# Bandwidth Control Method and Available Bandwidth Estimation Method for Aggregated Traffic

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Regular Paper

# Bandwidth Control Method and Available Bandwidth Estimation Method for Aggregated Traffic

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***Abstract:*** When multiple applications at two sites connected by a best-effort service network through gateway (GW) equipment communicate simultaneously, the receive rate of a high-priority application communication flow can be smaller than its necessary bandwidth (BW). In this paper, we refer to this problem as the deficit in bandwidth of a high-priority flow (DBHPF) problem. In order to handle this problem, we consider controlling the BW assigned to each flow based on the available bandwidth (ABW) estimated by the GW. The estimated ABW can be larger than the actual ABW due to the error in the estimation. Thus, the receive rate of a high-priority application can be smaller than its necessary BW, even if the actual ABW is larger than the necessary BW. In this paper, we propose a priority-based BW control method that estimates the receive rate of each flow using estimated ABW and related information, and mitigates the effect of the DBHPF problem by controlling the transmission BW of each flow in order to compensate for the difference between the estimated receive rate and the necessary BW according to the priorities of flows. We call the proposed method estimated-receive-rate-based bandwidth control (eR2BC). We also propose a method for ABW estimation with less overhead than existing methods. We conducted experiments using the proposed methods in a virtual network constructed with virtual machines and confirmed that the proposed methods can mitigate the effect of the DBHPF problem better than existing methods.

***Keywords:*** bandwidth control, available bandwidth estimation, aggregated traffic, scheduler, AIMD

## 1. Introduction

When multiple applications at two sites connected by a best-effort service network through gateway equipment (GW) communicate simultaneously in a system (**Fig. 1**) such as a remote maintenance system for ITS roadside units, the receive rate of a high-priority application communication flow can be smaller than its necessary bandwidth (BW), even if the available bandwidth (ABW) between the two sites is larger than the necessary BW. In this paper, we refer to this problem as the deficit in bandwidth of a high-priority flow (DBHPF) problem. If the receive rate of an application is less than its necessary BW, the application may not receive the necessary data in time or it may fail to receive the necessary data due to packet losses. For example, the surveillance video image can be disrupted and the surveillance can be adversely affected in the case of a video surveillance application using streaming video. Thus, we consider that it is useful to mitigate the DBHPF problem and make the receive rate of a high-priority flow more likely to be equal to or more than the necessary BW. If a GW does not control the bandwidth of each flow when forwarding the aggregated traffic composed of multiple flows, the network, including GWs, drops packets regardless of the priority of the flows. Thus, if the sum of the necessary BW of multiple flows is larger than the ABW, high-priority and low-priority flows can be dropped, regardless of their priorities.

A packet scheduler is often used in GWs to control the priority and the BW of flows [1]. A packet scheduler schedules the packet transmission of each flow, so that the transmission rate of the aggregated traffic is below the configured upper limit of the transmission rate of the aggregated traffic. In the following, we refer to the upper limit of the transmission rate of the aggregated traffic configured in a packet scheduler as the upper limit of the transmission rate. If the upper limit of the transmission rate of the packet scheduler in the GW is larger than the ABW, a number of the packets forwarded by the GW are dropped, regardless of their priorities in the best-effort service network. On the other hand, if the upper limit of the transmission rate of the packet scheduler in the GW is smaller than the ABW, the ABW is not fully utilized. Therefore, it is desirable to set the upper limit of the transmission rate of the scheduler in the GW at the ABW. The GW, however, must estimate the ABW used for packet scheduling because the ABW is not fixed and always changes in best-effort service networks. These discussions lead to the idea of estimating the ABW at the GW, so that it can adaptively control the BW of the aggregated traffic.

The estimated ABW usually has some error and can be larger than the actual ABW, which leads to the following problem. If the estimated ABW is larger than the actual ABW, packets of a high-priority flow are more likely to be dropped at the bottleneck link in the best-effort service network. If packets of a high-priority flow are dropped, the receive rate of the flow becomes smaller than its transmission rate (**Fig. 2**). In the case of TCP, the transmission rate of flows can become smaller due to the behavior of

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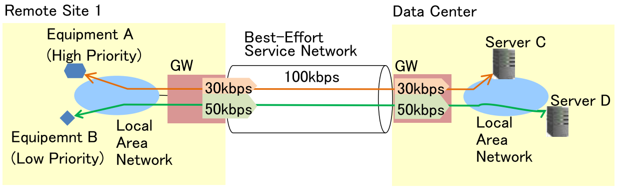


**Fig. 1** Example of communication between two sites connected through a best-effort service network.

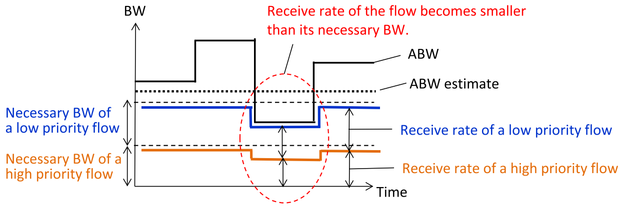


**Fig. 2** Example of the occurrence of the deficit in bandwidth of high-priority flow problem.

the congestion control algorithm [2]. Therefore, the receive rate of a high-priority flow becomes smaller than the necessary BW, even if the GW sets the upper limit of the transmission rate at the estimated ABW and allocates the necessary BW of the flow to the transmission rate of the flow. Therefore, the GW must allocate a larger transmission BW than the necessary BW to the transmission rate of a high-priority flow in order to mitigate the effect of the DBHPF problem.

This paper proposes a method to mitigate the effect of the DBHPF problem and evaluates its effectiveness. The contributions of this paper are summarized as follows:

i) We propose a priority-based BW control method executed by a GW for mitigating the effect of the DBHPF problem, which solves the drawbacks of the related studies. We call the proposed method estimated-receive-rate-based bandwidth control (eR2BC). Even though the related studies do not mention the DBHPF problem directly, they deal with larger problems which cover the DBHPF problem. The drawbacks of the related studies are as follows:
  - The drawback of the combination of ABW estimation and Priority Queueing is that multiple flows may not be able to share the estimated ABW according to the necessary BW of flows because the highest-priority flow can use all of the estimated ABW.
  - The drawback of the combination of ABW estimation, priority control and BW control based on the necessary BW of flows is that no recovery measure is taken when the DBHPF problem is caused.
  - The drawback of OverQoS [3] is that the transmission of the aggregated traffic can use only part of the estimated ABW.
  - The drawback of CM [4] is that the applications need to be changed to utilize the APIs provided by CM for mitigating the DBHPF problem.

  In the proposed method, GWs estimate the receive rate of flows using information obtained from ABW estimation, and control the transmission BW of each flow in order to compensate for the difference between the estimated receive rate and the necessary BW according to the priorities of flows.

ii) We propose an ABW estimation method that works with smaller additional traffic as compared to existing methods.

iii) Through the evaluation of the proposed methods, we confirmed that the proposed methods can mitigate the effect of the DBHPF problem.

  We experimentally investigated the proposed methods in a virtual network constructed with virtual machines. The results revealed that the proposed methods can mitigate the effect of the DBHPF problem better than existing methods.

The remainder of this paper is organized as follows. Section 2 describes related studies, and Section 3 explains the proposed methods for mitigating the effect of the DBHPF problem and estimating the ABW. Section 4 shows the evaluation method and the results of the proposed methods, and Section 5 concludes this paper.

## 2. Related Work

The DBHPF problem is a problem in which the receive rate of a high-priority flow in aggregated traffic becomes less than the necessary BW of the flow when the aggregated traffic is transmitted by GWs connected by a best effort service network. The combination of priority control and BW control of flows based on the estimated ABW of the aggregated traffic is relevant to mitigating the DBHPF problem. In addition to handling the priority of flows, BW control is necessary so that the multiple flows can share the ABW while mitigating the DBHPF problem. In this section, we review the related work that can be used for mitigating the DBHPF problem in Section 2.1 and the related work for ABW estimation in Section 2.2 respectively.

### 2.1 Related Work for the Mitigation of the DBHPF Problem

Priority Queueing packet scheduler (PQ) is generally used to control the priority of flows. PQ transmits a packet of the highest-priority flow that has some packets in the queue. When PQ is used with the upper limit of the transmission rate set at the estimated ABW obtained by an ABW estimation method, the highest-priority flow can transmit packets at any rate up to the estimated ABW. Thus, the combination of ABW estimation and PQ can mitigate the DBHPF problem to some extent. However, the DBHPF problem can be caused by packet losses in the best effort service network when the estimated ABW is larger than the actual ABW. Since PQ transmits a packet of the highest-priority flow that has some packets in the queue, the highest-priority flow can use all of the estimated ABW if it tries to use all usable BW like bulk data transmission by TCP. This leads to a problem where multiple flows cannot share the estimated ABW while mitigating the DBHPF problem. We need to use BW control in addition to priority control to allow multiple flows to share the estimated ABW while mitigating the DBHPF problem.

A combination of ABW estimation, priority control and BW control of flows based on their necessary BW can be used to allow multiple flows to share the estimated ABW while mitigating the DBHPF problem. Hereafter, we call this method “the basic priority-based BW control method”. The basic priority-based BW control method sets the transmission rate of each flow in the packet scheduler at the necessary BW of flows in the descending order of the priority of each flow under the condition that the sum of the transmission rate of flows does not exceed the estimated ABW. If the estimated ABW is not large enough, the transmission rate of a low-priority flow in the packet scheduler can be less than the necessary BW of the flow. The DBHPF problem can be caused by packet losses in the best effort service network with the basic priority-based BW control method. The drawback of the basic priority-based BW control method is that no recovery measure is taken when the DBHPF problem is caused. References [5], [6], [10] explained in Section 2.2 use a packet scheduler to control the transmission rate of each flow, and it is considered that they adopt the basic priority-based BW control method.

Subramanian et al. propose OverQoS [3], which controls the priority and BW of flows in aggregated traffic and aims to guarantee the receive rate and the packet loss rate statistically. Reference [3] proposes a) a method to calculate the minimum estimated ABW ($C_{\min}$) which is expected to be available in the network with the probability specified by a configuration parameter and b) redundant transmission method which maintains the packet loss rate of the flow less than the specified value given as a configuration parameter. OverQoS can mitigate the DBHPF problem by using a packet scheduler with the upper limit of the transmission rate set at $C_{\min}$ for BW control in order to allocate the necessary BW to high-priority flows. However, the upper limit of the transmission rate of the packet scheduler needs to be set at $C_{\min}$ which is usually less than the estimated ABW. This leads to a problem where the transmission of the aggregated traffic can use only part of the estimated ABW.

Balakrishnan et al. propose Congestion Manager (CM) [4], which aims to enable applications to perform better by allowing the applications to track the congestion and the changes of the ABW and adapt to them. CM provides a framework which allows a sender application to receive a feedback from a receiver application and request CM to allocate transmission BW to its flows. The sender application can determine the transmission BW of flows based on the feedback, the estimated ABW and the priority of flows. With the framework provided by CM, the sender application can receive the feedback from the receiver application and modify the transmission BW of flows based the feedback, the estimated ABW and the priority of flows in order to mitigate the DBHPF problem. However, both the sender and the receiver applications need to be modified to use the APIs provided by CM to mitigate the DBHPF problem. Not all applications can be changed. Even if the applications can be changed, it needs effort to modify the applications. In addition, Ref. [4] does not show how applications control the transmission BW of flows to mitigate the DBHPF problem.

In summary, related studies that can be used for mitigating the DBHPF problem have the following drawbacks. In the case of the combination of ABW estimation and Priority Queueing, multiple flows may not be able to share the estimated ABW according to the necessary BW of flows because the highest-priority flow can use all of the estimated ABW. In the case of the basic priority-based BW control method, no recovery measure is taken when the DBHPF problem is caused by a packet loss in the best effort service network. In the case of OverQoS, the transmission of the aggregated traffic can use only part of the estimated ABW. In the case of CM, the applications need to be changed to utilize the APIs provided by CM for mitigating the DBHPF problem. In this paper, we propose a priority-based BW control method which can solve these drawbacks.

### 2.2 Related Work for ABW Estimation

In this section, we review the related work for ABW estimation by GWs focusing on the amount of the additional traffic used for ABW estimation (overhead). The reason why we focus on the overhead of ABW estimation method is as follows. When a system uses a pay-as-you-use communication service, such as some mobile communication services, the reduction of overhead leads to the reduction of operational costs. For such cases, the reduction of overhead can be useful. Note that we focus on only ABW estimation method which may be a part of a flow rate control algorithm. For existing studies which we consider use the basic priority-based BW control method, we briefly mention their flow BW control method.

Damjanovic et al. propose MulTFRC [5], [6], which estimates ABW using an extension of the transmission rate formula for TCP Friendly Rate Control (TFRC) [7], [8]. TFRC calculates the transmission rate of a flow that does not support congestion control, so that the transmission rate is fair to the transmission rate of TCP flows competing with the flow at a bottleneck link. The use of a packet scheduler is proposed for flow BW control [6]. The overhead of MulTFRC for ABW estimation is equal to that of TFRC.

The overhead of TFRC consists of additional header fields, such as the sequence number of a packet and feedback packets sent by the receiver for every RTT. Therefore, the overhead of TFRC is proportional to the number of transmitted packets. In implementations of TFRC as a part of the IETF Datagram Congestion Control Protocol (DCCP) [9], the additional header length is 32 bytes. If the MTU size is 1,500 bytes, then the overhead is 32/1,500 (approximately 2%) of the transmitted data.

Singh et al. propose Multi-Probe Aggregate TCP (MPAT) [10], in which the GW manages the congestion window of multiple TCP flows and estimates the ABW for multiple TCP flows between two sites. For BW control, MPAT schedules packet transmission so that the ratio of the transmission rate of each TCP flow to that of other TCP flows can be the same as the ratio given by a user. The overhead for MPAT for ABW estimation is 0 for TCP flows and is equal to that for TFRC for non-TCP flows.

Subramanian et al. propose OverQoS [3], which estimates the ABW as the sum of the transmission rate of multiple TCP connections or TFRC connections. The overhead of OverQoS for ABW estimation is equal to that of TFRC.

Balakrishnan et al. propose Congestion Manager (CM) [4], which estimates the ABW through a method similar to the TCP congestion control method using header information, such as the sequence number added to a transmitted packet. The overhead for CM for ABW estimation is similar to that for TFRC.

In addition to the studies mentioned above, MulTCP [11] and PA-MulTCP [12], which estimate the ABW for aggregated traffic composed of multiple TCP flows, were proposed. MulTCP and PA-MulTCP deal with only TCP flows and the overhead for

ABW estimation is zero.

In addition to the above-mentioned ABW estimation methods using additional header information attached to data packets, ABW estimation methods using probe packets have been widely researched [13], [14], [15], [16], [17], [18], [19], [20]. These methods can be classified into two groups: methods that use packet pairs for probing [17] and methods that use packet trains for probing [13], [14], [15], [16], [18], [19], [20]. In packet-pair-based methods, probe packets are sent in the unit of two consecutive packets. In packet-train-based methods, probe packets are sent in units of more than two consecutive packets.

The amount of probe packets is the main cause of overhead in methods that use probe packets. The overhead for one estimation is more than several tens of kbytes when the ABW is approximately 10 Mbps [21]. Even though the overhead does not depend on the amount of data traffic and is proportional to the frequency of the transmission of probe packets, the overhead of one ABW estimation is large.

In summary, the overhead for ABW estimation of existing methods which can handle non-TCP flows using additional header information attached to data packets is equal to that for TFRC. As described above, the overhead for TFRC is proportional to the number of transmitted packets. The overhead is more than several tens of kbytes per estimation with methods that use probe packet when the ABW is approximately 10 Mbps. In this paper, we propose an ABW estimation method which estimates the ABW with less overhead than the existing methods and evaluate the proposed ABW estimation method with the proposed method for mitigating the DBHPF problem.

## 3. Proposed Method

In this section, we propose a priority-based BW control method that mitigates the effect of the DBHPF problem and an ABW estimation method that can reduce the overhead for ABW estimation as the ABW estimation method that we use to evaluate the proposed priority-based BW control method.

### 3.1 Proposed Priority-based BW Control Method

We propose a priority-based BW control method for mitigating the effect of the DBHPF problem. The proposed method estimates the receive rate of flows using information obtained through ABW estimation and controls the transmission BW of each flow in order to compensate for the difference between the estimated receive rate and the necessary BW according to the priority of each flow. We call the proposed method estimated-receive-rate-based bandwidth control (eR2BC). The key idea is that a GW assigns larger BWs to higher-priority flows so that their receive rate can be larger than their necessary BW, even if packets are dropped in the best-effort service network, regardless of their priorities. Specifically, a GW estimates the receive rate of flows using information obtained from ABW estimation and controls the transmission BW of each flow in order to compensate for the difference between the estimated receive rate and the necessary BW according to the priority of each flow.

First, we explain the basic strategy used in eR2BC and introduce the variables and parameters used in the following discussion. Second, we explain the details of the strategy of BW control for flows with retransmission, such as TCP, and for flows without retransmission, such as UDP.

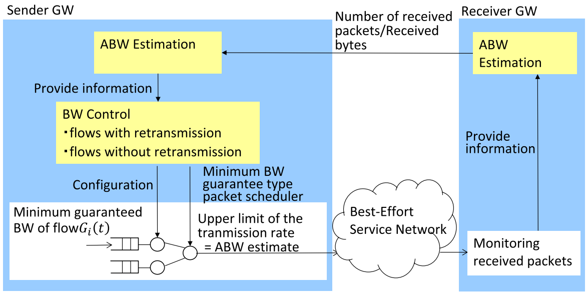


**Fig. 3** Structure of GWs that eR2BC assumes.

#### 3.1.1 Basic Strategy of the Proposed Priority-based BW Control Method

**A) Overview of the strategy**

First, we explain the basic strategy used in eR2BC. In **Fig. 3**, we explain the structure of GWs that eR2BC assumes. In eR2BC, a sender GW estimates the ABW and guesses the receive rate of flows at the receiver GW based on the new estimated ABW, the receive rate of the aggregated traffic, and packet loss events obtained through ABW estimation. The sender GW then sets the transmission BW of a flow used in the packet scheduler at a value larger than the necessary BW for the flow in descending order of the priorities of the flows under the condition in which the sum of the transmission BW of the flows does not exceed the estimated ABW. Therefore, the transmission BW of a low-priority flow used in the packet scheduler can be less than the necessary BW of the flow. eR2BC uses a packet scheduler that guarantees that the BW of each flow is larger than the given minimum BW value (Fig. 3). **Table 1** shows the variables used in the following explanation of eR2BC.

**B) Assumptions for the proposed method**

We assume that each flow to be controlled satisfies the following condition. Each flow is indexed in descending order of priority. Let $F_r$ be the set of indexes of flows with a retransmission function, and $F_u$ be the set of indices of flows without a retransmission function. We assume that each flow$_i$ $(i \in F_r)$ is given a time period to calculate the average receive rate at the receiver GW and evaluate whether the average receive rate satisfies the necessary BW. This time period is referred to herein as the average receive rate calculation period. Even if one or more data packets of a flow$_i$ $(i \in F_r)$ are not received due to packet losses in a congested network, the transport layer protocol of the flow can resend data afterward. In this case, the total transmission rate of the flow at the sender can be larger than the necessary BW. In **Fig. 4**, we explain how eR2BC assumes the application layer protocol sends data of a flow without retransmission. If the flow does not have a retransmission function, then the application layer protocol sends data at a rate larger than the necessary BW in order to compensate for packet losses in a congested network in order to satisfy the necessary BW at the receiver. We assume that a forward error correction (FEC) technique [22] is applied to the application data. Thus, the application layer protocol of flow$_i$ $(i \in F_u)$ sends redundant data for packet loss recovery by FEC

**Table 1** Variables used in the explanation of eR2BC.

| Variables | Explanation |
|---|---|
| $G_i(t)$ | Minimum guaranteed BW of a packet scheduler for flow$_i$ at the $t$-th update of the estimated ABW. |
| $R_e(t,i)$ | Estimated receive rate of flow$_i$ at the $t$-th update of the estimated ABW. |
| $R_f(i)$ | The necessary BW of flow$_i$. Configuration parameter. |
| $\delta_i(t)$ | Instantaneous deficit estimate of receive rate. Flow$_i$'s deficit of the estimated receive rate for the necessary BW at the $t$-th update of the estimated ABW. $R_f(i) - R_e(t,i)$. |
| $\Delta_i(t)$ | Sum of $\delta_i(t)$ over the latest $C$ times update of the estimated ABW for flow$_i$. |
| $W(t)$ | Estimated ABW at the $t$-th update of the estimated ABW. |
| $R(t-1)$ | Receive rate of the aggregated traffic at the receiver GW, which is calculated at the $t$-th update of the estimated ABW. |
| $S_d(t,i)$ | Desired transmission rate. Transmission rate that is necessary to compensate for the deficit of the estimated receive rate for the necessary BW for flow$_i$ at the $t$-th update of the estimated ABW. |
| $s(t)$ | Reception ratio of the aggregated traffic. The aggregated traffic's ratio of receive rate to transmission rate calculated at the $t$-th update of the estimated ABW. |
| $M$ | The number of the latest $s(t)$ used as input to calculate $s_p(t+1)$. Configuration parameter. |
| $s_p(t+1)$ | The prediction of the lower bound of $s(t+1)$ calculated at the $t$-th update of the estimated ABW. It is calculated using the latest $M$ times $s(t)$ as input. |
| $F_r$ | The set of flows with retransmission. |
| $F_u$ | The set of flows without retransmission. |
| $F$ | The set of flows that are the targets of BW control. $F = F_r \cup F_u$. |
| $C$ | The number of the updates of the estimated ABW over which $\delta_i(t)$ is summed for flows with retransmission to calculate $\Delta_i(t)$. Configuration parameter. |

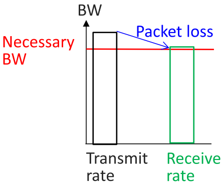


**Fig. 4** Transmission rate of a flow without retransmission.

(Fig. 4).

We assume that packets of the aggregated flows are dropped with the same probability. We also assume that, for all flows in the aggregated flows, the reception ratio for each flow, which is the ratio of the receive rate of a flow at the receiver GW to the transmission rate of the flow at the sender GW, is the same as the reception ratio of the aggregated traffic $s(t)$, which is the ratio of the receive rate at the receiver GW of the aggregated flows to the transmission rate at the sender GW of the aggregated flows.

### C) Bandwidth control for compensating for the deficit of the receive rate for the necessary BW

In **Fig. 5**, we explain the overview of the way how eR2BC calculates the minimum guaranteed BW to compensate for the deficit of the estimated receive rate for the necessary BW. In order to compensate for the deficit of the receive rate for the necessary BW, eR2BC makes the minimum guaranteed BW $G_i(t)$ of a higher priority flow larger than the necessary BW. eR2BC may make the minimum guaranteed BW $G_i(t)$ of a lower-priority flow less than the necessary BW, so as to maintain the upper limit of the transmission rate of the packet scheduler to be equal to the estimated ABW $W(t)$ (Fig. 5).

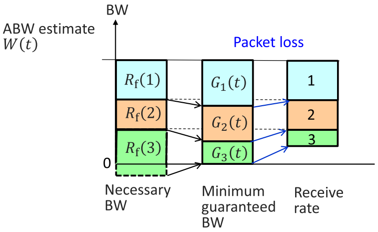


**Fig. 5** Overview of the way how eR2BC calculates the minimum guaranteed BW.

Instead of measuring the receive rate of each flow, the sender GW estimates the receive rate of each flow at the receiver GW using the information obtained through ABW estimation. In order to measure the receive rate of each flow at the receiver GW, the receiver GW must classify each received packet into a flow and calculate the accumulated amount of packets for each flow in addition to forwarding received packets. The sender GW uses the estimated receive rate of each flow at the receiver GW instead of the measured value in order to avoid the increase of processing load for packet forwarding at the receiver GW.

The sender GW, at the $t$-th update of the estimated ABW, calculates the desired transmission rate of flow$_i$ $S_d(t,i)$ in order to compensate for the deficit of the estimated receive rate for the necessary BW and computes $G_i(t)$ of each flow according to the following equation by descending order of the priority of the flows:

$$G_i(t) = \min\left(S_d(t,i),\, W(t) - \Sigma_{j=1}^{i-1} G_j(t)\right) \tag{1}$$

Thus, the higher the priority of a flow, the more likely that the receive rate of the flow is larger than the necessary BW, although the receive rates of lower-priority flows decrease.

There are two ways to calculate the reception ratio for the aggregated traffic $s(t)$: (a) the receive rate of the aggregated traffic $R(t-1)$/the transmission rate of the aggregated traffic, and (b) $R(t-1)$/the estimated ABW $W(t-1)$. We adopt (b) in this paper. We explain the reason why the effect of the DBHPF problem can be mitigated using (b). Since eR2BC sets $W(t-1)$ to the upper limit of the transmission rate of the packet scheduler, as explained above, the transmission rate of the aggregated traffic at the sender GW is equal to the transmission rate at the traffic source if the transmission rate of the traffic source is less than $W(t-1)$, and is $W(t-1)$ otherwise. Thus, $s(t)$ calculated by (b) is less than that calculated by (a) if the transmission rate at the traffic source is less than $W(t-1)$, and $s(t)$ calculated by both (a) and (b) are the same otherwise. According to the method of calculating the desired transmission rate of flow$_i$ $S_d(t,i)$ described in Sections 3.1.2 and 3.1.3, smaller $s(t)$ leads to a larger desired transmission rate $S_d(t,i)$ in order to compensate for the larger deficit of the estimated receive rate of a flow for the necessary BW.

Based on Eq. (1) and this relationship between $s(t)$ and $S_d(t,i)$, we can conclude that the minimum guaranteed BW of a higher-priority flow becomes larger with (b) than with (a) when the transmission rate of the traffic source is less than $W(t-1)$. Even though the minimum guaranteed BW of a lower-priority flow can be further decreased, additional BW is assigned to higher-priority-flows in order to compensate for the deficit of the estimated receive rate for the necessary BW with (b) as compared to that with (a), and

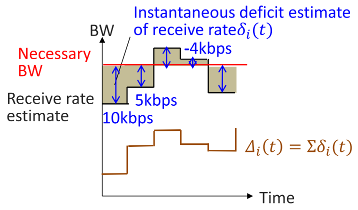


**Fig. 6** Example of the relationship between $\delta_i(t)$ and $\Delta_i(t)$.

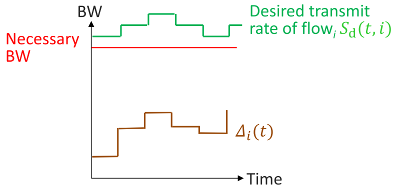


**Fig. 7** Example of the relationship between $S_d(t, i)$ and $\Delta_i(t)$.

the effect of the DBHPF problem can be mitigated.

### 3.1.2 Calculating $S_d(t, i)$ for Flows with Retransmission

In this section, we explain how to calculate the desired transmission rate $S_d(t, i)$ for flow$_i$ with retransmission. A flow with retransmission can later send data that could not be sent at one time. We define the instantaneous deficit estimate of receive rate $\delta_i(t)$ as the difference between the estimated receive rate of flow$_i$ and its necessary BW. Then, $\Delta_i(t)$ is calculated as the sum of $\delta_i(t)$ over a number of periods (**Fig. 6**). The numbers such as 10 kbps, 5 kbps, −4 kbps in Fig. 6 show the instantaneous deficit estimate of received rate $\delta_i(t)$ of flow$_i$. The area of the shaded part in Fig. 6 corresponds to $\Delta_i(t)$. $S_d(t, i)$ is determined such that $\Delta_i(t)$ becomes below 0 (**Fig. 7**).

The receive rate of flow$_i$ is estimated as follows. If no packet loss occurs, then the estimated receive rate $R_e(t, i)$ of flow$_i$ is regarded as the transmission rate of flow$_i$ $G_i(t-1)$. If packet losses occur, then the receive rate of the flow drops to the transmission rate multiplied by the reception ratio $s(t)$. As for flows with retransmission, packet losses can cause congestion control of each flow to work, and transmission rates at the traffic sources can become smaller. Therefore, the average transmission rates at the traffic sources are expected to be calculated by dividing the sum of BW allocated to flows with retransmission evenly among flows with retransmission, $\sum_{j\in F_r} G_j(t-1)/|F_r|$. Taking this effect into consideration, eR2BC calculates the estimated receive rate by using the following equation:

$$R_e(t, i) = s(t)\min\left(G_i(t-1), \left(\frac{\sum_{j\in F_r} G_j(t-1)}{|F_r|}\right)\right) \quad (2)$$

We define the instantaneous deficit estimate of receive rate $\delta_i(t)$ as the difference between the necessary BW of the flow and the estimated receive rate.

$$\delta_i(t) = R_f(i) - R_e(t, i) \quad (3)$$

We define the deficit of the estimated receive rate for the necessary BW $\Delta_i(t)$ as the sum of $\delta_i(t)$ over the latest $C$ time updates of the estimated ABW, as follows:

$$\Delta_i(t) = \Sigma_{k=t-(C-1)}^{t}\delta_i(k) \quad (4)$$

The value of $C$ is determined based on the average receive rate calculation period for an application and the frequency of update of the estimated ABW.

The desired transmission rate $S_d(t, i)$ is determined such that $\Delta_i(t) \leq 0$ can be satisfied in order to compensate for the deficit of the estimated receive rate for the necessary BW. The difference between the desired transmission rate and the necessary BW $R_f(i)$ is, however, bounded by $B_{\mathrm{lim}}$ in order to prevent harming TCP congestion control behavior by fluctuating the desired transmission rate too much in a short time. Based on the above discussion, $S_d(t, i)$ for flow$_i$ with retransmission is calculated as follows at the $t$-th update of the estimated ABW:

$$S_d(t, i) = \begin{cases} \min(R_f(i) + \Delta_i(t), R_f(i) + B_{\mathrm{lim}}) & (\Delta_i(t) > 0) \\ R_f(i) & (\Delta_i(t) \leq 0) \end{cases} \quad (5)$$

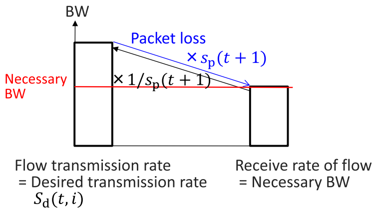


**Fig. 8** Calculation of $S_d(t, i)$ of a flow without retransmission.

### 3.1.3 Calculating $S_d(t, i)$ for Flows without Retransmission

Next, we explain how to calculate the desired transmission rate $S_d(t, i)$ for flow$_i$ without retransmission. Assuming error recovery by FEC, the receive rate of flows without retransmission must be controlled so as to be larger than the necessary BW.

According to the description in Section 3.1.1, the estimated receive rate of a flow without retransmission is regarded as the product of transmission rate of the flow and the reception ratio $s(t)$ for the aggregated traffic. If no packet loss occurs, then the estimated receive rate is assumed to be equal to transmission rate ($s(t) = 1$). The reception ratio $s(t + 1)$ for the aggregated traffic for $W(t)$ calculated at the $(t + 1)$-th update of the estimated ABW depends on the decrease rate of the ABW caused by the increase in the cross traffic. Even though $s(t + 1)$ is unknown at the $t$-th update of the estimated ABW, the system can predict the lower bound of $s(t + 1)$ if the system knows the upper limit of the decrease rate of the ABW. In this paper, we assume that the upper limit of the decrease rate of the ABW is the maximum value of the decrease rate of the ABW in the past period of some duration and the lower limit of $s(t + 1)$ is the minimum value of $s(t)$ in the same past period.

According to the precondition of the flows described in Section 3.1.1, we can increase the probability of the receive rate of flow$_i$ to be larger than the necessary BW if $S_d(t, i)$ is set at the product of the necessary BW and $1/s_p(t + 1)$ (**Fig. 8**). eR2BC calculates $s_p(t + 1)$, the predicted value of the lower bound of $s(t + 1)$, as follows. As the premise for the prediction, we assume that the fluctuation of cross traffic is similar to that in the latest M times updates of the estimated ABW. Based on this assumption, $s_p(t+1)$ is calculated as $\min(s(t), \ldots, s(t-(M-1)))$ based on the latest $M$ values of $s(t)$. Although time series analysis methods such as the ARIMA model [23] can be used to predict $s_p(t + 1)$ based on the latest M values of $s(t)$, we adopted the above method because the above method does not depend on the cross traffic model and can be processed easily. The value of $M$ is determined based on the length of the period in which the fluctuation of the cross traffic recurs and the frequency of update of the estimated ABW.

Based on the above discussion, GW calculates $S_d(t, i)$ for flow$_i$ without retransmission by the following equations at the $t$-th update of the estimated ABW:

$$S_d(t, i) = R_f(i)/s_p(t + 1) \tag{6}$$

$$s_p(t + 1) = \min(s(t), \ldots, s(t - (M - 1))) \tag{7}$$

### 3.1.4 Summary of the Merit of eR2BC

We explain that the procedures of eR2BC described in Sections 3.1.1, 3.1.2 and 3.1.3 solve the drawbacks of the existing studies in the following. eR2BC enables high-priority flows and low-priority flows to share the estimated ABW while compensating for the difference between the estimated receive rate and the necessary BW by determining the minimum guaranteed BW of the flows based on the necessary BW. Thus, eR2BC solves the drawback of the combination of ABW estimation and Priority Queueing, where multiple flows may not be able to share the estimated ABW because the highest-priority flow can use all of the estimated ABW. eR2BC estimates the deficit of the receive rate of a flow for the necessary BW and determines the minimum guaranteed BW of the flow to compensate for the deficit as explained in Sections 3.1.2 and 3.1.3. Thus, eR2BC solves the drawback of the basic priority-based BW control method, where no recovery measure is taken when the DBHPF problem is caused. As explained in Section 3.1.1 A), eR2BC uses the estimated ABW as the upper limit of the transmission rate of the packet scheduler and the sender GW can fully utilize the estimated ABW to transmit the aggregated traffic. Thus, eR2BC solves the drawback of OverQoS, where the transmission of the aggregated traffic can use only part of the estimated ABW. In eR2BC, the GWs execute the procedures described in Sections 3.1.1, 3.1.2 and 3.1.3 without interacting with applications. Thus, eR2BC solves the drawback of CM, where the applications need to be changed to utilize the APIs provided by CM for mitigating the DBHPF problem.

## 3.2 ABW Estimation Method

We propose a method of ABW estimation with less overhead for eR2BC. The main features of the proposed method are summarized as follows.

-A sender GW asks a receiver GW the number of received packets by a message and detects packet losses by comparing the number of received packets with that of transmitted packets.

-Based on the result of packet loss detection, the sender GW updates the estimated ABW by the additive increase multiplicative decrease (AIMD) method.

**Table 2** shows the variables used in the explanation of the proposed method, and **Table 3** shows the configuration parameters of the proposed method.

### 3.2.1 Details of the Proposed ABW Estimation Method

The proposed ABW estimation method consists of the following two stages:

**Table 2** Variables used in the proposed method of ABW estimation.

| Variables | Explanation |
|---|---|
| $P_s(t)$ | Cumulative number of sent packets recorded by the sender GW at the $t$-th update of the estimated ABW. |
| $T_s(t)$ | The time when the sender GW records the cumulative number of sent packets at the $t$-th update of the estimated ABW. |
| $P_r(t)$ | The cumulative number of received packets recorded by receiver GW at the $t$-th update of the estimated ABW. |
| $B_r(t)$ | The cumulative bytes of received packets recorded by receiver GW at the $t$-th update of the estimated ABW. |
| $T_r(t)$ | The time when the receiver GW recorded the cumulative number of received packets at the $t$-th update of the estimated ABW. |
| $L(t)$ | Number of lost packets calculated at the $t$-th update of the estimated ABW. |
| $R(t-1)$ | Receive rate of the aggregated traffic at the receiver GW calculated at the $t$-th update of the estimated ABW. |
| $W(t)$ | The estimated ABW calculated at the $t$-th update |
| $D(t)$ | The increase in the estimated ABW calculated at the $t$-th update of estimated ABW. |

**Table 3** Configuration parameters of the proposed ABW estimation method.

| Parameter | Explanation |
|---|---|
| $T_c$ | The cycle at which the sender GW sends "Read Request for the amount of received packets". |
| $\theta_H, \theta_L$ | Threshold values used to determine whether the estimated ABW is too large or not. $\theta_H \geq \theta_L$. |
| $D_{\text{ini}}$ | The initial value of the increase of the estimated ABW. |
| $D_{\max}$ | The upper bound of the increase of the estimated ABW. |
| $\alpha$ | The multiplier used to make the increase of the estimated ABW larger. $\alpha > 1$. |
| $\beta$ | The value to be subtracted from $R(t-1)$ to calculate the new estimated ABW if the number of lost packets is larger than $\theta_H$. |
| $W_{\text{ini}}$ | The initial value of the estimated ABW. |

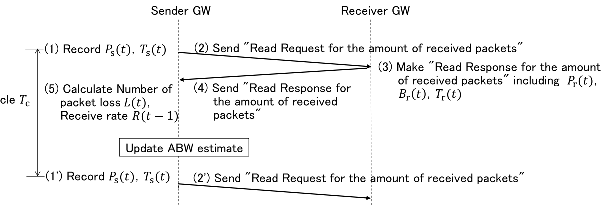


**Fig. 9** Procedure to obtain information necessary for packet loss detection.

(i) The sender GW asks the receiver GW the number of received packets by a message to obtain the information necessary for packet loss detection.

(ii) The sender GW updates the estimated ABW.

**Figure 9** shows the procedure by which the sender GW obtains the information necessary for packet loss detection at the $t$-th estimation of the ABW. The sender GW records its $P_s(t)$ and $T_s(t)$ in Step (1) and receives $P_r(t)$, $B_r(t)$, and $T_r(t)$ from the receiver GW in Step (4). We assume that the order of data packets and control messages (request for the amount of received packets) at the sender GW is the same as that at the receiver GW. Then, $L(t)$ and $R(t-1)$ thus can be calculated by the following eqeuations in Step (5) of Fig. 9:

$$L(t) = (P_s(t) - P_s(t-1)) - (P_r(t) - P_r(t-1)) \tag{8}$$

$$R(t-1) = (B_r(t) - B_r(t-1))/(T_r(t) - T_r(t-1)) \tag{9}$$

The sender GW calculates the new estimated ABW based on the AIMD method using the results of packet loss detection and

$D(t)$, i.e., the increase in the estimated ABW. The proposed method uses two threshold values, $\theta_H$ and $\theta_L$, to judge whether the estimated ABW is too large.

The estimated ABW $W(t)$ is updated as follows. If $\theta_H < L(t)$, the estimated ABW is judged to be too large, and the new estimated ABW, $W(t)$, is set at the value of receive rate $R(t-1)$ minus a configuration parameter $\beta$ for the multiplicative decrease operation. This subtraction is for making room in the buffer of a bottleneck link and preventing packet losses. If $\theta_L < L(t) \leq \theta_H$, then the estimated ABW is judged to be slightly larger and the new estimated ABW, $W(t)$, is set to the average of the receive rate $R(t-1)$ and the current estimated ABW $W(t-1)$. If $L(t) \leq \theta_L$, then the estimated ABW is judged to be smaller, and the new estimated ABW, $W(t)$, is set to be equal to the sum of the current estimated ABW $W(t-1)$ and the current increase in estimated ABW, $D(t-1)$.

The increase in estimated ABW $D(t)$ is updated as follows. If $L(t) \leq \theta_L$, $D(t)$ is set to be the product of $D(t-1)$ and $\alpha$, while bounded by $D_{\max}$, to emulate the behavior of TCP congestion control that increases the transmission rate exponentially in the slow start phase and increases the transmission rate linearly in the following additive increase phase. If $\theta_L < L(t)$, $D(t)$ is set to the initial value $D_{\text{ini}}$.

These operations are summarized as follows:

$$\begin{cases} W(t) = R(t-1) - \beta & (\theta_H < L(t)) \\ W(t) = (W(t-1) + R(t-1))/2 & (\theta_L < L(t) \leq \theta_H) \\ W(t) = W(t-1) + D(t-1) & (L(t) \leq \theta_L) \end{cases} \tag{10}$$

$$\begin{cases} D(t) = D_{\text{ini}} & (\theta_L < L(t)) \\ D(t) = \min(\alpha D(t-1), D_{\max}) & (L(t) \leq \theta_L) \end{cases} \tag{11}$$

As initial values, $W(1) = W_{\text{ini}}$ and $D(1) = D_{\text{ini}}$.

### 3.2.2 Overhead of the Proposed ABW Estimation Method

The overhead of the proposed ABW estimation method is the transmission of packets of read request/response for the amount of received packets exchanged between the sender GW and the receiver GW. The overhead is independent of the number of transmitted data packets and is proportional to the frequency of the ABW estimation. Each read request for the amount of received packets must have a message type (two bytes) and a sequence number (two bytes) for associating a request and the response. Such a request packet can be implemented as a 32-byte-long UDP/IPv4 packet. The read response for the amount of received packets must contain the message type (two bytes), the sequence number (two bytes), the number of received packets (eight bytes), the number of bytes of received packets (eight bytes), and the time (eight bytes). These values can be implemented in a 56-byte-long UDP/IPv4 packet. Therefore, the overhead of the ABW estimation is 88 bytes per ABW estimation. If the ABW estimation is performed every second, then the overhead is 0.704 kbps.

As explained in Section 2, the overhead of existing research based on TFRC is approximately 2% of the traffic. For example, in the case of 1 Mbps of traffic, the overhead is 20 kbps, and the overhead of the proposed ABW estimation method is smaller. The proposed ABW estimation method updates the estimated ABW every $T_c$, which must be sufficiently large compared to the round trip time. Therefore, the ability of the proposed ABW estimation method to track the change in the ABW is inferior to that of existing methods, which update the estimated ABW every round trip time.

## 4. Performance Evaluation

### 4.1 Evaluation Items and Evaluation Environment

We evaluated the proposed methods to confirm that they can mitigate the effect of the DBHPF problem better than existing methods and that the change in the ABW can be tracked. We ran the proposed methods in an emulated network environment constructed with virtual machines. Evaluation items and evaluation methods are as follows:

1) The ability to mitigate the effect of the DBHPF problem
   We measured the receive rates of five TCP or UDP flows that are the targets of BW control with multiple periodic UDP cross traffic.
2) The ability to track the change in the ABW
   We measured the receive rates of five TCP or UDP flows that are targets of BW control with multiple random UDP cross traffic.

We used six Linux OS virtual machines (VM) connected by internal networks on Oracle VirtualBox [24] running in a PC with eight cores and 16 GB of memory for the evaluation. In addition to the program implementing the proposed methods, we executed iperf3 [25] on VMs as the senders and receivers of the BW control target traffic and the cross traffic. TCP congestion control algorithm was TCP Cubic [26]. We used htb [27] in Linux as the minimum BW guarantee type packet scheduler. Since the minimum guaranteed BW of a flow cannot be set at 0 with htb, the minimum guaranteed BW of a flow is configured to be 80 kbps or above.

**Figure 10** shows the structure of a virtual network used for the evaluation. In order to emulate the bottleneck link and delay of the best-effort service network, the bidirectional traffic between VM3 and VM4 are shaped at 5 Mbps and delayed by 25 ms in each direction. We set the BW of the link between VM3 and VM4 at 5 Mbps to ensure that no overload of the PC which runs the emulated network environment is caused. We set the one way delay of the link between VM3 and VM4 at 25 ms so that the order of the round trip delay can be similar to the order of the round trip delay between domestic locations in the Internet.

**Table 4** shows the parameters for the proposed methods used in the evaluation. We explain how we chose the parameter values shown in Table 4 in the following. $T_c$ is set at 1 second so that it can be large enough compared with 50 ms round trip delay. $\theta_L$, $\theta_H$ are set at 0 and 1 respectively assuming a wired network, where

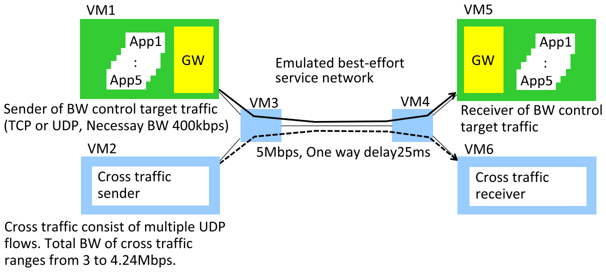


**Fig. 10** Structure of virtual machines for evaluation.

**Table 4** Configuration parameter values for the proposed methods used in the evaluation.

| | Parameter | Value |
|---|---|---|
| ABW estimation method | $T_c$ | 1.0 sec. |
| | $\theta_H$ | 1 |
| | $\theta_L$ | 0 |
| | $D_{\mathrm{ini}}$ | 50 kbps |
| | $D_{\mathrm{max}}$ | 1 Mbps |
| | $\alpha$ | 1.2 |
| | $\beta$ | 100 kbps |
| | $W_{\mathrm{ini}}$ | 1 Mbps |
| eR2BC | $C$ | 10 |
| | $M$ | 10 |
| | $B_{\mathrm{lim}}$ | 50 kbps |

packets are rarely lost unless congestion occurs. The larger $D_{\mathrm{ini}}$ is, the faster the value of the estimated ABW increases but the more unstable the estimated ABW becomes. Thus, $D_{\mathrm{ini}}$ is set at 50 kbps. The larger $D_{\mathrm{max}}$ is, the faster the value of the estimated ABW increases but the more widely the estimated ABW fluctuates. Thus, we set $D_{\mathrm{max}}$ at 1 Mbps considering that the maximum value of ABW is 5 Mbps. $W_{\mathrm{ini}}$ is the initial value of the estimated ABW and we set $W_{\mathrm{ini}}$ at 1 Mbps considering that the ABW in the evaluation is between 760 kbps and 2 Mbps. $C$ is set at 10 so that eR2BC aims to make the average receive rate of a TCP flow in 10 seconds equal to or more than the necessary BW of the flow. $M$ is set at 10 so that eR2BC uses the value of $s(t)$ in the past 10 seconds. The larger $B_{\mathrm{lim}}$ is, the larger the minimum guaranteed BW of a high-priority flow can be and the more widely the minimum guaranteed BW of the high-priority flow fluctuates. Since the fluctuation may adversely affect the congestion control of the high-priority flow, we set $B_{\mathrm{lim}}$ at 50 kbps. The values of $\alpha$ and $\beta$ in Table 4 are chosen based on the results of the behavior of the ABW estimation and the ability to mitigate the effect of the DBHPF problem for four cases ($\alpha$ being 1.1 and 1.2 and $\beta$ being 150 kbps and 100 kbps, respectively). The larger $\alpha$ is, the faster the estimated ABW increases but the more widely the estimated ABW fluctuates. Thus, we chose 1.1 and 1.2 as the value of $\alpha$ for the trial. The larger $\beta$ is, the more the congestion can be mitigated when it is detected but the longer it takes for the estimated ABW to increase. Thus, we chose 100 kbps and 150 kbps as the value of $\beta$ for the trial.

### 4.2 Ability to Mitigate the Effect of the DBHPF Problem

In this section, we compare the ability to mitigate the effect of the DBHPF problem for the case in which GW does not control BW, the existing method of setting the minimum guaranteed BW at the necessary BW and eR2BC based on the ratio of duration when the receive rate of a BW control target flow is smaller than the necessary BW for the simulation period (ratio of time in shortage). The existing method corresponds to the basic priority-based BW control method described in Section 2.1. If the effect of the DBHPF problem is mitigated, it is expected that the receive rate of flows decreases in ascending order of their priority when the ABW decreases, and the receive rate of flows increases in descending order of their priority when the ABW increases. In order to observe the above behavior, we used one stationary 3-Mbps CBR UDP flow and four 310-kbps CBR UDP flows that are transmitted periodically. The periods of four 310-kbps CBR UDP flows are 1) 105 seconds transmission and 15 seconds no transmission with initial 15 seconds no transmission, 2) 75 seconds transmission and 45 seconds no transmission with initial 30 seconds no transmission, 3) 45 seconds transmission and 75 seconds no transmission with initial 45 seconds no transmission and 4) 15 seconds transmission and 105 seconds no transmission with initial 60 seconds no transmission respectively. With the four flows, we varied the ABW as 2 Mbps → 1.69 Mbps → 1.38 Mbps → 1.07 Mbps → 760 kbps → 1.07 Mbps → 1.38 Mbps → 1.69 Mbps → 2 Mbps every 15 seconds. We varied the ABW in such a way so that the number of flows which can be accommodated in the ABW changes by one when the ABW changes by one step. We set the cycle of ABW variation at 15 seconds so that the estimated ABW can stabilize after the ABW changes by one step.

**Table 5** Ratio of duration in shortage.

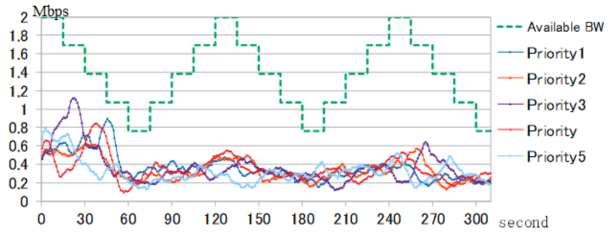
| Priority | TCP | | | UDP | | |
|---|---|---|---|---|---|---|
| | No BW Control | Existing method | eR2BC | No BW Control | Existing method | eR2BC |
| 1 | 75.7% | 82.1% | 0% | 100% | 60.7% | 14.5% |
| 2 | 69.6% | 87.9% | 32.5% | 20.3% | 70% | 37.6% |
| 3 | 75.7% | 90.7% | 67.9% | 97.2% | 79% | 63.4% |
| 4 | 73.9% | 94.3% | 96.1% | 62.1% | 91% | 88.3% |
| 5 | 86.1% | 100% | 100% | 87.9% | 97.6% | 98.6% |

We used five BW control target flows that transmit for 320 seconds having necessary BW of 400 kbps. We evaluated two cases, one with five TCP flows with different priorities and another with five CBR UDP flows with different priorities. With both TCP and UDP, priority 1 is the highest priority. As the priority number increases, the priority decreases. The average receive rate of a TCP flow in 10 seconds and receive rate of a UDP flow in 1 second are calculated by reading received bytes of each flow from conntrack entry [28] every second. The conntrack entry is a mechanism to accelerate packet forwarding in Linux OS. The conntrack entry is created for each flow and records the accumulated amount of forwarded packets for the flow.

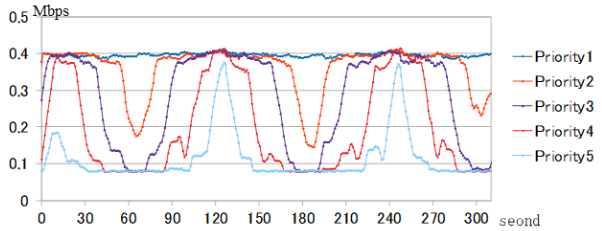
**A) The result of Ratio of duration in shortage**

**Table 5** shows the ratio of the duration in shortage for no control by the GW case, the existing method of setting the minimum guaranteed BW at the necessary BW and eR2BC. In the case of no BW control by GW, the receive rates of five TCP flows are similar, regardless of their priorities, and their ratios of duration in shortage are 69% or above. With UDP flows, the ratio of duration in shortage for Priority 2 and 4 flows are less than on the above results, we confirmed that the DBHPF problem is caused with no BW control by GW.

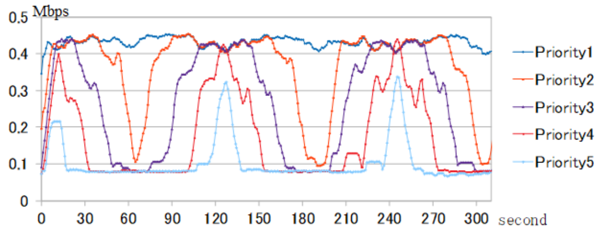
In the case of the existing method of setting the minimum guaranteed BW at the necessary BW, the higher the flow priority, the lower the ratio of duration in shortage. Thus, the existing method can mitigate the effect of the DBHPF problem. However, the ratio of duration in shortage is rather high, i.e., 82% or above. In the case of eR2BC, the ratio of duration in shortage for a higher-priority flow is less than those of other methods. Thus, eR2BC mitigates the effect of the DBHPF problem. By comparing the evaluation results of the existing method with those for eR2BC, the ratio of duration in shortage for Priority 1 through 3 is smaller for eR2BC. We can therefore conclude that eR2BC mitigates the



(a) No control by GW



(b) Existing method



(c) eR2BC

**Fig. 11** Receive rate of TCP flows.

effect of the DBHPF problem better than the existing method.

The higher-priority TCP flows achieve a smaller ratio of duration in shortage with eR2BC. As for Priority1, 2 and 3 TCP flows, the higher the priority of the flow is, the larger the difference between the ratio of duration in shortage with eR2BC and the ratio of duration in shortage with the existing method is. On the other hand, the ratio of duration in shortage for Priority 4 and 5 flows with eR2BC is larger than those with the existing method. From this result, we confirmed that eR2BC mitigates the DBHPF problem for TCP flows better than the existing method and the effect of eR2BC is more significant for higher-priority flows. Similarly, as for UDP flows, the higher-priority flows achieve a smaller ratio of duration in shortage with eR2BC. As for Priority 1, 2, 3 and 4 UDP flows, the higher the priority of the flow is, the larger the difference between the ratio of duration in shortage with eR2BC and the ratio of duration in shortage with the existing method is. From this result, we confirmed that eR2BC mitigates the DBHPF problem for UDP flows better than the existing method and the effect of eR2BC is more significant for higher-priority flows. However, with eR2BC, the ratio of duration in shortage for Priority 1 and 2 UDP flows are larger than those for TCP flows and the ratio of duration in shortage for Priority 3, 4 and 5 UDP flows are smaller than those for TCP flows. We can conclude that eR2BC mitigates the DBHPF problem better with TCP than with UDP for higher-priority flows. We also confirmed that the reduction in the receive rate of lower-priority flows is smaller with UDP than with TCP.

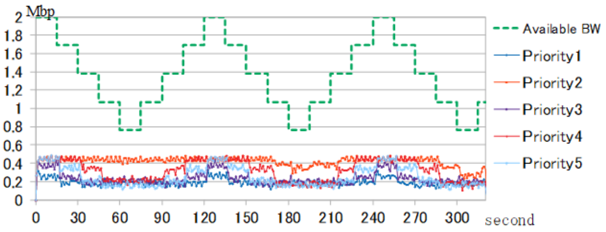
**B) The result of receive rate of TCP and UDP flow**

**Figure 11** shows the average receive rates in 10 seconds of TCP flows for no control by GW, existing method and eR2BC. In the case of no control by GW, the receive rates of the flows tend to increase and decrease as the ABW increases and decreases regardless of the priorities of the flows. When the ABW decreases (from 15 seconds to 75 seconds, from 135 seconds to 195 seconds and from 255 seconds to 300 seconds), the receive rates of all flows decrease in a similar way and become less than the necessary BWs of the flows regardless of the priorities of the flows. We consider that TCP congestion control mechanism is the reason why the receive rates of all flows decrease in a similar way. While the ABW is less than 1.38 Mbps (from 45 seconds to 90 seconds, from 165 seconds to 210 seconds and 285 seconds to 300 seconds), the receive rates of most flows are less than the necessary BW 400 kbps even though the ABW is always more than 400 kbps, which is the necessary BW of one flow. From these observations, we confirmed that the DBHPF problem is caused with no BW control by GW.

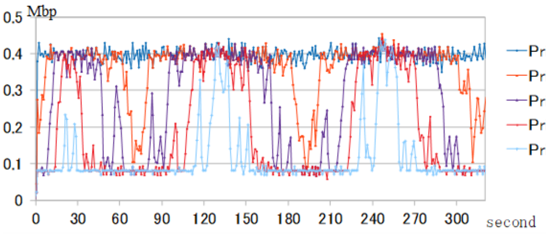
In the case of the existing method, the receive rates of flows decrease in ascending order of priority when the ABW decreases (from 15 seconds to 75 seconds, from 135 seconds to 195 seconds and from 255 seconds to 300 seconds). The receive rates of flows increase in descending order of priority when the ABW increases (from 75 seconds to 135 seconds and from 195 seconds to 255 seconds). These behaviors are expected for the case in which the effect of the DBHPF problem is mitigated. The maximum value of the receive rates of Priority 1, 2, 3 and 4 flow is about 400 kbps and the maximum value of the receive rate of Priority 5 flow is less than 400 kbps. The receive rate of Priority 5 flow is less than 400 kbps when the ABW is 2 Mbps because the average estimated ABW in 10 seconds is less than 2 Mbps due to the estimation error of the ABW.

In the case of eR2BC, similarly as in the case of the existing method, the receive rates of flows decrease in ascending order of priority when the ABW decreases (from 15 seconds to 75 seconds, from 135 seconds to 195 seconds and from 255 seconds to 300 seconds). The receive rates of flows increase in descending order of priority when the ABW increases (from 75 seconds to 135 seconds and from 195 seconds to 255 seconds). These behaviors are expected for the case in which the effect of the DBHPF problem is mitigated. However, the maximum value of the receive rates of Priority 1, 2, 3 and 4 flow is more than 400 kbps. The maximum value of the receive rate of Priority 5 flow is less than 400 kbps and the maximum value is less than that of the existing method. This is because eR2BC may assign a larger minimum guaranteed BW to high-priority flows than to low-priority flows in order to compensate for the deficit for the receive rate of high-priority flows and eR2BC may assign a smaller minimum guaranteed BW to low-priority flows than the existing method.

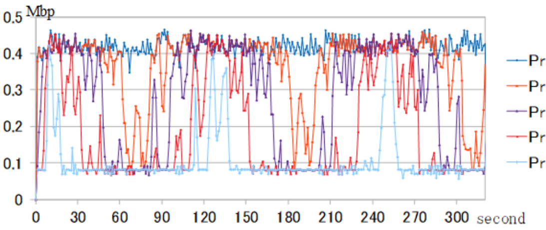
**Figure 12** shows the receive rates of UDP flows for no control by GW, the existing method and eR2BC respectively. In the case of no control by GW, the receive rate of Priority 2 flow is equal to or more than the necessary BW most of the time. The receive rates of the flows except Priority 2 flow are less than the necessary BW most of the time. The receive rate of Priority 3, 4 and 5 flows are larger than the receive rate of Priority 1 flow most of the time between 90 seconds and 165 seconds and 210 seconds and 285 seconds. From these observations, we confirmed that the DBHPF problem is caused with no BW control by GW.



(a) No control by GW

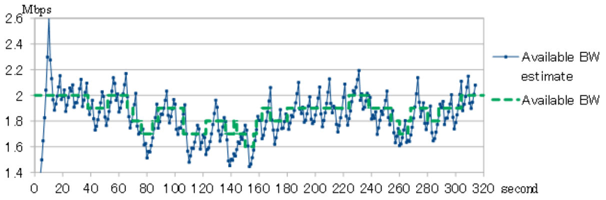


(b) Existing method

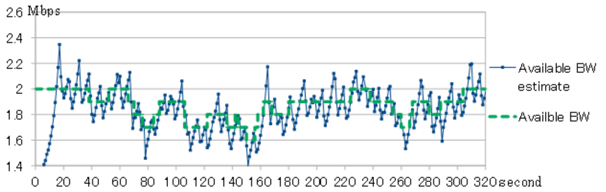


(c) eR2BC

**Fig. 12** Receive rate of UDP flows.



(a) TCP flows are the BW control target



(b) UDP flows are the BW control target

**Fig. 13** Change in ABW estimate.

In the case of the existing method, similarly as with TCP, the receive rates of flows exhibit the expected behaviors for the case in which the effect of the DBHPF problem is mitigated. However, the receive rates of the flows are more likely to be less than the necessary BW with UDP than with TCP. The alternation of the increase and the decrease of the receive rate is more frequent with UDP than with TCP because the plotted values for TCP are averaged receive rates in 10 seconds and the plotted values for UDP are averaged receive rates in one second. In the case of the existing method, the maximum value of the receive rate of all flows is between 400 kbps and 440 kbps. The maximum value of the receive rate of Priority 5 flow is more than 400 kbps when the ABW is 2 Mbps because the estimated ABW can be larger than 2 Mbps due to the estimation error of the ABW.

In the case of eR2BC, similarly as with TCP, the receive rates of flows exhibit the expected behaviors for the case in which the effect of the DBHPF problem is mitigated and receive rates of the flows are more likely to be less than the necessary BW with UDP than with TCP. For the same reason as in the case of the existing method, the alternation of the increase and the decrease of the receive rate is more frequent with UDP than with TCP. In the case of eR2BC, the maximum value of the receive rate of all flows is between 400 kbps and 460 kbps and the maximum value tends to be larger than the maximum value in the case of the existing method. When the receive rate of a flow is less than 400 kbps, the receive rate tends to be less than the receive rate at the same time in the case of the existing method. This is because eR2BC may assign a larger minimum guaranteed BW to high-priority flows than to low-priority flows in order to compensate for the deficit for the receive rate of high-priority flows and eR2BC may assign a smaller minimum guaranteed BW to low-priority flows than the existing method.

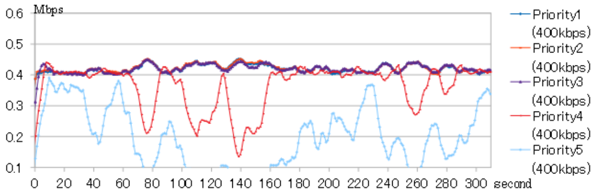
The result in Table 5 shows that the ratios of duration in shortage for high-priority flows (Priority 1–3) with eR2BC are less than those with the existing method for both TCP and UDP. The ratio of duration in shortage indicates the percentage of time in which the receive rate of a flow is less than the necessary BW of the flow. From these points, we confirmed that eR2BC mitigates the effect of the DBHPF problem better than the existing method.

### 4.3 Ability to Track the Changes in the ABW

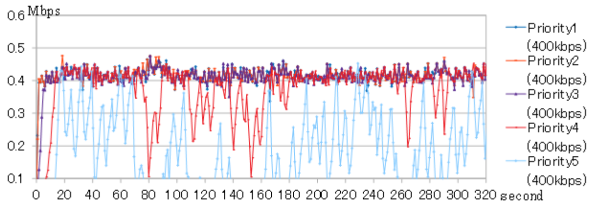
We present the measurement result for the estimated ABW and the receive rates of BW control target flows in the environment in which the ABW changes randomly in order to evaluate the ability of the proposed ABW estimation method to track changes in the ABW. In order to emulate the situation in which the ABW varies randomly in real networks, we used one stationary 3-Mbps CBR UDP flow cross traffic and generated 100 kbps CBR UDP flow cross traffic with an exponential distribution communication duration ($\mu = 0.2$, the average duration is 15 seconds) and an exponential distribution interval ($\mu = 0.2$, average interval is 10 seconds) and used at most four 100 kbps UDP flows. We used five BW control target flows that transmit for 320 seconds having necessary BWs of 400 kbps. We evaluated two cases: one with five TCP flows with different priorities, and another with five CBR UDP flows with different priorities.

**Figure 13** shows the change in the estimated ABW for both TCP and UDP BW control target flows. As shown in Fig. 13, the estimated ABW tracks the changes in the ABW of 100 kbps or 200 kbps with a 3 to 5-seconds delay and with at most approximately 300 kbps overshoot or undershoot for both TCP and UDP flows. The estimated ABW by the proposed ABW estimation method shows similar behavior for both TCP and UDP in Fig. 13.

**Figure 14** shows the change in the receive rates. By comparing the result for TCP in Fig. 14 (a) and the result for UDP in Fig. 14 (b), we can see that the alternation of the increase and the decrease of the receive rate is more frequent with UDP than with TCP. This is because the plotted values for TCP are averaged



(a) Receive rate of TCP flows



(b) Receive rate of UDP flows

**Fig. 14** Receive rate of flows.

**Table 6** Ratio of duration in shortage (Evaluation of the ability to track the change in the ABW).

| | Priority1 | Priority2 | Priority3 | Priority4 | Priority5 |
|---|---|---|---|---|---|
| TCP | 0% | 0% | 0% | 48.2% | 100% |
| UDP | 19.2% | 19.6% | 21.3% | 44.7% | 95.2% |

receive rates in 10 seconds and the plotted values for UDP are averaged receive rates in one second. Except for this point, the change of the receive rate of UDP shows a trend similar to the change of the receive rate of TCP in Fig. 14.

**Table 6** shows the ratio of duration in shortage. In this evaluation scenario, the expected behavior is that the receive rates of Priority 1 through 4 flows are larger than the necessary BWs because the minimum ABW is 1,600 kbps. The result in Table 6 indicates that the ratio of duration in shortage for a higher-priority flow is lower than that for a lower-priority flow for both TCP and UDP. From this result, we confirmed that the DBHPF problem is mitigated for both TCP and UDP. This result reveals that the algorithm of eR2BC that allocates more transmission BW to higher-priority flows works effectively. With TCP, the ratio of duration in shortage for Priority 1, 2 and 3 flows are 0% and the ratio of duration in shortage for Priority 4 flow is 48.2%. On the other hand, with UDP, the ratio of duration in shortage for Priority 1, 2 and 3 flows are about 20% and the ratio of duration in shortage for Priority 4 flow is 44.7%. The reason for a higher ratio of duration in shortage for Priority 4 flow is that the estimated ABW is sometimes smaller than the actual ABW. The ratio of duration in shortage for Priority 1, 2 and 3 UDP flows are larger than those for TCP flows and the ratio of duration in shortage for Priority 4 and 5 UDP flows are smaller than those for TCP flows. From this result, we confirmed that eR2BC mitigates the DBHPF problem better with TCP than with UDP for higher-priority flows. We also confirmed that the reduction in the receive rate of lower-priority flows is smaller with UDP than with TCP.

In Fig. 13, we can see that the proposed ABW estimation method can track changes in the ABW of 100 kbps or 200 kbps with a delay of 3 to 5-seconds for both TCP and UDP. The result in Table 6 shows that the ratio of duration in shortage for a higher-priority flow is less than those of the lower-priority flow for both TCP and UDP. From the result in Table 6, we confirmed that eR2BC can mitigate the effect of the DBHPF problem when the ABW changes.

## 5. Conclusion

In this paper, we proposed a method by which to control the transmission BW of flows to mitigate the effect of the DBHPF problem, which causes the receive rate of a high-priority flow to be lower than the necessary BW when the ABW between two sites connected through GWs changes. The proposed method, referred to herein as eR2BC, estimates the receive rate of each flow using information obtained from the ABW estimation and mitigates the effect of the DBHPF problem by controlling the transmission BW of each flow in order to compensate for the difference between the estimated receive rate and the necessary BW according to the priority of each flow. We showed that eR2BC mitigates the effect of the DBHPF problem better than the existing method by evaluating the performance by using its implementation in a virtual network environment.

In addition to eR2BC, we proposed a new ABW estimation method with less overhead compared to the existing ABW estimation method. The proposed ABW estimation method is used in the evaluation of eR2BC. We also showed that the proposed ABW estimation method can track the changes in the ABW of 100 kbps or 200 kbps with a delay of 3 to 5 seconds.

The improvement of the estimation method for the difference between the receive rate of a flow and the necessary BW and the improvement of the ability of the proposed ABW estimation method to track changes in the ABW remains for future study.

## References

[1] Linux Advanced Routing & Traffic Control HOWTO, available from ⟨https://www.tldp.org/HOWTO/Adv-Routing-HOWTO/lartc.qdisc.classful.html⟩ (accessed 2018-07-04).

[2] Afanasyev, A., Tilley, N., Reiher, P. and Kleinrock, L.: Host-to-Host Congestion Control for TCP, *IEEE Communications Surveys & Tutorials*, pp.304–342 (2010).

[3] Subramanian, L., Stoica, I., Balakrishnan, H. and Katz, R.H.: OverQoS: An overlay based architecture for enhancing Internet QoS, *Proc. USENIX Symposium on Networked Systems Design and Implementation* (*NSDI 2004*), pp.11–16 (2004).

[4] Balakrishnan, H., Rahul, H.S. and Seshan, S.: An Integrated Congestion Management Architecture for Internet Hosts, *Proc. SIGCOMM 1999*, pp.175–187 (1999).

[5] Damjanovic, D. and Welzl, M.: MulTFRC: Providing weighted fairness for multimedia applications (and others too!), *ACM SIGCOMM Computer Communication Review*, Vol.39, No.3, pp.5–12 (2009).

[6] Damjanovic, D. and Welzl, M.: An extension of the TCP steady-state throughput equation for parallel flows and its application in MulTFRC, *IEEE/ACM Trans. Networking*, Vol.19, No.6, pp.1676–1689 (Dec. 2011).

[7] Floyd, S., Handley, M., Padhye, J. and Widmer, J.: Equation-Based Congestion Control for Unicast Applications, *Proc. SIGCOMM 2000*, pp.43–56 (2000).

[8] Floyd, S., Handley, M., Padhye, J. and Widmer, J.: IETF RFC 5348: TCP Friendly Rate Control (TFRC): Protocol Specification (Sep. 2008).

[9] Kohler, E., Handley, M. and Floyd, S.: IETF RFC 4340: Datagram Congestion Control Protocol (DCCP) (Mar. 2006).

[10] Singh, M., Pradhan, P. and Francis, P.: MPAT: Aggregate TCP congestion management as a building block for internet QoS, *Proc. International Conference on Network Protocols* (*ICNP 2004*), pp.129–138 (2004).

[11] Crowcroft, J. and Oechslin, P.: Differentiated end-to-end internet services using a weighted proportional fair sharing TCP, *SIGCOMM Computer Communication Review*, No.3, pp.53–69 (1998).

[12] Kuo, F. and Fu, X.: Probe-Aided MulTCP: An aggregate congestion control mechanism, *SIGCOMM Computer Communication Review*, Vol.38, No.1, pp.17–28 (2008).

[13] Oshiba, T. and Nakajima, K.: Quick end-to-end available bandwidth estimation for QoS of real-time multimedia communication, *Proc. IEEE Symposium on Computers and Communications* (*ISCC*), pp.162–167 (2010).

[14] Oshiba, T. and Nakajima, K.: Quick and simultaneous estimation of available bandwidth and effective UDP throughput for real-time communication, *Proc. IEEE Symposium on Computers and Communications* (*ISCC*), pp.1123–1130 (2011).

[15] Jain, M. and Dovrolis, C.: End-to-end available bandwidth: measurement methodology, dynamics, and relation with TCP throughput, *Proc. SIGCOMM 2002*, pp.295–308 (2002).

[16] Ribeiro, V.J., Riedi, R.H., Baraniuk, R.G., Navratil, J. and Cottrell, L.: pathChirp: efficient available bandwidth estimation for network paths, *Proc. Performance Analysis and Modeling* (*PAM*) *Workshop 2003* (2003).

[17] Strauss, J., Katabi, D. and Kaashoek, F.: A measurement study of available bandwidth estimation tools, *Proc. ACM Internet Measurement Conference* (*IMC 2003*), pp.39–44 (2003).

[18] Croce, D., En-Najjary, T., Urvoy-Keller, G. and Biersack, E.W.: Fast available bandwidth sampling for ADSL links: Rethinking the estimation for larger-scale measurements, *Proc. Passive and Active Measurement* (*PAM*) *Conference 2009*, pp.67–76 (2009).

[19] Liu, Q. and Hwang, J.: End-to-end available bandwidth estimation and time measurement adjustment for multimedia QoS, *Proc. IEEE International Conference on Multimedia & Expo* (*ICME 2003*), Vol.3, pp.373–376 (2003).

[20] Wang, S.S. and Hsiao, H.F.: Fast end-to-end available bandwidth estimation for real-time multimedia networking, *Proc. IEEE International Workshop on Multimedia Signal Processing* (*MMSP 2006*), pp.415–418 (2006).

[21] Satoda, K., Oshiba, T., Yoshida, H. and Nakajima, K.: Network Traffic Estimation and Prediction Technologies for Improving User-perceived Quality, *IEICE SIG-Network System Technical Report NS2013-120*, pp.29–34 (2011). (in Japanese)

[22] Bouras, C. and Kanakis, N.: Online AL-FEC protection over mobile unicast services, *Proc. European Conference on Networks and Communications* (*EuCNC*), pp.229–233 (2015).

[23] The functionality and application of time series analysis (ARIMA model), available from ⟨https://www.i-juse.co.jp/statistics/jirei/sympo/10/arima-model.html⟩ (accessed 2018-07-10).

[24] iPerf - The ultimate speed test tool for TCP, UDP and SCTP, available from ⟨https://iperf.fr/iperf-download.php⟩ (accessed 2018-07-08).

[25] VirtualBox, available from ⟨https://www.virtualbox.org/⟩ (accessed 2018-10-11).

[26] Rhee, I. and Xu, L.: CUBIC: A new TCP-friendly high-speed TCP variant, *ACM SIGOPS Operating Systems Review*, Vol.42, No.5, pp.64–74 (July 2008).

[27] HTB Linux queuing discipline manual - user guide, available from ⟨http://luxik.cdi.cz/˜devik/qos/htb/manual/userg.htm⟩ (accessed 2018-07-08).

[28] The conntrack-tools user manual, available from ⟨http://conntrack-tools.netfilter.org/manual.html⟩ (accessed 2018-10-11).

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