Routing and Congestion Control in ATM Networks

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Abstract

A new routing and, performed by the leaky bucket regulators, congestion control strategy in ATM networks is proposed. The "potential" source provides the network with its characteristics and required quality of service. Based on this information the network makes the admission and routing decisions, and also selects parameters of the leaky bucket regulators "reinforcing" the contract. The strategy minimizes the weighted average delay in the network, subject to the constraints on the average delays for the individual sessions and on the nodes buffers' overflow probabilities.

1: Introduction

The paper proposes a new routing and congestion control strategy in ATM networks. The strategy minimizes the weighted average delay in the network, subject to the constraints on the average delays for the individual sessions and on the nodes buffers' overflow probabilities. Decisions on the admission and routing for a "potential" session are made at the beginning of the session through negotiation between the source and the network. The source provides the network with its characteristics and requirements to the quality of transmission. Based on this information, the network makes the admission and routing decisions, and also selects parameters of the leaky bucket regulator reinforcing the "contract".

A Leaky Bucket Regulator is a 4-parameter device LBR(r,B_T,B_D,R) [1] where r is the constant tokens arrival rate, B_T is the token buffer size, B_D is the data buffer size and R is the parameter which bounds the flow rate of priority cells leaving the regulator. An important parameter is $B = B_T + B_D$, the total buffer space in the device. The LBR(r,R,B_T,B_D) separates traffic generated by the source into 2 substreams: "priority" and "marked". The marked cells which overflow the data buffer, enter the network bypassing the leaky bucket regulator. A cell accepted into the data buffer enters the network as a priority cell as soon as the token buffer is not empty. The marked cells have low priority in terms of transmission and even can be discarded (with possible retransmission) to provide space for the priority cells.

The paper is organized as follows. Section 2 defines the effective bandwidth of a bursty traffic and of the leaky bucket regulator. Section 3 introduces the diffusion approximation for the effective bandwidth and gives some examples. Section 4 discusses input-output description of the LBR(r,R,B_T,B_D). Section 5 proposes the approach to the network management.

2: Effective bandwidth

To define the effective bandwidth of a homogeneous in time source, assume that this source is served by a channel of capacity C through the infinite buffer. The steady-state probability that the buffer's content exceeds B packets is the function of the parameters C, B: $p = p(C,B)$. We define the effective bandwidth of the source as the solution $e = e(\zeta,B)$ of the following equation:

$$p(e,B) = e^{-\zeta B}, \tag{1}$$

where $\zeta \in (0,\infty)$, $B=0,1,\ldots$ In this paper we consider case of large buffers:

$$e(\zeta) = e(\zeta,B)|_{B=\infty}.$$

The effective bandwidth $e(\zeta)$ indicates the bandwidth needed to transmit bursty traffic with required quality of service characterized by the parameter ζ. The effective bandwidth $e(\zeta)$ monotonously increases from the average rate $e(0) = \lambda$ to the peak rate $e(\infty) = \Lambda$ as parameter ζ increases from $\zeta=0$ to $\zeta=\infty$. The practical importance of the effective bandwidth is the result of its additiveness for statistically multiplexed sources: the effective bandwidth e_Σ of the composition of n asynchronous (i.e. statistically independent) sources is the sum of the corresponding effective bandwidths e_i of the sources:

$$e_\Sigma(\zeta) = e_1(\zeta) + \ldots + e_n(\zeta).$$

Since an accepted sources accesses the network through the leaky bucket regulator, the quality of transmission for the priority traffic is determined by the effective bandwidths of the priority outputs of the leaky bucket regulators. The effective bandwidth $e_{out}(\zeta)$ of the priority output of the $LBR(r,R,B_T,B_R)$ is a function of the parameters (r,R,B_T,B_R) and a functional of the effective bandwidth $\{e_{in}(\eta):\eta \geq 0\}$ of the incoming traffic:

$$e_{in} \rightarrow LBR(r,R,B_T,B_R) \rightarrow e_{out}. \tag{2}$$

Even if the input-output description (2) is available, the admission and routing strategy has to deal with uncertainties in the effective bandwidth $e_{in}(\eta)$. The admission and routing decisions based on the estimates of the effective bandwidths e_{out} can lead to unacceptably high overflow probabilities and delays in the nodes' buffers if these estimates turn out to be too optimistic. The natural way to handle this situation is to apply the methodology developed in the decision theory. For instance, the guaranteed quality of transmission can be provided (of course, by the cost of underutilization of some capacity) if the admission decisions are based on the worst case scenario: on the effective bandwidths of the leaky bucket regulators. We define the effective bandwidth of the $LBR(r,R,B_T,B_R)$ as the supremum of the effective bandwidths of the priority outputs over all possible inputs:

$$e(\zeta) = \sup\{e_{out}(\zeta) \mid \forall e_{in}(\eta), \eta \geq 0\}.$$

The effective bandwidth of the $LBR(r,R,B_T,B_R)$ depends only on the parameters (r,R,B_T,B_R) and does not depend on the incoming traffic, $e = e(\zeta | r,R,B_T,B_D)$.

3: Diffusion approximation

Consider the following expansion of the effective bandwidth of a bursty source:

$$e(\zeta) = b_0 + b_1\zeta + b_2\zeta^2 + \ldots$$

Coefficients b_i together with the peak rate Λ may be interpreted as the aggregated parameters describing the source. In particular, parameters b_0 and b_1 correspond to the flow and diffusion approximations respectively. It can be shown that

$$b_0 = \lambda,$$
$$b_1 = v/2$$

where

$$\lambda = \lim_{t\to\infty} E\{x(t)/t\}$$

is the average rate, and

$$v = \lim_{t\to\infty} E\{[x(t)-at]^2/t\}$$

is the variability rate of the homogeneous in time source generating x(t) packets during time interval [0,t). Operator E{.} means the averaging.

Consider the following examples of the sources:

1. Renewal source generates bursts of b_n packets at moments t_n, $n=1,2,\ldots$ Random variables b_n have average b and standard deviation σ_b, and variables $\tau_n=t_{n+1}-t_n$ have average τ and standard deviation σ_τ for all n = 1,2,... For the renewal source:

$$\lambda = b/\tau,$$
$$v = (\sigma_b^2 + \lambda^2\sigma_\tau^2)/\tau.$$

2. On-off source [2] generates packets with constant rate λ_{on} and λ_{off} in on and off states respectively. On and off periods have averages τ_{on}, τ_{of}, and standard deviations σ_{on}, σ_{of} respectively. For the on-off source:

$$\lambda = (\lambda_{on}\tau_{on}+\lambda_{of}\tau_{of})/(\tau_{on}+\tau_{of}),$$
$$\Lambda = \lambda_{on},$$
$$v = (\lambda_{on}-\lambda_{of})^2(\sigma_{on}^2\tau_{of}^2+\sigma_{of}^2\tau_{on}^2)/(\tau_{on}+\tau_{of})^3$$

3. Video teleconferencing source [2]-[3] generates packets with constant rate $\lambda_{\xi(t)}$. The modulating process $\xi(t) \in \{1,\ldots,N\}$ stays in state i during time interval with average τ_i and standard deviation σ_i. Then the process $\xi(t)$ switches to the new state j with probability q_j. For the teleconferencing source:

$$\lambda = \textstyle\sum_i(q_i\lambda_i\tau_i)/\sum_i(q_i\tau_i),$$
$$\Lambda = \max_i\{\lambda_i\},$$
$$v = \{\textstyle\sum_i q_i[(\lambda_i-\lambda)^2(\tau_i^2+\sigma_i^2)]\}/\sum_i q_i\tau_i.$$

Note that the average, pick, and variability rates of the composition of n asynchronous (i.e. statistically independent) sources are the sums of the corresponding rates of the sources:

$$\lambda = \lambda_1 + \ldots + \lambda_n,$$
$$\Lambda = \Lambda_1 + \ldots + \Lambda_n,$$
$$v = v_1 + \ldots + v_n.$$

4: Input-output description of the leaky bucket regulator

Let

$$e_{in}(\zeta) = \lambda_{in} + 0.5v_{in}\zeta + \ldots \quad (3)$$

$$e_{out}(\zeta) = \lambda_{out} + 0.5v_{out}\zeta + \ldots \quad (4)$$

be the expansions of the effective bandwidths of the input and of the priority output of the LBR(r,R,B_T,B_R), respectively.

We approximate the average, peak and variability rates of the priority output of the LBR(r,R,B_T,B_R) as follows:

$$\lambda_{out} = \lambda_{in}(1-\pi), \quad (5)$$

$$\Lambda_{out} = \min\{\Lambda_{in}, R\}, \quad (6)$$

$$v_{out} = v_{in}(1-q^{BT-1}) \quad (7)$$

where the data buffer overflow probability:

$$\pi = q^B(1-q)/(1-q^{B+1}),$$

parameter

$$q = \exp[-2(r-\lambda_{out})/v_{in}]$$

if $r < \Lambda_{in}$, and $q = 0$ otherwise.

Taking into consideration only 2 terms in the expansions (3), (4), one can approximate the effective bandwidth of the priority output of the LBR(r,R,B_T,B_R). Two possible approximations are the follows:

$$e_{out}(\zeta) = \min\{\Lambda_{out}, \lambda_{out}+0.5v_{out}\zeta\},$$

$$e_{out}(\zeta) = \Lambda_{out} - (\Lambda_{out}-\lambda_{out})\exp[-0.5\zeta v_{out}/(\Lambda_{out}-\lambda_{out})]$$

Equations (5)-(7) provide approximate input-output description of the LBR(r,R,B_T,B_R). Smoothing of the incoming bursty traffic by the leaky bucket regulator is achieved by the cost of some delay. Assuming that the data buffer overflow probability π is small: $\pi \ll 1$, we approximate the average waiting time for the priority packets in the data buffer as follows:

$$w = 0.5v_{in}/(r-\lambda_{in})$$

if $r < \Lambda_{in}$, and $w = 0$ otherwise.

Let

$$e(\zeta) = e(0) + 0.5v\zeta + \ldots$$

be the effective bandwidth of the LBR(r,R,B_T,B_R). It can be shown that

$$e(0) = r,$$
$$e(\infty) = R,$$
$$v = 2r(B_T-1).$$

Given parameters $e(0)$, $e(\infty)$, v, one can approximate $e(\zeta)$.

5: The network management

Consider the following network management strategy. Any source seeking the network's service, declares its average λ_{in}, peak Λ_{in}, and variability v_{in} rates as well as the allowable average delay T_{max}. The acceptance and routing decisions made by the network are based on the solution of the following optimization problem:

$$\sum\alpha(s)T(s) \rightarrow \min \tag{8}$$

subject to the constraints:

$$T(s) \leq T_{max}(s) \tag{9}$$

$$\sum_{R(s)\supseteq(n,k)} e_{out}(\zeta_{nk}|s) \leq C_{nk} \tag{10}$$

where T(s) is the average delay for the s-th session carried on route R(s), $\alpha(s)$ are some non-negative weights, $e_{out}(\zeta|s)$ is an estimate of the effective bandwidth of the priority output of the leaky bucket regulator for s-th session, ζ_{nk} are some parameters determined by the allowable nodes buffers' overflow probabilities.

The average delay for the s-th session is:

$$T(s) = w(s) + \sum_{(n,k)\in R(s)}(\tau_{nk}+d_{nk})$$

where w(s) is the average delay on the **LBR**$[r(s),R(s),B_T(s), B_R(s)]$ assigned to session s; τ_{nk} and d_{nk} are, respectively, the average delay and the propagation time on link (n,k). We approximate:

$$w(s) = 0.5v_{in}(s)/[r(s)-\lambda_{in}(s)]$$

if r(s) $< \Lambda_{in}(s)$, and w(s) = 0 otherwise;

$$\tau_{nk} = 0.5v_{nk}/(C_{nk}-\lambda_{nk})$$

if $C_{nk} < \Lambda_{nk}$, and $\tau_{nk} = 0$ otherwise, where

$$\lambda_{nk} = \sum_{R(s)\supseteq(n,k)}\lambda_s, \qquad \Lambda_{nk} = \sum_{R(s)\supseteq(n,k)}\Lambda_s,$$

the "effective variability":

$$v_{nk} = \exp(-\zeta^*_{nk}),$$

parameter ζ^*_{nk} is the solution of the following equation

$$\sum_{R(s)\supseteq(n,k)} e_{out}(\zeta|s) = C_{nk}.$$

The source seeking the network's service is admitted if the optimization problem (8)-(10) for the already "active" sessions and the "potential" session has a feasible solution.

Various scenarios are possible depending on the technical feasibility of altering the parameters of the leaky bucket regulators and routes for sessions in progress. Minimization in (8) is to be performed over parameters of the leaky bucket regulator and route assigned to the potential session as well as over parameters and routes which can be altered. The solution of the problem (8)-(10) gives the optimal congestion control and routing strategy. Simple methods of solving optimization problem (8)-(10) can be developed. In particular, the optimal maximum peak rate allowed by the LBR(r,R,B_T,B_R) and the optimal total buffer space $B = B_T + B_R$ are the follows:

$$R = \Lambda_{in}$$
$$B = -0.5(v_{in}\ln\pi_{max})/(r-\lambda_{in})$$

where λ_{in}, Λ_{in}, v_{in} are the average, peak and variability rates, and T_{max} is the maximum allowable average delay declared by the source; π_{max} is determined by the allowable probability of loosing a packet.

Note that replacing $e_{out}(\zeta_{nk}|s)$ with the effective bandwidth of the leaky bucket regulators, in the optimization problem (8)-(10), leads to the strategy based on the worst case scenario. The important feature of this strategy is that if any source violates the contract, it results in degrading quality of service only for the violator, not affecting the sources which comply with their contracts.

References

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