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Worst Case Performance Bounds for Multimedia Flows in QoS-enhanced TNPOSS Network

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Abstract. Network performance bounds, including the maximal end-to-end (E2E) delay, the maximal jitter and the maximal buffer backlog amount, are very important for network QoS control, buffer management and network optimization. QoS-enhanced To Next-hop Port Sequence Switch (QTNPOSS) is a recently proposed transmission scheme to achieve scalable fast forwarding for multimedia applications. However, the existing E2E delay bound of QTNPOSS network is not tight. To this end, this paper presents a lower E2E delay bound for QTNPOSS networks by using the network calculus theory, where the inherent properties (e.g. packet length and peak rate) of the flow are taken into account. Besides, the buffer size bound and the jitter bound of QTNPOSS network are also presented. Moreover, by extensive numerical experiments, we discuss the influences of the Long Range Dependence (LDR) traffic property and the Weighted Fair Queuing (WFQ) weight on the proposed network performance bounds. The results show that the WFQ weight influences the bounds more greatly than the LRD property.

Keywords: QTNPOSS network, performance bound, network calculus, fractal leak bucket, WFQ;

1. Introduction

Recently, network technology has been exploited so rapidly that more and more multimedia applications are expected to be delivered over packet networks. Such applications often have relative strict QoS requirements on network metrics, such as end to end (E2E) delay, jitter and packet loss probability. To cater for these transmission requirements, TNPOSS forwarding approach was proposed in [1], which adopts connection-oriented forwarding mechanism and works like explicit routing. Since TNPOSS network can perform scalable fast forwarding to achieve lower E2E delay, it is capable of improving the QoS ability of packet networks. However, no extra QoS tools were designed for TNPOSS network to further improve its QoS performances. To enhance the QoS ability of TNPOSS network, two important components, i.e., the traffic shaping module and the queue scheduling block, were introduced into the original TNPOSS model was proposed. Furthermore, the worst case E2E delay bound of QTNPOSSwas give in [2].

However, the bound proposed in [2] is not tight, because the self-constraints including the maximum packet length and peak rate, of a flow were neglected. Since in network performance metrics, E2E delay is one of the most important targets of QoS provision and the E2E bound plays a very important role in network congestion control, buffer-size adjustment and scheduling optimization, a relative tighter E2E delay bound of QTNPOSS network is very worth being investigated. To this end, this paper shall focus on pursuit of a tighter E2E delay bound for QTNPOSS network. Moreover, as far as we known, no work has been done on the other QoS bounds for QTNPOSS network, such as the jitter bound and the maximal buffer length bound, so we shall also investigate these bounds in this paper.

The analysis tool we use is the Network Calculus theory [3], which is an very effective mathematical tool on analyzing network performances quantitatively in the worst case. Two key concepts within Network Calculus referred to here are the arrival curve and service curve, where the arrival curve is used to characterize the traffic feature of an arriving flow and the service curve is used to characterize process ability of a given network node.

The main contributions and novelties of this paper are: 1) giving a new arrive curve for a multimedia flow by considering its peak rate and maximal packet length; 2) modeling the E2E delay of QTNPOSS networks; 3) presenting a tighter E2E delay bound for QTNPOSS networks; 4) giving the maximal buffer length for a single node QTNPOSS network in the condition of no packet loss; 5) presenting the jitter bound for QTNPOSS network; 5) analyzing the parameters' influences on the QoS bounds of the QTNPOSS network by numerical experiments.

The rest of this paper is organized as follows: Section 2 will introduce the original TNPOSS network, the traffic shaping models, the WFQ scheduler and then the model of QTNPOSS network. In Section 3, we will introduce relate concepts of network calculus and then analyze the QoS bound of QTNPOSS network. In Section 4, extensive numerical experiments are performed to show the proposed E2E delay bound is tighter than existing one. Moreover, the parameters' influences on the QoS bounds are discussed in this section. Finally, Section 5 will summarize the work of this paper with some concluding remarks.

2. QTNPOSS Network

Since QTNPOSS network is the improved version of TNPOSS network, here we shall introduce the original TNPOSS network at first.

2.1. TNPOSS network

In TNPOSS Network, a set of binary codes are used to identify the ports of a router. For example, consider the network shown in Figure 1, S and D are terminal devices. a, b, c, d and e represent the routing devices. The solid lines between any two nodes are the communication links. The binary code near each node is the port code of the corresponding link interface. Suppose $S \rightarrow a \rightarrow b \rightarrow d \rightarrow c \rightarrow e \rightarrow D$ is the selected path for delivering the packets from S to D, the path can be represented by the output port sequence 10 11 11 100 01 which actually consists of the ID code of the output link at each hop on the path.

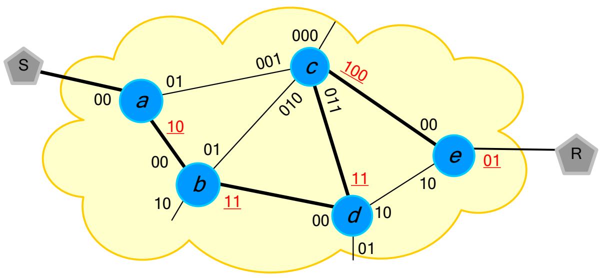

Fig. 1. TNPOSS network model

When a sender wants to send data to its destination, it will firstly initiate a request to setup one or more output-port code sequence paths. After this, the sender can use the output port sequence to do explicit routing. In TNPOSS network, since just during the path setup stage, routing tables need to be visited, while during the data transmission stage, each packet is only forwarded according to the output port code in the packet's header, the cost of routing lookup is greatly reduced and TNPOSS transmission can achieve fast switching. Moreover, TNPOSS is able to work on the basis of any routing protocol. If the routing protocol provides QoS routing, TNPOSS will transmit the packets on QoS-supported path. Since TNPOSS is able to deliver the packets of a flow on a pre-specified connection-based path, it has better QoS ability than today's IP networks. The detailed working process of TNPOSS network can be found in [1] and [9].

Although TNPOSS is suitable for transmitting multimedia flows due to its special working process and its explicit routing nature, it has no QoS tools to meet the strict QoS requirements of multimedia applications. Thus, authors in [2] proposed a QoS-enhanced version of TNPOSS network, i.e., QTNPOSS network. In QTNPOSS network, Fractal Leaky Bucket (FLB) model was introduced to shape the arriving traffic and the Weighted Fair Queuing (WFQ) model was introduced to schedule the packet before output. Thus in next two subsections, we shall introduce the FLB model and WFQ model.

2.2. Fractal Leaky Bucket (FLB)

To enhance network QoS ability, traffic is required to be policed in order to guarantee that the sender does not send more than specified by the contract of a connection into the network. Policing devices inside network often do buffering, which are called shapers. One of the simple and effective shaper models is token bucket (TB) [4]. TB regulates the traffic by a linear function of a time interval τ . If we denote the traffic the sender transmits over the time interval τ with $A(\tau)$, the traffic is said to be regulated by TB, if there exists a pair (ρ, b) such that:

$$A(\tau) \le \rho\tau + b \text{ for any } \tau > 0, \tag{1}$$

where ρ represents the long-term average rate of the traffic, which is also the output rate of the TB, and b represents the maximum burst allowed to be sent into the network in any time interval, which characterizes the buffer size of the TB. Although TB has good ability to describe the characteristic of the linear bounded arrival processor, it can not describe the traffic of internet very well. The reason is that, most internet flows often have very high and stochastic burst rate and have Self-similar (SS) and Long Range Dependence (LRD) properties [5][6], but TB cannot characterize such properties of internet traffic. As for the LRD property, authors in [5][6] stated that it may bring down network performances, including increasing the E2E delay, the buffer size and the packet loss probability, etc. Thus, it is necessary to select a proper traffic shaper for TNPOSS network to support multimedia traffic well. Authors in [4] proposed the FLB model to regulate the LRD traffic instead of TB model, and the numerical results showed that FLB outperforms TB. Now, let give the description of FLB. If we denote the traffic the sender transmits over the time interval τ with $A^*(\tau)$, the traffic is said to be regulated by FLB, if there exists a pair (ρ^*, b^*) such that:

$$A^*(\tau) \le \rho^*\tau + b^* \text{ for any } \tau > 0, \tag{2}$$

where

$$\rho^* = \rho + \sigma(1-H)\sqrt{2\gamma(\frac{H}{1-H})^{H-1}}, \tag{3}$$

and

$$b^* = \sigma(1-H)\sqrt{2\gamma(\frac{H}{1-H})^{H}}, \tag{4}$$

where γ is a positive constant, whose value is usually assumed to be 6 [7]. σ is the standard variation of $A(\tau)$, and H is the self-similar parameter, which is in fact the burst parameter.

2.3. Weighted Fair Queuing (WFQ)

In this subsection, we will introduce the WFQ model, which is also a key element in QTNPOSS network. As is known, scheduling is one of the most important mechanisms to provide QoS guarantee in packet networks. One of the most notable scheduling models is the Generalized Processing Sharing (GPS) model [3][8]. GPS can control the sharing of one link among packets of different classes, but it is only method with idea assumptions and is not implementable. To approximate GPS, WFQ is considered as the most effective one, which does not have the assumption of infinitesimal packet size. So, WFQ scheduler was introduced into QTNOSS network. Now, let us give the mathematical description of WFQ. Suppose a WFQ scheduler serves N flows and each flow is specified by a positive weight w_i. $g_i(\tau)$ denotes the amount of served traffic of flow i in the time interval τ. If R is the service rate of the network node, then

$$g_i(\tau) = \frac{w_i}{\sum_{1 \le k \le N} w_k} * R * \tau \tag{5}$$

2.4. Node Model of QTNPOSS Network

From the description in Section 2.1, it can be seen that TNPOSS network performs QoS provisioning just via explicit routing mechanism and the output-port code based fast forwarding. No additional tools are provided to enhance the QoS ability of TNPOSS network. Thus, FLB shapers and WFQ schedules were added into the nodes of QTNPOSS. Figure 2 gives inner structure of the node of QTNPOSS Network. When a packet of a flow arrives at a node of QTNPOSS network, it is shaped by the FLB shaper, and then is scheduled by the WFQ scheduler according to the weight of the flow it belongs to. More detailed information about QTNPOSS network can be seen in [2] and [9].

Suppose the service rate of a QTNPOSS node is R, in terms of Eqn. (5), the service rate for flow i can be written as

$$V_i = \frac{Rw_i}{\sum_{i=1}^{N} w_k} \tag{6}$$

Moreover, according to [10], the maximum delay of WFQ model is

$$T_{wfq} = \frac{l_i}{V_i} + \frac{L_{\max}}{R}, \tag{7}$$

where l_i is the maximal packet length of flow i and $L_{\max} = \max_{1 \le j \le N}(l_j)$ is the maximal packet length of all flows in the node.

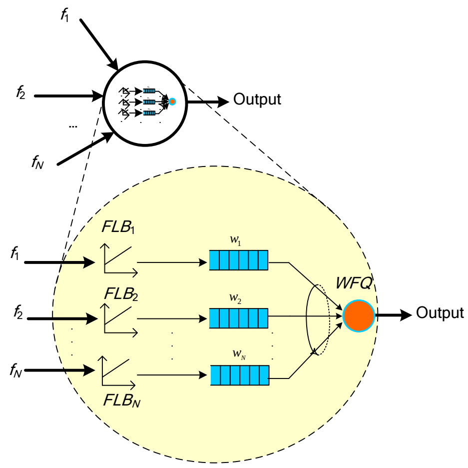

Fig. 2. QTNPOSS network model

3. Performance Bounds for QTNPOSS

In this section, we will analyze the QoS bounds for QTNPOSS network. The mathematical tool we use is the network calculus theory.

3.1. Network Calculus

Network calculus [3] is a collection of results based on Min-Plus algebra, which can be applied to analyze deterministic queuing systems in communication networks. Moreover, it is also a set of recent developments which provide a deep insight into flow problems encountered in networking, and is used with envelope bounded traffic models to provide a worst case analysis on network performance.

Note that 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, which means that traffic flows are constrained by shapers and then delayed by the nodes' schedulers. In network calculus, the shapers are often modeled by *arrival curves* and the schedulers are modeled by latency *service curves*, so the key question is to formulate a correct arrive curve and a correct service curve for the analyzed system. Now we introduce some important concepts and conclusions of network calculus as follows at first.

Definition 1. (*WIF: wide-sense increasing function*). $f(x)$ is a function, for any $\forall s \le t$, if $f(s) \le f(t)$, f is a wide-sense increasing function.

The WIF is used to describe flow functions such as the $A(\tau)$ and $A^*(\tau)$ in this paper. Because if the packets of a flow arrive and departure bit by bit, for a duration of any period of time t, both the amount of the arrived flow traffic and that of the depastured traffic can be characterized by WIFs with respect to time t.

Definition 2. (*arrival curve*). Give a WIF α defined for a shaper, a flow f is constrained by α if and only if for all $s \le t$,

$$f(s) - f(t) \le \alpha(t-s)\,. \tag{8}$$

The arrival curve actually defines an upper bound on the arrival rate of a flow to a particular node. The arrival curve of FLB is can be modeled by Eqn (2).

Definition 3. (*service curve*). If a system S has an input flow $f(t)$ and output flow $f_o(t)$, then S offers to the flow a service curve $\beta(t)$, if and only if for all $t \ge 0$,

$$f_o(t) \ge \inf_{s\le t}(f(s) + \beta(t-s))\,. \tag{9}$$

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

Definition 4. (*min-plus convolution*). Let f and g be two WIFs. The min-plus convolution of f and g is the function:

$$(f \otimes g)(t) = \begin{cases} \inf_{0\le s\le t}[f(t-s)+g(s)], & t \ge 0 \\ 0, & t < 0 \end{cases} \tag{10}$$

Definition 5. (*min-plus deconvolution*). Let f and g be two WIFs. The min-plus deconvolution of f and g is the function:

$$(f \varnothing g)(t) = \sup_{s\ge 0}[f(t+s) - g(s)] \tag{11}$$

Definition 6. (*virtual delay*). The virtual delay at time t is

$$d(t) = \inf\{\tau \ge 0: \ f(t) \le f_o(t+\tau)\} \tag{12}$$

The virtual delay at time t is the delay that would be experienced by a bit arriving at time t if all bits received before it are served before it.

Definition 7. (*backlog*). If a system S has an input flow $f(t)$ and output flow $f_o(t)$, the backlog at time t is defined as

$$\phi(t) = f_o(t) - f(t) \tag{13}$$

The backlog is the amount of bits that are held inside the system; if the system is a single buffer, it is the queue length.

Definition 8. (*horizontal deviation*). Let f and g be two WIFs. The horizontal deviation $h(f,g)$ is defined as

$$h(f,g) = \sup_{t\ge 0}\{\inf\{\tau \ge 0; f(t) \le g(t+\tau)\}\} \tag{14}$$

Definition 9. (*vertical deviation*). Let f and g be two WIFs. The horizontal deviation $h(f,g)$ is defined as

$$v(f,g) = \sup_{t\ge 0}\{f(t) - g(t)\} \tag{15}$$

Definition 10. (*BDF: burst-delay function*). WIF $\delta_T(t)$ is called burst-delay function, if

$$\delta_T(t) = \begin{cases} 0, & t < T \\ +\infty, & t \geq T \end{cases} \tag{16}$$

Definition 11. (*RLF: rate-latency function*). WIF $\beta_{V,T}(t)$ is called rate-latency function, if

$$\beta_{V,T}(t) = V[t - T_{lat}]^{+} = \begin{cases} V(t - T_{lat}) & t > 0 \\ 0 & t \leq 0 \end{cases}, \tag{17}$$

where T_{lat} is the latency delay and V is the service rate. The service curve of a GPS node can be represented by a RLF [3].

Property 1. (*service curve of concatenation nodes*). Assume a flow traverses systems S_1, S_2, …, and S_m in sequence. Suppose that S_i, $i \in [1, m]$, offers a service curve of β_i to the flow. Then the concatenation of the systems offers a service curve of $\beta_1 \otimes \beta_2 \otimes ... \otimes \beta_m$ to the flow.

Property 2. $d(t) \leq h(\alpha, \beta)$.

Property 2 shows that the virtual delay of a system is the horizontal deviation between its arrival curve α and service curve β.

Property 3. $\phi(t) \leq v(\alpha, \beta)$.

Property 3 shows that the backlog of a system is the vertical deviation between its arrival curve α and service curve β.

Property 4. $\delta_{T_1} \otimes \delta_{T_2} = \delta_{T_1+T_2}$.

Property 5. $\beta_{V,T_1} \otimes \delta_{T_2} = \beta_{V,T_1+T_2}$.

Property 6. $\beta_{V_1,T_1} \otimes \beta_{V_2,T_2} = \beta_{\min\{V_1,V_2\},(T_1+T_2)}$.

Given three WIFs f, g and ζ, the following properties hold in network calculus.

Property 7. $f \otimes g = g \otimes f$.

Property 8. $f \otimes g \otimes \zeta = f \otimes (g \otimes \zeta)$.

Property 9. $f \oslash g \oslash \hbar = f \oslash (g \otimes \hbar)$.

Property 10. If g is sub-additive and $g(0) = 0$, then $g \oslash g = g$.

Property 11. $h(f, g) = \inf_{d \geq 0}\{d: (f \oslash g)(-d) \leq 0\}$.

More detailed information can be found in [6].

Recently, many researches begin to analyze network QoS performances using network calculus [4][11][12]. Authors in [4] discussed the E2E delay bound of the Expedited Flow defined in RFC 3246. Authors in [11] analyzed the E2E delay bound of the wireless sensor networks via the statistical network calculus and authors in [12] proposed the E2E delay bound for LRD flows under the shaping model of FLB, which obtained a similar conclusion to that presented in [2]. All obtained results show that network calculus has very strong ability for analyzing internet flows, which outperforms traditional mathematical tools, such as queuing theory, random process and probability theory, in terms of characterizing the queuing system of internet flows. Thus, in this paper, we shall go on using network calculus to derive QoS bounds for QTNPOSS network.

3.2. QoS Bounds of QTNPOSS Network

As mention in Section 2.4, each node of QTNPOSS network has a FLB shaper and a WFQ scheduler. Thus, the components of the E2E delay of QTNPOSS network can be divided into two classes. The first class is denoted by D_v consisting of the shaping delay and the scheduling delay, and the second class is denoted by D_s consisting of the link propagation delay and the node processing delay, referred to as *processing delay* hereafter. D_v has close relationship with the traffic of flow, so it is variable. In contrast, D_s is relatively stable, which can be seen as a constant. Thus, the E2E delay of a flow can be expressed as

$$D_{e2e} = D_s + D_v \tag{18}$$

Consequently, if we want to obtain D_{e2e}, the main question is to derive D_v.

Lemma 1. The arrive curve of a flow through a QTNPOSS network node is

$$\alpha^Q(t) = \min\{\rho^* t + b^*, pt + l\} \tag{19}$$

where ρ^* and b^* has the same meaning with those in Eqn. (2), and p represents the peak rate of the flow and l is the maximal packet length of the flow.

Proof. The arrive curve of a TB shaper can be expressed by $\rho t + b$ [3], so the arrive curve of a FLB shaper must be $\rho^* t + b^*$. Moreover, a flow through the shaper, apart from being regulated with the FLB, it also has some inherent features. That is to say, the flow also satisfies the constraints from its own features. Here, we find that the peak rate and the maximal packet length are two inherent features of flow. Thus, the flow must satisfies the lower value of $\rho^* t + b^*$ and $pt + l$, i.e., $\alpha^Q(t) = \min\{\rho^* t + b^*, pt + l\}$. ☐

Lemma 2. The service curve of a signal-node QTNPOSS network is $\beta^Q_{V,T_{wfq}}$.

Proof. As the service curve of all GPS-based scheduling model can be express by the RLF described in Eqn. (17). Moreover, the output rate and latency of QTNPOSS network node are determined by WFQ model. So Lemma 2 is proved. ☐

Now, let consider a simple case at first. Consider a QTNPOSS network contains only one node, the following Theorem 1 and Theorem 2 can be derived.

Theorem 1. (*single node QTNPOSS network E2E delay bound*). Suppose a LRD flow goes through a QTNPOSS network consisting of only one node, whose arrive curve and service curve are α^Q and β^Q, respectively. The maximal delay caused by this node satisfies that

$$D \le \frac{(V-p)^+ l - (p-V)^+ (\rho^* t_0 - V t_0 + b^*)}{(V-p)V} + T_{wfq} + D_s \tag{20}$$

where $t_0 = (b^* - l)/(p - \rho^*)$.

Proof. According to Eqn. (18) and Property 2, it can be inferred that

$D_{e2e} \le D_v + D_s \le h(\alpha^Q, \beta^Q_{V,T_{wfq}}) + D_s$. Moreover, if no packet is expected to be lost, $\rho^* \le V$ and $l \le b^*$. If we denote the arrive curve and service curve in a time-bit coordinate plane, the result can be seen in Figure 3.

When $V \ge p$,

$$h(\alpha^Q, \beta^Q_{V,T_{wfq}}) = \frac{l}{V} + T_{wfq} . \tag{21}$$

When $V < p$,

$$h(\alpha^Q, \beta^Q_{V,T_{wfq}}) = \frac{\rho^* t_0 + b^*}{V} + T_{wfq} - t_0 \tag{22}$$

If we combine Eqn. (21) with Eqn. (22) to form a unified expression, we can have that

$$h(\alpha^Q, \beta^Q_{V,T_{wfq}}) = \frac{(V-p)^+ l - (p-V)^+ (\rho * t_0 - V t_0 + b^*)}{(V-p)V} + T_{wfq} , \tag{23}$$

where $(x-y)^+$ means that if $x \ge y$, $(x-y)^+ = x - y$. Else, $(x-y)^+ = 0$. Thus, Theorem 1 is proved. □

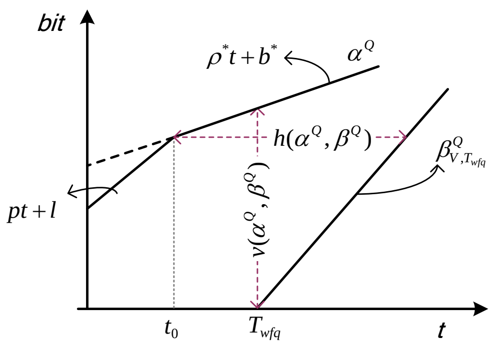

Fig. 3. Arrival curve and service curve of single node QTNPOSS network

Theorem 2. (*single node QTNPOSS network backlog*). Suppose a LRD flow goes through a QTNPOSS network consisting of only one node, whose arrive curve and service curve are α^Q and β^Q, respectively. The maximal backlog of the traffic within the network satisfies that

$$B \le \frac{(T_{wfq} - t_0)^+ (\rho^* T_{wfq} + b) - \frac{(t_0 - T_{wfq})^+ [(V-p)^+ (p T_{wfq} + l) - (p-V)^+ (V T_{wfq} + l + (p-V) t_0)]}{V-p}}{T_{wfq} - t_0} \tag{24}$$

Proof. According to the definition 7 and property 3, it is easily to be inferred that $B \le v(\alpha^Q, \beta^Q_{V,T_{wfq}})$. Moreover, from Figure 3, it can been seen that when $T_{wfq} \ge t_0$,

$$v(\alpha^Q, \beta^Q_{V,T_{wfq}}) = \rho^* T_{wfq} + b^* . \quad (25)$$

And when $T_{wfq} < t_0$, two cases should to be discussed. If $V \geq p$,

$$v(\alpha^Q, \beta^Q_{V,T_{wfq}}) = pT_{wfq} + l \quad (26)$$

else

$$v(\alpha^Q, \beta^Q_{V,T_{wfq}}) = pt_0 + l - V(t_0 - T_{wfq}) = (p-V)t_0 + l + VT_{wfq} . \quad (27)$$

If we express Eqn. (25), Eqn. (26) and Eqn. (27) with universal description, it can be derived that

$$v(\alpha^Q, \beta^Q_{V,T_{wfq}}) = \frac{(T_{wfq} - t_0)^+ (\rho^* T_{wfq} + b)}{T_{wfq} - t_0} + \frac{(t_0 - T_{wfq})^+}{t_0 - T_{wfq}} [\frac{(V-p)^+ (pT_{wfq} + l) - (p-V)^+ (VT_{wfq} + l)}{V-p} - (p-V)^+ t_0] .$$

Therefore, Theorem 2 is proved. ☐

Actually, the maximal backlog of a node also represents the minimal buffer length of a node, with which the single-node system can ensure no packet loss. Now we consider a more complex case, in which a QTNPOSS system is composed of many nodes rather than one. In order to keep the QoS ability of a multi-node QTNPOSS system, the concept of *greedy shaper* [13] is introduced. The greedy shaper is able to keep the packets of a flow away from loss and, at the same time, it can achieve the maximum output allowed by the shaper curve.

Lemma 3. Let S_Q be a QTNPOSS system characterized by the arrive curve α^Q and the service curve β^Q, and S_{QG} be a new system constructed by adding a greedy FLB shaper with a arrive curve of *αgs* into *SQ*, where the FLB shaper is placed between the shaper α^Q and the scheduler β^Q. Then, the E2E delay of a flow f traversing S_Q is equal to the E2E delay of f traversing S_{QG}. In other words, a greedy shaper does not increase the E2E delay of the system S_Q.

Proof. According to Property 2, the maximal E2E delay $D_{e2eS_{QG}}$ for f traversing the system S_Q is $h(\alpha^Q, \beta^Q)$. Meanwhile, it can be inferred that the maximal E2E delay $D_{e2eS_{QG}}$ for f traversing the system S_{QG} is $h(\alpha^Q, \alpha^{sg} \otimes \beta^Q)$. Since α^{sg} is greedy, from Eqn. (2) and Eqn. (20), it can be concluded that $\alpha^Q \leq \alpha^{sg}$. Thus, $\alpha^Q \varnothing \alpha^{sg} \leq \alpha^Q \varnothing \alpha^Q$. For a shaper, when $t = 0$, no traffic has come, so $\alpha^{sg}(0) = 0$. According to Property 10, $\alpha^{sg} \varnothing \alpha^{sg} = \alpha^{sg}$. Furthermore, based on Property 9, $\alpha^Q \varnothing (\alpha^{sg} \otimes \beta^Q) = \alpha^Q \varnothing \alpha^{sg} \varnothing \beta^Q = \alpha^Q \varnothing \beta^Q$. Additionally, Property 11 indicates that $D_{e2eS_{QG}}$ can be written as

$$\begin{aligned} D_{e2eS_{QG}} &= h(\alpha^Q, \alpha^{sg} \otimes \beta^Q) = \inf_{d \geq 0} \{d:\ (\alpha^Q \varnothing (\alpha^{sg} \otimes \beta^Q))(-d) \leq 0\} \\ &= \inf_{d \geq 0} \{d:\ (\alpha^Q \varnothing \beta^Q)(-d) \leq 0\} \\ &= h(\alpha^Q, \beta^Q) = D_{e2eS_Q} \end{aligned} .$$

Hence, Lemma 3 is proved. ☐

Lemma 4. Let S_Q be a QTNPOSS system characterized by the arrive curve α^Q and the service curve *βQ*, and S_{QG} be a new system which is constructed by adding a greedy FLB shaper with a arrive curve of α^{gs} in front of S_Q. Then, S_{QG} has the same arrive curve α^Q with S_Q.

Proof. Suppose the input flow is f and output flow if f_o. According to the definitionof arrive curve, it can be know that $f_o = f \otimes \alpha$. Moreover, Ref. [13] pointed that $f_o = f \otimes \alpha^{gs}$. Thus, it can be inferred that $f_o \le f \otimes \alpha^Q \otimes \alpha^{gs}$ $= f \otimes \alpha^{gs} \otimes \alpha^Q = f_o \otimes \alpha^Q$. In other words, the arrive curve of S_{QG} also is α^Q. So, Lemma 4 is proved. □

Lemma 4 actually shows that a multi-node QTNPOSS network has the same arrival curve α^Q with the signal-node QTNPOSS system.

Theorem 3. Suppose a flow f traverse a multi-node QTNPOSS network, each node offers a service curve of $\beta^Q_{V_1,T_1}$, $(1 \le i \le H)$ where H is the number of the nodes on the path of flow f. The processing delay of node i is D_{s_i}. Then, the service curve of f provided by the whole multi-node QTNPOSS network is

$$\beta^{EQ} = \beta^Q_{\min\{V_1,V_2,...,V_H\},\sum_k^H (T_k + D_{s_k})} \tag{28}$$

Proof. Proof by mathematical induction. When $H=1$, $\beta_1^{EQ} = \beta^Q_{V_1,T_1} \otimes D_{s_1}$. According to Property 5, it can be obtained that $\beta_1^{EQ} = \beta^Q_{V_1,T_1+D_{s_1}}$. So, when $H=1$, Theorem 3 holds. Suppose $H = j-1$, where $j \ge 2$, Theorem 3 holds. Then,

$$\begin{aligned}\beta_{j-1}^{EQ} &= \beta^Q_{\min\{V_1,V_2,...,V_{j-1}\},\sum_i^{j-1}(T_i + D_{s_i})} \\ &= \beta^Q_{\min\{V_1,V_2,...,V_{j-1}\},\sum_i^{k-1}T_i} \otimes \delta_{\sum_i^{j-1} D_{s_i}} \\ &= \beta^Q_{V_1,T_1} \otimes \beta^Q_{V_2,T_2} \otimes ... \otimes \beta^Q_{V_{j-1},T_{j-1}} \otimes D_{s_1} \otimes D_{s_2} \otimes \cdots \otimes D_{s_{i-1}}\end{aligned}$$

When $H = j$, according to Property 1, it can can be induced that

$$\begin{aligned}\beta_j^{EQ} &= \beta_{j-1}^{EQ} \otimes \beta^Q_{V_j,T_j} \otimes \delta_{D_{s_i}} \\ &= \beta^Q_{V_1,T_1} \otimes \beta^Q_{V_2,T_2} \otimes \cdots \otimes \beta^Q_{V_{j-1},T_{j-1}} \otimes \delta_{D_{s_1}} \otimes \delta_{D_{s_2}} \otimes \cdots \otimes \delta_{D_{s_{j-1}}} \otimes \beta^Q_{V_j,T_j} \otimes \delta_{D_{s_j}} \\ &= \beta^Q_{V_1,T_1} \otimes \beta^Q_{V_2,T_2} \otimes \cdots \otimes \beta^Q_{V_{j-1},T_{j-1}} \otimes \beta^Q_{V_j,T_j} \otimes \delta_{D_{s_1}} \otimes \delta_{D_{s_2}} \otimes \cdots \otimes \delta_{D_{s_{j-1}}} \otimes \delta_{D_{s_j}} \\ &= \beta^Q_{\min\{V_1,V_2,...,V_j\},\sum_i^j (T_i + D_{s_i})}\end{aligned}$$

Therefore, when $H = j$, Theorem also 3 holds. Theorem 3 is proved. □

Theorem 4. Suppose a flow f traverse a multi-node QTNPOSS network, each node offers an arrival curve of α_i^Q and a service curve of $\beta^Q_{V_i,T_i}$, $(1 \le i \le H)$ where H is the number of the nodes on the path of flow f. The processing delay of node i is D_{s_i}. Then, maximum E2E delay of f traversing the multi-node QTNPOSS network must satisfy that

$$D_{e2e} \le \frac{(V_{\min} - p)^+ l - (p - V_{\min}\})^+ (\rho_1^* t_0 - V_{\min} t_0 + b_1^*)}{(V_{\min} - p) V_{\min}} + \sum_k^H (T_k + D_{s_k}), \tag{29}$$

where $V_{\min} = \min\{V_1, V_2, ..., V_H\}$.

Proof. Since flow f is shaped by the FLB when it comes into the network and is constrained by its own property, the arrive curve of f provide by the first node must be $\alpha_1^Q = \min\{\rho_1^* t + b_1^*, pt + l\}$. Within the network, f will never be limited by (p,l), so $\alpha_k^Q = \rho_k^* t + b_k^*$, where $k \in [2,3,...,H]$. Moreover, according to Lemma 3 and Lemma 4, it can be known that α_k^Q will never increase the E2E delay of f, and f is always constrained by α_1^Q after being output by each node on the transmission path. Thus, the multi-node QTNPOSS network can be seen as a virtual system with arrival curve of α_1^Q and service curve of β^{EQ}. Then α_1^Q and β^{EQ} can be plotted on the time-bit coordinate plane, which is shown in Figure 4. From the formulation of β^{EQ} and Definition 11, it can be concluded that the T^E in Figure 4 must be $T^E = \sum_k^H (T_k + D_{S_k})$. Since $D_{e2e} \le h(\alpha^Q, \beta^Q)$, on the basis of Figure 4, Theorem 4 can be proved easily. □

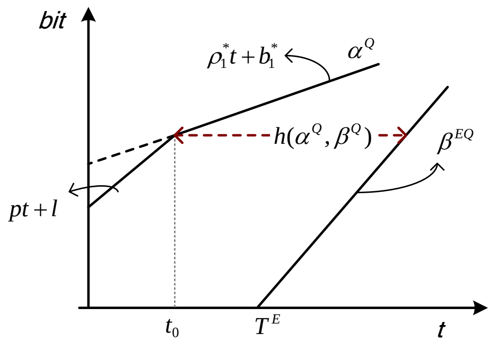

Fig. 4. Arrival curve and service curve of multi-node QTNPOSS network

Corollary 1. Theorem 1 is a special case of Theorem 4.
Proof. This corollary can be proved easily by assuming $H = 1$ in Eqn. (29). □

Corollary 2. $\sum_{i=1}^{H} D_{s_i} \le D_{e2e}$.

Proof. This corollary can be proved easily by the definition of D_{e2e}, where $\sum_{i=1}^{H} D_{s_i}$ is only one component of D_{e2e}. □

Theorem 5. Suppose a flow f traverse a multi-node QTNPOSS network, each node offers an arrival curve of α_i^Q and a service curve of β_{V_i,T_i}^Q, $(1 \le i \le H)$ where H is the number of the nodes on the path of flow f. The processing delay of node i is D_{s_i}. Then, maximum E2E delay jitter of f traversing the multi-node QTNPOSS network must satisfy that

$$J_{e2e} \le \frac{(V_{\min} - p)^+ l - (p - V_{\min}\})^+ (\rho_1^* t_0 - V_{\min} t_0 + b_1^*)}{(V_{\min} - p) V_{\min}} + \sum_k^H D_{s_k} , \qquad (30)$$

where $V_{\min} = \min\{V_1, V_2, ..., V_H\}$.

Proof. Since $D_{e2e} = \sum D_{V_i} + \sum D_{S_i}$, where only D_v can cause the jitter of delay, so $J_{e2e} \le D_{e2e} - \sum_k^H D_{S_k}$. Thus, Theorem 5 is proved. □

4. Numerical Analysis

In this Section, we will analyze the parameters influences on the QoS bounds of QTNPOSS network. The parameters, including the self-similar parameter H, the normalized WFQ weight w and the number of nodes m are taken into consideration in our analysis. The other parameters and their values used in the numerical experiments of this section are listed in the Table 1, where ρ, p and γ are defined in Eqn. (2) previously. R is the service rate of the node in QTNPOSS network. Since we aim to analyze the QoS bounds in the worst case, we assume that all the nodes and links have the same processing delay respectively. Moreover, l and $L_{\max}$ are assumed to be the maximal value of the maximum transmission unit (MTU), which is about 1500 bytes.

Table 1. Parameters Setting in Analysis

Parameter Name	ρ	p	σ	γ	l	L_{max}	D_v	R
value	3×10^2	9×10^3	20	6	1500	1500	2	10
unit	kbps	kbps	kbit	–	Byte	Byte	ms	mbps

4.1. Comparison of E2E delay bounds

Based on the parameters mentioned above, we compare the proposed E2E elay bound shown in Eqn. (29) with the existing E2E delay bound in [2] within $w \in [0.1, 1.0]$ and $H \in [0.5, 0.95]$. The two bounds are expressed by two curved surfaces as shown in Figure 5. Obviously, it can be seen that the E2E delay bound proposed in this paper is tighter than the existing one. The reason is that, the properties of the flow are taken into account to be constraints.

Note that Ref. [3] has pointed out that the rationality of considering the inherent properties of a flow when one analyze the arrive curve for the flow. According to property 2 offered by network calculus, the worst case E2E delay can be derived. Thus, the proposed E2E delay bound is rational and has superiority over existing one. Moreover, as the jitter bound shown in Eqn. (30) can be seen as the result of the E2E delay bound subtracting a constant, i.e., D_s, the curved surface of the jitter bound will has the same tendency with the E2E delay bound shown in Figure 5.

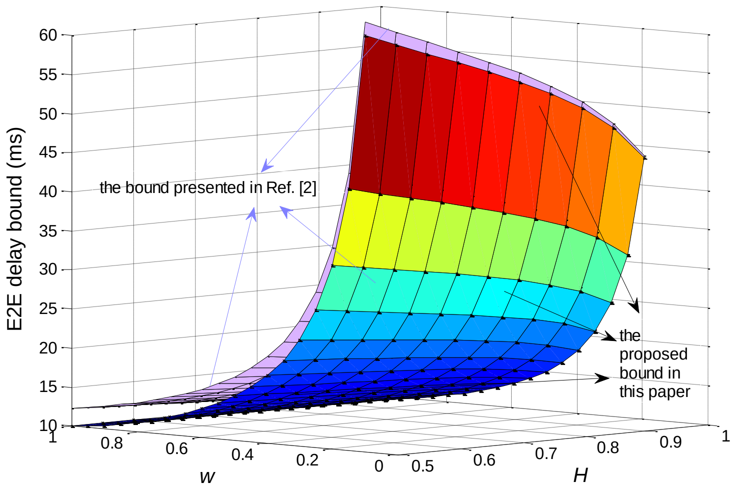

Fig. 5. Comparison of E2E delay bounds of multi-node QTNPOSS network

4.2. Analysis of proposed QoS bounds

In this subsection, we will discuss the influences of H and w on the QoS bounds.

QoS bounds of single node QTNPOSS network. Firstly, the QTPNOSS network is assumed to have only one node, which was introduced in Theorem 1. Figure 6 and Figure 7 show the influences of the H and the w on the buffer size bound of the single node QTNPOSS network, respectively. From Figure 6, it can be observed that for a given H the buffer size bound decrease with the increment of w. The reason is that the larger w is, the more bandwidth will be allocated for f. Thus, the data backlog will be reduced. Moreover, when H is relative large, the influence of w on the buffer size bound is small, and when H is relative small, the influence of w on the buffer size bound increases. From Figure 7, it can be seen that for a given w the buffer size bound also decrease with the increment of H. However, the influence of H on the buffer size bound seems much greater than that of w. Additionally, the curves marked with “1” in the two figures show the case of $T_{wfq} \geq t_0$, the curves marked with “2” show the case of $T_{wfq} < t_0$ and $V \geq p$, and the curves marked with “3” show the case of $T_{wfq} \geq t_0$ and $V < p$.

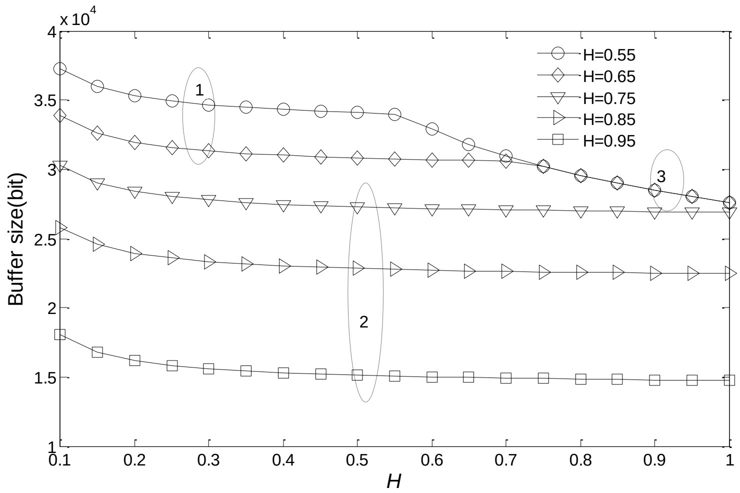

Fig. 6. Buffer size bound vs. w

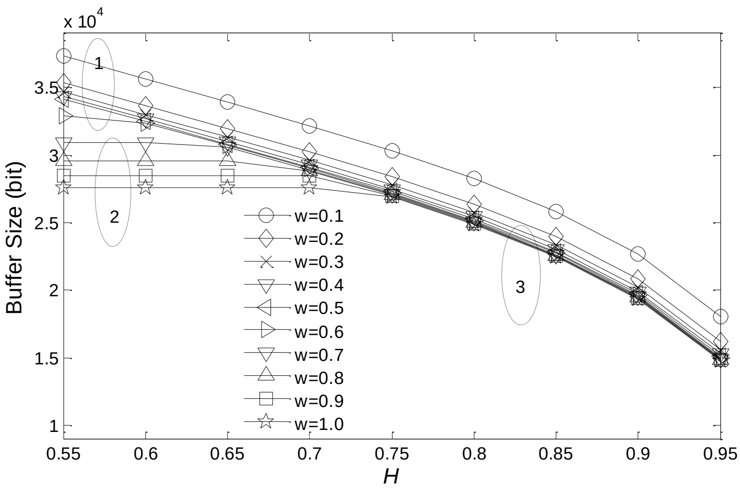

Fig. 7. Buffer size bound vs. H

Since the single-node QTNPOSS system is a special case of a multi-node QTNPOSS systems, so the impacts of H and w on the E2E delay of a single node QTNPOSS system are similar to those of H and w on the E2E delay of a multi-node QTNPOSS system, which can be seen in the next section.

QoS bounds of multi-node QTNPOSS network. In this subsection, a flow f is assumed to go through a path consisting of m nodes in the

QTNPOSS network. In the following experiments, m is assumed to be 15, because the measurement work in [14][15] show that the average number of hops between two communication nodes in Internet is about 15. Figure 8 and Figure 9 show the influences of H and w on the E2E delay bound of the QTNPOSS network, respectively. From Figure 8 and Figure 9, it can be observed that the E2E delay bound of Q TNPOSS network is influenced by both H and w. However, the influence of w is greater than that of H, especially when w is small. From all the experiments above, we can state that w influences the E2E delay bound more greatly than the other parameters do. The numerical results also indicate that by means of rising the degree of a flow's self-similar property or elevating the flow's WFQ weight, one can achieve acceptable low E2E delay.

5. Conclusions

This paper presented a lower E2E delay bound for QTNPOSS network by using network calculus. Besides, the buffer size bound, and the jitter bound of QTNPOSS network are also presented. To obtain these QoS bounds, the inherent properties (e.g. packet length and peak rate) of a flow were taken into account. We gave the arrive curve and service curve. Extensive numerical experiments show that both the long-range dependence property and the WFQ weight have influence on the E2E delay bound, and the WFQ weight has greater influence on the E2E delay bound than that of the long-range dependence property.

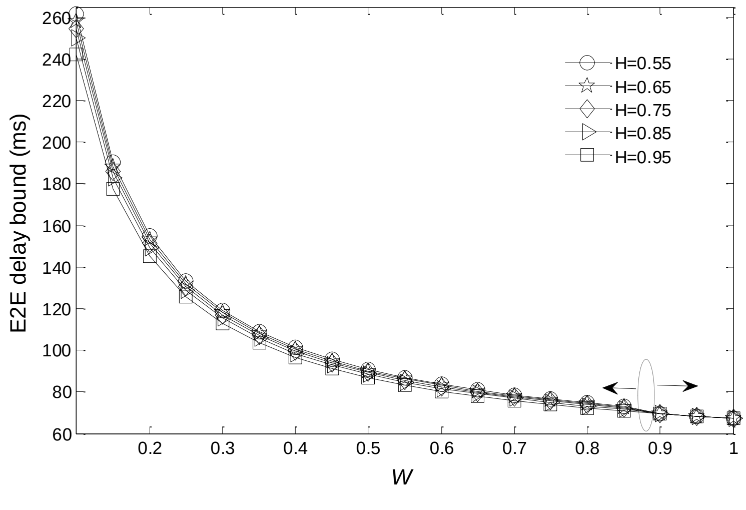

Fig. 8. E2E delay bound vs. w

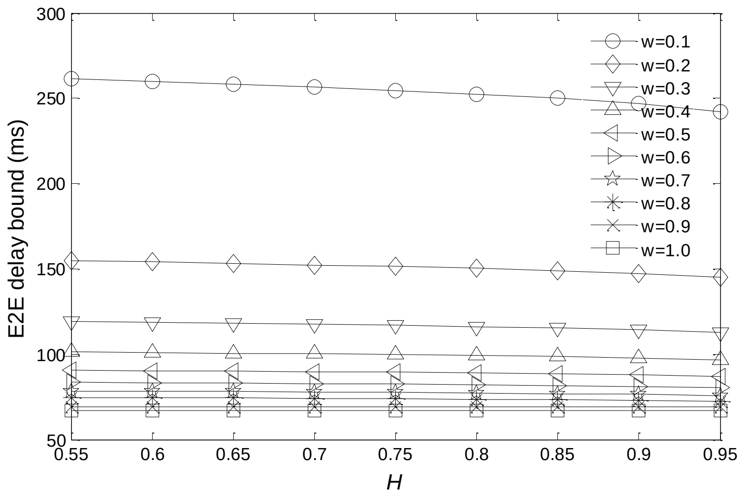

Fig. 9. E2E delay bound vs. H

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