TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.6, June 2014, pp. 4468 ~ 4474
DOI: 10.11591/telkomnika.v12i6.5484

The Design of Fine-grained Network QoS Controller and Performance Research with Network Calculus

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Abstract

In this paper a network QoS controller is designed. We use the controller to quantification ally control QoS under the random network traffic. The controller is built by min-plus algebra based on network calculus. The controller includes two parts, the lossless fractal regulator and the finite variable storage shaper (FVSS). We can get the arrival curve with the lossless fractal regulator. Then the FVSS control network traffic to realize the fine-gained QoS controller. At last, we analyze the performance of the network QoS controller. Research results show that the relationship between packet losses, packet delays and the buffer storage. We clearly observe the change of the packet loss and the packet delay with the storage of buffer. The results can be applied to evaluate the congestion and flow control strategies, as well as these are references to design network control device parameters.

***Keywords**: fine-grained, controller, QoS, network calculus, shaper*

1. Introduction

The Internet is a complex and huge system. The complexity is reflected in uncontrollability topology, traffic burstiness, network protocol diversity and complexity of network behavior and other aspects [1]. The views have attracted extensive attention in network research field that structure determining function, traffic burstiness impacting performance. We should clear the relationship between traffic characteristic parameters and the performance of network. Then we control and supervise the incoming traffic at the point of internet user access and network convergence by controlling the network traffic. The works are effective ways to increase the fairness of network resource allocation, avoid congestion and improve network performance.

In early times, the researchers began to study the shaper. While the original work by Cruz in defines a leaky bucket shaper based on min-plus algebra. The min-plus algebra defines a series of arrival curve and service curve to describe concisely the boundaries of network performance [2]. The traffic shaping strategy on account of leaky bucket shaper is adopted by the service model of IETF network and most industries, it monitors the rate of flow by changing the parameters of shaper, So that the blocked data is dropped or cached by shaper and then is transferred again at the appropriate time. While the leaky bucket simplifies the parameters of traffic control, it isn't enough to regulate the practical traffic. Recently, the research of shaper with network calculus obtains great progress. For instance, Zhang xinming systematically studies the general model of the greedy shaper, shaper with no buffer and shaper in fixed-length storage [3]. Zhang lianming has the research of lossless shaper, he proposes a new traffic shaping model and arrive the corresponding performance evaluation, while the capacity of shaper is generally limited in fact, then he studies lossy shaper and establish a general mathematical model of lossy shaper based on the determined network calculus.

The paper studies fine-grained network QoS controller and controller performance characteristics. We describe that controlling the network QoS by changing the storage length of buffer. We analyse the performance parameters of packet delay and packet loss with min-plus algebra. Then we discuss how the packet delay and packet loss change with variable storage.

Received December 24, 2013; Revised February 18, 2014; Accepted March 5, 2014

2. Network Calculus

Network calculus is a collection of results based on Min-Plus algebra, which can be applied to deterministic queuing systems found in communication networks. It is a set of recent developments which provide a deep insight into flow problems encountered in networking [4]. Network calculus is based on the idea that given a regulated flow of traffic into the network, one can quantify the characteristics of the flow as it travels from node to node through the network. This means that traffic flows are constrained by shapers and delayed by the nodes' schedulers. In network calculus a node behaviour is characterized by a function called the service curve which denotes how long a packet must be serviced after an arrival to a node [5]. The input traffic is characterized by a wide-sense increasing function of time and it is so-called the arrival curve. This function quantifies constraints on the number of bits of packet flow in the time interval at service node. Now we introduce some important tools and conclusions of network calculus as follows [6, 7]

Definition 1 WIF: wide-sense increasing function.

If *f(x)*is a function, for any $s \leq t$,if $f(s) \leq f(t)$, f(x)is a wide-sense increasing function.

Definition 2 WIFS: wide-sense increasing function set.

if

$$F = \{ f(t) \mid f(t) = 0, \forall t < 0; f(0) \geq 0; f(s) \leq f(t), \forall s \leq t, s, t \in [0, +\infty] \} \quad (1)$$

F is a wide-sense increasing function set.

Definition 3. Min-plus convolution.

Let f and g be two WIFS. The min-plus convolution of f and g is the function:

$$(f \otimes g)(t) = \inf_{0 \leq s \leq t} \{ f(\text{t-s}) + \text{g(s)} \} \quad (2)$$

Definition 4. Min-plus deconvolution.

Let f and g be two WIFS. The min-plus convolution of f and g is the function:

$$(f \phi g)(t) = \sup_{\tau \geq 0} \{ (t+s) - g(s) \} \quad (3)$$

Theorem 1. General properties of $\otimes$.

Let f, g and h be two WIFS.

Rule 1 (Closure of $\otimes$) $(f \otimes g) \in F$.

Rule 2 (Associativity of $\otimes$) $(f \otimes g) \otimes h = f \otimes (g \otimes h)$.

Rule 3 (Commutativity of $\otimes$) $f \otimes g = g \otimes f$.

Rule 4 (Distributivity of $\otimes$ with respect to $\wedge$) $(f \wedge g) \otimes h = (f \otimes h) \wedge (g \otimes h)$

Definition 5. Arrival curve.

Give a WIFα defined for a shaper, a flow f is constrained byα if and only if for all $s \leq t$, $R(t) - R(s) \leq \alpha(t-s)$.

We say that R has α as an arrival curve, or also that R is α-smooth. The arrival curve actually defines an upper bound on the arrival rate of a flow to a particular node.

Definition 6. Service curve.

If a system S has an input flow R(t) and output flow R*(t), then S offers to the flow a service curve β, if and only if β is wide sense increasing, $\beta(0) = 0$ for all $t \geq 0$, $R^* \geq R \otimes \beta$.

A service curve is a lower bound on the departure rate from a network node.

Definition 7. Subadditivity.

Let f be two WIFS. If $f(t+s) \leq f(t) + f(s)$, f is subadditive function.

Definition 8. Sub-additive closure.

Let f be a function or a sequence of F. Denote $f^{(n)}$ the function obtained by repeating (n-1) convolutions of f with itself. By convention, $f^{(0)} = \delta_0$,so that $f^{(1)} = f$, $f^{(2)} = f \otimes f$. Then the sub-additive closure of f, denoted by f^*, is defined by $f^* = \inf\{f^{(n)}\}$.

Theorem 2.

Let f(t) be two WIFS. If it's sub-additive closure f^* satisfies $f^* \le f$ and f^* is subadditive function.

Definition 9. Linear aliquots operator.

Let f and σ be two WIFS. The linear apiquotos operator is:

$$h_\sigma \left(f\left(t\right)\right) = \inf_{0 \le s \le t} \{\sigma\left(t\right) - \sigma\left(s\right) + f\left(s\right)\} \quad (4)$$

Theorem 3.

Sub-additive closure of linear aliquots operator $\overline{Q_H}$, $\overline{L_H} = Q_{\overline{H}}$

$$\overline{H}\left(t,s\right) = \inf_{n \in N}\{\inf_{u_1,u_2,\ldots,u_n}\{H\left(t,u_1\right) + H\left(u_1,u_2\right) + \ldots + H\left(u_n,s\right)\}\} \quad (5)$$

Corollary 1.

If Q_1 is a linear aliquots operator of F to F, and $\delta \in F$

$$\overline{Q_1 \wedge h_\delta} = \overline{h_\delta \otimes Q_1} \otimes h_\delta \quad (6)$$

3. Finite and Variable Storage Shaper

Traffic generated by sources cannot be expected to naturally satisfy some a priori arrival curve constraint .If we want to ensure in a network some QoS guarantees. We must, first of all, constrain its input flows. This condition can be achieved by shaping the input traffic with shaper. A shaper is used to force a flow to satisfy some arrival curve constraint.

Definition 10.

Finite and variable storage shaper

FVSS has a finite storage, we can change the length of the storage. Because the storage is limited, so the shaper can't guarantee packet loss to be zero. While the output flow of the shaper is maximum acceptable value.

In order to get a general conclusion, this section does not assume that the type of network traffic flows. We consider the varieties of packet loss and packet delay when the shaper changes the length of storage. If the length is set too small, most of packets will be dropped. While the length is set too large, the packet delay is increasing, both the settings of finite storage shaper affect the network performance.

We assume that L(t) is the total packet loss at the time t, and the L(0)=0.

Lemma 1.

If R(t) is the input flow at the time t, and α(t) is the arrival curve of FVSS, so the total packet loss as the follow:

$$L(t) = R(t) - \alpha(t), t \ge 0 \quad (7)$$

Theorem 4.

We suppose that the service curve of FVSS is β, the length of buffer is B, the arrival curve isα, the cumulative packet loss is:

$$L\left(t\right) = \sup_{\Gamma}\{\sup_{\Gamma}\{\sum_{i=1}^{n}[\alpha(t_{2i+1}) - \alpha\left(t_{2i}\right) - \beta(t_{2i+1} - t_{2i})] - nB\}\}$$

s.t. $\Gamma = \{0 \le t_1 \le t_2 \le ... \le t_{2n} \le t \mid n \in N\}$ (8)

Proof: By definition 9, ∀s, 0≤s≤t, the input flow of FVSS at the time t is R(t).

$R(t) \le \inf_{0\le s\le t}\{\alpha(t)-\alpha(s)+R(s)\} = h_\alpha(R(t))$ And $R(t) \le \alpha(t) \wedge h_\alpha(x(t)) \wedge \{\beta(t)+B\}$

So $R = (\overline{h_\alpha \otimes (\beta+B)} \otimes h_\alpha)\alpha = (\overline{h_\alpha \wedge (\beta+B)})\alpha$. By theorem 3 and corollary 1, we know:

$$\begin{aligned} L(t) &= \alpha(t) - R(t) = \alpha(t) - \overline{(h_\alpha \otimes (\beta+B))} \cdot \alpha(t) \\ &= \alpha(t) - \inf_{\Gamma}\{\{h_\alpha \otimes (\beta+B)\}^{(n)}\}\alpha(t) \\ &= \sup_{\Gamma}\{\alpha(t) - \inf_{\Gamma}\{\alpha(t) - \sum_{i=1}^{n}\alpha(t_{2i-1})\} - \alpha(t_{2i}) - \beta(t_{2i-1}-t_{2i}) - B\}\} \\ &= \sup_{\Gamma}\{\sup_{\Gamma}\{\sum_{i=0}^{n}\alpha(t_{2i+1}) - \alpha(t_{2i}) - \beta(t_{2i+1}-t_{2i})]\} - nB\} \end{aligned}$$

Theorem 5.

We assume that the maximum permissible of total packet loss is P, the service curve isβ, the arrival curve is α. Then we get the storage length of FVSS.

$$B_L = \frac{1}{n}\sup_{\Gamma}\{\alpha(t) - \sum_{i=1}^{n}[\beta(t_{2i}-t_{2i-1}) - P(t_{2i}) + P(t_{2i-1})]\}$$

s.t. $\Gamma = \{0 \le t_1 \le t_2 \le ... \le t_{2n} \le t \mid n \in N\}$ (9)

Proof: By definition 10, we know the follow:

$P(t) = \alpha(t) - (\beta(t)+B_L)$,then $P(t) \le \alpha(t) - \overline{(\beta(t)+B_L)}$,so

$P(t) \le \alpha(t) - \inf_{\Gamma}\{(\beta(t)+B_L)^{(n)}\}$, $nB_L \le \alpha(t) - \inf_{\Gamma}\{\overline{\beta(t)+P(t)}\}$

$$nB_L \le \alpha(t) - \inf_{\Gamma}\{\sum_{i=1}^{n}\beta(t_{2i}-t_{2i-1}) - (P(t_{2i}) - P(t_{2i-1}))\}$$

From the foregoing, the upper bound of the length storage satisfies the following formula.

$$B_L = \frac{1}{n}\sup_{\Gamma}\{\alpha(t) - \sum_{i=1}^{n}[\beta(t_{2i}-t_{si-1}) - P(t_{2i}) + P(t_{2i-1})]\}$$

Theorem 6.

We suppose that the storage length of FVSS is B, the arrival curve of the flow i is α^i, and the service curve of FVSS is β^i.The total number of scheduling queues is m. Then we get the maximum packet delays and the average packet delays d_{avg} .

$$d_{\max} = \sup_{i\in N, 1\le i\le m}\{\sup_{\tau\ge 0}\{\alpha^i(t) + \sum_{k=1}^{n}\beta^i(\tau) + nB \ge 0\}\} \quad (10)$$

$$d_{avg} = 1/m \cdot \sum_{i=1}^{m} \{\sup_{\tau \geq 0}\{\alpha^i(t) + \sum_{k=1}^{n} \beta^i(\tau) + nB \geq 0\}\}$$
$$t_k = \left\{t_k = 0 \leq t_1 \leq t_2 \ldots \leq t_{(n-1)} \leq t_n = t\right\} \quad (11)$$

Proof: At the time t, the queue length of the flow i is $C^i(t)$,and $C^i\left(0\right) = 0$. By the corollary 1, $C^i = (\alpha^i \wedge \overline{(\beta^i + B)} = \overline{(\alpha^i \otimes (\beta^i + B))}$, we know that the packet delay satisfies the follow:

$$d^i \leq \inf_{t \geq 0}\{C^i(t) - \beta^i(t+\tau)\} = \sup_{\tau \geq 0}\{C^i(t) - \beta^i(t+\tau) + \varepsilon \geq 0\}$$
$$= \sup_{t \geq 0}\{\overline{(\alpha^i(t) \otimes (\beta^i(t) + B_L))} - \overline{(\beta^i(t+\tau))} + \varepsilon \geq 0\}$$
$$= \sup_{\tau \geq 0}\{\alpha^i(t) + (\beta^i(t) + B)^{(n)} - (\beta(t+\tau)^{(n)} + \varepsilon \geq 0\}$$
$$= \sup_{\tau \geq 0}\{\alpha^i(t) + (\beta^i(t) + B)^{(n)} - (\beta(t+\tau))^{(n)} + \varepsilon \geq 0\}$$
$$= \sup_{\tau \geq 0}\{\alpha^i(t) + \sum_{i=1}^{n} \beta^i(\tau) + nB + \varepsilon \geq 0\}$$

So that:

$$d^i = \lim_{\varepsilon \to 0}\{\sup_{\tau \geq 0}\{\alpha^i(t) + \sum_{k=1}^{n} \beta^i(\tau) + nB + \varepsilon \geq 0\}\} = \sup_{t \geq 0}\{\alpha^i(t) + \sum_{k=1}^{n} \beta^i(\tau) + nB \geq 0\}$$

4. Performance Analysis on the Network QoS Controller

In this section we analyze the performance of the the network QoS controller with random network traffic. The controller includes two parts, one part is the lossless fractal regulator, the another is the FVSS. The lossless fractal is used to provide specific arrival curve. The FVSS controls the network QoS by the specific arrival curve and service curve. Many researchers build models to study the actual network traffic, and obtain that the network traffic is self-similar [8, 9]. In the literature, Zhang lianming has a research about upper bound models of performance in self-similar network based on fractal shaper. After passing traffic shaper, envelope curve of the traffic is a linear function. The shaper introduces more characteristic parameter to describe the self-similar traffic accurately. He proposed a lossless fractal regulator. The end-to-end delay and the length storage in buffer don't increase with using lossless fractal regulator in network.

In view of these advantages of lossless fractal regulator, we introduce the regulator to our system. Our network QoS controller is shown in Figure 1. When the network traffic enters the controller, the traffic is shaped by lossless fractal regulator. So that the arrival curve of the FVSS is fractal curve α. The service curve of the FVSS is set β.

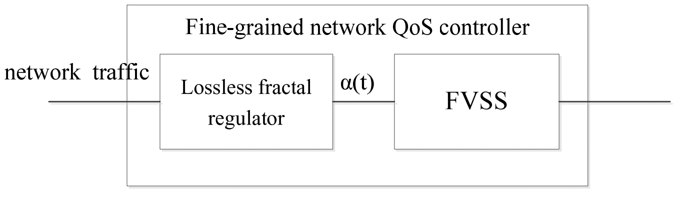

Figure 1. Network QoS Controller

The arrival curve α is:

$$\alpha(t) = r^* \cdot t + b^*, t > 0 \quad (12)$$

$$r^* = r + \sigma(1-H)\sqrt{2\gamma(\frac{H}{1-H})^{H-1}} \quad (13)$$

$$b^* = \sigma(1-H)\sqrt{2\gamma(\frac{H}{1-H})^{H}} \quad (14)$$

In the formula, r is the long-term average of input traffic, σ is standard deviation and H is self-similar parameter, γ is a positive constant. We set thatγ is 6.

The service curve of the FVSS is β.

$$\beta(t) = Rt, t > 0 \quad (15)$$

R is the service rate of FVSS.

We set the parameter of the FVSS based on the arrival curve higher than the service curve. The parameters is that r=700kbit/s, σ=100kbit, R=400Mbit/s. At the time t, $t = 1.2 \times 10^{-3} s$, we observe the variation of packet loss and packet delay with the variable length shaper in buffer. The variations are shown in Figure 2 and Figure 3.

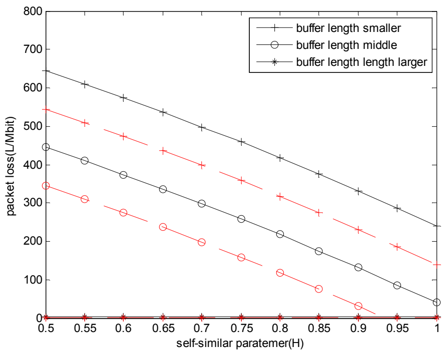

Figure 2. The Variation of Packet Loss

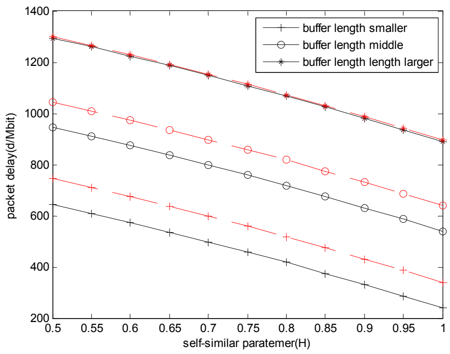

Figure 3. The Variation of Packet Delay

From the above two figures, we draw some conclusions. With the appropriate length in buffer, the FVSS can effectively improve network performance. For instance, the packet loss and packet delay are able to be tolerable. When the length storage increasing, the packet delay is increasing and the packet loss is reducing. While with the oversize storage, the packet loss will not reduce, the design of hardware is difficult. When the length storage reducing, the packet delay is reducing and the packet loss is increasing. While with too small storage, most of packets will be dropped, so that network performance deteriorate sharply.

5. Conclusions

The paper studies the fine-grained network QoS controller. We propose a general mathematical description of the design based on network calculus. Through the research, we get the relationship between the packet loss and packet delay with the length of storage. Then we discuss how the packet delay and packet loss change with variable storage. The works in the paper have practical significance to evaluate the control of traffic and the design of network device parameters. The related results can be used for quantitative analysis of the performance parameters of network devices.

Acknowledgements

This work was supported by Beijing Natural Science Foundation (4131003) and National Natural Science Foundation of China (61271198) .

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