Modeling the Throughput of CMT-SCTP

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Abstract. Based on the multi-streaming and multi-homing features of SCTP, the researchers proposed Concurrent Multipath Transfer (CMT). In order to aggregate bandwidth and improve the transmission throughput of end-to-end network, many new paradigms, such as Information Centric Network (ICN), are created. These new network architectures contain massive redundant paths, which provide more opportunities for CMT enhancement. However, most previous analytic models of throughput only focus on single path. Although some scenarios take into account multiple paths, the performance parameters of the paths are supposed to be the same, which is hard to achieve in practical circumstance. In this paper, we develop a simple analytic mechanism for CMT-SCTP throughput. Sending rate is selected as a function of loss rate, bandwidth and Round-Trip Time (RTT). Different with previous models, our mechanism considers different performance parameters for multiple paths. The simulation results show that our model is able to predict CMT-SCTP sending rate accurately under various network conditions.

Introduction

The mobile communication network and the intelligent mobile devices have profoundly changed human’s life style. Lots of mobile apps put forward higher requirements of communication quality and transmission rate. For example, nowadays people are used to watching online videos and making video calls using their smartphones. Since the clarity of video service advances to ultra-clear from standard definition, the increasing resolution of video service put forward a huge challenge on the network. The continuous improvement of users’ demands and expansion of network services make current network more and more difficult to meet the rapid growth of transmission demand.

In order to improve the utilization of the network resource and efficiently integrate all the existing resources, multiple paths are considered to provide multiple guarantees especially in the new network paradigms, such as Information Centric Network (ICN). Multipath transmission means that the service can use multiple paths simultaneously rather than one conventional single path for data transmission, resulting in better performance and higher quality assurance. The realization of multipath transmission can improve the utilization of network resources, thereby improving the quality and efficiency of network services. Meanwhile, multipath transmission can also enhance network services with higher anti-jamming capability and fault recovery capabilities, which will further improve network services stability.

Recently, researchers have proposed several methods to implement multipath transmission at the transport layer. Among them CMT-SCTP protocol based on the multi-streaming and multi-homed features of SCTP becomes one of the most active implementations and was adopted by the IETF organization in the form of RFC files.

Previous analytic models focus on SCTP with only single path like [1], while models in [2, 3] take into account multipath scenarios. Several efforts have been done in [4, 5] developed a simple analytic characterization of the steady-state send rate of a bulk transfer TCP flow as a function of loss rate and round-trip time. Similar work has been done with a model of TCP Vegas in [6]. And TCP behavior in a differentiated services network is modeled in [7]. Unlike the recent work of [8, 9] just took the single path scenario, this model considers CMT-SCTP throughput in concurrent multipath and also
ICN network condition. In this paper, we develop a simple analytic characterization of CMT-SCTP send rate as a function of loss rate, bandwidth and round-trip time (RTT). By comparing our model’s predictions with the results of simulation, this paper demonstrates that our model is able to predict send rate accurately under a wide variety of path conditions.

Model for CMT-SCTP

Premises and Assumptions

Similar to TCP protocol, SCTP protocol has a complex congestion control mechanism including slow start, congestion avoidance, fast retransmission and fast recovery. Coupled with the complex conditions of today’s network, CMT-SCTP multipath network shows a variety of complex behaviors. This section will focus on CMT-SCTP congestion control mechanism and the relationship between network send rate and congestion control mechanism. Assuming that one path whose congestion window is $W$, whenever the sender receives an ACK from receiver, the congestion window increases by $1/W$, correspondingly, once a packet loss has been detected by duplicate ACKs or by time-out, the congestion window will decrease. In CMT-SCTP multipath transmission system, since there exits more than one path, the stat and communication parameters of each path need to be considered about.

It is assumed that a packet is lost in a round independently of any packet lost in other paths or in other rounds under ICN network. In order to derive a clear description, “rounds” is defined to model the congestion avoidance behavior of SCTP. A round starts with transmission of $W$ packets, where $W$ is the current size of congestion window. Once all $W$ packets have been sent, because total $W$ congestion window is full, no other packets will be sent until the sender receives the first ACK for one of $W$ sent packets, which represents the end of current round and the start of next round. In this model, the duration of a round is very close to one RTT and the duration of a round can also be assumed to be independent of window size.

Assuming that the sender always has data to send in ICN network, consider a CMT-SCTP flow starts at time $t = 0$, for any given time $t > 0$, define $N_t$ to be the number of packets that are transmitted during $[0, t]$, then the send rate is $B_t = N_t/t$ during this interval. Therefore, the long-term steady-state send rate of a CMT-SCTP connection can be defined as:

$$B = \lim_{t \to \infty} B_t = \lim_{t \to \infty} \frac{N_t}{t}$$

(1)

Stage Division

This model only considers about packet loss detected by the reception at the sender of “triple-duplicate” acknowledgments, which is denoted as a TD (triple-duplicate) loss indication. The congestion control over time of CMT-SCTP multipath transmission system is described in Figure 1. In this case, the duration between two TD loss indication throws a TDP (triple-duplicate period), which consists of multiple rounds. In the $i$th TDP, define $A_i$ to be the duration of the period and $Y_i$ the number of packets sent in the period, $B$ is denoted by the mean of $Y$ and $A$. Thus, in order to derive an expression for $B$, the send rate for CMT-SCTP multipath, the expressions for the mean of $Y$ and $A$ must be derived first, that is

$$B = \frac{E[Y]}{E[A]}$$

(2)

Since the CMT-SCTP multipath transmission system has more than one path at the same time, in order to derive the overall send rate, it is necessary to fully consider the mean of $Y$ and $A$ under multiple paths conditions. Due to the consideration of path fairness and congestion balance, once a packet loss occurs in the network path, multiple paths need to enter the fast retransmission stage from congestion avoidance stage. After TD loss, it has entered a new TDP period. The initial congestion
window of the path is half of the congestion window at the end of the previous TDP period, namely \( W_{i-1} / 2 \), where \( a, b, \) and \( c \) represent the serial number of different paths. Since the congestion window is limited by the receiving congestion window size of receiver, that is, \( CWND \leq RWND \), the maximum value of the congestion window is \( RWND \).

![Figure 1. Evolution of window size over time.](image)

CMT-SCTP multipath transmission system can be split into some of TDP periods and the packets sent during TDPs is showed in Figure 2.

![Figure 2. Packages sending during TDPs.](image)

**Model Derivation**

Consider a TDP period in Figure 2, the mean duration of one TDP follows that

\[
E[A] = (E[r] + E[l] + E[d] + E[h]) \times RTT. \tag{3}
\]

where \( RTT \) is denoted by the average value of round trip time, \( E[r] \) is the mean number of rounds that packets successfully transmitted, \( E[l] + E[d] \) counts the number of rounds needed to retransmit, usually it needs one or two rounds during fast retransmission period, and the number of rounds during recovery period is given by \( E[h] \). The definition of RTT is denoted by \( RTT = avg(rtt_i) \) which means the average value of round trip time.

The introduction of multiple paths leads to more complicated congestion control situation where both paths are in a dynamic state of equilibrium. Define \( e_i \) to be the parameter that the \( i \)th path weights among others, \( e_i \) is a function of the bandwidth \( w_i \), packet loss rate \( p_i \) and round-trip time \( rtt_i \), that is

\[
e_i = fun(w_i, p_i, rtt_i). \tag{4}
\]

Thus, during the \( i \)th round, the probability that the \( j \)th packet is lost \( P_{ij} \) is

\[
P_{ij} = \sum_{j=1}^{n} (e_j \times p_j). \tag{5}
\]

Then the probability that packet loss occurred in the \( i \)th round \( P_i \) is
\[ P_i = 1 - \prod_{j=1}^{E[W_i]} (1 - P_j) . \]  

(6)

Where \( E[W_i] \) is the mean number of packets that successfully transmitted in the \( i \)th round, which equals the sum of all the packets transmitted in each path. Thus \( E[W_i] \) can be represented as

\[ E[W_i] = \sum_{n=1}^{E[W]} Cwnd_i \approx Rwnd . \]  

(7)

From Eq. 6 and Eq. 7, the mean number of rounds that packets successfully transmitted in a TDP is

\[ E[r] = \sum_{i=1}^{E[W]} \left( i \times \left( \prod_{j=1}^{E[W]} (1 - P_j) \right) \times P_i \right) . \]  

(8)

During one TDP period, \( L \) round and \( H \) round each is going to happen definitely, so there comes

\[ E[l] = E[h] = 1 . \]  

(9)

Let \( b \) be the number of packets that are acknowledged by a received ACK. The number of rounds of \( D \) round depends on the probability of occurrence of \( D \) round, that is

\[ E[d] = P[D] = \sum_{j=1}^{E[W]-3ob} E[W] - \prod_{j=1}^{E[W]} (1 - P_j) - \sum_{j=1}^{E[W]} P_j . \]  

(10)

Until now, the mean duration of TDP flow can be calculated using Eq. 10. Then consider about \( E[Y] \), the mean number of packets sent during a TDP, which can be expressed by:


(10)

Where \( E[R] \) represents the mean number of packets of data successfully transmitted before the TD loss is detected and is equal to the total packets transmitted successfully in the first \( E[r] \) rounds, that is

\[ E[R] = \sum_{i=1}^{E[r]} E[W_i] = E[r] \times Rwnd . \]  

(12)

Note that \( E[L] + E[D] \) is the mean number of packets transmitted over the retransmission rounds, which equals to the number of packets transmitted during retransmission period and follows

\[ E[L] + E[D] = Rwnd \times \sum_{j=1}^{E[W]} \left( (j + 3 \times b + 1) \times P_j \right) . \]  

(13)

The \( H \) round is the recovery round and also the start of the next TDP, where the congestion window is decreased to half of the previous one. The mean number of packets transmitted in \( H \) round follows

\[ E[H] = \frac{1}{2} \times E[W] \approx \frac{1}{2} Rwnd . \]  

(14)

From Eq. 3 and Eq. 11, the long-term steady-state sent rate of a CMT-SCTP connection can be expressed as


(15)

According to Eq. 15, with the help of Eq. 8, 9, 10, 12, 13, 14, the mean number of packets that was successfully transmitted in a TDP can be mathematically calculated.
Simulation Validation

In order to verify the accuracy of this model, this section uses the SCTP module of the University of Delaware with the NS2 [10] simulator to perform simulation verification, which has been modified to incorporate multiple simultaneous transmission functions and support different transmission strategies. To simplify the simulation model, it is assumed that this model contains only two paths both with bandwidth of 100MB/s.

Then consider these two paths have all the same parameters except RTT, model calculations and simulation experiments have been done over a variety of RTTs. In this case, it can be assumed that these two paths weigh the same and the comparison results with different loss rate over a range of RTTs are shown in the following Figure 3. The title of each graph in Figure 3 indicates the loss rate of those two paths.

![Figure 3. Comparisons of the analytical and simulation results with different loss rate p_1 and p_2. (a) p_1 = p_2 = 0; (b) p_1 = p_2 = 0.001; (c) p_1 = p_2 = 0.002; (d) p_1 = p_2 = 0.003; (e) p_1 = p_2 = 0.004; (f) p_1 = p_2 = 0.005.](image)

As shown by the graphs in Figure 3, the calculated results of the proposed model are well fit the results of simulation.

And then consider the case where two paths contain different path parameters, Figure 4 (a) and (b) show the send rate varies with the RTTs. The title of Figure 4 (a) and (b) indicate two different loss rate p_1, p_2 and rtt_1, rtt_2. (a) p_1 =0.002, p_2 = 0.005; (b) p_1 =0.005, p_2 = 0.01; (c) rtt_1 = 20ms, rtt_2 = 50ms; (d) rtt_1 = 50ms, rtt_2 = 100ms.

![Figure 4. Comparisons of the analytical and simulation results with loss rate p_1, p_2 and rtt_1, rtt_2. (a) p_1 =0.002, p_2 = 0.005; (b) p_1 =0.005, p_2 = 0.01; (c) rtt_1 = 20ms, rtt_2 = 50ms; (d) rtt_1 = 50ms, rtt_2 = 100ms.](image)

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rate of each path. It can be seen from Figure 4 (a) and (b) that in most cases, the approximate model provides a quite close prediction compared to the result of simulation.

Another condition is that the RTTs parameters of these two paths are different with each other, just like the title of Figure 4 (c) and (d) indicates, the graph (c) and (d) in Figure 4 compare the send rate with the predictions of the proposed model and simulation results while these two paths have the same loss rate changing from 0 to 0.01. All these graphs show that this model provides a good fit to the ICN network send rate of CMT-SCTP connections under a wide variety of network conditions.

Summary
In this paper, we presented a simple model for CMT-SCTP transmission in ICN scenarios. The model captures the essence of congestion control mechanism and expresses send rate as a function of RTT and packet loss rate. We considered different performance parameters for multiple paths. The simulation result shows that it is able to predict send rate accurately over a wide range of loss rate.

For the future work: First, this model only account for TD loss indication, which can be enhanced to capture the effects of TO (timeouts) loss indication. Then, it would be interesting to make a comparison with MPTCP which is also a protocol for multipath transmission.

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