that QoS is directly affected by the channel capacity c. In this equation, when other parameters are fixed, the choice of $B_t = (B_1, B_2, \ldots, B_{J-1})$ determines the channel capacity required to guarantee the QoS for all J classes. Let $B_t^* = (B_1^*, B_2^*, \ldots, B_{J-1}^*)$ be the optimal threshold vector that minimizes the required capacity c.

Let c_j be the solution to $G(B_j) = \varepsilon_j \quad (1 \leq j \leq J)$, for the QoS satisfaction, it is required that $c \geq \max\{c_1, c_2, \ldots, c_J\}$

$$\prod_{r=1}^{j} \exp[z_1^r(c_j)(B_r - B_{r-1})] = \varepsilon_j \quad (1 \leq j \leq J) \quad (7)$$

In [6], we have an approach to find the optimal threshold vector B_t^*. Under the QoS constraint, the required channel capacity c achieves its minimal value c^*, if B_t is adjusted to B_t^* such that $c_1 = c_2 = \ldots = c_J \triangleq c^*$

A. Two loss priorities

Consider a Markov-modulate fluid source generates two classes (J=2) of fluid at each state, with $M, \Lambda_1, \Lambda_2, \varepsilon_1, \varepsilon_2$ (M: generator matrix, Λ_j: diagonal rate matrix, ε_j: loss probability). The buffer begins from B_{start} (B_0) and ends at B_{end} (B_2), which is divided into two parts by threshold B_1. From (7), we have:

$$z_1^1(c_1)(B_1 - B_{start}) = \ln \varepsilon_1$$

$$z_1^1(c_2)(B_1 - B_{start}) + z_1^2(c_2)(B_2 - B_{end}) = \ln \varepsilon_2$$

With the optimal threshold $B_1^*, c_1 = c_2 = c^*$ and (8), (9) we have

$$\left[\frac{\ln \varepsilon_1}{z_1^1(c^*)} + B_{start}\right] - \left[B_{end} - \frac{\ln \varepsilon_1 - \ln \varepsilon_2}{z_1^2(c^*)}\right] = 0 \qquad (10)$$

From [7] we know that, the dominant eigenvalue for any j is monotonic, strictly decreasing function of c^* with value between the mean and peak rates of source. We can solve c^* from (10) by using standard iterative root-finding techniques. After that we can calculate B_t^* from (8).

B. Multiple loss priorities (calculation goes forward from level 1 to level J-1)

We consider how to optimally partition a buffer with J-1 threshold to provide J loss probabilities. At $B_t = B_t^*$, we have J equations:

$$\exp[z_1^j(c^*)(B_j^* - B_{j-1}^*)] = \frac{\varepsilon_j}{\varepsilon_{j-1}} \qquad (1 \le j \le J) \qquad (11)$$

that are satisfied simultaneously with the solution pair (c^*, B_t^*), where $B_0^* = 0, B_J^* = B$ and $\varepsilon_0 = 1$. We extend $B_t^* = (B_0^*, B_1^*, ..., B_{J-1}^*, B_J^*)$ and define the QoS vector $\varepsilon = (1, \varepsilon_1, \varepsilon_2, ..., \varepsilon_J)$. Estimate of B_t^*.

Step 1: Consider a virtual system, buffer B is divided into two parts by $\vec{\tilde{B}}_1^*$ with QoS vector $\varepsilon = (\varepsilon_1, \varepsilon_J)$. Use approach in section A, we obtain $(\vec{\tilde{c}}_1^*, \vec{\tilde{B}}_1^*)$

Because QoS of traffic from class 2, 3,..., J-1 is the same QoS of traffic from class J, for the satisfaction of QoS requirements $\vec{\tilde{c}}_1^* > c^*$. Because of monotonic decreasing characteristic $z_1(\square)$, $z_1(\vec{\tilde{c}}_1^*) < z_1(c^*)$. In case the input rate of virtual system is exactly the same as that of the original system, we have $\exp[z_1^1(\vec{\tilde{c}}_1^*).\tilde{B}_1^*] = \exp[z_1^1(c^*).B_1^*] = \varepsilon_1$. With negative eigenvalues, we have $\vec{\tilde{B}}_1^* < B_1^*$

Step j $(2 \le j \le J-1)$: partition the high-end of buffer in the previous step, $[\vec{\tilde{B}}_{j-1}^*, B]$, by threshold $\vec{\tilde{B}}_j^*$. Look at (11) and use approach in section A with parameters $M, \Lambda_j, \frac{\varepsilon_j}{\varepsilon_{j-1}}, \Lambda_{j+1}, \frac{\varepsilon_J}{\varepsilon_{j-1}}, \vec{\tilde{B}}_{j-1}^*, B$. And like step 1, we have $\vec{\tilde{B}}_j^* < B_j^*$.

We find $\vec{\tilde{B}}_t^*$, the calculation goes from level 1 to level J-1.

C. Multiple loss priorities (calculation goes backward from level J-1 to level 1)

Step 1: Consider a virtual system, buffer B is divided into two parts by $\overleftarrow{\tilde{B}}_{J-1}^*$ with QoS vector $\varepsilon = (\varepsilon_1, \varepsilon_J)$. Use approach in section A, we obtain $(\overleftarrow{\tilde{c}}_{J-1}^*, \overleftarrow{\tilde{B}}_{J-1}^*)$

Because QoS of traffic from class 1, 2,...,J-2 is the same QoS of traffic class 1 and less stringent QoS requirement, thus $\overleftarrow{\tilde{c}}_{J-1}^* < c^*$. $z_1(\square)$ has monotonic decreasing characteristic, $z_1(\overleftarrow{\tilde{c}}_1^*) > z_1(c^*)$. In case the input rate of virtual system is exactly the same as that of the original system, we have $\exp[z_1^{J-1}(\overleftarrow{\tilde{c}}_{J-1}^*).\tilde{B}_1^*] = \exp[z_1^{J-1}(c^*).B_1^*] = \varepsilon_{J-1}$.

With negative eigenvalues, we have $\overleftarrow{\tilde{B}}_{J-1}^* > B_{J-1}^*$

Step j $(1 \le j \le J-2)$: partition the low-end of buffer in the previous step, $[0, \overleftarrow{\tilde{B}}_{j+1}^*]$, by threshold $\overleftarrow{\tilde{B}}_j^*$. Look at (11) and use approach in section A with parameters $M, \Lambda_j, \frac{\varepsilon_1}{\varepsilon_{j+1}}, \Lambda_{j+1}, \frac{\varepsilon_j}{\varepsilon_{j+1}}, 0, \overleftarrow{\tilde{B}}_{j+1}^*$. And like step 1, we have $\overleftarrow{\tilde{B}}_j^* > B_j^*$.

We find $\overleftarrow{\tilde{B}}_t^*$, the calculation goes from level J-1 to level 1.

D. Optimal algorithm

We have calculated forward $\vec{\tilde{B}}_t^*$ and backward $\overleftarrow{\tilde{B}}_t^*$. The estimation initial value is $\tilde{B}_t^* = (\vec{\tilde{B}}_t^* + \overleftarrow{\tilde{B}}_t^*)/2$. For each estimate $\tilde{B}_t^*$, a capacity vector $\tilde{c}^* = (\tilde{c}_1^*, \tilde{c}_2^*, ..., \tilde{c}_J^*)$ is calculated. Then the estimation $\tilde{B}_t^*$ is valuated by checking the associated capacity vector $\tilde{c}^*$ that $\tilde{B}_t^*$ reaches B_t^* when it results in that $\tilde{c}_1^* = \tilde{c}_2^* = ... = \tilde{c}_J^*$.

V. Heterogeneous multiplexing

In homogeneous multiplexing system, the optimal threshold vector B_t^* can bi found. Given the buffer size B, the channel capacity c and QoS vector $[\varepsilon_1, \varepsilon_2, ..., \varepsilon_J]$, the optimal threshold vector is determined by the main eigenvalue vector

$(z_1^1(c), z_1^2(c), \ldots, z_1^J(c))$. When K homogeneous sources enter the system, the main eigenvalue vector can be calculate as $(z_1^1(\frac{c}{K}), z_1^2(\frac{c}{K}), \ldots, z_1^J(\frac{c}{K}))$. But the linear relation does not exit with heterogeneous multiplexing system.

We suppose that there are K sources characterized by (M^k, λ^k) $(k = 1, 2, \ldots, K)$. Assume that for every k, source k has $N^{(k)}$ states and the generator $M^{(k)}$ is irreducible.

Let $\Lambda^{(k)} = diag(\lambda^{(k)}).S^{(k)} = \{1, 2, \ldots, N^{(k)}\}$ is the state space of source k.

The aggregate source is a continuous-time Markov chain with state space

$S = \{s \mid s = (s^{(1)}, s^{(2)}, \ldots, s^{(K)}), s^{(k)} \in S^{(k)}, 1 \le k \le K\}$.

The states of the sources are statistically independent, and consequently the infinitesimal generator of the aggregate source is M

$$M = M^{(1)} \otimes I \otimes \ldots \otimes I + I \otimes M^{(2)} \otimes I \otimes \ldots \otimes I + \ldots + I \otimes I \otimes \ldots \otimes M^{(K)} \quad (12)$$

$\otimes$ denotes the Kronecker product. The standard compact representation of the form M is a K-fold Kronecker sum:

$$M = M^{(1)} \oplus M^{(2)} \oplus \ldots \oplus M^{(K)} \quad (13)$$

The system rate matrix Λ is

$$\Lambda \square \Lambda^{(1)} \oplus \Lambda^{(2)} \oplus \ldots \oplus \Lambda^{(K)} \quad (14)$$

The system drift matrix is $D \square \Lambda - cI$

Then the buffer can be optimally partitioned to serve this aggregate source. But the difficulty is the large dimension of the aggregate source makes the calculation very complex.

We propose an approximation approach. When each source arrives, it is classified into a traffic type m according to its statistical parameters and QoS, the number of sources in each traffic type is recorded and denoted by N_m. Each optimal threshold vector $\tilde{B}^*_{t,m}$ can be calculated for each traffic type m. The overall B^*_t can be determined by averaging those vectors

$$B^*_t = \sum_m \frac{N_m}{N} \tilde{B}^*_t \quad (15)$$

where $N = \sum_m N_m$ is total traffic sources. The basic idea is to adaptively adjust the threshold vector for a high resource utilization in a heterogeneous multiplexing system.

VI. Conclusions

We have presented an approach for adaptively adjusting the threshold vector for a high resource utilization in a heterogeneous multiplexing system. An algorithm to find the optimal partitioned buffer, which provides multiple loss priorities to a Markov-modulated fluid source. This approach is simple way to calculate optimal partitioned buffer.

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