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Multimedia streaming using partially reliable concurrent multipath transfer for multihomed networks

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Abstract: The authors propose a partially reliable-concurrent multipath transfer (PR-CMT) protocol for multimedia streaming. The novelty of PR-CMT is to combine techniques of CMT's concurrent multipath transfer, PR-SCTP's partially reliable transmission and prioritised stream transmission. Moving picture experts group (MPEG) frames are with varying priorities and lifetime. PR-CMT can transmit important frames before other frames but does not transmit lifetime expired frames. The combination of the aforementioned techniques, however, causes imprecise congestion window and receiver buffer blocking problems without suitable control. Consequently, the throughput and video quality degrade. PR-CMT adopts the concept of delay abandoning data to resolve the imprecise cwnd and the receiver buffer blocking problems. The simulation results show that PR-CMT can precisely infer cwnd. Most importantly, PR-CMT can prevent large gaps between two playable frames to have good video quality.

1 Introduction

Consumers are becoming accustomed to accessing media such as video, movies, TV shows and music via the Internet. Multimedia streaming technology plays an important role in these changes. The properties of multimedia streaming applications are increased bandwidth requirements and data with varying priorities and time constraints. Important data must be transmitted before other data. If data do not arrive at the receiver before the playout time (lifetime), then they become unplayable. Current MPEG streaming technologies employ three frames in the MPEG encoding scheme: intra-VOP (I), predicted (P), and bidirectional interpolated (B) frames [1]. The I frames are encoded independently, P frames are encoded from preceding I or P frames, and B frames are encoded from preceding and succeeding I or P frames [2]. The I, P and B frames form a pattern called group of pictures (GOP). Typically, an MPEG stream is constructed by repeating the GOP. The I frames are the first frames of a GOP, and B frames appear between I and P frames. Without I frames, the entire GOP is unplayable. Without P frames, the succeeding P and B frames are unplayable. Thus, the relative importance of I, P and B frames can be expressed as importance of I > importance of P > importance of B.

Fig. 1 shows a multihomed network, which a computing device connects to the Internet via more than one interface. The newly proposed transport layer protocol, stream control transmission protocol (SCTP), which supports multihoming and multistreaming, provides robust data transmission and identifies data in different streams. Since multimedia streaming applications consume more bandwidth, it is important to utilise all available paths for data transmission in multihomed networks. However, SCTP does not exhaust the capabilities of the multihomed technology, because SCTP uses only one path for data transmission and leaves other paths for retransmission [3]. Concurrent multipath transfer (CMT) employs the multihoming technology to transfer data over all available network interfaces and paths based on SCTP [4, 5]. The total useful bandwidth of CMT exceeds that of SCTP. Thus, CMT is superior to SCTP for multimedia streaming applications.

Although CMT achieves better throughput than SCTP does, CMT still has some limitations in multimedia streaming. As mentioned above, multimedia streaming data are with varying priorities and time constraints. For priorities consideration, I frames must be transmitted before P and B frames. CMT must support prioritised stream transmission, that is, I, P and B frames must be separated into different streams with different priorities. Thus, the high-priority I and P frames can be transferred before the low-priority B frames. Regarding time-constrained data, if data do not arrive at the receiver before the given lifetimes, they are unplayable [6, 7]. Reliable transmission is not necessary for streaming data. The SCTP and CMT transmission modes are reliable, that is, lost data will be retransmitted. The original SCTP essentially does not support the partially reliable data transmission mode. Thus, SCTP partial reliability extension (PR-SCTP) was proposed for real-time applications [8]. PR-SCTP enables applications to indicate the reliability level for data based on their lifetimes. PR-SCTP does not transmit or retransmit expired data.

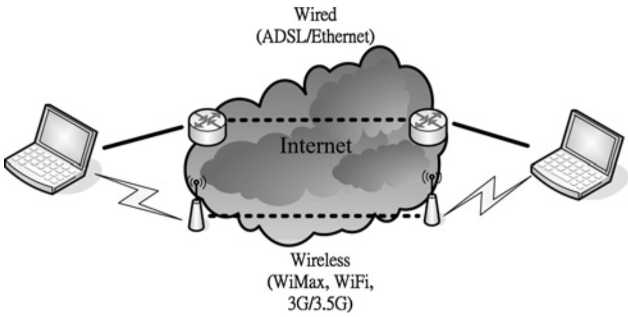

Fig. 1 *Multihomed network environment*

To enhance the support of multimedia streaming applications in the transport layer, this study proposes the partially reliable-concurrent multipath transfer (PR-CMT) protocol. The novel feature of PR-CMT is combing techniques of CMT, partially reliable transmission and prioritised stream transmission.

PR-CMT is more suitable than other protocols for multimedia streaming. PR-CMT improves throughput by transmitting data over all available paths. A 'timed reliable service' concept based on that of PR-SCTP was adopted in PR-CMT. Lifetime-expired frames are abandoned and are not transmitted. Each stream in PR-CMT is associated with different priorities. PR-CMT can prioritise multimedia streaming data. Transmitting high-priority streams before low-priority streams prevents the transmission of I and P frames from being blocked by the succeeding frames. The coding dependency of I, P and B frames can be preserved.

Several problems arise when combining the aforementioned three techniques. Overly conservative cwnd growth and falsely acknowledged transmission sequence number (TSN) occurs when applying the partially reliable transmission of PR-SCTP. The growth of cwnd in PR-SCTP is overly conservative. Data are abandoned when their lifetimes expire. The transmitted but abandoned data cannot be credited for cwnd. PR-SCTP cannot tell whether lifetime-expired data are received by the receiver or not. Consequently, the cwnd cannot be precisely inferred.

A frame that exceeds the maximum transmission unit (MTU) is divided into multiple data chunks. The CMT receiver may discard the whole frame owing to the late arrival of certain data chunks. Such discard is unnecessary. The receiver still can use the lifetime-expired frame, which may be the important I frame, to decode the other frames. Moreover, the abandoned data are considered as loss. The receiver buffer could be blocked if the receiver does not receive the notification of the abandonment of data.

The rest of the paper is organised as follows: In Section 2, the related works on PR-CMT are presented. In Section 3, the main issues of the partially reliable transmission and prioritised stream transmission are discussed. In Section 4, the related concepts and techniques of the PR-CMT protocol are presented. In Section 5, the transmission behaviour of PR-CMT is analysed. In Section 6, PR-CMT is evaluated and investigated in comparisons with several other transport protocols. Finally, concluding remarks are presented in Section 7.

2 Related works

Many researchers focus on adapting existing transport layer protocols for multimedia streaming in wireless network. Lee *et al.* [9] proposed a TCP-friendly congestion control based on differentiation of packet losses owing to congestion and wireless link error. Chou *et al.* [10] proposed a multicast-based redundant streaming architecture to overcome the vertical handoffs for the time-sensitive streaming media services. Jammeh *et al.* [11] proposed a closed-loop congestion controller, which dynamically adapts the bitstream output of a transcoder or video encoder to a rate less likely to lead to packet loss. Recently, more and more researchers turn their eyes on the promising transport layer protocol, SCTP, for multimedia streaming.

SCTP is a transport layer protocol that supports multihoming and multistreaming [12]. SCTP transmits data via the primary path and retransmits data via other secondary or retransmission paths. Although SCTP supports multihoming, it does not utilise all paths for data transmission. Several researchers have developed transport layer protocols that use all paths for data transmission concurrently [4, 13–15]. Iyengar *et al.* [16, 17] proposed the CMT, which uses SCTP multihoming over independent end-to-end paths. They identified the sender-induced reordering issue, which results from path diversity and can greatly impact performance when transmitting data over all paths. By applying the proposed algorithms to reduce the sender-introduced reordering, CMT performs better than SCTP does. Qiao *et al.* [18] studied the performance of multihomed transport protocols tolerant of network failure. They found that retransmission of all data on the same path with the path failure detection threshold set to one or zero gives the most stable performance in all path configurations. Since SCTP and CMT are reliable transport protocols, neither is suitable for real-time data transmission.

Thus, PR-SCTP was proposed to provide data transmission between reliable transmission and unreliable transmission. However, PR-SCTP introduces overly conservative cwnd growth and falsely acknowledged TSN issues. Molteni and Villari [19] used PR-SCTP for multimedia streaming. However, that study did not examine overly conservative cwnd growth and falsely acknowledged TSN issues. Dermi and Elshikh developed an SCTP-friendly rate control for MPEG-4 video that adjusts transmission of I, P and B frames according to network congestion status [20]. The partially reliable transmission feature was not used. Thus, the proposed method would transmit expired frames.

Xu *et al.* [21] evaluated the performance of distributing real-time video using CMT and PR-SCTP with different retransmission polices. The evaluation results showed that the combination of CMT and PR-SCTP can improve the PSNR and the dropped frame rate. The imprecise cwnd and receiver buffer blocking issues, however, were not discussed. Aydin and Shen [22] evaluated CMT in multihop wireless network. They suggested that the retransmission of packets should be made on the path with highest cwnd and SSTHRESH.

On the other hand, SCTP does not prioritise streams. Several researchers have attempted to improve the quality of service (QoS) of SCTP for multistreaming. Heinz II [23] proposed prioritised stream transmission for SCTP. The evaluation results showed that the transmission of high-priority data would be unaffected by suddenly applied large amount of low-priority data. Zou *et al.* [24] proposed a method of grouping streams into subflows and using independent congestion control parameters to avoid the false sharing problem. Subflows are given different priorities. The methods proposed in the above studies outperform SCTP.

The novelty of PR-CMT is that PR-CMT resolves imprecise cwnd and falsely acknowledged TSN issues

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while combing CMT and PR-SCTP. PR-CMT with prioritised stream transmission is more suitable for multimedia streaming.

3 Main issues

The concept of PR-CMT is combining techniques of CMT, partially reliable transmission and prioritised stream transmission. This section discusses related problems that may occur when PR-SCTP is combined with CMT for multimedia streaming.

3.1 Issues in PR-SCTP

Although PR-SCTP provides partially reliable transmission for the multimedia streaming data, PR-SCTP throughput may be compromised in some cases. Application data have a limited lifetime. Before the lifetimes of data expire, data are considered reliable, that is, they can be transmitted and retransmitted. When lifetimes expire, data are abandoned and cannot be transmitted and retransmitted. The PR-SCTP sender must send the FORWARD TSN chunk to advance the cumulative TSN of the receiver for the expired data that are already assigned TSNs. Otherwise, the receiver would wait for the abandoned data forever. However, two issues associated with PR-SCTP are overly conservative cwnd growth and falsely acknowledged TSN.

3.1.1 Overly conservative congestion window growth: PR-SCTP states that the abandoned data cannot be credited for cwnd. In the example depicted in Fig. 2, the sender sends data chunks with TSNs 1, 2, 3 and 4 to the receiver, and the lifetimes of data chunks with TSNs 1 and 2 expire after transmission. Although the receiver receives data chunks with TSNs 1 and 2, and acknowledges TSNs 1 and 2 in the selective acknowledgement (SACK), TSNs 1 and 2 cannot be credited for cwnd. This causes overly conservative cwnd growth. Therefore PR-SCTP throughput is degraded.

The purpose of the FORWARD TSN is to prevent the receiver waiting for the abandoned data chunk, which is lost. However, if the abandoned data are not lost, the sending for FORWARD TSN is unnecessary. PR-SCTP marks data as abandoned at inappropriate time. It is the main reason that overly conservative cwd growth and falsely acknowledged TSN occur. Although PR-SCTP allows the PR-SCTP implementation to delay the FORWARD TSN for the efficiency concern, the abandoned data still cannot be credited for the cwnd.

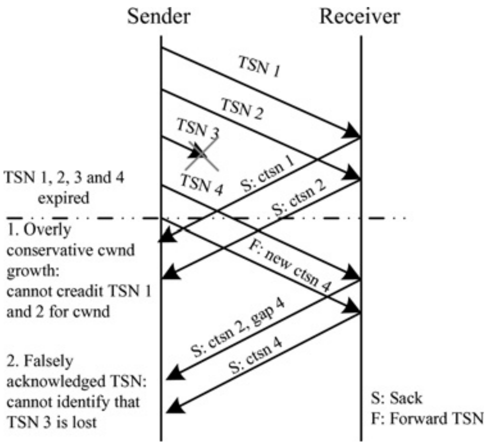

Fig. 2 *Overly conservative cwnd growth and falsely acknowledged TSN issues for PR-SCTP*

3.1.2 Falsely acknowledged TSN: Fig. 2 shows that TSN 3 is lost during transmission. After the lifetimes of TSNs 3 and 4 expire, the sender sends the FORWARD TSN chunk with the new cumulative TSN 4 to the receiver. However, when the sender receives SACK with the new cumulative TSN 4, the sender cannot infer that TSN 3 is lost during transmission. Therefore the sender cannot precisely infer lost packets. The corresponding action for packet loss would not be taken, for example, half the cwnd.

The overly conservative cwnd growth decreases cwnd, and the falsely acknowledged TSN increases cwnd. It seems that the combination of these two does not to have serious impacts. However, the concern is that the cwnd of PR-SCTP cannot reflect the actual cwnd as that in SCTP. The inference of cwnd in PR-SCTP is not as precise as SCTP. The overly conservative congestion window growth and falsely acknowledged TSN may not occur at the same time. If the network condition is not allowed to transmit all the data from the upper layer, lots of data would be abandoned. Data are transmitted before their lifetime but cannot be acknowledged. As a result, the growth of cwnd is limited and cannot reflect the network condition precisely.

3.2 Multimedia streaming in CMT

3.2.1 Unnecessary discarding data: In PR-SCTP, the FORWARD TSN is transmitted after data are abandoned. When applying partially reliable transmission to CMT, several problems occur. Consider the following situation. Let the Path1 have less end-to-end delay than Path2 have. An I frame message is divided into data chunks of TSN 1–4. The data chunks with TSN 1–3 are transmitted over Path1 and acknowledged. After transmitting the data chunk with TSN 4 over Path2, the data chunk is expired. Thus, the sender abandons the data chunks with TSN 1–4 and sends the FORWARD TSN with the new cumulative TSN 4 to the receiver. The receiver only receives an incomplete message of an I frame, for example, data chunks with TSN 1–3.

On the other hand, when the receiver receives the FORWARD TSN for the abandoned data, it must skip the abandoned data chunk. If the abandoned data chunk belongs to a message, the other received data chunks of the same message must be discarded. When the receiver receives the FORWARD TSN, it would discard the data chunks with TSN 1–3. The message is incomplete now. Consequently, the upper layer cannot receive a complete message from the transport layer. Owing to the path diversity, the receiver may receive the abandoned data after the FORWARD TSN is received. Even though the receiver receives the abandoned data later, the upper layer is unable to receive a complete message. The transport layer has discarded the data chunks in the incomplete message.

Since the abandoned data chunk is part of an I frame, the whole I frame and other received P or B frames in the same GOP become useless. Even though the abandoned I frame cannot be played, it still can be used for decoding. Abandoning a data chunk may only cause a small degradation on throughput. However, it may also cause the entire GOP become useless. Even though the abandoned data chunk indeed arrives at the receiver later, the transport layer cannot deliver to the complete message to the upper layer. Besides the overly conservative congestion window growth and falsely acknowledged TSN issues, partially reliable transmission in CMT causes the unnecessary discarding data problem.

3.2.2 Receiver buffer blocking owing to abandoned data: Another issue is the receiver buffer blocking caused by the abandoned data. If the abandoned data are lost, the sender must send the FORWARD TSN to the receiver to skip the abandoned data. However, data must be delivered from the transport layer to the upper layer in sequence. If data are lost, the transport layer cannot deliver data to the upper layer in sequence. As a result, the receiver buffer blocking occurs. If the FORWARD TSN is transmitted over a path with high end-to-end delay, then the receiver buffer blocking cannot be released quickly.

3.2.3 Prioritised stream transmission: On the other hand, CMT features with multistreaming. Application data can be assigned to different streams. For example, I, P and B frames can be assigned to different streams, respectively. The delivery order can be maintained in each steam. As a result, CMT can reduce the effect of head-of-line blocking. CMT treats all streams equally. All streams have equal transmission priority. If bandwidth is insufficient, the transmission of I frames is delayed by P and B frames. In the worst case, I frames are abandoned. The abandoned I frames make the frames received in the same GOP be useless.

4 Partially reliable-concurrent multipath transfer

This section introduces and the concept and the implementation of PR-CMT.

4.1 Overview

PR-CMT is based on CMT and PR-SCTP. It provides a timed reliable service for applications to indicate the reliability level of the application data in terms of lifetime. PR-CMT throughput is maximised by transmitting data over all paths in a single association. On the other hand, PR-CMT adopts prioritised stream transmission to guarantee the QoS on a per stream basis.

Fig. 3 depicts the implementation architecture of PR-CMT. The PR-CMT architecture includes a prioritised stream scheduler (PSS) and a scheduler. The data in PR-CMT are associated with lifetimes. Streams in PR-CMT have different priorities. The PSS is responsible for inserting the application data for different streams to the application data queue according to the stream priority. The scheduler is responsible for generating and inserting data from the application data queue to the sending queue, and abandoning expired data. The following subsections describe partially reliable transmission, CMT and prioritised stream transmission.

4.2 Partially reliable transmission

The data transmission rules are essentially the same in PR-CMT and PR-SCTP. To resolve the issues of overly conservative cwnd growth and falsely acknowledged TSN, the concept of the delayed data abandonment is proposed. The delayed data abandonment is based on the concept of our previous work [25]. Fig. 4 shows the way that PR-CMT handles the expired data.

Before the lifetime of data expires, data can be transmitted and retransmitted. After the lifetime of data expires, PR-SCTP and PR-CMT handle expired data in different ways. PR-SCTP marks the expired data as abandoned and acknowledged. Therefore the expired data cannot be credited for cwnd. The FORWARD TSN chunk is generated and sent to the receiver.

PR-CMT delays abandoning data. PR-CMT marks the expired data as expired. The expired data are treated as non-acknowledged and can be credited for cwnd. However, if the expired data are lost, PR-CMT functions like PR-SCTP and marks expired data as abandoned. The FORWARD TSN chunk is generated and sent to the receiver.

PR-CMT delays abandoning data until data are lost. If expired data are not lost and acknowledged later, they can be credited for cwnd. Consequently, PR-CMT can precisely infer cwnd than PR-SCTP does. If the expired data are lost, PR-CMT can detect the loss of data through the fast retransmission event or timeout retransmission event. Thus, the falsely acknowledged TSN problem is reduced in PR-CMT. Since PR-CMT delays abandoning data until data are lost, the sending frequency of the FORWARD TSN chunk is low.

Fig. 5 shows the steps for handling lifetime-expired data. Let the lifetime-expired data chunk be with TSN t. When the lifetime-expired event occurs, the state of TSN t is changed to EXPIRED. When a retransmission event occurs on the data chunk with TSN t whose state is equal to EXPIRED, then the state and the acked attribute of the data chunk is changed to ABANDONED and set to TRUE,

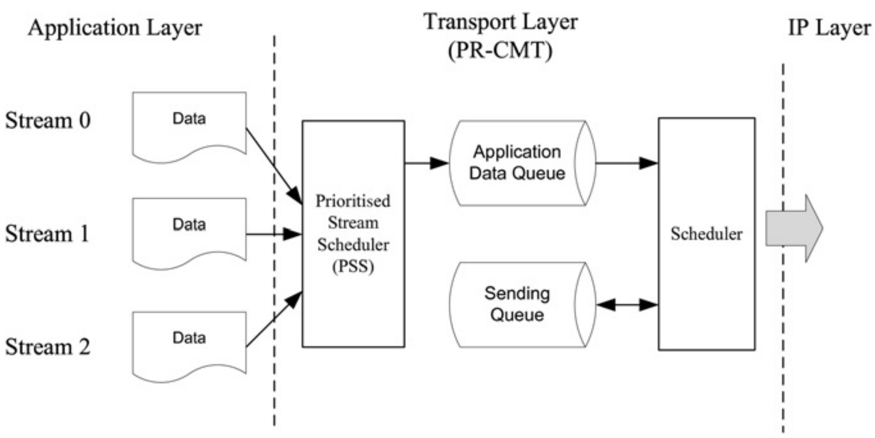

Fig. 3 *PR-CMT architecture*

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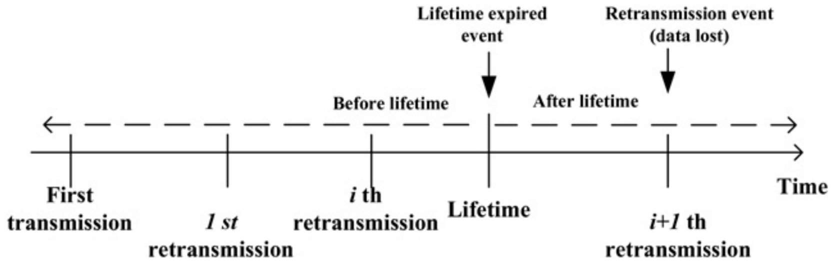

Fig. 4 *Time line for a data chunk*

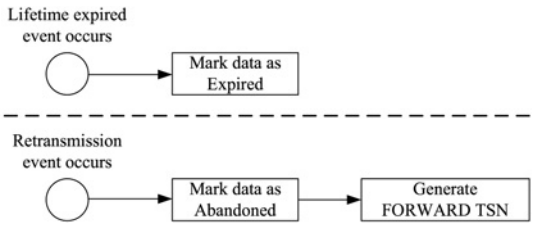

Fig. 5 *Steps of the delay abandoning data*

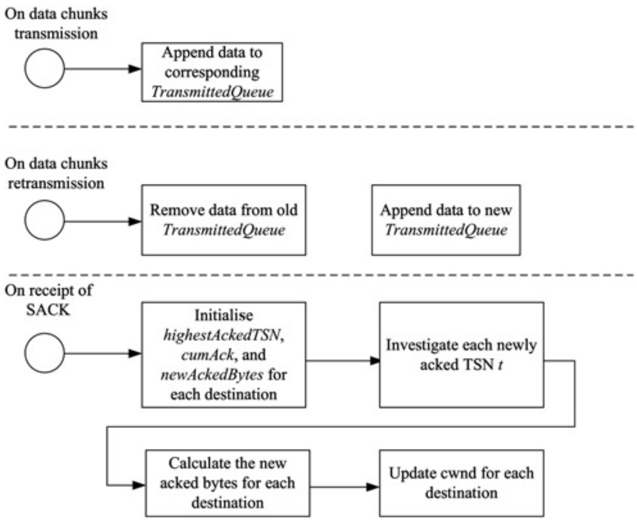

Fig. 6 *Steps for handling data transmission and processing SACK*

respectively. Then, the corresponding FORWARD TSN chunk is generated for the data chunk.

4.3 Concurrent multipath transfer

To minimise side effects caused by the reordering issue in PR-CMT, PR-CMT adopts the similar concept proposed by Iyengar *et al.* A path is identified by the destination address. Each destination address has its own cwnd. Fig. 6 shows the steps for handling data transmission and processing SACK.

In the steps of data transmission, the PR-CMT sender keeps a TransmittedQueue for each destination address. The TransmittedQueue keeps TSNs of the transmitted data chunks of a certain destination address. When the data chunk with TSN *t* is transmitted over a destination address *d*, the data chunk with TSN *t* is appended to TransmittedQueue of *d*.

In the steps of data retransmission, the data chunk with TSN *t* must be removed from TransmittedQueue of the latest transmitted destination address and then appended to TransmittedQueue of the new retransmission destination address. PR-CMT can therefore determine which TSN is assigned to which destination address.

In the steps of processing SACK, variables for inferring cwnd must be initialised first. The highestAckedTSN keeps track of the highest acknowledged TSN for each destination address; the cumAck determines whether or not a destination address can update its cwnd after receiving a SACK; the newAckedBytes counts the newly acknowledged bytes that are not credited for cwnd so far.

In the step of investing newly acknowledged TSNs, let destination *d* be the destination address to which the outstanding data chunk with TSN *t* is transmitted. To eliminate unnecessarily fast retransmission, the missing report count of the data chunk with TSN *t* is increased only when the data chunk with TSN *t* is not being acknowledged by the SACK and is less than highestAckedTSN of *d*. If the missing report count reaches 3, the fast retransmission is triggered on the destination address *d*.

In the step of calculating the newly acknowledged bytes for each destination, if the data chunk with TSN *t* is newly acknowledged by the SACK and the state of the data chunk with TSN *t* is not ABANDONED, then the size of the data chunk with TSN *t* is added to newAckedBytes. Consequently, if the data chunk with TSN *t* is the head of transmittedQueue of *d*, d.cumAck is set to TRUE.

In the final step, if cumAck of a destination address is set to TRUE, the cwnd of that destination address can be updated as defined in RFC 4960 [12].

In PR-SCTP, the sender can send the FORWARD TSN via any path. In order to prevent the abandoned data causing the receiver buffer blocking, once the data chunk is abandoned, the FORWARD TSN is sent to every path. PR-CMT follows the following rules to send the FORWARD TSN:

- When data are abandoned, the FORWARD TSN is sent to every active destination address.
- Start the F-Timer for each destination address to which the FORWARD TSN is sent.
- Upon receiving a SACK, if the cumulative TSN of the SACK is larger than or equal to the cumulative TSN of the FORWARD TSN, disable F-Timer on all destination address.
- If F-Timer is expired, retransmit the FORWARD TSN over every active destination address.

The main difference between the Iyengar CMT algorithm and PR-CMT is that PR-CMT must consider abandoned data. If data are expired, the state of data is changed to expired. The expired data can be credited for cwnd. However, when data are abandoned after loss, the sender must not credit the abandoned data for the cwnd. The original CMT does not handle the expired and abandoned data for cwnd. On the other hand, the FORWARD TSN is

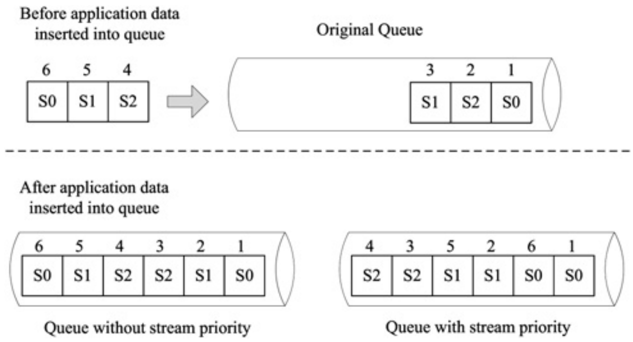

Fig. 7 *Application data insertion with/without stream priorities*

transmitted over multiple paths concurrently. PR-CMT maintains F-Timers for each destination address when sending the FORWARD TSN. As a result, PR-CMT reduces the occurrence of the receiver buffer blocking caused by the abandoned data.

4.4 Prioritised stream transmission

The prioritised stream transmission is realised by inserting the application data into the application data queue according to their stream priorities. Fig. 7 shows that without stream priority, application data are inserted into the application data queue on a first-come, first-served (FCFS) basis. When streams are associated with priorities, new application data are inserted into the application data queue according to their stream priorities.

To implement the prioritised stream transmission, when new data come from the upper layer, the PSS inserts the new data into the application data queue. The PSS seeks the application data whose stream priority exceeds or equals that of the new application data from the tail of the application data queue. The new data are appended to the found application data in the application data queue. The application data queue is therefore ordered by stream priority. Implicitly, the application data with the same stream priority are ordered based on FCFS. The scheduler retrieves the application data for transmission from the head of the application data queue. The application data in the application data queue are ordered based on the stream priorities Consequently, the scheduler could transmit the application data according to their stream priorities.

5 Transmission behaviour analysis

In this section, the transmission behaviour of PR-CMT is analysed. For convenience, PR-CMTf is named PR-CMT with partially reliable transmission, and PR-CMTfs is named PR-CMT with partially reliable transmission and prioritised stream transmission. Since all data have lifetimes, PR-CMTf must transmit data before lifetimes expire. Let D_d be the time that the data is delivered from the application to PR-CMT, let D_t be the time instant that the data is transmitted, let D_{lt} be the lifetime of the data, D_{size} be the size of the data and let D_r be the remaining time for transmission, where

$$D_r = D_{lt} - \text{CurrentTime}$$

D_r changes over time. To simplify the analysis, assume that D_r is initially the same for all data. Let *BW* be the aggregated bandwidth of all available paths. If *BW* is larger enough to transmit all data, then no data are abandoned. However, in a congested environment or a high loss rate environment, the increased transmission delay causes PR-CMT to abandon the expired data. Let the time instance in which PR-CMTf begins abandoning data be the abandoning point. For data with unexpired lifetimes, their D_r must approximate to 0.0 s. This implies that each data chunk is queued in PR-CMTf for almost $(D_{lt}{-}D_d)$ seconds.

However, if the path loss rate is high, retransmitting lost data is difficult since the D_r of the lost data are probably close to 0.0 s. As a result, by the time PR-CMTf detects a loss of data, the lifetime of the data are probably be expired. The lost data with expired lifetime cannot be retransmitted. Thus, PR-CMTf must send the FORWARD TSN chunk to advance the cumulative TSN of the receiver for the lost data.

When combining partially reliable transmission and prioritised stream transmission, PR-CMTfs abandons low-priority data to ensure the transmission of high-priority data. Let S_n be the nth stream, S_n^{dr} be the data rate for the S_n stream and $S_0 > S_1 > \cdots > S_n$ be the stream priorities. The transmission behaviour of the prioritised stream transmission ensures that data of S_j are transmitted only when there are no queued data of S_i, where $i < j$. If BW is insufficient to transmit all data, that is

$$\text{BW} < \sum_{i=0}^{N} S_n^{dr}$$

PR-CMTfs finds an S_k to fit the bandwidth limitation, that is

$$\text{BW} \geq \sum_{i=0}^{k-1} S_n^{dr}$$

For those S_j, PR-CMTfs does not transmit S_j data to ensure the transmission of S_i data, where $i < k$ and $j \geq k$.

High-priority data occupy the front portion of the sending queue in PR-CMTfs, which abandons low-priority data before abandoning high-priority data. As a result, the queued high-priority data have a D_r value, which is not close to 0.0 s. The end-to-end transmission delay of S_i would be approximately

$$(D_{lt} - D_d) + D_{size}/\text{BW} + P_d$$

where P_d is the end-to-end path delay. If $(D_{lt} - D_d)$ is close to 0.0 s, then the end-to-end transmission delay would approximate $(D_{size}/\text{BW} + P_d)$. Retransmitting the lost data in PR-CMTf is difficult after the abandoning point. However, such a situation rarely occurs in PR-CMTfs, because the transmitted data have a higher D_r value. As a result, the lost data may be retransmitted in PR-CMTfs. The sending frequency of the FORWARD TSN chunk is also reduced in PR-CMTfs.

In summary, data still can be acknowledged and credited after the abandoning point with the delay abandoning data. Thus, the cwnd growth would not be impacted by the expired data. However, if the bandwidth is insufficient to transmit all data after the abandoning point, the lifetime of the queued data is approaching to the deadline. Data are transmitted and abandoned frequently. As a result, the sender has no chance to retransmit the lost data. The combination of delay abandoning data and priority stream transmission can solve this problem. Since the priority

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stream transmission would delay the transmission of the low-priority data for high-priority data. The transmitted data would have larger lifetime. The retransmission on the lost data becomes possible. As a result, the sender has more chance to retransmit the lost I frame. This feature of PR-CMTfs is very import for multimedia streaming, because PR-CMTfs is able to retransmit lost I frames in a congested or high loss rate environment, but PR-CMTf is not.

6 Evaluation

The performance of PR-CMT was evaluated using NS2 [26]. PR-CMT was modified from the NS2 CMT module developed by University of Delaware [16]. Fig. 8 depicts the simulation topology. There are two paths from the sender to the receiver in which Path1 has 10 M bps bandwidth and 300 ms transmission delay whereas Path2 has 15 M bps bandwidth and 200 ms transmission delay. The buffer size of each router is 100 MUT, that is, 100 × 1500 bytes. To have more precise network traffic in the simulation, the collected network traffic at the department of Computer Science and Information Engineering in National Cheng Kung University (NCKU) was injected into the simulation network as the background traffic. The bottleneck occurs in the Path1 and Path2 routers.

Evaluated transmission modes for PR-SCTP, CMT and PR-CMT are as follows:

• PR-SCTP: original, unmodified PR-SCTP.
• PR-SCTPf: PR-SCTP with delay abandoning data.
• CMT: unmodified CMT.
• PR-CMTf: PR-CMT with partially reliable transmission, but without using delay abandoning data.
• PR-CMT: PR-CMT with partially reliable transmission, delay abandoning data and prioritised stream transmission.

The partially reliable transmission is an important feature of streaming multimedia data. Partially reliable transmission in PR-SCTP, however, causes overly conservative congestion window growth and falsely acknowledged TSN issues. The following experiment results demonstrate that delay abandoning data helps to precisely infer cwnd and loss of data. Thus, the partially reliable transmission can be used to transmit the multimedia streaming data. The video quality achieved by PR-CMT is superior to the other protocols.

6.1 Evaluation of delay abandoning data

This subsection evaluates the effect of adopting delay abandoning data by comparing PR-SCTP and PR-SCTPf. In this simulation, Path1 is the primary path and Path2 is for retransmission only. Both PR-SCTP and PR-SCTPf sent data to the receiver at full speed. The lifetime of data was set to 5 s. Fig. 9 shows that the increase in the cwnd of PR-SCTPf is more precise than that of PR-SCTP. Owing to the limited path capacity, some data were abandoned in PR-SCTP after the abandoning point and could not be credited for cwnd. The congestion control of PR-SCTP and PR-SCTPf got into slow-start state after 5 s. The cwnd could be increased only if the current congestion window is

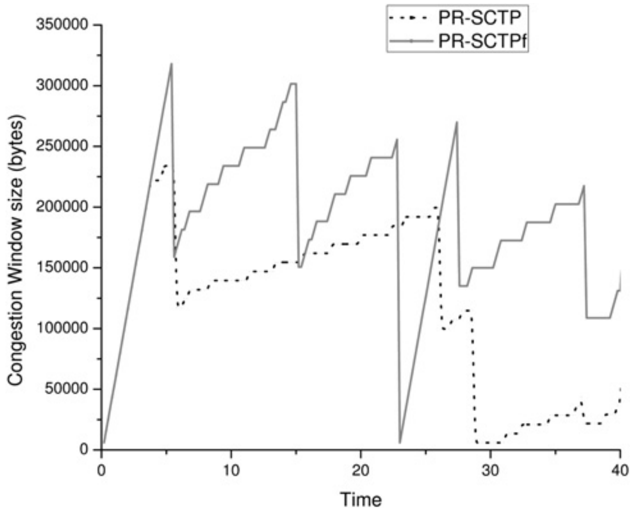

Fig. 9 *Comparison on cwnd growth*

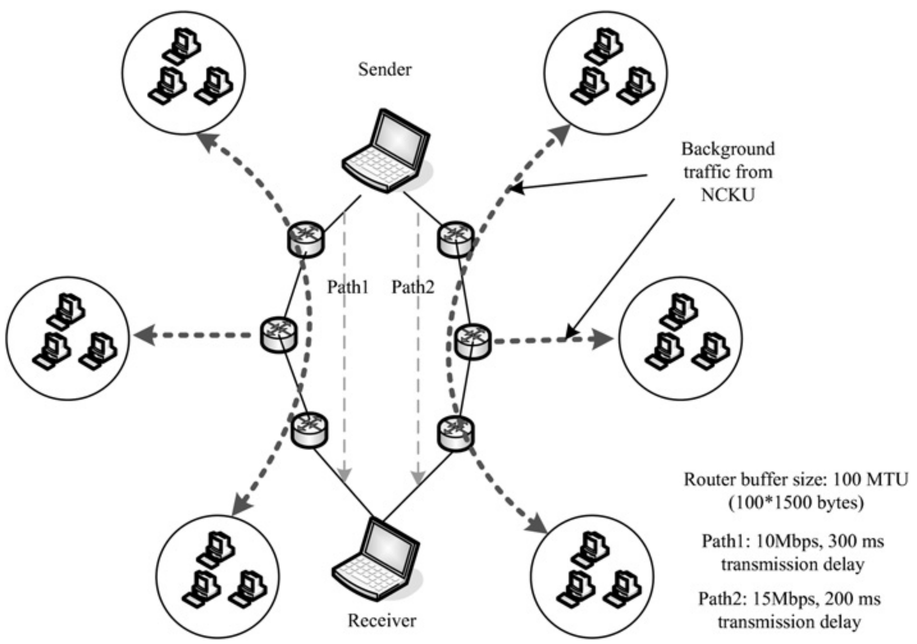

Fig. 8 *Simulation topology*

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being fully utilised. The cwnd growth was much slower in slow-start state than in the state of congestion avoidance.

After the abandoning point, many queued data were approaching the lifetime. When the end-to-end delay was large, the sender was hard to receive SACKs for the transmitted data. The transmitted data were abandoned before receiving the SACK. However, PR-SCTPf only marked expired data as expired. The expired data could be credited for cwnd if the receiver acknowledged the expired data. As a result, the cwnd growth of PR-SCTP was much slower than that of PR-SCTPf after the abandoning point. When timeout retransmission occurred, that is, the 29th second in PR-SCTP, the cwnd was cut to 1 MTU. Since the cwnd growth of PR-SCTP became very slow, the cwnd of PR-SCTP could not be recovered as fast as PR-SCTPf.

Fig. 10 shows the throughput of PR-SCTP and PR-SCTPf. The throughput of PR-SCTP and PR-SCTPf was limited by the cwnd. When the cwnd was cut owing to congestion loss, the cwnd growth of PR-SCTP was much slower than PR-SCTPf. This phenomenon directly impacted the throughput of PR-SCTP. PR-SCTP could not recover its cwnd as soon as PR-SCTPf did after the packet loss. Once the cwnd was small, the throughput was degraded. Therefore since the cwnd growth was slow in PR-SCTP after the abandoning point, PR-SCTPf outperformed PR-SCTP.

On the other hand, we also evaluated the performance of PR-SCTP and PR-SCTPf in a network with loss. In this simulation, 5% packet loss rate was added into Path1. The 5% packet loss rate reflects the packet loss rate in wireless network [27]. Fig. 11 shows the cwnd of PR-SCTP and PR-SCTPf. In the high loss rate environment, many packets were lost randomly. If the sender received three consecutive SACKs, which implied that there was a missing on a certain data chunk, then the sender retransmitted the missing data chunk via the fast retransmission, and the cwnd was halved. In Fig. 11, PR-SCTPf detected much packet loss than PR-SCTP did. After the abandoning point, PR-SCTP started to send the FORWARD TSN for the lost data chunk. Consequently, the falsely acknowledged TSN occurred. As a result, PR-SCTP could not reflect the fact that data were lost on the cwnd. Since PR-SCTP did not cut the cwnd for the lost data chunk, the cwnd of PR-SCTP should be larger than PR-SCTPf. However, with the impacts of overly conservative cwnd growth, PR-SCTP could not have a larger cwnd than PR-SCTPf. PR-SCTP still could detect packet loss in some situations. Once the PR-SCTP cut the cwnd for the loss data, the growth of cwnd of PR-SCTP was slow. Although the overly conservative cwnd growth decreased cwnd, and the falsely acknowledged TSN increased cwnd, the concurrent occurrence of the two problems did not help PR-SCTP to have a precise cwnd. Fig. 12 shows the throughput for PR-SCTP and PR-SCTPf during the 40 s period. PR-SCTPf improved the throughput of PR-SCTP by 20% during the 40 s period.

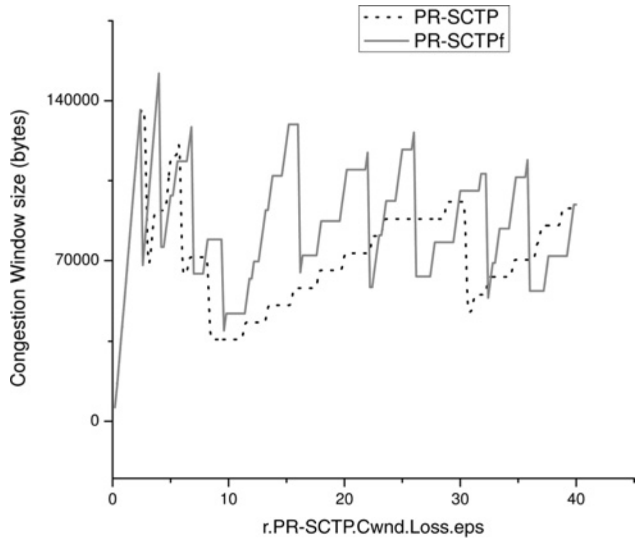

Fig. 11 *Comparison on cwnd growth*

We also evaluated the long-term throughput in the congested and high loss rate environment (5% loss rate in Path1). The average throughput was obtained by running the same simulation ten times for 20 min. The NCKU background traffic was randomly injected into the simulated network to cause congestion in routers. Fig. 13 shows the statistical results. In the congested environment, the average throughput of PR-SCTP and PR-SCTPf were 320 and 414 Kb/s, while in the high loss rate environment, the average throughput became 183 and 222 Kb/s. PR-SCTPf improved the throughput of PR-SCTP by 29 and 21% in the congested and high loss rate environment, respectively.

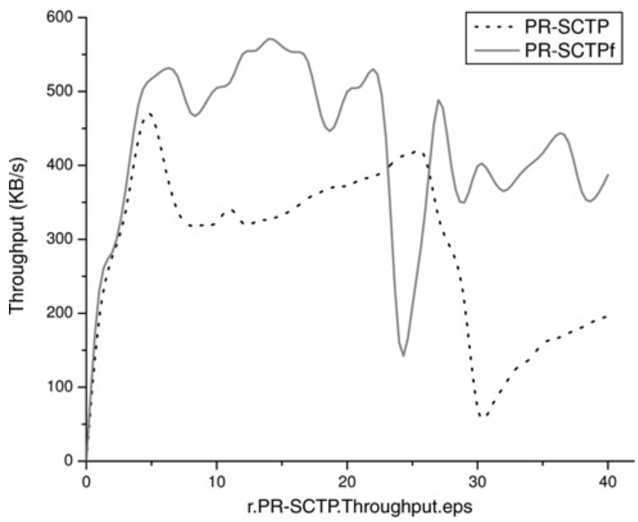

Fig. 10 *Comparison on throughput*

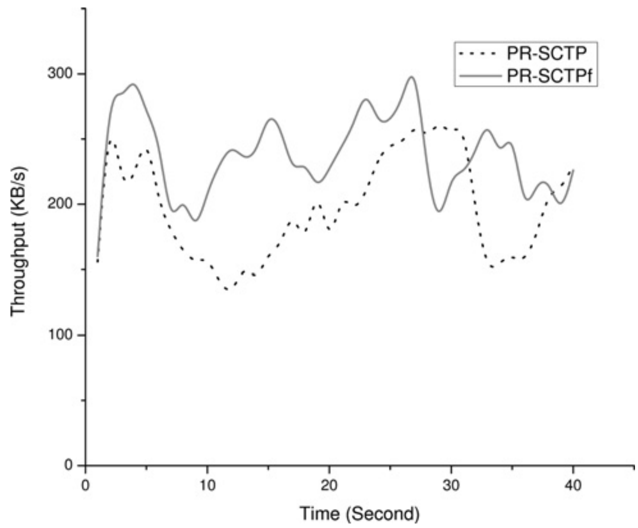

Fig. 12 *Comparison on throughput*

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Congested Environment	Average	SD.	SE.
PR-SCTP	320KB/s	15.1	4.77
PR-SCTPf	414KB/s	16.5	5.22

High Loss rate Environment	Average	SD.	SE.
PR-SCTP	183KB/s	12.8	4.05
PR-SCTPf	222KB/s	17.2	5.47

Fig. 13 *Statistical results on throughput*

The statistical results show that PR-SCTPf is able to tackle the imprecise cwnd and falsely acknowledged TSN problems.

In summary, after the abandoning point, the growth of cwnd of PR-SCTP becomes much slower than that of PR-SCTPf. The imprecise and small cwnd degrade the throughput of PR-SCTP. Once the state of congestion control gets into slow-start state, the growth of cwnd of PR-SCTP becomes very limited. Consequently, small growth of cwnd leads to the throughput degradation. Even though the falsely acknowledged TSN may imprecisely increase the cwnd, the throughput of PR-SCTP is not as good as PR-SCTPf.

6.2 Evaluation of multimedia streaming quality

This subsection compares multimedia streaming quality of CMT, PR-CMTf and PR-CMT. The used MPEG stream was a famous Japanese animation, Naruto. The frame rate of the encoded stream was 30 fps. The used MPEG GOP pattern was 'IBBBPBBBPBBBPBBBPBBBPBBBPBBBP'. Fig. 14 shows I, P and B frames being sent in stream S0, S1 and S2, respectively. Thus, streaming priority is S0 > S1 > S2. The receiver is assumed to have 10 s buffer time before the playout. Each frame has 10 s lifetime. The sender starts to stream data to the receiver during 0–50 s. The 10 s buffer time is reasonable. The popular multimedia streaming application, PPStream, which has more than 10 000 channels, also adopts 10–20 s to buffer the streaming data before the first playout of frames [28].

In this simulation, more background traffic, which was gathered from NCKU, was injected into the network. The available bandwidth was fewer and less sufficient to transmit all frames than previous simulation. Some frames must be abandoned. Received frames that did not arrive at the receiver before their lifetimes expired were unplayable. If the dependent frames were not playable, the received frames were also unplayable. For example, let the received frames sequence in a GOP be $I_0B_1B_2B_3P_4B_5B_6B_7$-$B_9B_{10}B_{11}P_{12}$. $I_0B_1B_2B_3P_4$ are all playable. Since P_8 was not received, $B_5B_6B_7$ and $B_9B_{10}B_{11}P_{12}$ were unplayable. Thus, loss of I or P frames substantially degraded video quality.

Fig. 15 shows that the receiver buffered the received frames in the first 10 s and started playing the first frame from the 11th second. Owing to the cwnd limitation, PR-CMTf and PR-CMT could not transmit frames at full speed. Numerous I and P frames were queued in the buffer of PR-CMTf and PR-CMT. The abandoning point of PR-CMT occurred quickly. PR-CMT transmitted I or P frames in the first–tenth GOPs before any B frames. However, in CMT and PR-CMTf, B frames were not delayed by I frames or P frames. As a result, initially, CMT and PR-CMTf had higher playable frame rate than PR-CMT had. The bandwidth was insufficient. The delay transmission of B frames in PR-CMT was reasonable. After the abandoning point, many transmitted frames were approaching their lifetimes. PR-CMTf abandoned lots of I and P frames. The playable frame rate of PR-CMTf dropped heavily. No I frame was received in the short period after the abandoning point of PR-CMTf. Moreover, the receiver had no chance to acknowledge the abandoned frames in PR-CMTf. As aforementioned previously, under the impact of overly conservation cwnd growth, the cwnd of PR-CMTf was smaller than that of PR-CMT. Consequently, the throughput and the playable frame of PR-CMTf were smaller than that of PR-CMT. Thus, the playable frame rate of PR-CMTf is smaller than that of PR-CMT.

	# of frames	total size(kb)	send rate (kbit/s)
I	29	2312.53	76.66
P	198	7887.13	261.45
B	678	19307.16	640.02
Total	905	29506.81	978.13

Fig. 14 *MPEG stream statistics*

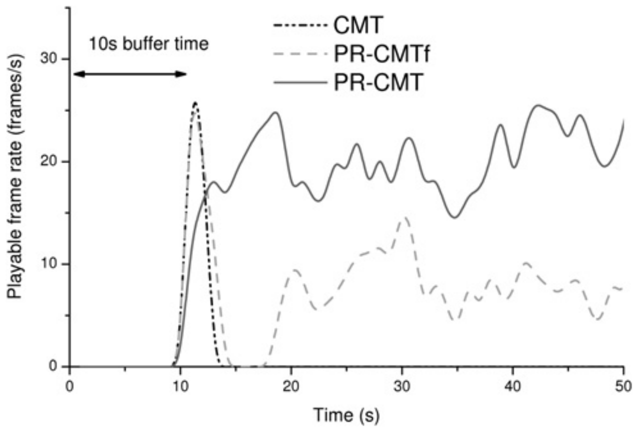

Fig. 15 *Comparison on playable frame rate*

On the other hand, because of the prioritised stream transmission of PR-CMT, PR-CMT transmitted I and P frames of the latter GOPs before the B frames of other GOPs. PR-CMT could eliminate the impact of overly conservation cwnd growth, and had better throughput than PR-CMTf had. Thus, PR-CMT had larger playable frame rate than PR-CMTf had. For CMT and PR-CMTf, without the prioritised stream transmission, many important I and P frames were abandoned or could not arrive at the receiver before their lifetimes expired. Thus, many received P and B frames were not playable.

Another phenomenon was the larger gaps between two player frames. Fig. 16 shows the playable frame distribution. Notice that CMT did not have any playable frame after the 55th frame. There is no line for CMT in Fig. 16b. PR-CMTf had larger gaps between playable frames than PR-CMT had. Many frames were not playable when the network was congested. PR-CMTf did not consider the code dependency of frames. The I, P and B frames had equal priority in PR-CMTf. PR-CMTf did not delay the transmission of B frames for I or P frames. When the bandwidth was insufficient to transmit all frames, PR-CMTf abandoned important I or P frames. Once I and P frames are abandoned, many transmitted P and B frames in the same GOP cannot be played. In this way, even though B frames were transmitted and received before the lifetime, B frames were unplayable. Therefore large gaps appeared in the playable frame distribution of PR-CMTf. In PR-CMT,

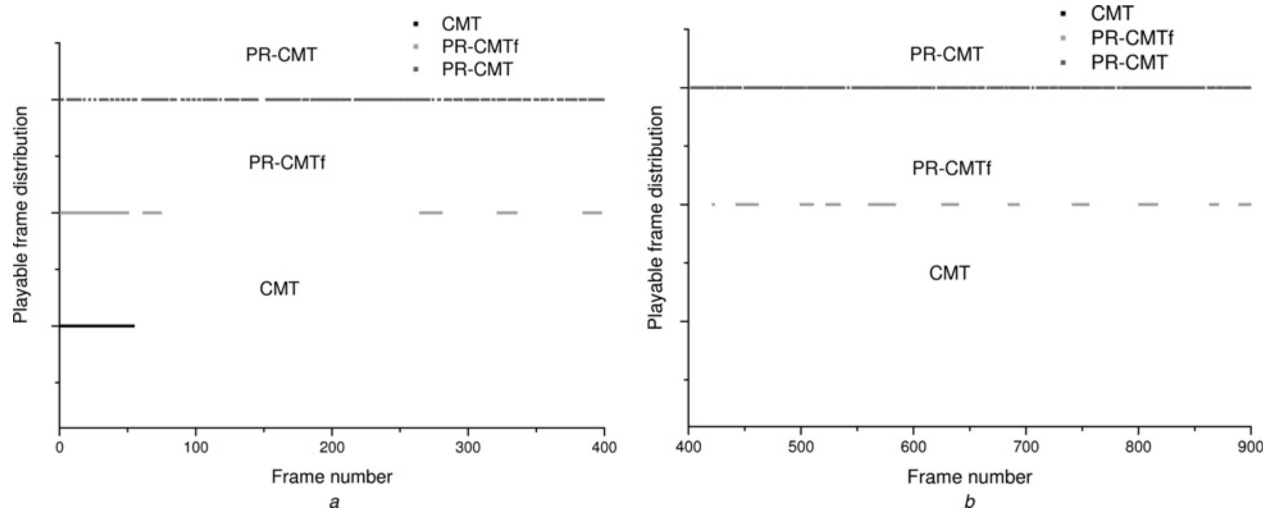

Fig. 16 *Comparison on playable frame distribution*

a From 1st to 400th frame
b From 400th to 900th frame

when the bandwidth was insufficient, PR-CMT abandoned B frames to preserve the transmission of I and P frames. Most frames received in PR-CMT are playable. According to the GOP pattern, one P frame appeared after three consecutive B frames. If P frames were playable, then the large gaps between playable frames would not occur. The coding dependency could be kept in PR-CMT. Thus, the playout did not stop for several seconds.

Fig. 17 shows the PSNR for PR-CMTf and PR-CMT. The PSNR is computed by comparing the frame before and after transmission. The PSNR value for a playable frame is infinity. Thus, in the figures, the peak value of 100 dB is infinity. In Fig. 17*a*, PR-CMT was able to maintain the PSNR value at the peak level. When some frames were abandoned or unplayable, the PSNR was down to the range of 20–40 dB.

As for PR-CMTf, many received frames were unplayable. The number of peak values in PR-CMTf was few. The large gaps problem damaged the PSNR value very much. When large gaps occurred, the PSNR value could be down to below 10 dB. The span of non-peak values in PR-CMTf was larger than that of PR-CMT. The P and B frames were interleaving in a GOP. Since PR-CMT would abandon B frames for I or P frames, the span of non-peak values in PR-CMT was small. However, PR-CMTf did not adopt the priority stream transmission. If I frame was unplayable, then the received succeeding P and B frames were unplayable too. Consequently, the span of the non-peak value in PR-CMTf was larger than that in PR-CMT.

Moreover, other ten videos, which use the same coding method, were evaluated under the same network conditions mentioned before. Fig. 18 shows the statistical results of the playable frames from ten different videos. The standard deviations were calculated based on the percentage of the playable frames for different protocols. The statistical results show that PR-CMT outperforms CMT and PR-CMTf for various videos. The average percentage of the playable frames for CMT, PR-CMTf and PR-CMT were 5.9, 30.6 and 67.4%, respectively. Only a small portion of frames were playable in CMT. Most frames could not arrive at the receiver before their lifetimes. PR-CMT had twice

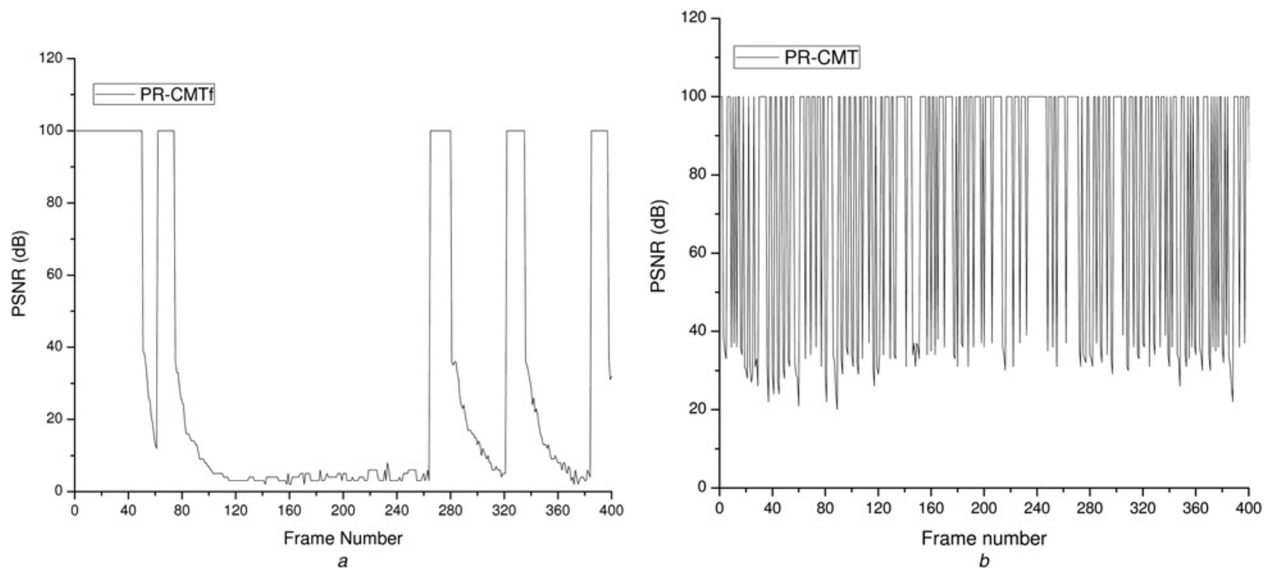

Fig. 17 *Comparison on PSNR*

a PSNR of PR-CMTf
b PSNR of PR-CMT

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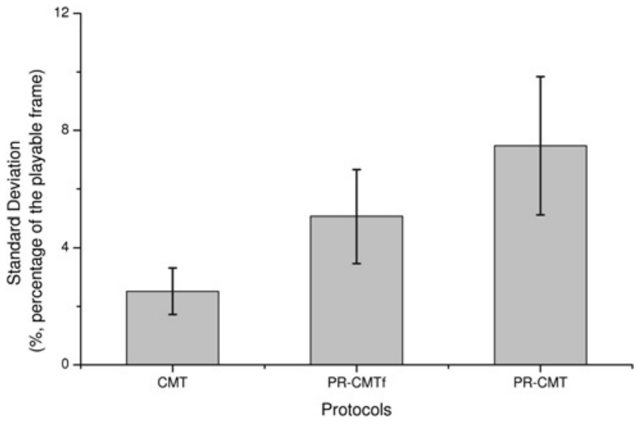

Fig. 18 *Standard deviations of ten different videos*

average playable frames than PR-CMTf had, but PR-CMT did not have twice throughput than PR-CMTf did. In PR-CMTf, many received frames that arrived at the receiver before their lifetimes are unplayable owing to the coding dependency. The received but unplayable frames still consumed bandwidth in PR-CMTf. Large gaps between two playable frames still appeared frequently. In summary, only PR-CMT can handle the large gap problem well.

7 Conclusion

The proposed PR-CMT combines techniques of CMT, partially reliable transmission and prioritised stream transmission for multimedia streaming. PR-CMT can eliminate the overly conservative cwnd growth problem and precisely infer the loss of packets. PR-CMT improves about 29 and 21% of throughput when using only one path for transmission in the two simulated network conditions. As for multimedia streaming, PR-CMT can keep the coding dependency of I, P and B frames during transmission. Consequently, the large gaps phenomenon is reduced in PR-CMT. The value of PSNR is kept at the peak level. The playout of video is not suspended for seconds when the network is congested or unreliable. PR-CMT improves the percentage of the playable frame from 30.6 to 67.4% after applying delay abandoning data and prioritised stream transmission.

In the future work, PR-CMT can be evaluated in a more complicated environment, such as the vehicular network. The links between vehicles and road site units (RSU) are not reliable; the handoff between vehicles and RSUs occurs frequently. PR-CMT can be adapted to deal with the high handoff frequency and the high packet loss rate for data with limited lifetime and different importance.

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