ADAPTIVE MULTIMEDIA FLOW REGULATION AND DELAY ANALYSIS FOR END-HOSTS IN P2P NETWORKS

Weijia Jia

Department of Computer Science, City University of Hong Kong
83 Tat Chee Ave. Kowloon, Hong Kong, SAR China, email: itjia@cityu.edu.hk

ABSTRACT

This paper proposes a novel adaptive algorithm based on a new soft-regulator (σ, ρ, λ) for concurrent multimedia flows at end hosts. Our algorithm has the following features: (1) does requires the support of the network layers (routers and switches); (2) is scalable as it can be installed into any intermediated nodes for the delay control; (3) uses network resource efficiently, in particular, when the bandwidth of network is very limited. Performance experimental data have shown that (σ, ρ, λ) and related algorithm are efficient and applicable as compared with network layer solutions.

1. INTRODUCTION

End-host transmission has emerged as one of the major stream for the transmission of multimedia flows in P2P networks through a set of underlying unicast connections. The host will have to handle the concurrent transmission of the flows. Real-time flows are characterized with the high flow rates, the end hosts that on the intermediate path are apt to suffer from transmission bottleneck which incurs unacceptable delays (i.e., the packet end-to-end delays exceeding the delay bound etc.) and compromised scalability and performance of the networks.

To avoid such bottleneck problem, many approaches have been proposed on the network or link layers using flow regulators. However, implementation on the network layer may be costly and difficult to install; particularly, layer 2 or 3 network may not support such installation. A popular way is to design the capacity-aware end host multicast protocol [2,3]. The capacity-aware protocol assigns the direct output ports to next hop (end-host), taking the output capacity into consideration. Thus, the end host has enough capacity to output the received packets to all direct children and will not become the communication bottleneck. However, such a bottleneck-avoidance performance is achieved at the cost of increased paths from the source to the destinations. Such longer delays are partially formed by the propagation delays in the increased end-host routing paths, and also include the delays caused by the flow transmission. In P2P network, flows forwarded at the end hosts experience the delays transmitting between the IP layer and the application layer. The end hosts usually take longer latency to replicate and forward packets than the routers. A flow will pass through more end hosts if the paths are increased and therefore longer delays are introduced. Under the heavy network traffic load, the network transmission delays can be even larger. In general, multimedia flows have stringent requirements for the bounded delay performances. The longer paths will introduce the unacceptable delay performances. The capacity-aware approach may not be able to effectively use the network resource. Simple and efficient traffic control mechanisms are necessary for the end-host to deal with the simultaneously entering flows at the end-host to eliminate such end-host bottleneck problem.

This paper provides a simple approach to regulate the incoming concurrent multimedia flow, reduce and analyze the worst delay bound (WDB) for end-host high rate concurrent multimedia flow transmission in overlay network. There are two classical traffic control methods: the leaky-bucket mechanism [5] and (σ, ρ) regulator [4]. The leaky-bucket mechanism enforces a rigid output pattern at the average rate ρ. We propose an application layer modified (σ, ρ) regulator for the analysis of delay bound for flows where σ representing the bursts and ρ denoting the rate of the corresponding flow. Our objectives are to analyze the worst-case delay bounds for the real-time flows for the application layer. We refer to the worst-case delay of end host as the longest delay at the end host who is the last one to receive the flow packets. We also propose a novel and simple *adaptive control algorithm* for effective delay control and resource utilization without depending on the service reservation and control feedback of the networks. Unlike the capacity-aware protocols, the *adaptive control algorithm* adaptively employs a new soft-regulator (σ, ρ, λ) at each end host based on the instantaneous network situations. The regulator (σ, ρ, λ) works in one of the two states: *on* and *off* in turn to control the traffic output at each end host. Parameter λ is used for such *on* and *off* status control so as to coordinate the multiple flow traffic at the end-hosts. To the best of our knowledge, this is the initiative work to incorporate the traffic regulator into the end host to adaptively regulate and control the simultaneous flow traffic at end

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hosts. Employing such soft-regulator at the application layer has the following attractive features: 1) no requirement for the support of underlying network components or hardware, such as routers, switches and hubs; 2) the burden of these underlying network components to implement the traffic regulator is removed to the upper layer. Thus, it enables the scalability and inter-operability; 3) the regulator can be implemented by software without involving hardware at the end hosts.

2. MODEL AND ADAPTIVE CONTROL AND REGULATION ALGORITHM

Low layer network calculus (regulators) have been discussed extensively [4,5]. To regulator the multimedia flows on the application layer, we adopt network calculus into P2P networks and we propose each end host is programmed with two soft-controllers: Multiplexer (SMUX) that merges the concurrent flows arriving at its two or more input ports into the only one output port; Demultiplexer (SDEMUX) that splits up the flow arriving at the only one input port into two or more flows and routes each to the appropriate next end-host. We will treat SDEMUX as the separate issue and will not discuss here. To make things simple, in this paper, we only consider the first-come first-served (FCFS) SMUXs service disciplines. We define an end host consisting of a SMUX with one (σ, ρ, λ) and one (σ, ρ) soft-regulators on each of its input ports for regulating the incoming flow.

Without loss of generality, we assume there are K concurrent flows f_j $(j \in [1, K])$ entering into an end host g_i. Denote the input rate of f_j as ρ_j and the flow rate function as $R_j = \sigma_j + \rho_j * t$ and also write as $R_i \sim (\sigma_j, \rho_j)$. Assume that each host possesses the uniform available output capacity C to the next hop (end-host). The inequality $\sum_{i=1}^{K} \rho_i \leq C$ at each end host g_i is regarded as the *stability condition*. For K concurrent homogeneous flows with the same input rate ρ, the *stability condition* can be simplified as $K\rho \leq C$.

The basic idea of our *adaptive control algorithm–ACR*, for an end-host, is to adaptively use (σ, ρ) regulator for normal network traffic load situation, but to provide adaptive regulations using a new (σ, ρ, λ) regulator to smooth the bursts and rates of concurrent flows to single output in the heavy load situation. The (σ, ρ, λ) regulator blocks the some of the entering flows in a short period of time when the concurrent flow rates exceed the host out capacity C so as to ensure the network stability and to keep the output fluent. To make the analysis simple, hereafter, we assume $C = 1$. Thus, the *stability condition* is simplified as $\sum \rho < 1$. The algorithm is shown below:

Algorithm: Adaptive Control and Regulation running at g_j

Input: Concurrent flows: $\{f_1, ..., f_i, .., f_K\}$, with rate functions $R_i = \sigma_i + \rho_i t$ for flow f_i and rate threshold ρ^*;

1. Calculates the average rate $\bar{\rho}$ of K flows;
2. If $(\bar{\rho} \in (0, \rho^*))$ {
   Employ (σ_i, ρ_i) regulator for traffic regulation;}
3. Else if $(\bar{\rho} \in [\rho^*, \frac{1}{K}))$ {
   Use $(\sigma_i, \rho_i, \lambda_i)$ regulator to control the output of K concurrent input flows with following on-off switch:
   (1) *On*: Regulate f_i in $W_i = \frac{\sigma_i}{1-\rho_i}$ time units;
   (2) *Off*: Block f_i in $V_i = \frac{\lambda_i \sigma_i}{\rho_i} - \frac{\sigma_i}{1-\rho_i}$ time units.}

It can be seen that the key problem of *adaptive control algorithm* is to identify such input rate threshold ρ^* at which the *adaptive control algorithm* should change the traffic regulation strategy. We will prove the existence of ρ^* and address how ρ^* is calculated later. The operations of (σ, ρ, λ) regulator is illustrated in Fig. 2. In order to smooth the *simultaneous* bursts of K flows, the (σ, ρ, λ) regulator blocks V time units after working W time unit. Once the duration of one flow's blocking period expires, the regulator starts to serve the flow again. In our algorithm, λ is used to decide such blocking period V. We now focus on how λ is decided and its impact on the delay introduced.

In the heavy traffic situation, consider the input flow f_j at the end host g_j with the rate function $R_i \sim (\sigma_i, \rho_i)$. In order to enable its output to satisfy $mW_i \leq \sigma_i + [mW_i + (m-1)V_i]\rho_i$, i.e., the total amount of flow output at the end host g_j should be not greater than the total input flows for the m round of *on* and $(m-1)$ round of *off* in the regulator. More specifically, we have $\frac{m\sigma_i}{1-\rho_i} \leq \sigma_i + (\frac{(m-1)\lambda_i\sigma_i}{\rho_i} + \frac{\sigma_i}{1-\rho_i})\rho_i$. That is, $\lambda_i \geq \frac{1}{1-\rho_i}$. Obviously, the smaller λ_i generates the shorter blocking period. In order to reduce the worst delay, we set

$$\lambda_i = \frac{1}{1-\rho_i}. \tag{1}$$

Equation (1) infers $V_i = \frac{\sigma_i}{\rho_i}$ that shows how σ_i affects the blocking interval. For the influence of ρ_i to V_i, it can be illustrated from a high input rate scenario. For simplicity, we consider K homogeneous flows (i.e., $\rho_i = \rho$, $i \in [1, K]$). By *stability condition*, we assume that $\rho \to \frac{1}{K}$ in the worst case. Then we have $V_i = \frac{\sigma_i}{\rho_i} \approx K\sigma_i = \frac{(K-1)\sigma_i}{(1-\frac{1}{K})} \approx (K-1)W_i$. It implies that when input flow rates are very high, the blocking interval of each regulator approaches the sum of the working intervals of other $(K-1)$ regulators. Therefore, the blocking and working processes among the K soft-regulators can achieve perfect distributed synchronization at the end-host. In the following sections, we give the worst-case delay bound for applying on a single end host, then we extend the analysis for the regulated end-host path.

3. DELAY BOUND ANALYSIS

We will analyze the worst delay bound for the single regulated end host. We omit all the proof details for saving space. The similar proof details can be found in [1]. The results obtained can be extended to the worst delay bound analysis for an end-host path (we omit the discussions). The following lemma characterizes the delay of any input flow with the rate function of $R \sim (\sigma^*, \rho)$ at the (σ, ρ, λ) regulator.

Lemma 1. *If the rate function R of input flow satisfies the burst constraint by (σ^*, ρ) regulator, i.e., $R \sim (\sigma^*, \rho)$, then the delay incurred by the (σ, ρ, λ) regulator is upper bounded by*

$$D = \frac{(\sigma^* - \sigma)^+}{\rho} + \frac{2\lambda\sigma}{\rho}. \tag{2}$$

In fact, Fig. 1 illustrates that the (σ, ρ, λ) regulator may introduce extra delay. However, the delay will be analyzed and counted in the rest of the sections.

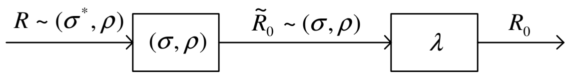

Fig. 1. A concatenation of two network elements.

3.1. Derivation of Worst Delay Bound (WDB) for a Single Host

We present two theorems for the WDBs with K heterogeneous (Theorem 1) and homogeneous (Theorem 2) real-time flows respectively by applying Lemma 1 in the $(\sigma_i, \rho_i, \lambda_i)$-regulated FCFS SMUXs, $1 \le i \le K$.

Theorem 1: *Let the rate function of the input flow f_i be given by R_i such that $R_i \sim (\sigma_i, \rho_i)$, $1 \le i \le K$, and $\sigma_i^* = \rho_i(1-\rho_i)\cdot \min_{1 \le j \le K}\{\frac{\sigma_j}{\rho_j(1-\rho_j)}\}$, then the maximum delay experienced by any traffic packet of the flow f_j ($j \in [1, K]$) passing through a SMUX with $(\sigma_i^*, \rho_i, \lambda_i)$ regulators, by Lemma 1, is upper bounded by*

$$D' = \sum_{i=1, i \ne j}^{K} \frac{\sigma_i^*}{1-\rho_i} + 2 \min_{1 \le i \le K}\{\frac{\sigma_i}{\rho_i(1-\rho_i)}\} + \max_{1 \le i \le K}\{\frac{\sigma_i - \sigma_i^*}{\rho_i}\}.$$

Theorem 2: *For a regulated SMUX with K homogeneous input flows, let the input traffic rate functions be R_i such that $R_i \sim (\sigma_0, \rho)$, $1 \le i \le K$, and $\rho \le \frac{1}{K}$. Then, the maximum delay experienced by any data packet using (σ, ρ, λ) regulator is upper bounded by*

$$D' = \frac{(K-1)\sigma}{1-\rho} + \frac{(\sigma_0 - \sigma)^+}{\rho} + \frac{2\lambda\sigma}{\rho}. \tag{3}$$

3.2. Derivation of Rate Threshold ρ^*

We will derive the control threshold ρ^* to operate on our *adaptive control algorithm* to distinguish the high rate real-time traffic from the normal rate traffic. We first introduce the following inequality:

$$\frac{\xi_{max} - \xi_{min}}{\xi_{max}} \le \frac{\rho_{min}}{\bar{\rho}}. \tag{4}$$

Theorem 3 *Assume K input flows R_i entering in a host regulated by (σ, ρ, λ) with rate functions $R_i \sim (\sigma, \rho_i)$, $1 \le i \le K$, and $\sum_{i=1}^{K} \rho_i \le 1$. If $K \ge 3$, then there exists a rate threshold $0 < \rho^* < \frac{1}{K}$ such that*
(i) If $\rho^* \le \bar{\rho} < 1/K$ then $D' \le D$; if $0 < \bar{\rho} \le \bar{\rho}^*$, then $D \le D'$, where D' and D are the worst-case delay bounds of the flows regulated by (σ, ρ, λ) and (σ, ρ) respectively, and $\bar{\rho}$ is the average input rate of K flows.
(ii) When K goes to infinity, the ratio of the range (the control range) $[\rho^*, \frac{1}{K})$ to the total range of $(0, \frac{1}{K})$ is approximately

$$\frac{1/K - \rho^*}{1/K} \approx \frac{5 - \sqrt{21}}{2} \approx 0.21.$$

Theorem 4 *Assume that a (σ, ρ, λ)-regulated SMUX for K input flows with rate function $R_i \sim (\sigma_0, \rho)$, $1 \le i \le K$ and $\rho \le \frac{1}{K}$. When $K \ge 4$, there exists $0 < \rho^* < \frac{1}{K}$ such that*
(i) If $\rho^* \le \rho < \frac{1}{K}$ then $D' \le D$; if $0 < \rho \le \rho^*$, then $D \le D'$, where D' and D are the same as in Theorem 3.
(ii) When K goes infinity, the ratio of range $[\rho^*, \frac{1}{K})$ with respect to overall range $(0, \frac{1}{K})$ is about

$$\frac{\frac{1}{K} - \rho^*}{\frac{1}{K}} \approx 2 - \sqrt{3} \approx 0.27.$$

The two theorems state that using (σ, ρ, λ) for adaptive control of high rate flows can effectively work for the flows up to the 79 and 73 percentages of output capacity of the end-host. In the performance data, we can see that using adaptive control can improve the performance by 10-20 percent as compared with the traditional network layer regulator control.

4. EXPERIMENTAL EVALUATION

We have evaluated the worst delay bounds of end-host communications and compared our *adaptive control* algorithm with that do not use adaptive control through *ns*-2 [15] and run on a group of SUN SOLARIS workstations. The simulations are done to evaluate the worst-case delay bounds of the single end host with (σ, ρ) and (σ, ρ, λ) (adaptive) soft-regulator respectively. We observed the WDB performances of single (σ, ρ, λ)/(σ, ρ)-regulated end host. The simulation topology is shown in Figure 2. Three concurrent real-time flows enter the source node and output to the same destination. The intermediate node is equipped with the (σ, ρ, λ)-regulated and (σ, ρ)-regulated SMUXs respectively. Two types of real-time flows are employed in the simulations: 64Kbps audio streams and 1.5Mbps MPEG-1 video flows. For the homogeneous performances, we compare the WDB performances of (σ, ρ, λ)

and (σ, ρ) soft regulators with three video flows and three audio flows respectively. For the heterogeneous performances, we compare the WDB performances using (σ, ρ, λ) and (σ, ρ) regulators with two audio flows and one video flow.

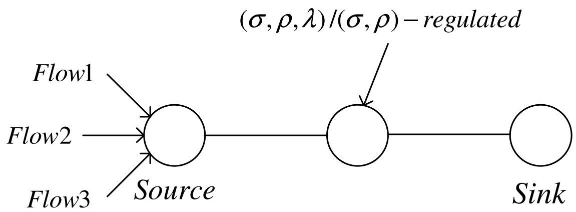

Fig. 2. The simulation topology with only one $(\sigma, \rho, \lambda)/(\sigma, \rho)$-regulated at end host and the link budget are all the same as input flow rate.

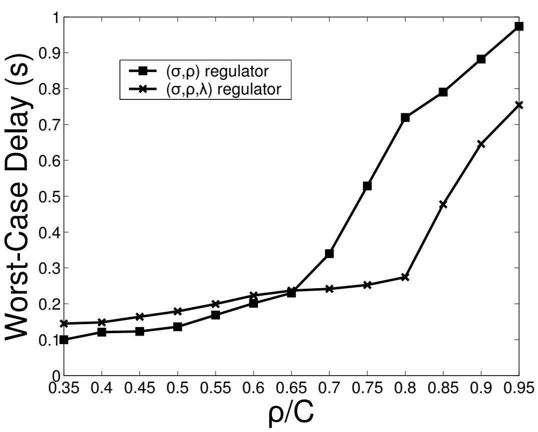

Fig. 3. The worst-case delay performances when there are three 64Kbps audio flows in the network of Fig. 2.

Fig.3 illustrates the worst-case delay performances when three 64Kbps audio steams passing through the network in Fig.2. The simulation results meet our theoretic analysis. The cross point of the two curves is 0.66, i.e., the input rate threshold in this simulation is 0.66. When $\rho < 0.66$, the worst-case delays with the (σ, ρ, λ) regulator are longer than the worst-case delays with the (σ, ρ) regulator. When $\rho \geq 0.66$, the worst-case delays with the (σ, ρ, λ) regulator are shorter than the worst-case delays with the (σ, ρ) regulator. The difference between the simulation rate threshold (0.66) and the theoretic rate threshold (0.73) is because our theoretic analysis does not take into account of the fluctuation of network throughput in the practical network. Also, it can be seen from the figure when $\rho \geq 0.66$, the maximum worst-case delay improvement of the (σ, ρ, λ) regulator over the (σ, ρ) regulator is at $\rho = 0.8$ and has the value of $\frac{0.72}{0.26} \approx 2.8$. According to Theorem 4, we can derive $n \approx 1$ from the simulation parameter $K = 3$.

Fig.4 illustrates the WDB performances of the three homogeneous video streams when the streams pass through the network in Figure 2. Also, the simulation results prove our

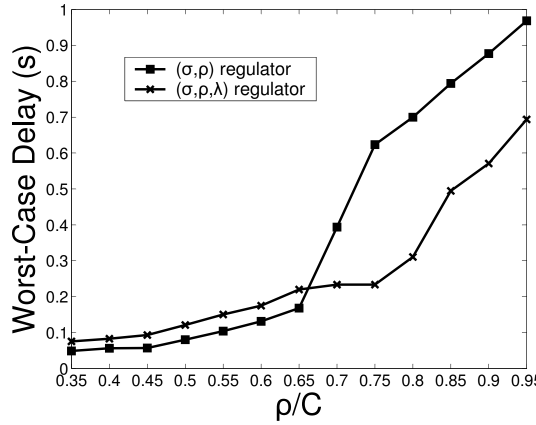

Fig. 4. The worst delay performances when there are three 1.5Mbps video flows in the network of Fig. 2.

theoretic analysis. The rate threshold in this simulation is 0.67 that is less than the theoretic result 0.73 because of the fluctuation of network throughput. The maximum improvement in worst-case delays of (σ, ρ, λ) regulator over (σ, ρ) regulator is at $\rho = 0.8$ and has the value of $\frac{0.72}{0.26} \approx 2.82$. In lines of Theorem 4, we can also derive $n \approx 1$ from the simulation parameter $K = 3$.

5. CONCLUSIONS

We have presented a novel *adaptive control algorithm* that adaptively employs the soft-regulators (σ, ρ) and (σ, ρ, λ) for normal flow rate and intensive (concurrent) flow rates at the same output. Our algorithm is based on the instantaneous network situations without depending on any network feedback and service reservation. We have presented a set of theoretic analysis and results on the worst delay bound and calculated the *worst-case delay bounds*. We derived the *input rate threshold* at which the *adaptive control algorithm* should change the traffic regulation strategy.

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