

# Adaptive Congestion Control of mSCTP for Vertical Handover Based on Bandwidth Estimation in Heterogeneous Wireless Networks

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**Abstract** This paper proposes a new congestion control scheme of mobile Stream Control Transmission Protocol (mSCTP) for vertical handover across heterogeneous wireless/mobile networks. The proposed scheme is based on the estimation of available bandwidths in the underlying network as a cross-layer optimization approach. For congestion control of mSCTP, the initial congestion window size of the new primary path is adaptively configured, depending on the available bandwidth of the new link that a mobile node moves into. By ns-2 simulation, the proposed scheme is compared with the existing congestion control schemes in the throughput perspective. From the numerical results, we can see that the proposed mSCTP congestion control scheme could give better performance than the existing schemes in the wireless networks with an amount of background traffic.

**Keywords** mSCTP · Vertical handover · Adaptive congestion control · Heterogeneous wireless networks

## 1 Introduction

With the evolution of the wireless access technologies and the multi-homing capability of mobile terminals, the vertical handover across heterogeneous networks will become one of the critical issues in the future wireless/mobile networks. In the vertical handover, it is required to provide seamless services for a mobile terminal that moves across different types of access networks. Such seamless services could be realized by minimizing the data loss and delay during handover and by maximizing the data transmission throughput with an enhanced congestion control scheme.

It is noted that the Stream Control Transmission Protocol (SCTP) is proposed to support IP handover in the transport layer with the help of the multi-homing feature and

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dynamic address reconfiguration extension, which is called mobile SCTP (mSCTP) [4]. mSCTP handover allows a mobile node (MN) to dynamically add a new IP address or delete an old IP address to or from the current SCTP association, as MN moves across different IP networks. During mSCTP handover, MN is required to switch the primary path from the old IP address to a new IP address.

In this paper, we consider the congestion control of mSCTP for vertical handover. The mSCTP is used for vertical handover between heterogeneous wireless networks. However, there are still a lot of challenging issues to be solved in the mSCTP vertical handover. One of them is how to enhance the throughput of data transmission during vertical handover. In the mSCTP handover, each time the primary path is switched, the congestion control parameters of the new primary path will be initialized, and further the congestion window begins in the slow start phase [2]. This may cause the data transmission throughput to be degraded during handover. Such the throughput degradation could be more severe when MN moves across heterogeneous networks with quite different network bandwidths, as shown in the example of the vertical handover between 3G wireless and WLAN.

A couple of schemes have been made to enhance data transmission throughput during handover for the Transmission Control Protocol (TCP) over Mobile IP (MIP) [5]. The work of [5] proposed to immediately initialize the congestion control parameters during vertical handover. In the works of [6,7], the authors proposed that the congestion control parameters should be adjusted based on the estimated bandwidth-delay product under the assumption that MN and corresponding node (CN) can know the available bandwidth beforehand. However, it is noted that TCP could not realize the change of IP address during movement, since it cannot exploit the transport-layer multi-homing capability in nature.

In the meantime, several works have been made on the mSCTP handover. The work of [8] proposed an mSCTP handover, called SIGMA, and compared the handover latency of SIGMA and MIP on the various experimental testbeds. [9] In the mSCTP was compared with the MIP fast handover, in which the authors argue that mSCTP handover gives lower handover latency than MIP fast handover. The work of [10] proposed a new transport layer protocol based on SCTP, which is called Wireless SCTP Extension (WiSE), so as to improve the resource utilization by switching the primary path into an alternate path. On the other hand, a novel mSCTP handover scheme was proposed [11] which is called Cellular SCTP (C-SCTP). In the C-SCTP scheme, a bicasting is used by CN to send duplicate data packets to both of the old and new IP addresses in the handover region. In particular, the C-SCTP sets the congestion window size of the new path to be the same with the congestion window size of the old path. This scheme will be helpful to avoid the under-utilization of the new link, but it did not consider the available network bandwidth of the new path. Thus, it may lead to the performance degradation due to the over-utilization of the new link.

In this paper, we propose a new congestion control scheme of mSCTP for vertical handover, in which the congestion window size is configured based on the available bandwidth estimated in the concerned network, so as to provide efficient data transmission during handover. For performance analysis, we perform ns-2 simulations and compare the proposed scheme with the existing schemes for a variety of test environments.

The rest of this paper is organized as follows. Section 2 briefly describes the mSCTP handover with the existing congestion control schemes. Section 3 presents the proposed congestion control scheme for mSCTP vertical handover. Section 4 discusses the simulation results. Finally, we conclude this paper in Sect. 5.

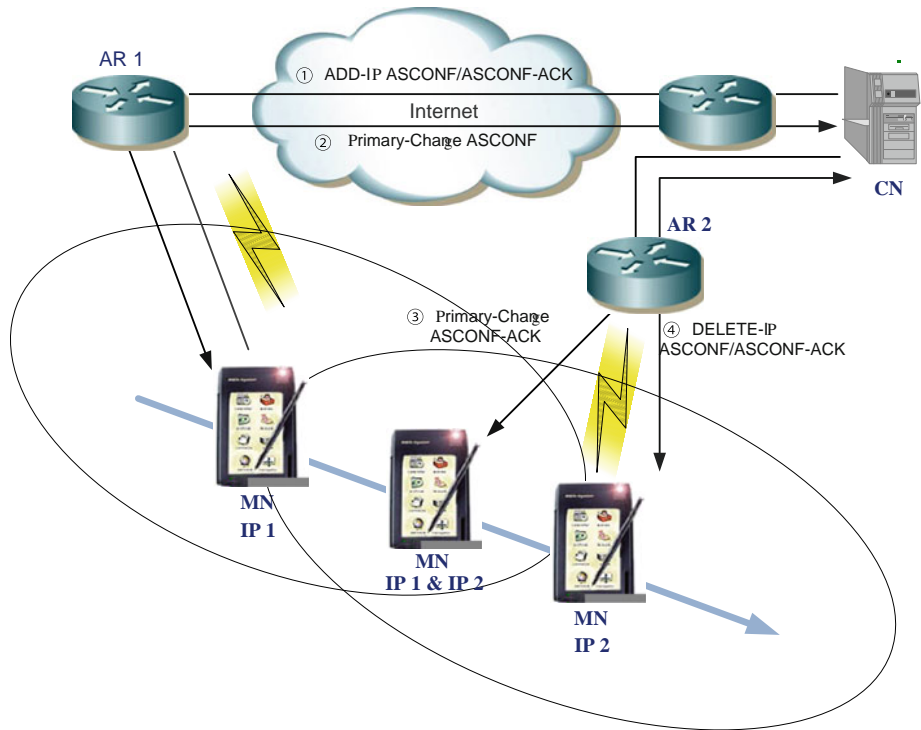


Fig. 1 mSCTP handover operations

## 2 mSCTP for Vertical Handover

### 2.1 mSCTP Handover

In mSCTP handover, each endpoint is able to add or delete an IP address to or from the existing association, and also to change its primary IP address. Figure 1 illustrates the protocol operation of mSCTP handover across different IP networks [10].

In the figure, we assume that MN initiates an SCTP association with CN, and moves from AR1 region to AR2 region. For the SCTP association, MN initially uses 'IP address 1' in the AR1 region. Then, the overall mSCTP handover procedures could be performed as follows.

When MN moves into AR2 region, it obtains a new address 'IP address 2' by using IP address configuration scheme such as Dynamic Host Configuration Protocol (DHCP). After that, the newly obtained IP address 2 will be informed to CN in the transport layer. This is done by sending an SCTP Address Configuration (ASCONF) chunk to CN. MN receives the responding ASCONF-ACK chunk from CN. This is called the 'Add-IP' operation, during which the old IP address 1 is still used as the primary address. As MN further continues to move toward AR2 region, it will set the new IP address to be its primary address. For this purpose, MN sends an ASCONF chunk over IP address 1 and receives the responding ASCONF-ACK chunk from CN over IP address 2. Once the primary address is changed, CN sends the subsequent data packets over the new primary IP address of MN (IP address 2). This is called the 'Primary Path Switching' operation. As MN continues to move toward

AR2, it will delete the old IP address from the association. This is called the 'Delete-IP' operation. These procedural steps will be repeated each time MN moves to a new network.

## 2.2 Existing Schemes for mSCTP Congestion Control

Data transmission between two endpoints is performed as per the SCTP congestion control. When MN is multi-homed with two or more IP addresses, CN will separately manage the congestion control parameters per IP address of MN. For example in Fig. 1, when MN enters the AR2 region in the multi-homing state, CN has to configure the congestion control parameters for the new IP address of MN.

The existing configuration schemes of the congestion window can be classified as follows:

- (a) Conservative scheme: initialize the congestion window size and perform the congestion control in the slow start mode, as per IETF RFC 4960 [10].
- (b) Aggressive scheme: inherit the congestion window size of the old path at the time of the primary path switching (handover), as shown in the C-SCTP [11].

In the conservative scheme of case (a), when MN switches the primary path, CN begins transmission of data packets with an initial congestion window in the slow start phase. We assume that the initial congestion window starts with  $1 \times \text{MTU}$ , even though the IETF RFC 4960 [10] says that the initial congestion window is set to the minimum value between  $1 \times \text{MTU}$  and the maximum of  $2 \times \text{MTU}$  and 4380 bytes. In the aggressive scheme of case (b), the congestion window size of the new path is identical to that of the old path at the time of primary path switching.

It is noted that these two extreme cases did not consider the current network conditions such as the available network bandwidth. Accordingly, the network bandwidth of the new path tends to be under-utilized in the conservative scheme, or over-utilized in the aggressive scheme. Such the problem may become more severe, when MN moves across heterogeneous wireless access networks with quite different link characteristics such as 3G wireless (with the link capacity of 384 Kbps) and WLAN (with the link capacity of 11 Mbps). When MN moves from 3G wireless to WLAN, the conservative scheme may result in the low utilization of the network bandwidth. On the reverse, when MN moves from WLAN to 3G, the aggressive scheme may induce over-utilization of network bandwidth for the new path, together with much packet loss or congestion.

Therefore, we propose an adaptive congestion control scheme of mSCTP for vertical handover, in which the congestion window size of the new path is adaptively configured, based on the estimation of the available bandwidth in the new network so as to provide the efficient data transmission during handover.

## 3 Adaptive Congestion Control Scheme of mSCTP

### 3.1 Overall Procedures

In the proposed congestion control scheme, the initial congestion window size of the new primary path is configured adaptively based on the estimation of the available network bandwidth. To describe the proposed scheme, we will focus on the data transmission from CN to MN, and consider the movements of MN from 3G to WLAN and then from WLAN to 3G, as depicted in Fig. 2.

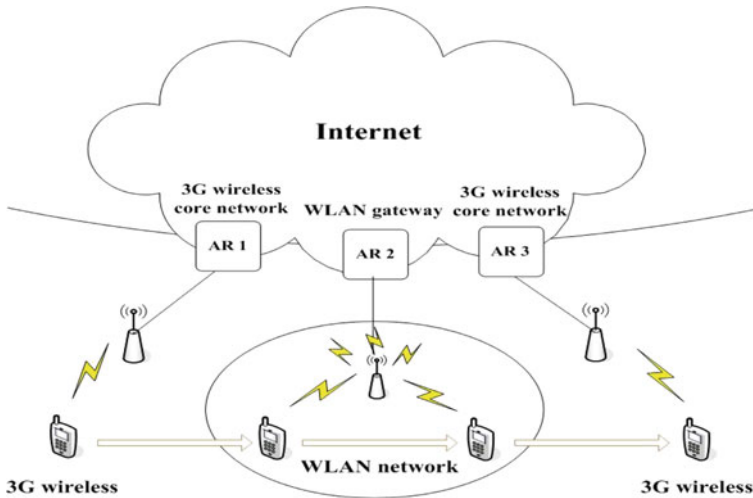


Fig. 2 Vertical handover between 3G and WLAN

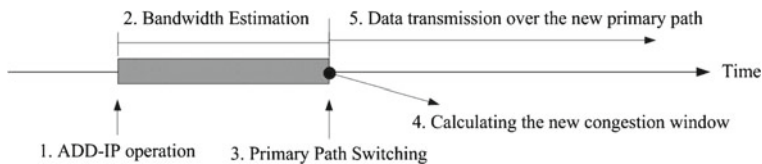


Fig. 3 Proposed congestion control procedures

In the AR1 region, MN communicates with CN via 3G link. When MN moves into WLAN hotspot, it will automatically configure a new IP address using DHCP. Then, MN adds the new IP address to the SCTP association by performing the mSCTP 'Add-IP' operation. After that, MN performs the primary path switching operation in the WLAN network. When MN leaves WLAN hotspot toward 3G wireless, it deletes the old IP address from the association by performing the mSCTP 'Delete-IP' operation.

The congestion control scheme of mSCTP proposed in this paper can be summarized as follows:

- (1) MN performs the Add-IP operation with the help of the underlying link-layer trigger (e.g., link-up);
- (2) CN estimates the available network bandwidth of the new path, until the primary path is switched;
- (3) CN is informed from MN about the primary path switching event;
- (4) CN calculates the initial congestion window of the new path, based on the estimated bandwidth; and
- (5) CN transmits the data transmission to the new primary path, as per the congestion control scheme.

Figure 3 depicts the overall procedures of the proposed congestion control scheme described above.

### 3.2 Estimation of Available Network Bandwidth

For efficient data transmission during vertical handover, the proposed congestion control scheme configures the congestion window size of the new primary path, adaptively based on the estimated network bandwidth. If the estimated bandwidth is too much over-estimated or under-estimated, the subsequent data transmission may lead to the performance degradation. Thus, the network bandwidth needs to be estimated accurately.

Until now, a lot of bandwidth estimation techniques have been proposed to determine the available network bandwidth on the bottleneck link. The self-loading techniques, including the Train of Packet Pairs (TOPP) [2], *pathLoad* [13] and *pathChirp* [14], are used to probe the end-to-end network path using the multiple probing rates. When the probing rate exceeds the available bandwidth, the probing packets will be queued at the routers, which results in the increased delay. By analyzing the packet delay, the available bandwidth is calculated from the probing rate when the queuing delay begins to increase. In these self-loading techniques, the probing rates are changed appropriately to improve the accuracy of bandwidth estimation. The *pathLoad* scheme uses a binary search to adjust the probing rate, and the TOPP scheme uses a linearly increasing probing rate, while the *pathChirp* scheme uses an exponentially increasing probing rate.

Packet dispersion techniques, such as the packet pair or packet train probing [15,16], are used to measure the end-to-end capacity of a network path. In the packet dispersion techniques, two or more packets are transmitted into the network in the back-to-back fashion. After the packets traverse the narrow link, the time dispersion between the two packets is linearly related to the narrow link capacity. This packet dispersion scheme for capacity estimation may be vulnerable to crossing trafics that interfere with the probing packets and cause some estimation errors under variable channel conditions of wireless networks. In particular, the packet dispersion scheme can estimate the available bandwidth, when the link capacity is given as a constant value.

In the meantime, the Wireless Bandwidth Estimation Tool (WBEST) [17,18] was designed to estimate the effective capacity and the available network bandwidth in the wireless networks. The WBEST employs the packet dispersion techniques to provide capacity and available bandwidth information for the underlying wireless networks. In the work [17,18], the two metrics for packets dispersion are *effective capacity* and *achievable throughput*. By combining these two metrics, the WBEST uses a two-step algorithm, which can be used to firstly estimate the effective capacity and then statistically detect the available fraction of the effective capacity. In the first step, so as to estimate the effective capacity, CN sends the  $n$  pairs of packets to MN, and then receives the responding packet pairs from MN. For each of the received packet pairs, CN calculates the packet dispersion time (i.e., the packet inter-arrival time between a pair of packets) for  $i = 1, \dots, n$ . Then, the effective capacity  $C_i$  for the  $i$ -th packet pair is calculated as  $C_i = L/T_i$ , where  $L$  represents the length of the transmitted packets. To minimize the impact of crossing and contending trafics, the median of the estimated values is taken as follows:  $C = \text{median}(C_i)$  for  $i = 1, \dots, n$ . In the second step, a packet train (pairs) of packets will be transmitted at the rate  $C$  in the similar way as in the first step, so as to estimate the available network bandwidth. Then,  $B$  is calculated with the average packet dispersion rate  $R = L/\text{mean}(T_i, i = 1, \dots, m)$  and the effective capacity  $C$ , as follows:  $B = C \times [2 - (C/R)]$ . When some packet losses are detected during the estimation, the available network bandwidth will be determined by  $B \times (1 - p)$  for the measured packet loss rate.

Table 1 compares the WBEST scheme with the existing other bandwidth estimation schemes.

**Table 1** Comparison of the candidate schemes for bandwidth estimation

| Criteria/schemes    | Self-loading [14]               | Packet dispersion [5, 16]                     | WBEST [17, 18]                                   |
|---------------------|---------------------------------|---|--|
| Inference metric    | One-way delay or RTT            | Dispersion                                    | Dispersion                                       |
| Accuracy dependency | Depends on the probing rate $R$ | Depends on the probing rate and link capacity | Depends on the number of packet trains and pairs |
| Overhead dependency | Depends on probing rate $R$     | Depends on the probing rate $R$               | Depends on the number of packet trains and pairs |
| Estimation time     | Relatively large                | Relatively large                              | Relatively small                                 |

As described in the table, the self-loading and packet dispersion schemes do not consider the variations of the last hop wireless link, since they assume that the capacity of the bottleneck link is a constant. Thus, these schemes should inject a heavy probing traffic into the network so as to infer the significant changes between the bottleneck links. This may lead to the high intrusiveness, which tends to give an impact on the performance of the existing flows and also result in a larger estimation time until the bandwidth estimation has been converged as a stable value. On the other hand, the WBEST scheme sends the fixed number of packet trains and pairs, so as to estimate the effective capacity of the wireless bottleneck link and also to statistically detect the achievable throughput from the effective capacity. Thus, it seems that the WBEST scheme can achieve high accuracy and relatively low intrusiveness with a smaller estimation time.

In summary, for estimation of the available bandwidth, the WBEST scheme [17, 18] seems to be the most suitable in the wireless networks in terms of accuracy, intrusiveness and short convergence time than any other schemes. Accordingly, in this paper, we employ the WBEST scheme to estimate the available bandwidth of the new primary path.

To apply the WBEST algorithm to the proposed congestion control scheme, some minor modifications are made as follows:

### Modified WBEST Algorithm

When a new address of MN is informed in the Add-IP operation, CN performs the following iterations:

Set  $k = 1$  ( $k$  is the iteration number).

Step 1 Measure the effective capacity, as done in the first step of the WBEST scheme.

- (1.1) Send  $n$  pairs of the HEARTBEAT chunks to MN
- (1.2) Calculate the effective capacity based on the pairs of HEARTBEAT-ACK chunks from MN

Step 2 Measure the available network bandwidth, as done in the 2nd step of the WBEST scheme.

- (2.1) Send  $n$  pairs of HEARTBEAT chunk train at the rate  $R$  to MN
- (2.2) Calculate the available bandwidth, based on the responding HEARTBEAT-ACK chunks

Step 3 If the primary path was switched into the new path, then stop. Otherwise, go to Step 4.

Step 4  $B(k) = \alpha B(k) + (1 - \alpha)B(k - 1)$ , where  $0 < \alpha < 1$ . Set  $k = k + 1$ . Go to Step 1.



Note that the initial  $B(0)$  is given by the real capacity of the new link (e.g., 11 Mbps for WLAN).

CN begins the above algorithm when the Add-IP operation is performed, and stops when the Primary-Switching is completed, as described in Step 3. The algorithm is based on the existing WBEST scheme. However, instead of UDP-based probe packets, we use the SCTP HEARTBEAT chunk with 700 bytes and SCTP HEARTBEAT-ACK chunk with 40 bytes. In Step 4, the estimated network bandwidths are averaged with the weighting coefficient ( $\alpha$ ). In the proposed scheme,  $\alpha$  is set to 0.7, which is an empirically obtained value that has given the best performance in our prior simulations.

### 3.3 Adaptive Configuration of Congestion Window

Based on the effective capacity and available bandwidth estimated from the modified WBEST algorithm, CN will calculate a new congestion window size of the new path. The specific calculation of the new congestion window depends on the type of movement of MN.

First, when MN moves from 3G to WLAN, the bandwidth-delay product (BDP) will be drastically increased. In such a scenario, the aggressive scheme (described in Sect. 2) can be beneficial to fully utilize the link capacity of WLAN. In this case, it is preferred to set the new congestion window (of the new path) as the old congestion window (of the old path), if possible. Accordingly, we use the following equation to configure the initial congestion window of the new path:

$$CWND_{new} = CWND_{old} \times \frac{B_{new}}{C_{new}} \tag{1}$$

In Eq. (1),  $CWND_{new}$  is the initial congestion window of a new primary path and  $CWND_{old}$  is the current congestion window of the old path.  $B_{new}$  and  $C_{new}$  are calculated from the modified WBEST algorithm. In the equation,  $CWND_{new}$  will be set as large as  $CWND_{old}$  if the new path has the enough network bandwidth ( $B_{new}$  is nearly identical to  $C_{new}$ ). In the opposite case,  $CWND_{new}$  will be set to a small size.

On the other hand, in the movement from WLAN to 3G, the BDP will be reduced after handover. In this case, the aggressive scheme of Eq. (1) may lead to the over-utilization of the link. Therefore, we calculate  $CWND_{new}$  based on the BDP value of a new path, instead of the  $CWND_{old}$ , as expressed in the following equation:

$$CWND_{new} = BDP_{new} \times \frac{B_{new}}{C_{new}} \tag{2}$$

In Eq. (2),  $BDP_{new}$  is the BDP value of a new primary path, which is calculated with the effective capacity and the minimum Round Trip Time (RTT) value,  $BDP = C_{new} \times RTT_{min}$ . To measure the RTT between CN and MN, we exchange the SCTP HEARTBEAT and HEARTBEAT-ACK chunks with the timestamp fields in Step 2 of the modified WBEST algorithm.  $RTT_{min}$  is given by the minimum value among the measured RTTs.

Note that Eq. (1) and (2) can be summarized as follows:

$$CWND_{new} = MIN(CWND_{old}, BDP_{new}) \times \frac{B_{new}}{C_{new}} \tag{3}$$

As depicted in Eq. (3), the initial congestion window of the new primary path will be calculated as the minimum between the congestion window of the old path and the BDP value of the new path.



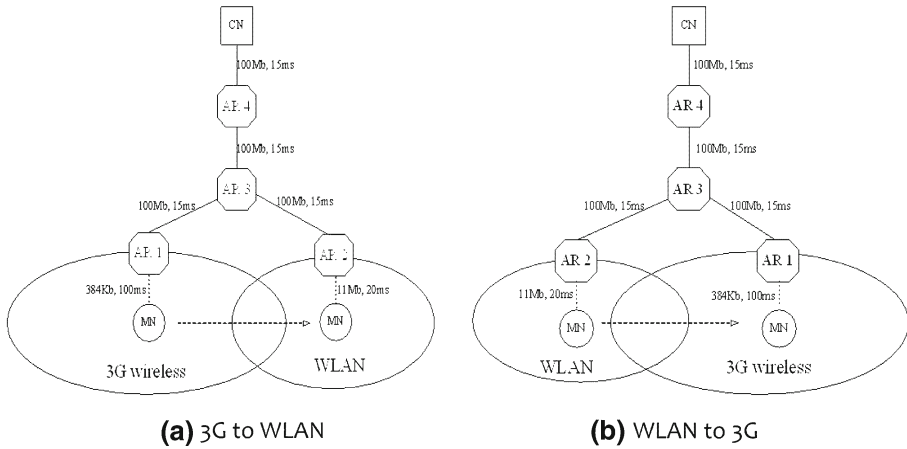


Fig. 4 Test movement scenarios

In the meantime, the slow start threshold for the congestion control may give an impact on the transmission throughput. That is, a larger value of slow start threshold may lead to over-utilization of the link, whereas a smaller value may lead to under-utilization of the link. Thus, based on the existing WiSECC scheme, we configure the slow start threshold of the new primary path as follows:  $\frac{B_{new} \cdot RTT_{min}}{2L}$ .

On the other hand, in the proposed scheme, the adjustment of the congestion window is performed based on only the available bandwidth (i.e., free bandwidth available in the network). This implies that the adaptive congestion window will not give a significant impact on the existing SCTP flows.

### 4 Numerical Results

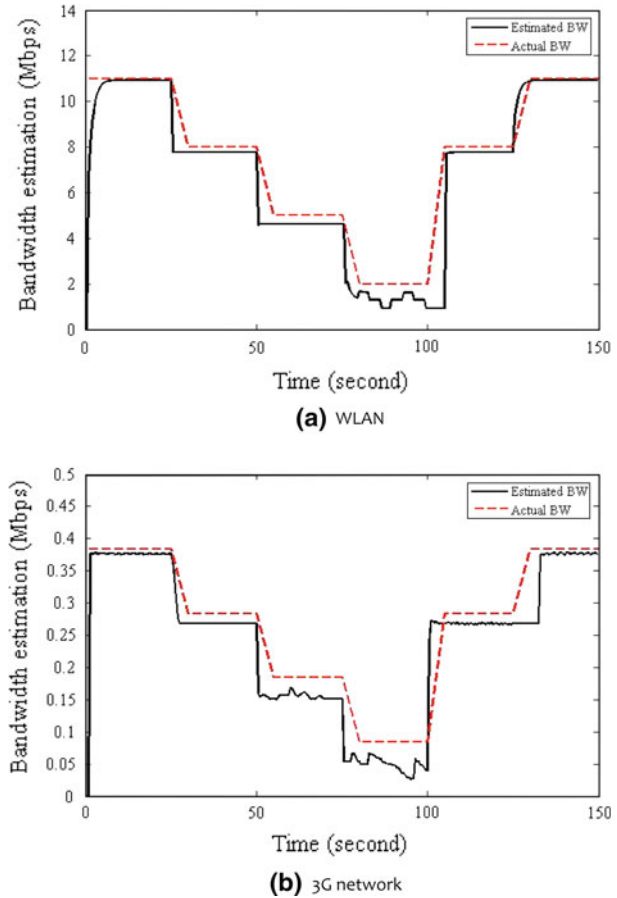
In this section, we present the performance analysis of the proposed mSCTP congestion control scheme using ns-2 network simulator. For simulation, we consider the two types of movement of MN: from 3G to WLAN and from WLAN to 3G, as shown in Fig. 4. Moreover, the data packets flow from CN to MN. We also note that the proposed scheme can be applied to data transmissions from MN to CN, if CN is also in the heterogeneous networks, in which the bandwidth estimation will be done at the MN side.

In Fig. 4a, MN initially receives the data packets of the file transfer application in the 3G network. Then, MN moves into the WLAN and switches the primary path to the new IP address. In Fig. 4b, MN begins the data communications in the WLAN and then moves into the 3G network.

The parameters used for simulation are set as follows. The fixed/wired links between CN and the access routers are all set to be 100 Mbps of bandwidth and 15 ms of transmission delay. 3G wireless link of MN is set to 384 Kbps and 100 ms, whereas WLAN link of MN is set to 11 Mbps and 20 ms. Maximum Transfer Unit (MTU) is set to 1500 bytes. On the other hand, the primary path is switched from 3G wireless to WLAN links at the time of 30 s. The simulation is performed over the 60 s. All the simulation results are averaged for the 10 test instances.

To perform the bandwidth estimation, we set the number of packet pairs and the length of packet trains ( $\mu$ ) to be 6 and 30 for the movement from 3G to WLAN, as recommended

**Fig. 5** Bandwidth estimation in WLAN and 3G

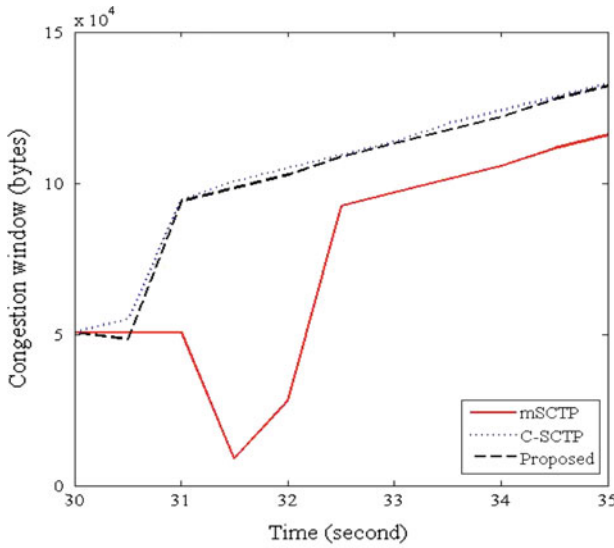


in [17, 18]. On the other hand, in the case of the movement from WLAN to 3G, we set  $m$  as 4 and 12, respectively, which are based on the prior empirical simulations.

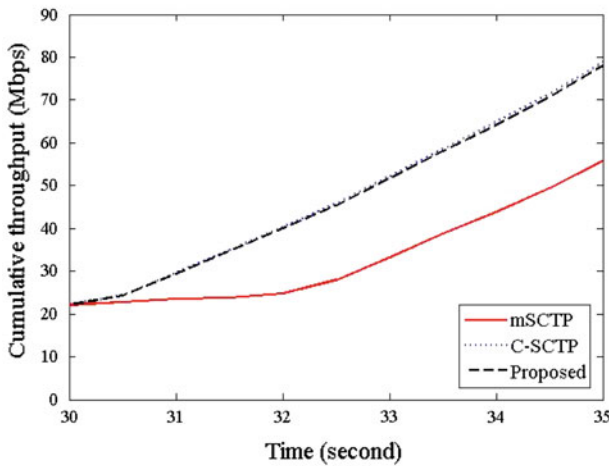
#### 4.1 Accuracy of Bandwidth Estimation

Before going further to the performance analysis of the proposed scheme, we first evaluate the accuracy of the modified WBEST algorithm in the viewpoint of the bandwidth estimation. For this purpose, we first run an SCTP association in the test networks of Fig. 4. Each of three UDP-based CBR sources generates background traffics irregularly at the rate of 2 Mbps for WLAN and 100 Kbps for 3G.

Figure 5 shows the actual bandwidth and the estimated bandwidth given by the modified WBEST scheme, when MN moves from 3G to WLAN (Fig. 5a) and from WLAN to 3G (Fig. 5b). At the beginning of the simulation (i.e., at the time of 0 s), all the UDP connections are off. At the time of 25 s, the first UDP connection is activated; the second UDP connection is at the time of 50 s; the third connection is at the time of 75 s; the first and second UDP connections are off at the time of 100 s; finally, the third connection is off at the time of 125 s.



(a) Congestion window

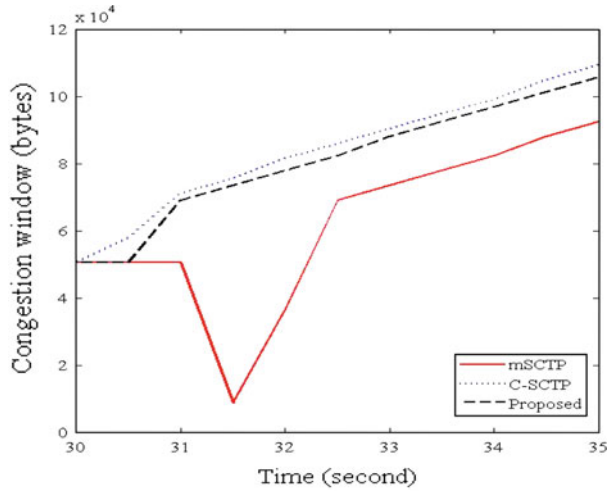


(b) Throughput

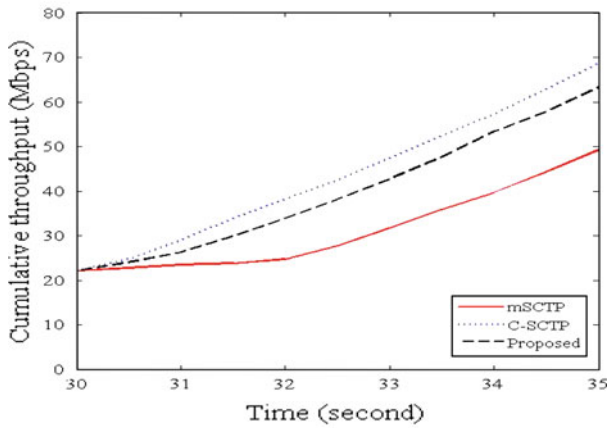
Fig. 6 Performance of mSCTP handover without background traf c

In Fig. 5a and b, it is shown that the estimated bandwidth is almost identical to the actual bandwidth when there is no background traf c (i.e., until the time of 25 s). As the background traf c increases, the estimated bandwidth seems to be slightly lower than the actual bandwidth. This is because the probing packets used for bandwidth estimation are lost due to the congestion, and the modified WBEST tends to reduce the estimated bandwidth according to the loss rate. Such the pattern continues as the amount of background traf c becomes larger, as shown at the time of 75 and 100s in Fig. and b. It is noted that this slight under-estimation can be helpful to prevent the excessive data transmission when the new path is in congestion. From these empirical results, we can see that the modified WBEST

**Fig. 7** Performance with the background traffic of 40% of the WLAN link capacity



**(a)** Congestion window



**(b)** Throughput

scheme can give a reasonable estimation of the available network bandwidth even in the congested networks.

Now, we will compare the performance of the proposed congestion control scheme with the two existing schemes: the normal mSCTP (conservative) scheme and the Cellular SCTP (aggressive) scheme. In particular, we consider Cellular SCTP (C-SCTP) without bicasting mechanism, since the main purpose of this paper is to analyze the performance of the congestion control schemes during handover. In the experiments, all the candidate schemes use a common value of the slow start threshold, as described in Sect.

#### 4.2 Movement from 3G to WLAN

First, we compare the performance of the three candidate schemes for congestion control, when there is no background traffic, as shown in Fig. 6a, CN initially sends the data

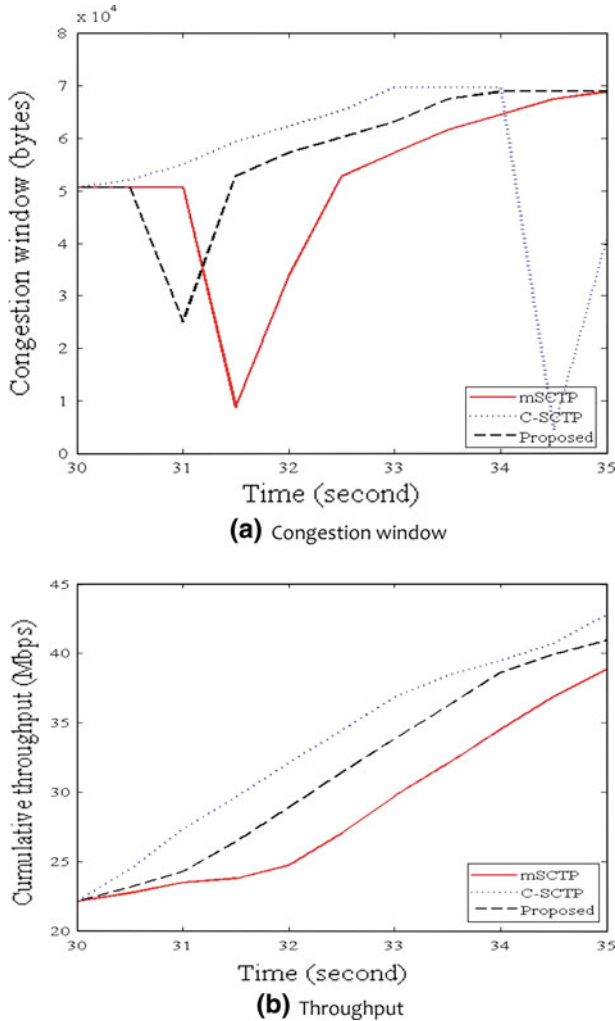
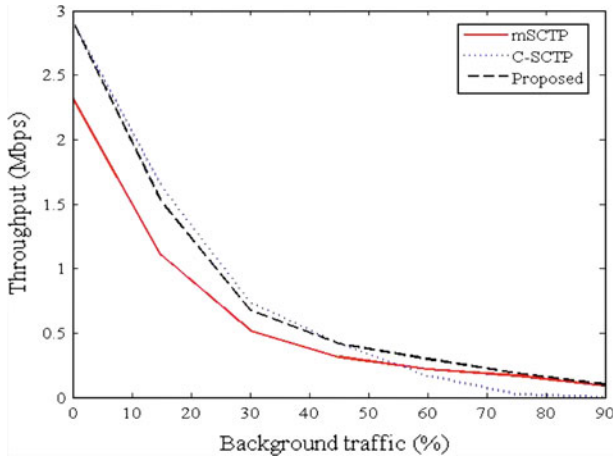


Fig. 8 Performance with the background traffic of 80% of the WLAN link capacity

packets in the 3G network. When MN enters the WLAN network, CN switches the primary path into the WLAN link at the time of 30s. At this time, we can see that the proposed scheme increases the congestion window faster than the normal mSCTP scheme does. Thus, the proposed scheme gives better throughput than the normal mSCTP scheme, as shown in Fig. 6b. Such a performance gain comes because the proposed scheme adaptively calculates a new congestion window based on the bandwidth estimation for the new primary path (i.e., WLAN). On the other hand, it is observed in Fig. 6b that the throughput of the proposed scheme is almost identical to that of C-SCTP. This is because the congestion window size obtained in the proposed scheme is nearly equivalent to the congestion window size of the old path (i.e., 3G), as done in the C-SCTP scheme.

Figure 7 shows the performance of the proposed and existing schemes when the background traffic is generated by 40% of the WLAN link capacity. In Fig. 7a, it is observed that the proposed scheme increases the congestion window faster than the normal mSCTP



**Fig. 9** Comparison of throughput for various background traffic levels

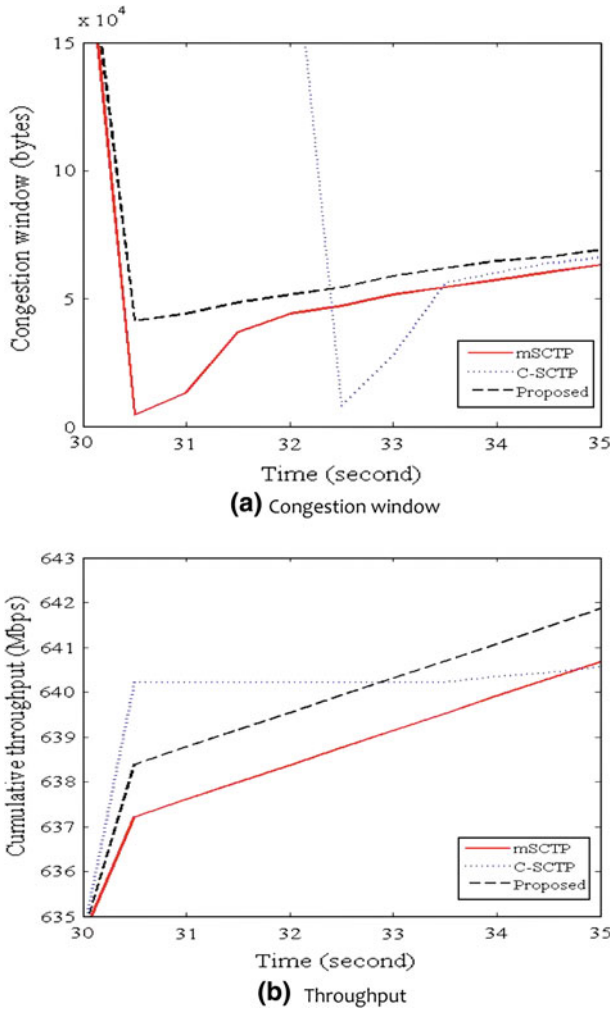
scheme, even when there is the background traffic with 40% of the WLAN link capacity. In Fig. 7b, the proposed scheme outperforms the normal mSCTP scheme, as similarly in Fig. 6b. On the other hand, we can see in Fig. 7a and b that a new congestion window of the proposed scheme is a little less than that of C-SCTP scheme. This is because the proposed scheme tends to slightly underestimate the available network bandwidth, when there is the background traffic.

Figure 8 compares the performance of the candidate schemes when the background traffic is loaded by 80% of the WLAN link capacity. In Fig. 8a, we can see that the congestion windows are fluctuated for all the schemes due to the heavy background traffic. In particular, the congestion window of C-SCTP drastically falls down around the time of 35 s, because C-SCTP tends to over-utilize the available bandwidth in the new network, which induces the frequent packet losses and subsequent retransmission timeouts. Therefore, the throughput performance of the C-SCTP scheme gets worse than the other schemes as the simulation goes on, as shown in Fig. 8b. On the other hand, the proposed scheme configures the new initial congestion window to be as small as possible, according to the bandwidth estimation. This ensures that the proposed scheme can achieve better performance than the existing two schemes in the highly congested networks.

Figure 9 compares the throughputs of mSCTP handover for the candidate schemes for different network loads (background traffic), in which the total throughputs are plotted over the entire simulation period. In the figure, we can see that the C-SCTP and the proposed schemes give better performance than the mSCTP scheme, until the background traffic is loaded by 45% of the WLAN capacity. When the offered background traffic is greater than 45% of the WLAN capacity, the proposed scheme outperforms the C-SCTP scheme as well as the mSCTP scheme. On the other hand, the proposed scheme tends to give a similar throughput as the mSCTP scheme in the highly congested network.

#### 4.3 Movement from WLAN to 3G

Figure 10 shows the performance comparison of the candidate schemes for movement from WLAN to 3G, in which no background traffic is given. In Fig. 10a, MN begins data communications in the WLAN and then switches the primary path into the 3G network at the

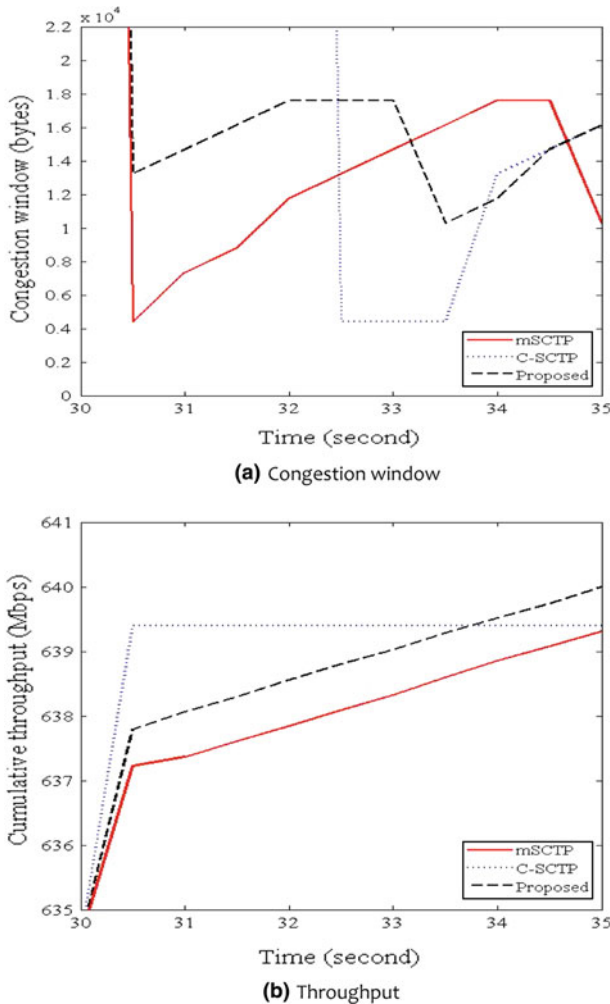


**Fig. 10** Performance of mSCTP handover without background traffic

time of 30 s. At this time, we can see that the congestion windows of the all the schemes are decreased because the respective BDP values are reduced after handover (WLAN to 3G). In particular, the congestion window of the C-SCTP scheme begins to decrease around the time of 32 s, which is slightly later compared to the other schemes. This is because in the C-SCTP scheme the congestion window is decreased just after CN experiences some packet losses with the retransmission timeouts. Therefore, the corresponding throughputs will be degraded, as the simulation time goes on, as shown in Fig. 10. On the other hand, the proposed scheme outperforms the existing two schemes in the throughput perspective.

Figure 11 shows the performances when the background traffic is generated by 40% of the 3G link capacity. In Fig. 11a, the congestion window of C-SCTP continues to fall down until the time of 35 s, since it induces the frequent packet losses and the subsequent retransmission timeouts due to the background traffic. The proposed scheme tends to configure the congestion window size larger than the mSCTP scheme, and thus the proposed scheme provides better throughput than the mSCTP scheme, as shown in Fig. 11b.





**Fig. 11** Performance with the background traffic of 40% of the 3G link capacity

Figure 12 compares the performance of mSCTP handover when the background traffic is loaded by 80% of the 3G link capacity. In Fig. 2a, it is shown that the congestion window of the proposed scheme tends to change in the similar pattern with the normal mSCTP scheme. This is because in the overloaded network condition, the proposed scheme operates in the conservative way, and thus the congestion window size of the new primary path is configured as the similar value with the initial congestion window size of the normal mSCTP scheme. In Fig. 12b, we can see that the cumulative throughput of the proposed scheme is nearly the same with that of the normal mSCTP scheme. However, the throughput of C-SCTP is degraded, as the simulation time goes on.

Figure 13 shows the throughput of the candidate schemes for a variety of background traffic. In Fig. 13, we can see that the proposed scheme outperforms the existing two schemes in the throughput perspective, until the background traffic is loaded by 70% of the 3G link capacity. When the offered background traffic is greater than 70% of the link capacity (i.e., in the highly congested networks), all of the candidate schemes seem to provide the similar

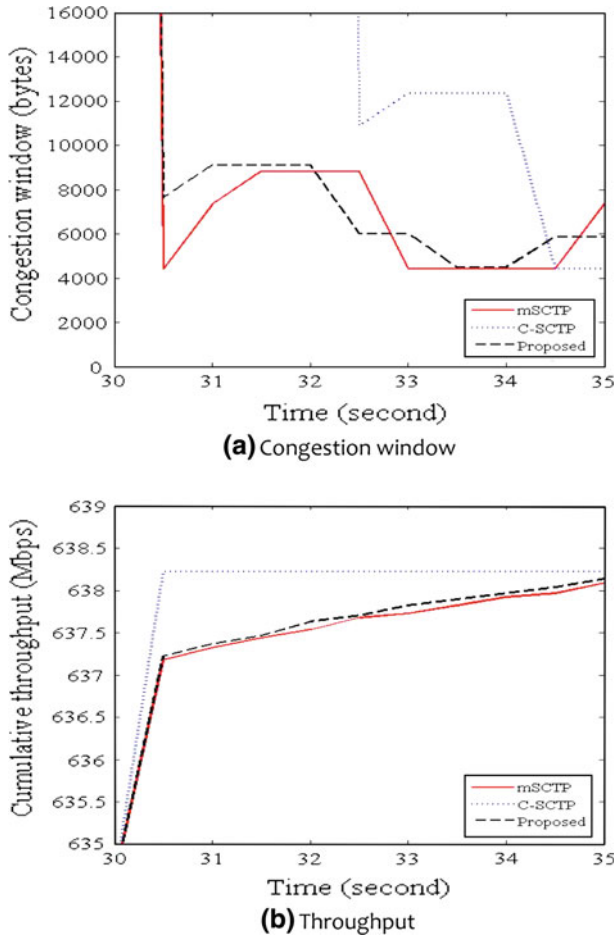


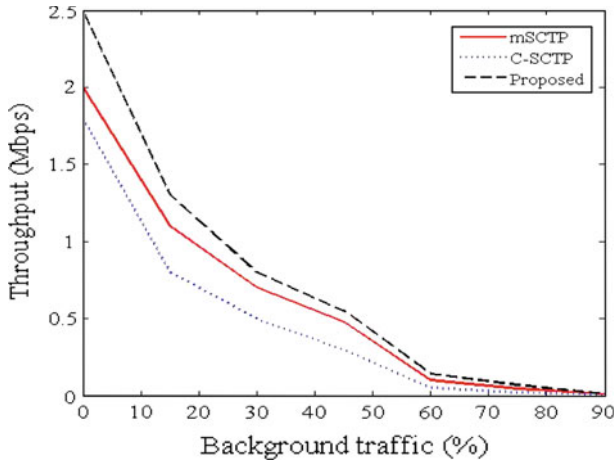
Fig. 12 Performance with the background traf c of 80% of the 3G link capacity

throughputs. This is because all of the candidate schemes experiences the frequent packet losses and thus retransmission timeouts in the highly congested networks.

### 5 Conclusions

In this paper, we have proposed an adaptive congestion control scheme of mSCTP for vertical handover across heterogeneous wireless networks. In the existing schemes, the initial congestion window size of the new primary path is con gured in the conservative or aggressive way, irrespective of the network conditions such as available network bandwidth. These schemes tend to induce the under- or over-utilization of the bandwidth in the new network.

To cope with such a problem, we proposed an adaptive mSCTP congestion control scheme, in which the available network bandwidth is estimated and then the congestion window of the new primary path is calculated based on the estimated network bandwidth. By the ns-2 simulations, we compared the proposed scheme and the two existing schemes for mSCTP vertical handover between 3G wireless and WLAN.



**Fig. 13** Comparison of throughput for various background traf cs

From the simulation results, we can see that the proposed scheme gives better throughput than the two existing schemes by adaptively con guring the congestion window of the new primary path according to network conditions. However, it seems that all of the candidate schemes tend to give similar throughputs in the highly congested network.

To the best of our knowledge, this paper is the rst to provide an adaptive congestion control of mSCTP vertical handover, which is based on the estimation of available wireless link bandwidths in the heterogeneous networks. To apply the proposed scheme in real networks, some further works are still needed, which may include the consideration of different mobility patterns such as ping-pong movement, the performance analysis with a variety of performance metrics, such as the fairness and the control overhead associated with bandwidth estimation, and the study of mSCTP with various bandwidth estimation techniques under different network environments.

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