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Network Calculus Based Performance Analysis of ForCES SCTP TML in Congestion Avoidance Stage

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Abstract: TML (Transport Mapping Layer) is the ForCES (Forwarding and control separation) protocol message transporting layer in the ForCES framework. Its communication performance will directly affect the efficiency and availability of ForCES NE (Network Element). In this study, the congestion control mechanism of SCTP (Stream Control Transmission Protocol) transport mapping layer is introduced and in a stochastic network calculus framework, the service model and service curve of SCTP which is in the congestion avoidance state by using the AIMD (Additive Increase and Multiplicative Decrease) algorithm is studied. At the same time, based on the EBB (Exponentially Bounded Burstiness) input model, the stochastic performance is also analyzed and the bounds on backlog and delay are derived. Numerical examples are presented to test the bounds. These performance analysis results can be used to optimize the SCTP TML to improve the efficiency of the ForCES communication channel.

Key words: ForCES TML, SCTP TML, SCTP performance analysis, SCTP congestion avoidance, AIMD service curve, stochastic network calculus

INTRODUCTION

Transport Mapping Layer (TML) addresses the protocol message transportation issues between Control Element (CE) and Forwarding Element (FE) in the ForCES (Forwarding and control element separation) protocol architecture for IP Network Element (NE, Such as, router, firewall, or load balancer, etc.) (Yang *et al*., 2004). It isolates Protocol Layer (PL) from the underlying network to solve mapping problem in different link layer (such as TCP/IP layer, Ethernet layer, ATM, etc.) (Doria *et al*., 2010). That improves the flexibility of ForCES system.

SCTP (Stream Control Transmission Protocol) TML (Salim and Ogawa, 2010) is a TML standard which has been published by ForCES working group in IETF. Before it became the RFC, exactly, there were several TML drafts in the WG. Apart from the SCTP TML draft, Wang *et al*. (2007) also proposed a TML service primitives draft based on TCP/UDP transport protocol. The main idea of this draft is using TCP and UDP to transmit control protocol messages and redirection protocol messages separately. At the same time, some researches which are related with this TML were conducted. Such as, Li *et al*. (2012) proposed a scheme of reliable multicast between CE and FE in ForCES architecture NE based on TCP/UDP TML. Zhuge *et al*. (2011) proposed a scheduling scheme to schedule ForCES messages in this kind of TML. Khosravi *et al*. (2006) proposed a TCP/IP based TML which uses TCP transmit control protocol messages. However, it uses DCCP protocol to transmit redirection protocol messages.

SCTP is a reformative transport layer of next generation IP network, in order to overcome the shortcoming of traditional TCP/UDP protocol. The same as TCP, SCTP also uses AIMD (Additive Increase and Multiplicative Decrease) algorithm to avoid the congestion (Stewart, 2007). Many researchers paid attention to the AIMD congestion avoidance. Altman *et al*. (2005) analyzed the performance of AIMD-like flow control mechanism. They employ a fluid approach based on a multi-state to model the controlled flow. Jasem *et al*. (2010) introduced a new AIMD algorithm and analyzed its delay, efficiency and fairness. Kim and Hou (2009) proposed to speed up the simulation performance for TCP-operated networks by incorporating network calculus-based models in a simulation framework. They analyzed TCP AIMD behavior and the service process. We used the same method of this literature to obtain the general expression of AIMD service curve. Then with this service curve, we studied the performance of the SCTP TML under EBB (Exponentially Bounded Burstiness) input flow model.

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PRELIMINARY WORKS

Network calculus is a tool which can be used to analyze the delay and other characteristics of QoS in computer network. It provides an effective approach to model the more and more complicated and diverse network. The network calculus's theoretical basis is the min-plus algebra and max-plus algebra which were introduced by Cruz (1991a, b). Since then network calculus has been continuously developed and generates two branches: deterministic network calculus and stochastic network calculus. Deterministic network calculus is mainly used in the occasion which provides certain service guarantees. However, many actual applications can tolerate a small amount of packet loss and delay. Stochastic network calculus is used in this situation to get the statistic performance. The detailed principles of network calculus was studied by Le Boudec and Thiran (2001) and Chang (2000).

In traditional algebra, the two most basic operations are plus and multiply in the integer or real number field. We can express it as (R, +, x). In Min-Plus algebra, the plus in traditional algebra evolved into an operator to find a minimum, multiplication operation evolved into plus and $+\infty$ is introduced into the computing field. Its algebraic structure can be expressed $(R\cup\{+\infty\}, \wedge, +)$, where, $\wedge$ denotes the infimum or, when it exists, the minimum. For the convenience of description, we list some concepts and operations in min-plus algebra. The detailed principles of network calculus can be found by Jiang and Liu (2008).

- Wide-sense increasing functions set F:

$$F = [f(t)\,|\,f(0) = 0, \forall t<0;\ f(0)\geq 0,\ f(s)\leq f(t),\ \forall s\leq t,\ s, t\in [0, +\infty]$$

- Wide-sense decreasing functions set $\bar{F}$:

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

- Pointwise infimum: $f\wedge g(t) = \inf[f(t), g(t)]$
- Pointwise supremum: $f\vee g(t) = \sup[f(t), g(t)]$
- Min-plus convolution: $(f\otimes g)(t) = \inf\{f(t-s)+g(s)\}, \forall f, g\in F$
- Min-plus deconvolution: $(f\oslash g)(t) = \sup\{f(t+s)-s(s)\}, \forall f, g\in F$
- Maximum horizontal distance h (f, g): $h(f, g) = \sup_{s\geq 0}\{\inf\{\tau\geq 0: f(s)\leq s(s+\tau)\}\}, \forall f, g\in F$
- Maximum vertical distance v (f, g): $v(f, g) = \sup_{s\geq 0}\{f(s)- g(s\}, \forall f, g\in F$

Arrival curve and service curve are two very important concepts in network calculus. Jiang and Liu (2008) introduced weak stochastic service curve, t.a.c (traffic-amount-centric) stochastic arrival curve.

Assume traffic arrival process is denoted by A(t), the output process, A*(t) and the accumulative arrivals in interval [0, t], A(s, t), respectively. A service system S is said to provide a weak stochastic service curve $\beta\in F$ (non-negative wide-sense increasing functions) with bounding function $g\in\bar{F}$ (non-negative wide-sense decreasing functions), denoted by $S\sim_{ws}\langle g, \beta\rangle$, if for all $t\geq 0$ and $x\geq 0$, there holds:

$$\Pr\{A\otimes\beta\text{-}A^*(t)>x\}\leq g(x) \quad (1)$$

A flow is said to have a t.a.c stochastic arrival curve $\alpha\in F$ with bounding function $f\in\bar{F}$, denoted by $A(t)\sim_{ta}\langle f, \alpha\rangle$, if for all $0\leq s\leq t$, there holds:

$$\Pr\{A(s,t)-\alpha(t-s)>x\}\leq f(x) \quad (2)$$

When we analyze the performance of SCTP AIMD, we will use the EBB as the traffic arrival model (Yaron and Sidi, 1993). A flow is said to have EBB with parameters (ρ, a, b), if for all s, $t\geq 0$ and all $x\geq 0$, there holds:

$$\Pr\{A(s,s+t)-\rho t>x\}\leq ae^{-bx} \quad (3)$$

Apparently, EBB is a special case of the definition of t.a.c stochastic arrival curve.

ForCES SCTP TML

ForCES protocol interface include PL and TML. PL is mainly responsible for the work of encapsulating the data into the ForCES protocol message which can be transmitted by TML. It is also responsible for the management and control TML; TML is responsible for the transmission messages issued by the PL, shielding the underlying transport implementation details.

The message transmission mechanism between CE and FE restricts the performance of the entire NE. In order to guarantee the reliability and real-time, the choice of transport protocol is vital to the performance of the whole system.

The single channel communication model of SCTP TML: SCTP is an end-to-end transport protocol which can do most of what UDP, TCP, or DCCP can achieve. It also can do most of what a combination of them can achieve (e.g., TCP and DCCP or TCP and UDP). Comparing with TCP, SCTP can also provide reliable, ordered, connection-oriented, flow-controlled, congestion-controlled data exchange, but it cannot provide byte streaming and instead provides message boundaries. Comparing with UDP, SCTP can provide unreliable, unordered data exchange but it cannot provide multicast support. Comparing with DCCP, SCTP can provide unreliable, ordered, connection-oriented, congestion controlled data exchange (Salim and Ogawa, 2010; Stewart, 2007).

SCTP has all the features required to provide a robust TML. As a transport that is all-encompassing, it negates the need for having multiple transport protocols in order to satisfy the TML requirements that in Section 5 of [RFC5810] (Doria *et al*., 2010). As a result, it allows for simpler coding and therefore reduces a lot of the interoperability concerns.

Figure 1 shows the interfacing between PL and SCTP TML and the internals of the SCTP TML. TML core interfaces to the PL utilizing the TML API and interfaces to the SCTP layer utilizing the standard socket interface.

In TML core, there are three channels used to group and prioritize the work for different types of ForCES traffic. The Higher-priority (HP) channel is used for transporting configuration\query messages and their response messages. The Medium-priority (MP) channel is used for event notification messages. The Lower-priority (LP) channel is for redirect and heartbeat messages.

The SCTP TML processes the channel work in strict priority. For example, if there are messages incoming from an FE on the HP channel, they will be processed first until there are no more left before processing the next priority work.

In user's implementation, if the all three channels using a single socket, analysis revealed that head-of-line blocking issues will be occurred. Packets in LP channel not needing reliable delivery could block packets in HP channel that needs reliable delivery under congestion situations for an indeterminate period of time. For this reason, we elected to go with mapping each of the three channels to a different SCTP socket (Salim and Ogawa, 2010).

SCTP slow-start and congestion avoidance: SCTP uses the same congestion control mechanism as TCP. The mechanism includes slow-start stage, congestion avoidance stage, fast retransmit and fast recovery stages. But the congestion control in SCTP is employed in regard to the association, not to an individual stream (Stewart, 2007).

Like TCP, an SCTP endpoint uses the following three control variables to regulate its transmission rate:

- Receiver advertised window size (rwnd, in bytes) which is set by the receiver based on its available buffer space for incoming packets
- Congestion control window (cwnd, in bytes) which is adjusted by the sender based on observed network conditions
- Slow-start threshold (ssthresh, in bytes) which is used by the sender to distinguish slow-start and congestion avoidance phases

Beginning data transmission into a network with unknown conditions or after a sufficiently long idle period

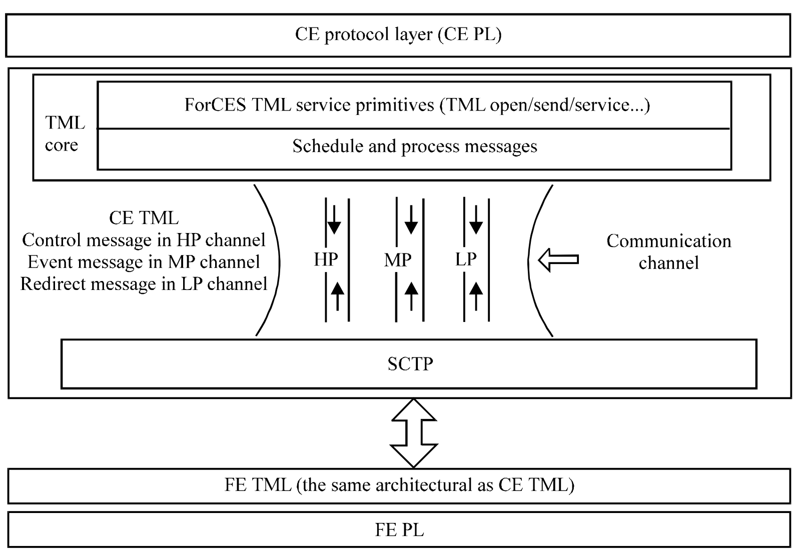

Fig. 1: The communication architecture of SCTP TML

requires SCTP to probe the network to determine the available capacity. The slow-start algorithm is used for this purpose at the beginning of a transfer, or after repairing loss detected by the retransmission timer.

When cwnd is greater than ssthresh, the congestion avoidance mechanism will be started. SCTP use AIMD policy to avoid the congestion. The AIMD algorithm can be described as below: cwnd will be incremented by 1*MTU per RTT (Round Trip Time) if the sender has cwnd or more bytes of data outstanding for the corresponding transport address. This is the additive increase process. Same as in the slow start, when the sender does not transmit data on a given transport address, the cwnd of the transport address should be adjusted to max(cwnd/2, 4*MTU) per RTO (Retransmission Timeout). This is the multiplicative decrease process.

SERVICE CURVE OF SCTP AIMD

As we have showed, AIMD is the congestion avoidance algorithm that used in SCTP. When SCTP discovered there is no congestion, the sending rate will be increased linearity; otherwise, the sending rate will be decreased multiplicatively. SCTP will know the congestion state according whether the sender has received the ACK message from the receiver.

Suppose the number of AIMD period (One AIMD period includes an additive increase process and a multiplicative decrease process.) is (m-1) in the interval Γ, the initial window size is w_0, the additive increase parameter AI (Additive Increase) is A and the multiplicative reduction parameters MD (Multiplicative Decrease) is B. As Fig. 2 showed, w_i (t) is capacity of the ith SCTP congestion window. T_{Ri} (t) is the RTT experienced by the data sent at time t. From Kim and Hou (2009), we have:

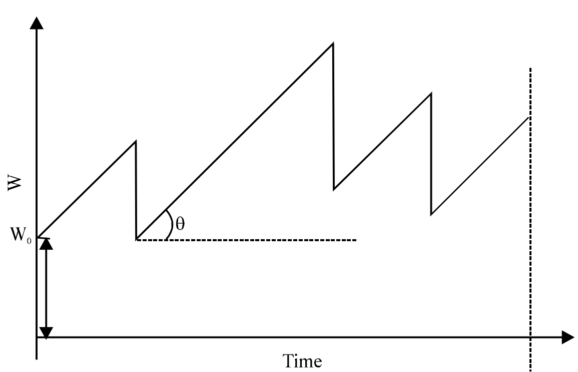

Fig. 2: AIMD algorithm window size

$$\tan\theta = A\frac{1}{t_{R_i}^{\ 2}} \tag{4}$$

Let S_i be the cumulate data flow in the ith AIMD period, then we have the following total service process $S_{\Gamma,\ m-1}$:

$$\begin{aligned} S_{\Gamma,m-1} &= \sum_{i=1}^{m} S_i = w_0\left(t_1 + Bt_2 + \ldots + B^{m-1}t_m\right) \\ &+ \tan\theta_\Gamma t_1\left(\frac{1}{2}t_1 + Bt_2 \ldots + B^{m-1}t_m\right) + \\ &\tan\theta_\Gamma t_2\left(\frac{1}{2}t_2 + Bt_3 \ldots + B^{m-2}t_m\right) \\ &+ \ldots + \tan\theta_\Gamma t_m\left(\frac{1}{2}t_m\right) \end{aligned} \tag{5}$$

Assume that the link bandwidth is L, then the model can provide services β (t) = min (Lt, $S_{t,m-1}$), because the size of the window AIMD cannot be more than L, so service curve is $S_{t,m-1}$.

Remarks: We make the following assumptions on TML communication mode. (1) Network is relatively stable, free from other external factors, (2) RTT of SCTP packets are stable, (3) A = $20RTT^2$, B = 0.8 in AIMD (4). In case that the size of sending window can changes from 80 to 100 Mbps in 1 sec, In the network, the maximum data packet L_{max} = 1 M. When there is enough data to send at all times, the AIMD window size will be Fig. 3.

When the constant rate arriving to a single SCTP channel is ρ_c<80 Mbps, because the data arrival rate is less than AIMD data service rate V_m = 90 Mbps, the buffer will be empty at some point and then the stagnation of SCTP send window will appear. The change of AIMD sending window depends on the network situation reflected by packet ACK. when there is no data to sent, AIMD sending window holds. The practical effect diagram is as Fig. 4.

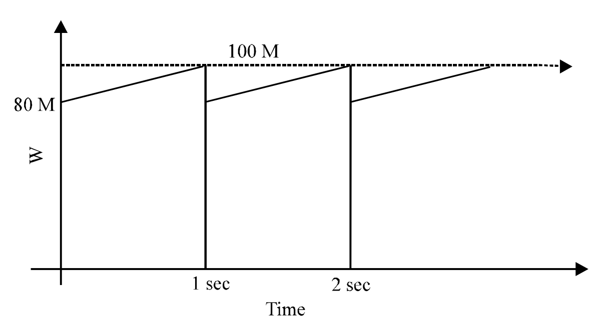

Fig. 3: The changes of AIMD window size in the given scenario

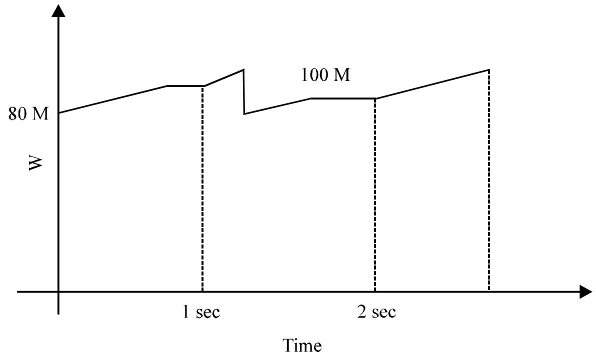

Fig. 4: The stagnation phenomenon of the window size

When the constant rate arriving to a single SCTP channel is $90 \le \rho_c \le 100$ Mbps, as the average data transmission rate of AIMD algorithm V_m = 90 Mbps, so SCTP channel buffer will not be empty. The change of sending window in this situation is shown in 0 and then we can get their arrival curve and service curve. Its data arrival curve is $\alpha(t) = \rho_c t$ and service curve is $\beta(t) = S_{\Gamma,m-1}$, where m is the complete number of cycles, Γ is the time experienced by the whole experiment.

STOCHASTIC PERFORMANCE ANALYSIS OF SCTP TML UNDER EBB INPUT MODEL

It is difficult to calculate $S_{t,m-1}$ accurately. Here, we study $S_{t,m-1}$ in an ideal AIMD situation which we called AMS (AIMD Metastable State) state.

Definition 1: Only when the AIMD window reaches a fixed threshold size, packet loss will appear on the link and this threshold may be total link capacity or a fixed bandwidth allocated to the link by the network node. AIMD window does not decrease consecutively while the packet loss occurred. To satisfy the above conditions, the system state is called AIMD Metastable State.

From the definition, we know the network will not be affected by other external conditions in the AMS state and the backlog will never be null.

We assume all packets' RTTs are the same. The fixed threshold of the AIMD window is C, when SCTP is in the AMS state. The change of AIMD algorithm window size will be like Fig. 5.

We can get the service process in the time interval t:

$$S_{t,m-1} = \sum_{i=1}^{m} S_i = S_1 + (m-1)S_2 + S_{m+1} = \left[w_0 t_1 + \frac{1}{2} t_1 (C - w_0) \right] + (m-1)\left[BCt_2 + \frac{1}{2} t_2 (C - BC) \right] + \left[BCt_{m+1} + \frac{1}{2} k t_{m+1}^2 \right] \quad (6)$$

where, S_{m+1} is the flow of the (m+1)th AI stage which is incomplete and $t_1 = C\text{-}w_0/k$, $t_2 = t_3 = \dots = t_m = T = C(1\text{-}B)/k$, $k = \tan\theta = A/t^2_{Ri}$, $m\text{-}1 = (t\text{-}t_1)/T$, $t_{m+1} = t\text{-}(m\text{-}1)T\text{-}t_2$.

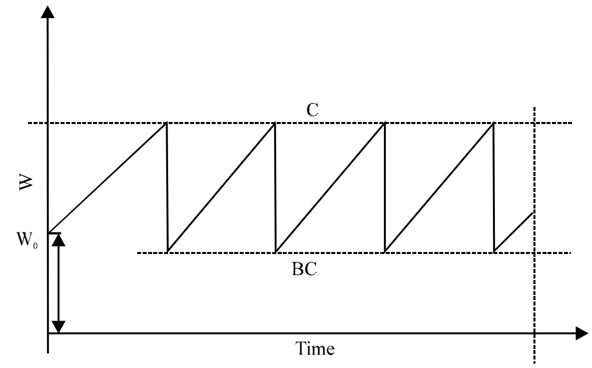

Fig. 5: The changes of AIMD window size in AMS state

Ignoring the slow-start stage and after the system reached AMS state, from the time that the window size w_0 = BC, in the time interval t, the total number of system services is:

$$S_{t,m} = \sum_{i=1}^{m} S_i = mS_1 + S_{m+1} = m\left[BCT + \frac{1}{2} T (C - BC) \right] + \left[BCt_{m+1} + \frac{1}{2} k t_{m+1}^2 \right] \quad (7)$$

where, $T = C(1\text{-}B)/T$, $k = \tan\theta = A/t^2_{Ri}$, $m = t/T$.

Apparently:

$$S_{t,m} > BCt + \frac{1}{2} T (C - BC) m \quad (8)$$

So, we can get the service envelop process of AIMD:

$$\tilde{S}_{t,m} = BCt + \frac{1}{2} TC(1 - B) m \quad (9)$$

where, $T = C(1\text{-}B)/k$, $k = \tan\theta = A/t^2_{Ri}$, $m = t/T$

The backlog bound of SCTP AIMD: Considering a work conserving system, according the Theory 5.2 and 5.5 in Jiang and Liu (2008): if the input has a t.a.c stochastic arrival curve $\alpha \in F$ with bounding function $f \in \bar{F}$ and the system provides to the input a weak stochastic service curve $\beta \in \bar{F}$ with bounding function $g \in \bar{F}$, then for all $t \ge 0$ and $x \ge 0$, the backlog Q(t) is bounded by:

$$\Pr\{Q(t) > x\} \le f^{\theta} \otimes g(x - \alpha \oslash \beta(0)) \quad (10)$$

and the delay D (t) is bounded by:

$$\Pr\{D(t) > h(\alpha + x, \beta)\} \le f^{\theta} \otimes g(x) \quad (11)$$

where, $f^{\theta}(x) = f(x) + \frac{1}{\theta}\int_x^{\infty} f(y)\,dy$, for any $\theta > 0$.

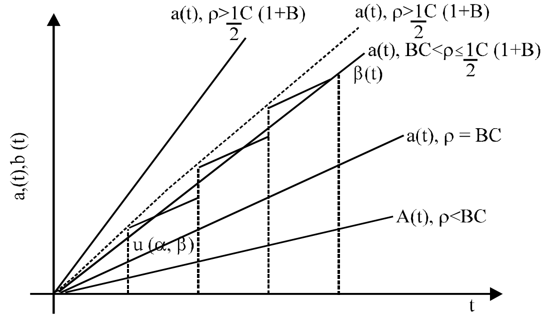

Fig. 6: The maximum vertical distance υ (α, β)

For the EBB arrival process, $f^\theta(x) = ae^{-bx}(1+\theta b)$. If the SCTP is in AMS state, then g (x) = 0. So:

$$\Pr\{Q(t)>x\} \le f^\theta(x-\alpha\oslash\beta(0)) = f^\theta(x-\upsilon(\alpha,\beta)) \qquad (12)$$

When, $BC<\rho\frac{1}{2}C(1+B)$ as showed in Fig. 6, the maximum vertical distance υ(α, β) locates at t which is close to the T's jump point, then υ (α, β) = (ρ-BC)T.

So we can get:

$$\upsilon(\alpha,\beta) = (\rho-BC)t - \frac{1}{2}TC(1-B)m\begin{cases}\le 0, \rho\le BC\\ \approx(\rho-BC)T, BC<\rho\le\frac{1}{2}C(1+B)\\ =\infty, \frac{1}{2}C(1+B)<\rho\le C\end{cases} \qquad (13)$$

Applying Eq. 13 to 12, we have:

$$\Pr\{Q(t)>x\}\le\begin{cases}ae^{-bx}\left(1+\frac{1}{\theta b}\right), \rho\le BC\\ a\left(1+\frac{1}{\theta b}\right)\exp\{-b(x-(\rho-BC)T)\}, BC<\rho\le\frac{1}{2}C(1+B)\end{cases} \qquad (14)$$

where, T = C(1-B)/k, k = tanθ = A/t^2_{Ri}.

Remarks:

- If the SCTP is in AMS state, the backlog bound is related to the parameter ρ of EBB. When ρ is less than the smallest window size (BC), the backlog bound will be tighter. That is, the probability of existing backlog will be smaller. Moreover, The backlog bound is irrespective of the AIMD parameters and it's only related with EBB parameters and x
- When ρ is greater than BC, the probability of existing backlog will be bigger. Furthermore, the bound is related with the AIMD parameters, x and the EBB parameters at the same time
- When, $BC<\rho\frac{1}{2}C(1+B)$ ρ smaller or BC greater, the backlog bound will be tighter

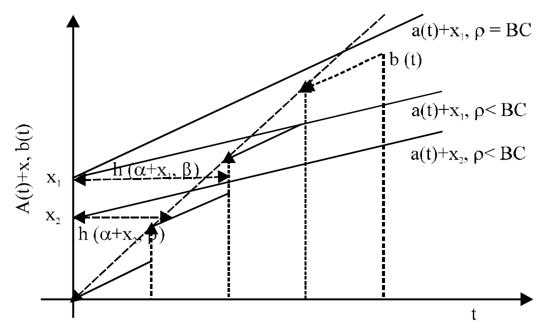

Fig. 7: The maximum horizontal distance h(α+x, β) (ρ≤BC)

The delay bound of SCTP AIMD: According Eq. 11 and the fact g (x) = 0 when the SCTP is in AMS state, we have:

$$\Pr\{D(t)>h(\alpha+x,\beta)\}\le f^\theta(x) \qquad (15)$$

We first compute the maximum horizontal distance h (α+x, β), then get the delay bound.

ρ≤BC: From Fig. 7, we can get:

$$h(\alpha+x,\beta)=\begin{cases}\dfrac{x-\frac{1}{2}TC(1-B)n}{BC}, nBCT+\frac{1}{2}nTC(1-B)\le x<(n+1)BCT+\frac{1}{2}nTC(1-B)\\ (n+1)T, (n+1)BCT+\frac{1}{2}nTC(1-B)\le x<(n+1)BCT+\frac{1}{2}(n+1)TC(1-B)\end{cases} \qquad (16)$$

where, n is any integer and n≥0.

- When $nBCT+\frac{1}{2}nTC(1-B)\le x<(n+1)BCT+\frac{1}{2}nTC(1-B)$

$$\Pr\left\{D(t)>\frac{x-\frac{1}{2}TC(1-B)n}{BC}\right\}\le ae^{-bx}\left(1+\frac{1}{\theta b}\right) \qquad (17)$$

Let $[x-\frac{1}{2}TC(1-B)n]/BC = b$, then $x = BCD+\frac{1}{2}TC(1-B)n$. So:

$$\Pr\{D(t)>d\}\le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b(BCd+\frac{1}{2}TC(1-B)n)\right\} \qquad (18)$$

where, nT≤d<(n+1)T, n is any integer and n≥0.

- When:

$$(n+1)BCT+\frac{1}{2}nTC(1-B)\le x<(n+1)BCT+\frac{1}{2}(n+1)TC(1-B)$$

$$\Pr\{D(t)>(n+1)T\}\le ae^{-bx}\left(1+\frac{1}{\theta b}\right) \qquad (19)$$

Apparently, if x is greater, the probability will smaller and the bound is tighter. So:

$$\Pr\{D(t) > (n+1)T\} \le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+1)BCT + \frac{1}{2}(n+1)TC(1-B)\right)\right\} \quad (20)$$

Combined Eq. 18 and 20, we obtain:

$$\Pr\{D(t) > d\} \le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left(BCd + \frac{1}{2}TC(1-B)n\right)\right\} \quad (21)$$

where, $nT \le d < (n+1)T$, n is any integer and $n \ge 0$.

Though equivalent transformation to the condition, when $\rho \le \beta C$, for any $d>0$, we have the following final delay bound result:

$$\Pr\{D(t) > d\} \le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left(BCd + \frac{1}{2}TC(1-B)n\right)\right\} \quad (22)$$

where, $n = [d/T]$.

$BC<\rho\frac{1}{2}C(1+B)$: As showed in Fig. 8, with the changes of x, the $h(\alpha+x, \beta)$ is different. Assume n is any integer and $n \ge 0$.

- When $nBCT + \frac{1}{2}nTC(1-B) \le x < (n+1)BCT + \frac{1}{2}nTC(1-B)$

$$h(\alpha+x,\beta) = (n+1)T - \frac{(n+1)BCT + \frac{1}{2}nTC(1-B) - x}{\rho} \quad (23)$$

Applying Eq. 22 to 15, so:

$$\Pr\left\{D(t) > (n+1)T - \frac{(n+1)BCT + \frac{1}{2}nTC(1-B) - x}{\rho}\right\} \le ae^{-bx}\left(1+\frac{1}{\theta b}\right) \quad (24)$$

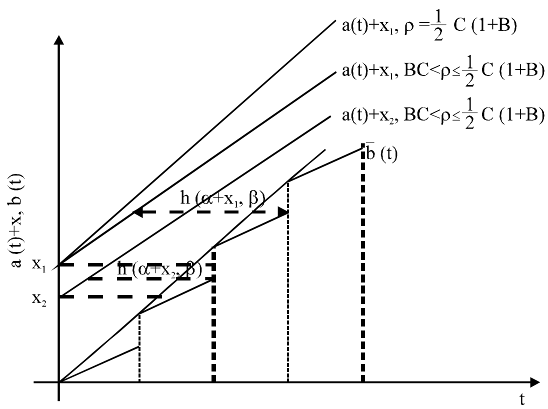

Fig. 8: The maximum horizontal distance $h(\alpha+x, \beta)$ $BC < \rho \le \frac{1}{2}C(1+B)$

Let:

$$(n+1)T - \frac{(n+1)BCT + \frac{1}{2}nTC(1-B) - x}{\rho} = d$$

then $x = (n+1)BCT + \frac{1}{2}nTC(1-B) - \rho((n+1)T - d)$ We obtain:

$$\Pr\{D(t) > d\} \le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+1)BCT + \frac{1}{2}nTC(1-B) - \rho((n+1)T-d)\right)\right\} \quad (25)$$

where, $(n+1)T - \frac{BCT}{\rho} \le d < (n+1)T$

- When:

$$(n+1)BCT + \frac{1}{2}nTC(1-B) \le x < (n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - \rho T$$

$$h(\alpha+x, \beta) = (n+1)T \quad (26)$$

Applying (26) to (15), so:

$$\Pr\{D(t) > (n+1)T\} \le ae^{-bx}\left(1+\frac{1}{\theta b}\right) \quad (27)$$

We obtain:

$$\Pr\{D(t) > d\} < a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - \rho T\right)\right\} \quad (28)$$

where, $d = (n+1)T$.

- When:

$$(n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - \rho T \le x < (n+1)BCT + \frac{1}{2}(n+1)TC(1-B)$$

$$h(\alpha+x,\beta) = (n+2)T - \frac{(n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - x}{\rho} \quad (29)$$

So:

$$\Pr\left\{D(t) > (n+2)T - \frac{(n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - x}{\rho}\right\} \le ae^{-bx}\left(1+\frac{1}{\theta b}\right) \quad (30)$$

Let:

$$(n+2)T - \frac{(n+2)BCT + \frac{1}{2}(n+1)TC(1-B) - x}{\rho} = d$$

then $x = (n+2)BCT + 1/2(n+1)TC(1-B) + \rho((n+2)T - d)$. We obtain:

$$\Pr\{D(t)>d\}\le a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+2)BCT+\frac{1}{2}(n+1)TC(1-B)-\rho((n+2)T-d)\right)\right\} \quad (31)$$

where, $(n+1)T \le d < (n+2)T - BCT/\rho$.

Based on the above results (25) (28) (31), when $BC > \rho \frac{1}{2} C\,(1+B)$, we have the following final delay bound result:

$$\Pr\{D(t)>d\}\le\begin{cases} a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+1)BCT+\frac{1}{2}nTC(1-B)-\rho((n+1)T-d)\right)\right\} & ,d<(n+1)T \\ a\left(1+\frac{1}{\theta b}\right)\exp\left\{-b\left((n+2)BCT+\frac{1}{2}(n+1)TC(1-B)-\rho((n+2)T-d)\right)\right\} & ,d\ge(n+1)T \end{cases} \quad (32)$$

Where:

$$n=\left\lceil \frac{d-\frac{BCT}{\rho}}{T} \right\rceil$$

$$T=\frac{C(1-B)}{k},\quad k=\tan\theta=\frac{A}{t_{R_i}^{\,2}}$$

$\frac{1}{2}C(1+B)<\rho\le C$: h ($\alpha$+x, β) will be infinity.

Remarks:

- The delay bound is closely related with the delay value. If $\rho \le BC$ and when d changed in a T-cycle, the change of the bound is continuous. But when d increases beyond T, a jump change of the bound will occur and the bound will be tighter
- When we fix the delay d, apparently, greater B is, then tighter the delay bound will be, that is, the probability of having that delay is smaller

Numerical example: This section shows numerically the performance of SCTP TML. The messages transmitted between CE and FEs can be considered to have the same flow model with different parameters. The MMOO (Markov-modulated On-Off) process can well describe these flows.

MMOO is defined by considering a homogenous and continuous-time Markov chain x(t) with two states denoted by 'On' and 'Off' and with the transition matrix:

$$Q=\begin{pmatrix} -\mu & \mu \\ \lambda & -\lambda \end{pmatrix}$$

Here, μ is the transition rates from the 'On' state to the 'Off' state and vice-versa for λ. So, in the steady state, the average dwell time of the process in 'On' state is $1/\mu$ and the average dwell time in 'Off' state is $1/\lambda$. Let the instantaneous arrival rate is either P (in 'On' state) or zero (in 'Off' state). According Courcoubetis and Weber (1996), Cuicu (2007), this MMOO process is an EBB process with:

$$\rho=\frac{1}{2?}\left(P\Delta-\mu-\lambda+\sqrt{(P\Delta-\mu+\lambda)^2+4\lambda\mu}\right) \quad (33)$$

and a = 1, b = Δ, where Δ is subject to numerical optimizations.

Assume the allocated upper limit bandwidth to SCTP channel C is 20 M and AIMD parameter A is 20RTT2, B = 0.6. We can obtain:

$$k=\tan\theta=\frac{A}{t_{R_i}^{\,2}}=20,\quad T=\frac{C(1-B)}{k}=0.4,\quad BC=12M,\ \frac{1}{2}C(1+B)=16$$

We select four sessions with different MMOO parameters showed in Table 1. Among them, ρ_1<BC, ρ_2~ρ_4 are all in (BC, 1/2C (1+B)). Through (14), we can get the backlog bounds showed in Fig. 9. Through using (22) and (32), we can get the delay bounds showed in Fig. 10.

From the simulation results, we can see the backlog and delay bounds for session 1 is tighter than the others. Moreover, the bounds with smaller average arrival rate

Table 1: Four sets of MMOO model parameters

Arrival process	$1/\mu$ (sec)	$1/\lambda$(sec)	P (Mb sec^{-1})	ρ (Mb sec^{-1})
Session 1	0.2	0.2	10	7.0711
Session 2	0.1	0.2	20	12.8078
Session 3	0.1	0.4	23	14.4729
Session 4	0.4	0.4	18	15.8408

$1/\mu$: The average dwell time of the process in 'On' state, $1/\lambda$: The average dwell time in 'Off' state; P: The instantaneous arrival rate in 'On' state; ρ: the parameter in EBB process

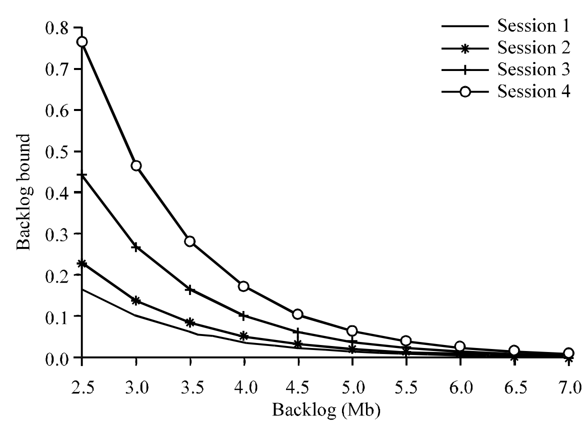

Fig. 9: Backlog bounds computed with Eq. 14

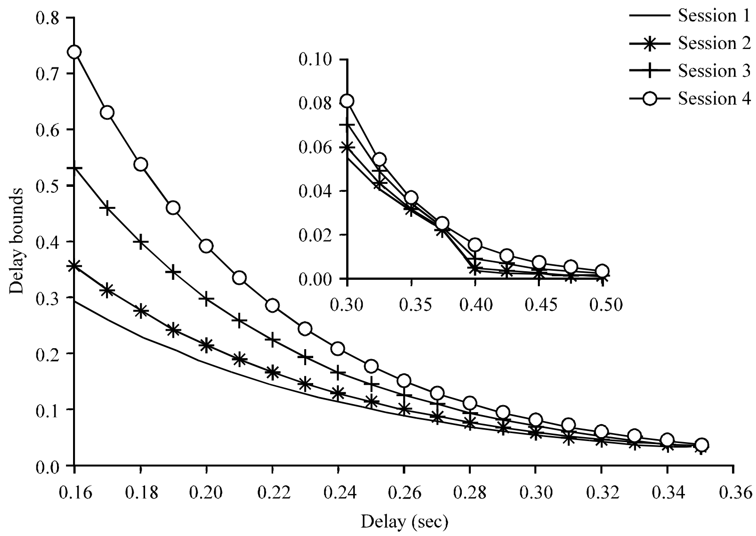

Fig. 10: Delay bounds computed with Eq. 22 and 32

decay much slower. These indicate that if the average arrival rate is smaller, the probability of backlog and delay will be also smaller. We also can see the bound of backlog will be near to zero, when the backlog is greater than 7 Mb and the bound of delay will be near to zero too, when the delay is greater than 0.5 sec. That is to say the backlog of the SCTP in AMS state with the given parameters will not exceed 7 Mb basically and the delay produced in SCTP congestion avoidance will not exceed 0.5 sec basically.

CONCLUSIONS

The performance of congestion control mechanism of SCTP TML is analyzed. In a stochastic network calculus framework, the service model and service curve of AIMD algorithm was studied. At the same time, in the assumption of the system being in the AMS state and based on the EBB input model, the bounds on backlog and delay were derived. Numerical examples were presented to test the bounds.

We had added many conditions when analyzing the service process of AIMD. Those would affect the accuracy and make the results not having universality. But if we didn't base on those conditions, the service curve would be very complex. It would bring more difficulty to derive the bounds of backlog and delay. So how to coordinate these problems and let the results having more universality is a work that needs to be studied.

Moreover, we only studied the performance of congestion avoidance stage of SCTP TML. The end to end performance between CE and FE is also one of our research directions.

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