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Research Article

Loss-Aware CMT-Based Multipathing Scheme for Efficient Data Delivery to Heterogeneous Wireless Networks

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With the rapid development of wireless networks, multiple network interfaces are gradually being designed into more and more mobile devices. When it comes to data delivery, Stream Control Transmission Protocol (SCTP)-based Concurrent Multipath Transfer (CMT) has proven to be quite useful solution for multiple home networks, and it could become the key transport protocol for the next generation of wireless communications. The CMT delay caused by data rearrangement has been noticed by researchers, but they have seldom considered the frequent occurrence of packet loss that occurs in the high-loss networks. In this paper, we proposed an original loss-aware solution for multipath concurrent transmission (CMT-LA) that achieves the following goals: (1) identifying packet loss on all paths, (2) distributing packets adaptively across multiple available paths according to their packet loss and loss variation, and (3) maintaining the features of bandwidth aggregation and parallel transmission of CMT while improving the throughput performance. The results of our simulations showed that the proposed CMT-LA reduces reordering delay and unnecessary fast retransmissions, thereby demonstrating that CMT-LA is a more efficient data delivery scheme than classic CMT.

1. Introduction

The development of wireless network technologies has been extremely rapid, leading to an increased amount of mobile equipment with multiple communication interfaces (e.g., WiFi, 4G, 5G) [1]. To support the wide use of wireless communication technology and the prevalence of multihoming terminals, properly equipped mobile devices can use multiple network interfaces to transfer network data, thereby increasing transmission efficiency, maximizing network resource utilization, and improving system robustness [2]. However, the traditional Transmission Control Protocol (TCP), with its single path structure, cannot make use of the multihoming characteristics of mobile terminal equipment to improve the data transmission rate and throughput performance.

Multihoming devices are capable of utilizing multiple wireless technologies to improve the content delivery of multimedia [3]. Moreover, users find it convenient to access multimedia streaming services (e.g., video and voice streaming) from anywhere at any time. Nevertheless, supporting real-time multimedia streaming services remains a challenging task, mainly because these applications require high bandwidth and delay intolerance [4].

More importantly, real-time services performance of diverse media also requires low latency and reliable data transmission. Being a solution to support multipath transmission, Stream Control Transmission Protocol (SCTP) [5] has already discussed by scholars [6, 7]. Like TCP, SCTP is a reliable protocol that offers dependable data transfer. In addition, SCTP can satisfy the bandwidth requirements for content-rich real-time multimedia streaming delivery, but only one primary path can be selected. Therefore, SCTP maintains the reliability of transmission but cannot transmit data in parallel paths. For this reason, SCTP may not be able to provide maximum utilization of network resources, and it barely meets the demand for efficient data delivery needed by next generation mobile communications.

Nowadays, CMT has been recognized as a promising means for improving network resource utilization. It not only supports the transmission of available paths in parallel, but

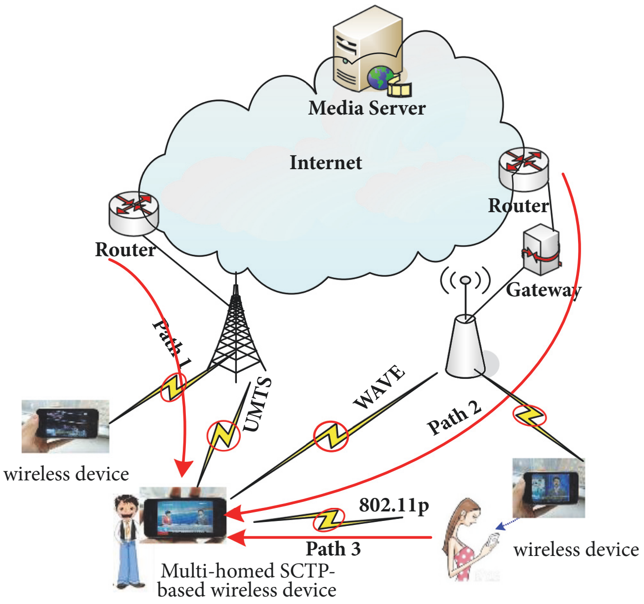

Figure 1: CMT-based multimedia streaming in heterogeneous wireless network.

also aggregates bandwidth. By applying SCTP's multihomed architecture, CMT can use heterogeneous network interfaces to transmit data among multiple paths simultaneously [8]. Figure 1 depicts a typical CMT-based heterogeneous wireless scenario for multimedia content delivery. From Figure 1, we can see that a multihoming wireless device can communicate with a media server via three paths simultaneously, illustrating how CMT supports heterogeneous wireless networks for delivery of real-time multimedia content. Consequently, CMT-based association paths can offer attractive benefits, such as end-to-end throughput, utilization of network resources, and load balancing.

However, critical issues remain to be considered regarding classic CMT because this approach primarily adopts a plain round-robin process for distributing application layer data to the multiple available paths. CMT rarely takes into consideration the quality differences of various paths in terms of quality-of-service (QoS)-related parameters. Thus, a plain round-robin distribution method inevitably results in receiver buffer blocking [9–12]. In order to reduce such blocking and achieve more reliable transmission, we try our best to ensure that the receiver will transmit ordered packets to the upper layer. Therefore, the receiver buffer must firstly store the out-of-order packet and wait for the arrival of the preamble packets (e.g., lost or delayed packets) before sending the data. Considering the characteristic of limited storage capacity, excessive place disorder packets will certainly lead to a severe buffer blocking problem. Once this happens, buffer blocking will affect the quality of the users experience, especially for content-rich streaming media.

To address the above issues, we proposed an original loss-aware packet scheduling scheme under the structure of CMT called CMT-LA. We designed CMT-LA to meet three functional goals: (1) to identify packet loss for the paths, (2) to distribute data packets across the multiple available paths adaptively according to their packet loss and loss variation, and (3) to maintain the features of bandwidth aggregation and parallel transmission of CMT while improving the throughput performance. Our research provided the following contributions to the field:

(i) The new model introduced an optimal packet loss detection algorithm to estimate the paths packet loss rate (PLR).

(ii) The proposed solution combined the PLR estimation and the jitter indicator of PLR at the transport layer to reflect the data transmission condition of the paths.

(iii) By utilizing the path-based loss-aware method, this novel, fast data distribution model improved the efficiency of data transmission and reduced packet loss differences.

In Section 2, readers can have a general understanding for currently research. Section 3 describes CMT-LA solution. In Section 4, we provide details of our simulations and an analysis, and Section 5 presents our conclusion and intentions for future work.

2. Related Work

For the transport layer, SCTP is recognized to be more reliable than most other transport protocols, which breaks TCPs limitations while retaining the advantages of the User Datagram Protocol (UDP). Nevertheless, unlike TCP and UDP, SCTP is equipped with two capacities, multihoming and multistreaming, that help to increase availability [13]. Liu et al. [9] developed a comprehensive retrospective view of SCTP and then discussed three aspects of the protocol: managing switching with an integrated approach, multipath transmission in a concurrent way, and cross-activity between layers. Baharudin et al. [14] presented a novel path selection solution based on ant colony optimization aimed at enhancing the efficiency of SCTPs selection of a primary path. Dreibholz et al. [15] provided an overview of SCTP and its extensions and then focused on the continuous SCTP standardization procedure.

While CMT is viewed as a promising means for enhancing the efficiency of data transmission, research has sought further improvements. Iyengar et al. [16] described three negative side effects of CMT and introduced three algorithms to avoid these side effects effectively. In addition, their paper proposed and estimated five retransmission policies for CMT. Yang et al. [17] introduced the limitations for throughput of CMT: receiving buffer size and the longest round trip time (RTT) in all transmission paths. The authors established a CMTs throughput model to analyze the selection of different paths via it and then applied the analysis results to selection strategy on the basis of available paths. Therefore, the throughput of the CMT has improved. Each of the above solutions is different in terms of data handling capabilities. However, all of the solutions continued to adopt the round-robin policy for transmitting data over all available paths.

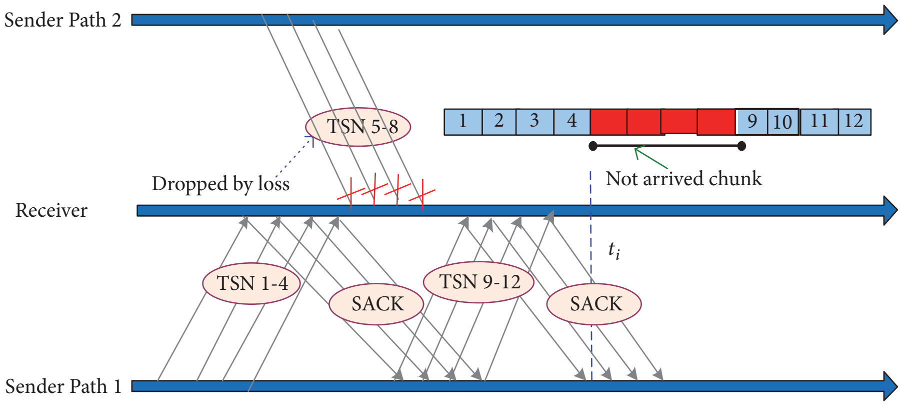

Figure 2: The delayed delivery occurred because of packet loss.

Recently, a growing volume of research has been directed toward applying the CMT technique for multimedia data delivery. Xu et al. [18] sought to improve the performance of real-time multimedia data distribution by adopting multihoming SCTP while making use of different Single Path Transfer (SPT) and CMT mechanisms separately. Within a certain loss range, Baek et al. [19] presented a multicast protocol based on improved SCTP. Its main purpose is to achieve partial reliability, reduce the message overhead dramatically, and tolerate partial loss. Huang et al. [20] attempted to conjunct with various techniques, including a prioritized stream, to provide services for multimedia streaming. Therefore, PR-CMT was produced on the basis of CMT with the characteristic of new and partial reliability. However, in general, the existing research failed to consider that path diversity is bound to data reordering, which severely affects CMT performance.

In recent years, many researchers have attempted to employ a cross-layer concept to solve some of the problems that may result from CMT [21–25]. Cao et al. [21] presented an innovative cross-layer QoS-aware adaptive CMT (CMT-CQA) to satisfy three requirements: identification of wireless errors, mitigation of buffer blocking problems, and efficient bandwidth aggregation. CMT-CQA was able to aggregate bandwidth by considering multiple factors, depict a suitable multimedia delivery strategy, and take on a reinforced fast recovery scheme. Xu et al. [23] designed an optimal solution for monitoring and analyzing the quality of paths. This method cleverly utilizes the concept of cross-layer based on SCTP and the fairness driving characteristics based on CMT, which improves the users experience of multimedia streaming services while maintaining fairness of competing TCP flows.

In addition, many researchers have been paying attention to CMT-based data reordering problems. Xu et al. [26] took Network Coding (NC) ideas to improve the performance of SCTP-based CMT and thus introduced an enhanced version of multipath concurrent transmission scheme, aiming to avoid data reordering and alleviate buffer blocking. Cao et al. [27] designed an adaptive receiver-cooperative path aggregation model to reduce data rearrangement and prevent buffer blocking. However, the above work did not consider the high-loss situation which suddenly lost packets in actual networks. Undoubtedly, if the losses occurred and CMT cannot recognize them, there is no good throughput performance.

In this paper, we have attempted to fill the gap by developing CMT-LA, an approach that includes a proper packet loss detection module along with a novel loss-aware packet scheduler to ensure that the SCTP packets arrive in order.

3. The CMT-LA Solution

Asymmetric paths with multihomed communications may suffer from disparate undesirable characteristics including packet loss rates, delays, round trip times, and bandwidth. These conditions may lead to out-of-order data and degraded data delivery. In addition, the packet loss rate is generally the most important feature of a transmission path considered when CMT utilizes all available paths to send data in parallel. To provide a better understanding of blocked data transmission in heterogeneous wireless networks, Figure 2 provides a representation of how delayed delivery occurs as a result of packet loss.

We record transmission sequence number transmitted by the sender as TSNs. It can be seen from Figure 2 that Path 1 has TSNs 1-4 and 9-12, and the transmitted sequence in Path 2 is TSNs 5-8. Due to differences in path quality loss, the packets of TSNs 5-8 at Path 2 that cannot arrive at time t_i will be dropped. While groups for TSNs 1-4 and 9-12 can get it before time t_i, so it is necessary to place them in the receiver buffer for reordering. However, the out-of-order packets will not be submitted because of the reliability of CMT. In this way, packet loss leads to out-of-order data problems and eventually degrades the overall performance.

To alleviate the differences of packet loss and improve the efficiency of data delivery, we extended our $R_{tx^+}+$ solution to propose CMT-LA, a packet loss detection and packet scheduling solution. This approach aimed to identify the packet loss of the various paths and then distribute data packets adaptively across multiple available paths according to their packet loss. CMT-LA can be associated with existing CMT solutions.

By using the Mathis model [21], the goodput of path P_i, which is denoted as G_{P_i}, can be calculated by

$$G_{P_i} = \frac{M}{RTT_{P_i} \times \sqrt{PLR_{P_i}}}, \tag{1}$$

where PLR_{P_i} denotes the packet loss rate of path P_i. RTT_{P_i} is path P_i's RTT, which can be calculated as

$$\begin{aligned} RTT_{P_i} &= \omega \times RTT_{P_i} + (1-\omega) \times \Phi_{P_i}, \\ \Phi_{P_i} &= t - T_{send} - \Delta T \end{aligned} \tag{2}$$

where RTT_{P_i} presents the current RTT value of path P_i. T_{send} is a timestamp to record the transmit time, while the timestamp t is the time when receiver sends Selective Acknowledgment (SACK) chunk to the sender. ω stands for the weighting parameter and its value is set to 7/8 by default according to [27]. ΔT represents time interval at which the receiver processes each packet. Meanwhile, we can estimate the PLR_{P_i} value from (1), so PLR_{P_i} can be obtained as shown:

$$PLR_{P_i} = \left(\frac{M}{G_{P_i} \times RTT_{P_i}} \right)^2, \tag{3}$$

where M uses the constant value $1.22 \times DCS$ by default, and DCS is set to 1,500 MTUs (maximum transmission units) in the simulations, i.e., $M = 1.22 \times 1500 = 1830$.

Further, Bisoy et al. [28] proposed the Vegas model to calculate the goodput of path P_i; namely, the value of G_{P_i}, introduced into (3), can be obtained as follows:

$$G_{P_i} = \frac{cwnd_{P_i}}{RTT_{P_i}^{min}}, \tag{4}$$

where $RTT_{P_i}^{min}$ is the minimum value in all paths RTT to decrease dispersive expense. $cwnd_{P_i}$ denotes the congestion window size of path P_i.

So far, the PLR_{P_i} of each path can be estimated by using (2), (3), and (4). However, the PLR_{P_i} cannot reflect the transmission condition for path P_i objectively. To address this issue, we can use ΔPLR_{P_i}, which represents the jitter indicator of PLR_{P_i}, to identify whether path P_i is in an unreliable transmission condition. ΔPLR_{P_i} can be expressed as

$$\Delta PLR_{P_i} = \frac{PLR_{P_i} - \overline{PLR_{P_i}^{avg}}}{PLR_{P_i}^{max} - PLR_{P_i}^{min}}, \tag{5}$$

where PLR_{P_i} is the current calculated PLR on P_i, and the $\overline{PLR_{P_i}^{avg}}$ value can be obtained by

$$\overline{PLR_{P_i}^{avg}} = \frac{1}{k} \times \sum_{n=1}^{k} PLR_{P_i}^{n}. \tag{6}$$

```
Definition:
$P_i$: the $i^{th}$ path within the SCTP association.
$PLR_{Pi}$: the estimated packet loss rate of path $P_i$
for all path $P_i$ within the SCTP association do
    if status of $P_i$ == ACTIVE then
        calculated $PLR_{Pi}$ by Eq. (2)
        calculated $\Delta PLR_{Pi}$ by Eq. (5)
        put $P_i$ into $P_{list}$
    end if
end for
```

Algorithm 1

Assuming the measured PLR values on P_i are $\{PLR_{P_i}^1, PLR_{P_i}^2, \ldots, PLR_{P_i}^k\}$, then $PLR_{P_i}^{max}$ and $PLR_{P_i}^{min}$ can be acquired as shown

$$\begin{aligned} PLR_{P_i}^{max} &= \max\left\{PLR_{P_i}^1, PLR_{P_i}^2, \ldots, PLR_{P_i}^k\right\} \\ PLR_{P_i}^{min} &= \min\left\{PLR_{P_i}^1, PLR_{P_i}^2, \ldots, PLR_{P_i}^k\right\}. \end{aligned} \tag{7}$$

As mentioned previously, ΔPLR_{P_i} can reflect the transmission condition for path P_i. Therefore, we determine that P_i is in an unreliable transmission condition if ΔPLR_{P_i} and $(\Delta PLR_{P_i})_{t_n} - (\Delta PLR_{P_i})_{t_{n-1}} > 0$ (where t_n and t_{n-1} are the observed time, and $t_n > t_{n-1}$). In other words, when $\Delta PLR_{P_i} > 0$, the increase of ΔPLR_{P_i} indicates that P_i is in an unreliable transmission condition. This detection method for packet loss is described in detail in Algorithm 1, which shows the pseudocode for the CMT-LA method. Finally, we can identify packet loss for the paths and distribute data packets adaptively according to the PLR and ΔPLR values, which also meets the goals of CMT-LA.

Algorithm 1 is one part of CMT-LA method and its pseudocode shows how we estimate the PLR and ΔPLR value of each path in the SCTP association.

As discussed above, the classic CMT adopts a plain round-robin method for data distribution on the multiple transmission paths within a multihomed SCTP association.

However, this approach seldom considers highly dissimilar path characteristics over a heterogeneous wireless network. For this reason, using the plain round-robin method may result in disorder packets and blocking the receiver buffer. Inspired by the fact that the number of sending packets is related mainly to the PLR value, we designed an optimal CMT-LA data distribution algorithm that includes the following steps.

(1) Use Algorithm 1 to estimate the PLR and ΔPLR values of all available paths for the ACTIVE state in the SCTP association.

(2) Arrange paths P_{list} in ascending order according to the corresponding PLR value.

(3) Choose the first path ($P_{list(0)}$) in P_{list} as the candidate path (P_{send}) for packets transmission.

(4) If two or more paths have the smallest P_{send}, select the path with the smallest ΔPLR as the P_{send}.

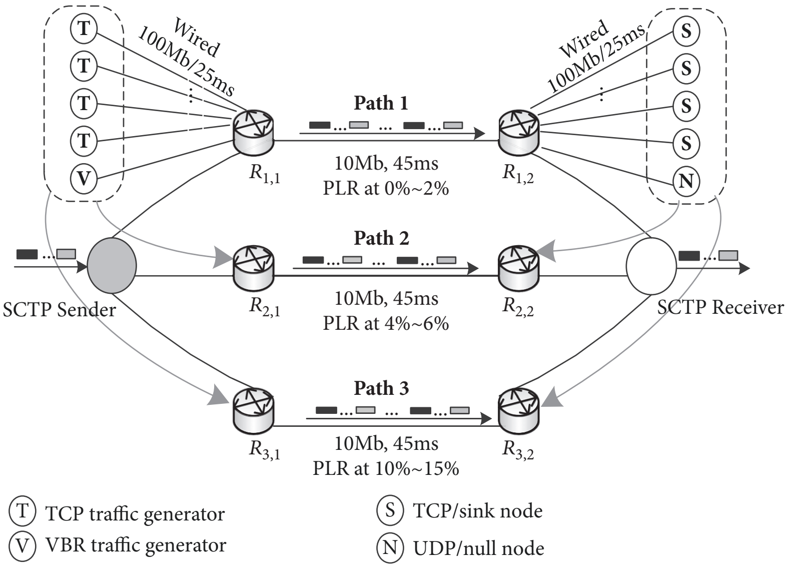

FIGURE 3: Simulation topology.

(5) Select the next path in P_{list} as the P_{send}, if the path cwnd is full.

The CMT-LA data distribution algorithm greatly improves data delivery throughput and realizes load balancing as well. A detailed description of the pseudocode for the CMT-LA data distribution method is given in Algorithm 2.

4. Simulations and Analysis

4.1. Simulation Steps. To evaluate CMT-LA, all simulation experiments were performed in Network Simulator version 3 (NS-3) [29]. In this paper the topology of the simulation experiment is mainly composed of four parts, namely, SCTP sender, receiver, terminals, and multiple transmission paths, as in Figure 3, but it just takes three transmission paths (Paths 1, 2, and 3) as examples to connect two terminals, respectively. The PLR of Path 1 took a varied value from 0% to 2%, the PLR of Path 2 changed from 4% to 6%, and the PLR of Path 3 ranged from 10% to 15%. We used 64KB as the default receive buffer (rbuf). As for the other SCTP parameters, we merely used the default value supplied by NS-3. In addition, we set 120 seconds as the total simulation time.

For the purpose of reflecting the advantages of CMT-LA, we injected background traffic to simulate a complex Internet environment. We would add four TCP generators to each router when a UDP generator is added in it, so about one-fifth of the total traffic generated by each path is UDP traffic, and four-fifths is TCP. All traffic generators (FTP/TCP and VBR/UDP) connected to routers ($R_{1,1}, R_{2,1}$ and $R_{3,1}$) were configured with 100Mb bandwidth and 25 ms propagation delay. For the sake of reasonable consumption of bandwidth, we set 1 Mbps as the transmission rate for VBR traffic, whereas the FTP used the system value supplied by NS-3.

```
Definition:
$P_i$: the $i^{th}$ path within the SCTP association.
$PLR_{P_i}$: the estimated packet loss rate value of path $P_i$
set $PLR_{P_j} = PLR_{P_{list(0)}}$;
for ($i = 1; i <= count(P_{list}); i++$) do
    sort $P_i$ in an ascending order
    if ($PLR_{P_j} > PLR_{P_{list(i)}}$) then
        set $j = i$
        set $PLR_{P_j} = PLR_{P_{list(i)}}$;
    end if
end for
if $!((P_k \in P_{list})$ && $(PLR_{P_k} = PLR_{P_j})$ && $(k \neq j))$ then
    set $P_{send} = P_j$;
else if ($\Delta PLR_{P_k} > \Delta PLR_{P_j}$)
    $P_{send} = P_k$
end if
while cwnd of $P_{send}$ is full do
    set $P_{send} = P_{send} \longrightarrow$ next;
end while
```

ALGORITHM 2

4.2. Simulation Results

4.2.1. Packet Sending and Receiving Times. Figure 4 depicts the sending and receiving times of several packets when taking advantage of classic CMT and CMT-LA, respectively. The results for time t from 0 to 120s are to make a better comparison. We can see that CMT-LA tends to send and receive TSNs better than classic CMT. The reason is that the loss difference among multiple paths is ignored when CMT delivers data within SCTP association. Such a loss-blind data scheduler leads the path to lose a larger volume of data chunks

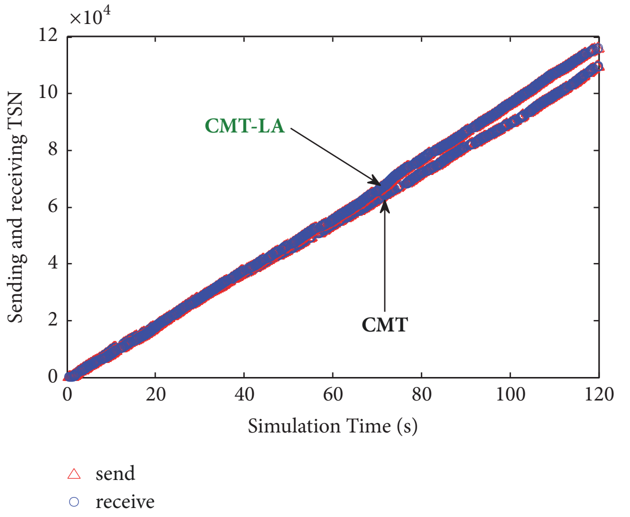

FIGURE 4: Comparison results in terms of sending and receiving time of packets (rbuf=64KB).

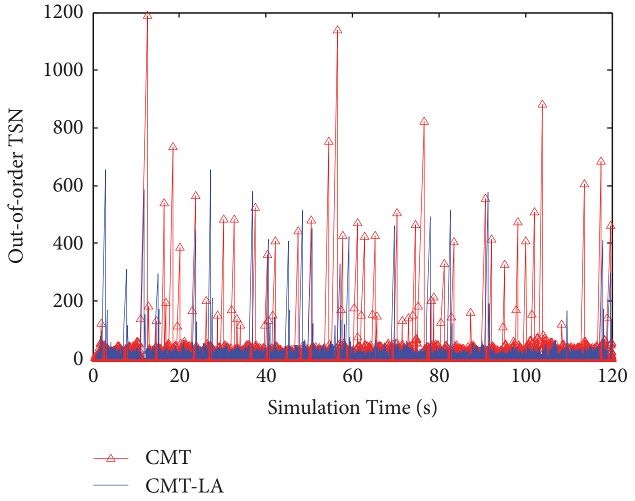

FIGURE 5: Comparison of disorder TSN (rbuf=64KB).

and possibly even fail. Failure to complete the data chunk may hinder the new data transfer work of the SCTP sender.

Conversely, in the SCTP association, CMT-LA can (a) accurately and timely recognize the loss conditions for each path, supported by its pass loss detection module, and (b) split SCTP packets over the paths according to their measured loss condition. Thereby, CMT-LA outperformed classic CMT.

4.2.2. Out-of-Order Packets. The disorder TSN metric is able to convey packet transport traits of CMT-based through multiple connection heterogeneous networks. Before using a disorder TSN metric, you must first acquire the currently and recently received data chunks of TSN. Next, we can calculate the difference using two data chunks received consecutively to get our desired metric. In our experiment, we applied the disorder TSN metric to compare the pros and cons of classic CMT and CMT-LA. Figure 5 presents the comparative results in terms of out-of-order TSNs for each method. The results of time t changing from 0 to 120s are presented to create a better comparison. As Figure 5 shows, classic CMT tended to produce more disorder data chunks and sorting again in increasing numbers when compared with CMT-LA. Additionally, it can also be observed that peak of TSN value at the SCTP receiver was about 1,200 when adopting classic CMT, but less than 700 when utilizing the CMT-LA method.

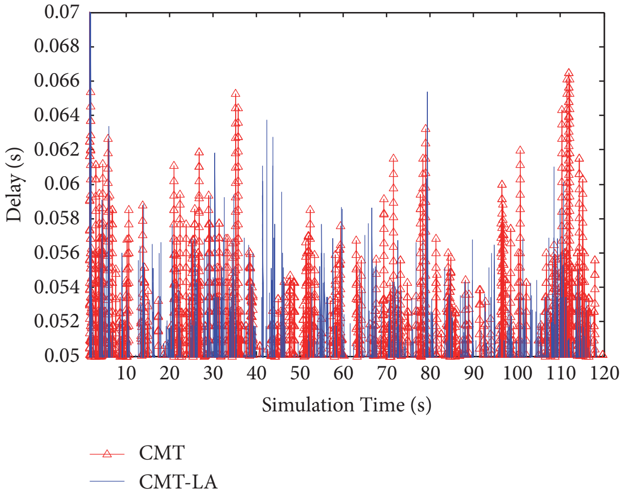

FIGURE 6: Comparison of end-to-end delay (rbuf=64KB).

4.2.3. End-to-End Delay. Figure 6 indicates the performance comparison of classic CMT and CMT-LA when it comes to the end-to-end (e2e) delay. The simulations demonstrated that CMT-LA could lower loss rate, as well as ameliorating the e2e delay when packets were assigned to a different path. This finding results from CMT-LA being equipped with a loss-aware data scheduling strategy that fully takes into account the loss differences on all available paths. In comparison with classic CMT, CMT-LA obtained better e2e delay performance. In addition, the results showed that the average e2e delay of CMT-LA and classic CMT was about 0.048 seconds and 0.051 seconds, respectively. Therefore, CMT-LA attained an advantage of 5.88% over classic CMT with respect to average e2e delay.

4.2.4. Average Throughput. We considered that the rbuf size varied between 32KB, 64KB, and 128KB in order to compare average throughput in the process of sending data chunks. The comparative results are shown in Figures 7, 8, and 9, respectively. Because of its path loss detection module and loss-aware packet scheduler, CMT-LA was able to assign as many SCTP packets as possible over the paths with low loss rates. As can be seen in Figures 7, 8, and 9, the average throughput increased as the rbuf size increased. Specifically, when 32KB, 64KB, and 128KB were used as the rbuf sizes, the CMT-LA throughput was, respectively, 14.0%, 28.4%, and 13.8% higher than the throughput of classic CMT. These results showed that CMT-LA had the ability to decrease the possibility of packet loss while enhancing the goodput.

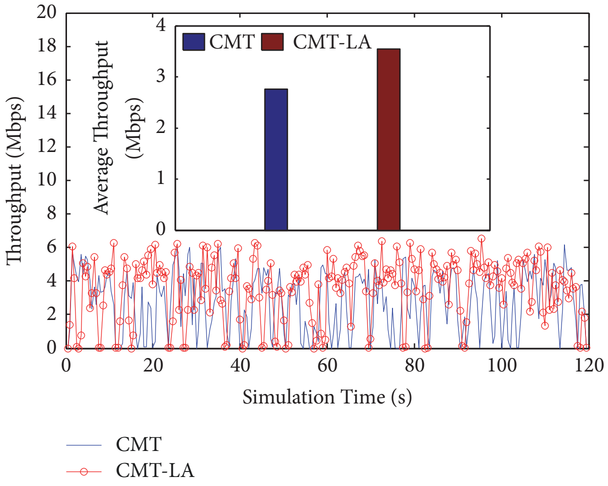

FIGURE 7: Comparison of average throughput (rbuf=64KB).

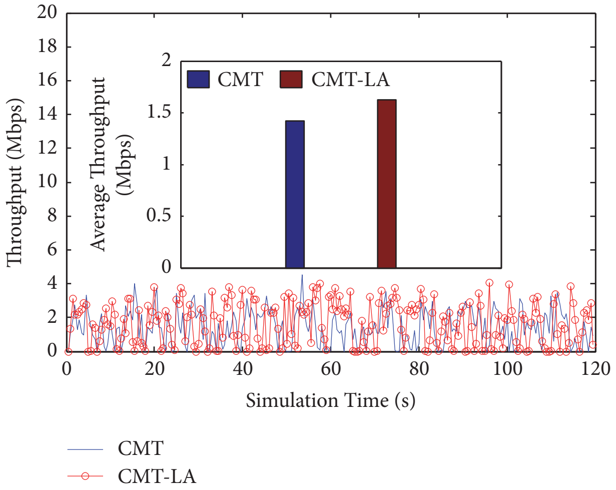

FIGURE 8: Comparison of average throughput (rbuf=32KB).

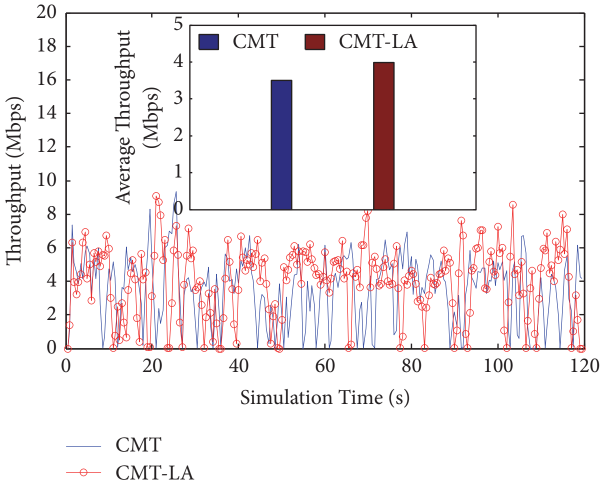

FIGURE 9: Comparison of average throughput (rbuf=128KB).

5. Conclusion and Future Work

This paper presents CMT-LA, a new loss-aware packet scheduling solution for CMT. CMT-LA makes full use of paths packet loss and the loss variation in order to distribute data packets across the multiple available paths adaptively. Experiments in the simulator show that CMT-LA provides better performance than classic CMT, including improved average throughput, reduced e2e latency, and lowered the amount of disorder data reception.

CMT-LA provides a novel data distribution model to improve the efficiency of data delivery and reduce data packet loss differences by utilizing the path-based loss-aware method. However, the complexity of deploying CMT-LA in the transport networks has led us to further research. Therefore, our future work will concentrate on deploying CMT-LA in real-world systems and satisfying the high-bandwidth requirements and latency zero tolerance for multimedia applications.

Data Availability

The research data can be got from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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