An Available Bandwidth Estimation Scheme in Simultaneous Multiple-Pair Connections

Yusuke Satoh and Eiji Oki

Abstract—**Grid networks are characterized by the simultaneous communication of different pairs of senders and receivers, i.e. multiple-pair connections. In multiple-pair connections, one link may carry the routes of different connections. Such a link is called a common link hereafter. The controller of multiple-pair connections needs to know the available bandwidth of the common link in order to schedule connections efficiently. An objective of scheduling is to complete all required connections as quickly as possible when each traffic demand is given. Conventional schemes are unable to estimate the available bandwidth of common links. This paper proposes a scheme that can estimate the available bandwidth under simultaneous multiple-pair connections, which is called a simultaneous available bandwidth. To achieve this, the proposed scheme estimates the available bandwidth of a common link by synchronizing packet streams at the common link if any common link exists because the link available bandwidth may limit the simultaneous available bandwidth. The proposed scheme employs the metrics used to estimate the available bandwidth of single-pair connection in the conventional scheme, to synchronize packet streams. This paper formulates an optimal adjustment width of transmission time of a packet stream to synchronize packet streams when a target synchronization ratio is given.**

Index Terms— **Available bandwidth estimation, Grid networks**

I. Introduction

In grid networks [1], [2] there are different communication pairs of senders and receivers that communicate simultaneously. Communications of different sender-receiver pairs are called multiple-pair connections. On the other hand, communication by a single sender and a single receiver is called a single-pair connection.

A controller is set in the network when implementing multiple-pair connections. Consider a controller that controls end hosts that are connected to a network. The controller is able to have them start, stop, and resume their communications. The controller may not know all internal information of the network because the network may be administered by an organization different from that of the controller.

The controller of multiple-pair connections should manage connections efficiently. The controller should try to complete all required connections as quickly as possible when a traffic demand is given. To achieve this, the controller allocates a usable bandwidth for each connection in a scheduled manner [3], [4]. This allocation is called scheduling [5]. Scheduling in grid networks is discussed in [6]–[11].

Figure 1 shows a single-pair connection. Single-pair connection occurs between two hosts on a network, which is composed of routers and links, and is not controlled by any controllers. Figure 2 shows multiple-pair connections scheduled by a controller.

Figures 2(a) and 2(b) illustrate scheduled multiple-pair connections at different times. In each figure, the triangles are hosts being directed by the controller and the circles are ordinary hosts, which are not controlled. Bold lines, both solid and dashed, represent communication routes.

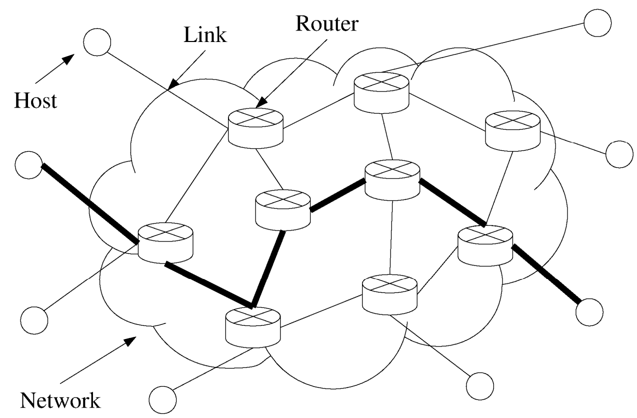

Fig. 1. Single-pair connection

Keeping the link utilization ratio as high as possible can shorten the communication time and can raise the efficiency of network utilization. The route from a sender to a receiver is determined before the two hosts communicate. The route consists of one or more links. In each link of the route, the link available bandwidth is defined as the difference between the capacity of the link and its used bandwidth. The route available bandwidth is defined as the minimum link available bandwidth in all links that constitute the route. The route available bandwidth is equal to the maximum bandwidth that the connection can use.

To realize an efficient scheduling, simultaneous multiple-pair connections have to be considered. Routes are determined independently in each connection pair and each route has its own route available bandwidth. If the route available bandwidth of a connection is given, the controller can allocate the route available bandwidth as the usable bandwidth

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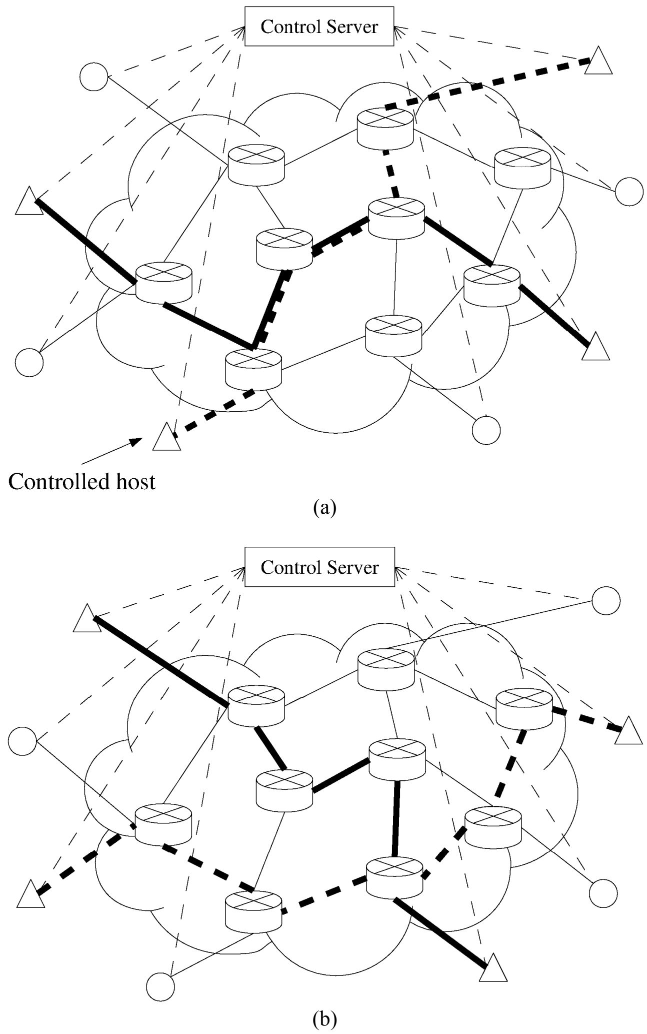

Fig. 2. Multiple-pair connections

to the connection in order to achieve an efficient scheduling. Two routes can share a same link. This link is called a common link. If multiple-pair connections with a common link occur simultaneously, each connection may not use up the allocated bandwidth by scheduling even if the allocated bandwidth is equal to the route available bandwidth of the connection. This implies a scheduling failure, which must be avoided. The controller must know the simultaneous available bandwidth to avoid the scheduling failure. The simultaneous available bandwidth depends on the link available bandwidth of the common link.

Conventional schemes [12]–[15] estimate the route available bandwidth of a single-pair connection. A conventional scheme [12], [13] uses packet streams for route available bandwidth estimation. A packet stream is a series of packets and there is a fixed interval between successive two packets. The packet stream is transmitted from a sender to a receiver at a constant transmission rate (bandwidth). Due to the magnitude relation between the transmission rate and the route available bandwidth, the packet interval in the packet stream varies at the receiver. When the transmission rate is greater than the route available bandwidth, the interval increases. On the other hand, when the transmission rate is smaller than the route available bandwidth, the interval does not increase. The variation of the interval is quantified by some metrics, and the magnitude relation between the route available bandwidth and the transmission rate is estimated by the metrics.

However, if a common link exists in the routes of multiple-pair connections, the conventional scheme is not able to estimate the simultaneous available bandwidth. This is because the conventional scheme link cannot estimate the available bandwidth of the common link. If the conventional scheme is used to estimate the link available bandwidth of the common link, the packet streams from the multiple-pair connections must be overlapped. Overlapping the packet streams is called *synchronization*.

This paper proposes a scheme to estimate an available bandwidth in simultaneous multiple-pair connections, which is called a simultaneous available bandwidth. To achieve this, the proposed scheme estimates the link available bandwidth of a common link by synchronizing packet streams at the common link if any common link exists because this available bandwidth may limit the simultaneous available bandwidth. The proposed scheme employs the metrics, which are used to estimate the magnitude relation between the route available bandwidth and the transmission rate of a packet stream in the conventional scheme, to synchronize packet streams. This paper formulates the adjustment width of transmission time of a packet stream for synchronization relating to a synchronization ratio and an optimal adjustment width is obtained from the formula when a target synchronization ratio is given. This paper is an extended version of our previous paper presented in [16]. This paper gives the detail analysis and theorems on the adjustment width with proofs.

The remainder of this paper is constructed as follows. Section II introduces end-to-end route available bandwidth estimation. Section III describes the conventional scheme, called Pathload. Section IV considers simultaneous connections on multiple-pair of senders and receivers in a network. Section V proposes a scheme for simultaneous available bandwidth estimation. Section VI shows the results of some experiments. Finally, Section VII summarizes this paper.

II. Route Available Bandwidth Estimation

The available bandwidth of a link is considered here. The available bandwidth is equal to the difference between the link's capacity and the used bandwidth of the link. The link available bandwidth A_i of link i is given by

$$A_i = C_i - U_i \, , \tag{1}$$

where C_i is the capacity of link i and U_i is the used bandwidth of link i.

In a similar way, the available bandwidth of a route, which consists of one or more links, can be considered. The route available bandwidth is equal to the minimum link available bandwidth in the links that constitute the route. The route available bandwidth A is defined by

$$A = \min_{i \in I} A_i \,, \tag{2}$$

where I is the set of links that constitute the route. A knowledge of the route available bandwidth is useful in shortening the communication time. By raising the sender's transmission rate to the route available bandwidth, the communication time can be minimized.

There are two approaches to obtaining the route available bandwidth. One is to calculate the bandwidth after gathering information of the network. As the route available bandwidth is equal to the minimum link available bandwidth in the links that construct the route, the route available bandwidth can be calculated if the capacity of each link and the link load are known. To gather this information can be hard, however, as the route may cross networks that are managed by different administrators. The other approach is to estimate the route available bandwidth without recourse to acquiring information of the networks involved.

The methodology of end-to-end route available bandwidth estimation is as follows. The sender transmits a series of packets at rate R. A fixed interval T separates successive packets. The receiver receives the packets and measures the arrival interval of the packets. If the route available bandwidth is A and $R > A$, the arrival interval tends to increase. If $R > A$, the arrival interval does not tend to increase. The relation between R and A is determined from the trend of arrival intervals. A range of the route available bandwidth, which is specified by both upper and lower bounds, is estimated by using different values of R. This methodology is called self-loading periodic stream (SLoPS) [13].

III. Conventional Scheme: Pathload

Pathload [12], [13] developed by Jain et al. is a tool based on SLoPS that estimates end-to-end route available bandwidth.

It proceeds as follows. Suppose the route available bandwidth is A. The sender transmits K packets at transmission rate R and packet interval T. This series of packets is called a packet stream. The receiver receives the packets stream and measures the arrival interval of the packets. In other words, the receiver measures the relative one-way delay (OWD). The receiver then decides whether the relative OWD tends to increase or not. The relative OWD trend of the packet stream is determined by two independent metrics, the pairwise comparison test metric and the pairwise difference test metric, which are detailed later.

If the relative OWD trend is determined as increasing, $R > A$ according to SLoPS. In the same way, if the relative OWD trend is not increasing, $R > A$. Pathload repeated transmits packet streams with different transmission rates. In the case of $R > A$, the transmission rate is decreased. Conversely, if $R \le A$, the transmission rate is increased. This iteration can estimate a range of the route available bandwidth. The relative OWD trend of a packet stream is determined by the pairwise comparison test (PCT) metric and the pairwise difference test (PDT) metric. These two independent metrics are designed to quantify the relative OWD variation of a packet stream from different points. The PCT metric quantifies the variation of successive relative OWD. The PDT metric quantifies the variation of relative OWD between the head and the tail of a packet stream. These metrics are defined to complement each other.

Both metrics are calculated from the relative OWDs of a packet stream as discerned by the receiver. The receiver measures the relative OWDs $D^i \left(i = \{1, \cdots, K\}\right)$. D^i are divided into $\Gamma = \sqrt{K}$ groups and each group consists of successive Γ OWDs. The receiver then finds $\hat{D}^k$ as the median of the relative OWDs in each group. These $\hat{D}^k$ are used to calculate the metrics for excluding outliers.

S_{PCT} of a packet stream is defined by

$$S_{\mathrm{PCT}} = \frac{\sum_{k=2}^{\Gamma} I\left(\hat{D}^k > \hat{D}^{k-1}\right)}{\Gamma - 1}, \tag{3}$$

where $I(X)$ is 1 if X holds, otherwise $I(X)$ is 0. The range of PCT metric is $0 \le S_{\mathrm{PCT}} \le 1$. If the relative OWDs are independent of each other, S_{PCT} is 0.5. If the relative OWDs of a packet stream exhibit a strong increasing trend, S_{PCT} approaches 1.

S_{PDT} of a packet stream is defined by

$$S_{\mathrm{PDT}} = \frac{\hat{D}^{\Gamma} - \hat{D}^1}{\sum_{k=2}^{\Gamma} \left|\hat{D}^k - \hat{D}^{k-1}\right|}. \tag{4}$$

The range of PDT metric is $-1 \le S_{\mathrm{PDT}} \le 1$. If the relative OWDs are of independent each other, S_{PDT} is 0. If the relative OWDs of a packet stream exhibit a strong increasing trend, S_{PDT} approaches 1. Pathload uses the metrics to determine the trend of the relative OWDs in a packet stream.

IV. Simultaneous Multiple-pair Connections

Compared with a single-pair connection, a multiple-pair connection can be considered. Multiple-pair connections are multiple single-pair connections; connections on multiple pairs of senders and receivers. Multiple-pair connections are considered as communications when either sender or receiver is at least more than one. The route between a sender and a receiver is fixed independently for each connection. Two connections may share a link that. This link is called a common link. If a common link exists in the route of a connection, the route available bandwidth can be estimated by conventional schemes. However, different connections that have a common link in each route may not use up own route available bandwidth because the link available bandwidth of the common link can be bottleneck.

Consider the two connections that have a common link in each route. Suppose A_1 is the route available bandwidth for one connection, A_2 for the other, and A_c is the link available bandwidth of the common link. The following two cases are considered:

i) $A_1 + A_2 \le A_c$
ii) $\min\{A_1, A_2\} \le A_c < A_1 + A_2$

In the case i), both communications can use up own route available bandwidth. In other words, the common link has no effect to the route available bandwidth of each connection. In the case ii), both connections can not use up own route available bandwidths because the link available bandwidth of the common link is smaller than the sum of each route available bandwidth.

When a common link exists, the link available bandwidth of the common link may limit the available bandwidth that is used for multiple-pair connections as described above. The bandwidth for multiple-pair connections is called a simultaneous available bandwidth. A controller of multiple-pair connections has to consider a presence of common links when estimating the simultaneous available bandwidth. In this paper, only 2-pair communications is considered as multiple-pair connections because the cases of more than 2-pair communications are extended from the case of 2-pair communications.

V. Proposed Scheme

A. Overview

Synchronization of packet streams at a common link is required to estimate the link available bandwidth of the common link by using Pathload. Synchronization of packet streams means the meshing of packet streams; one packet stream overlaps with another. The following three cases can be considered as the state of synchronization of packet streams at a common link:

a) Non synchronization
b) Partial synchronization
c) Full synchronization

a) Non synchronization occurs when no part of a packet stream overlaps the other packet stream. b) Partial synchronization occurs when only some part of a packet stream overlaps the other packet stream. c) Full synchronization occurs when both packet streams overlap completely with no omission. The transmission rate of overlapped packet streams is equal to the sum of the transmission rates of both packet streams.

Using Pathload to estimate the link available bandwidth demands full synchronization at the common link because Pathload uses the PCT and PDT metrics, which are described in Section III. Thus packet stream synchronization must be under control. To determine the state of packet stream synchronization, the proposed scheme uses the PCT and PDT metrics of each packet stream.

The magnitude relation between the sum of the transmission rate of each packet stream and the link available bandwidth of the common link should be quantified by the metrics. If A_{sum} is the sum of the transmission rate of each packet stream and A_c is the link available bandwidth, if $A_{\text{sum}} > A_c$, the PCT metrics should be more than 0.5 or the PDT metrics should be more than 0. If $A_{\text{sum}} < A_c$, the PCT metrics should be less than 0.5 or

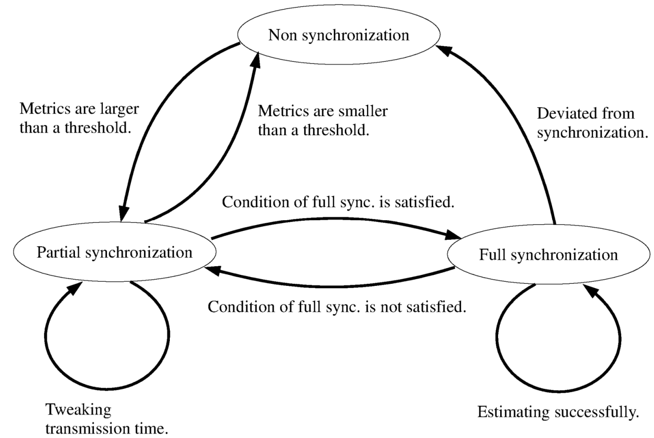

Fig. 3. State transition diagram of synchronization

the PDT metrics should be less than 0.

When the packet streams are full synchronized, the metrics are expected to be more than or equal to $1-\delta$, where δ is a minimal positive value, and the link available bandwidth of the common link is estimated by adjusting the transmission rate of one of packet streams. Figure 3 is the state transition diagram of packet stream synchronization while the link available bandwidth of a common link is being estimated.

B. Synchronization procedure

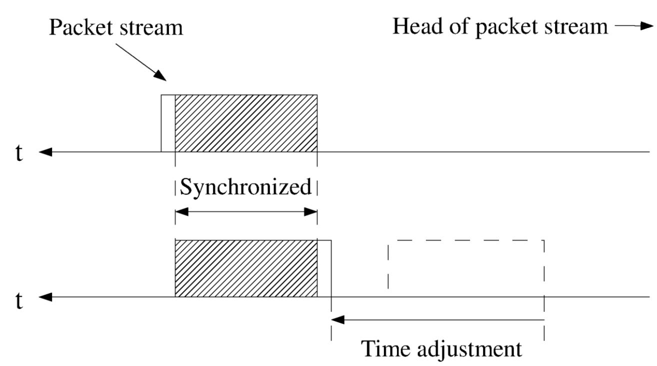

Fig. 4. Adjustment of transmission time of a packet stream

A control server manages the synchronization of packet streams. The control server sets the transmission time of one packet stream via an adjustment width and does not adjust the other. A packet stream whose transmission time is altered by the control server is called an adjusted packet stream and, the other packet stream is called non-adjusted packet stream. Figure 4 shows the adjustment of the transmission time of one packet stream.

Figure 5 shows a procedure of proposed scheme. A detailed description of the procedure is as follows:

Step 1: Measure the OWD from the control server to each sender.
Step 2: Estimate the route available bandwidth of each connection and send the estimation result to the control server from each receiver.

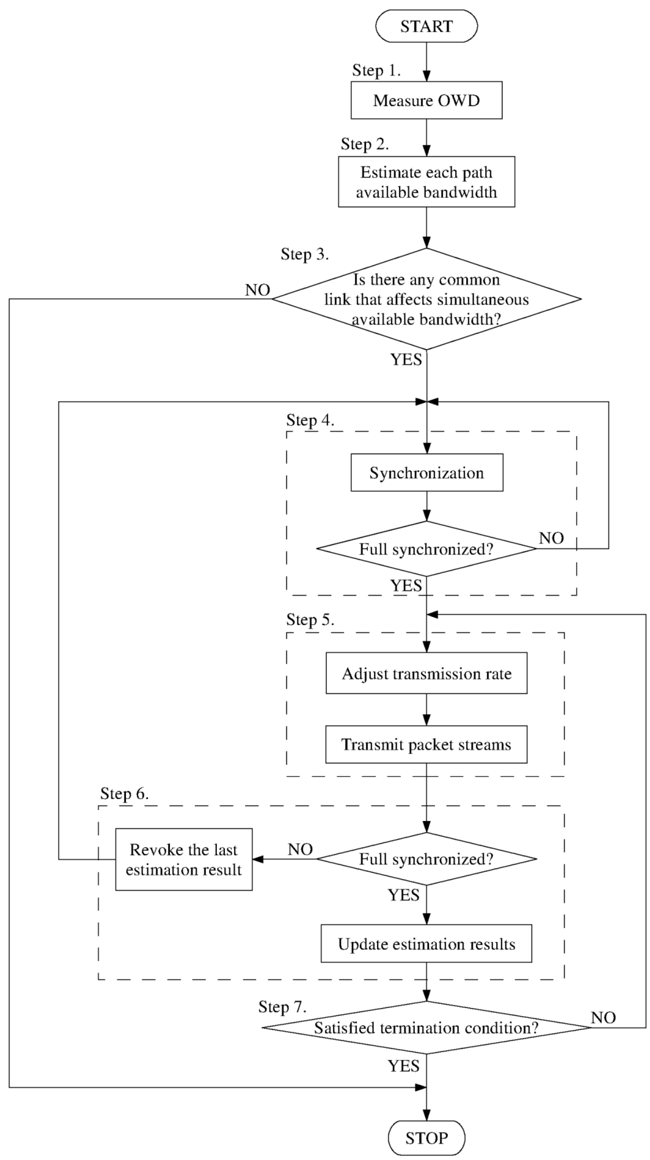

Fig. 5. Procedure of proposed scheme

Step 3: Attempt to synchronize packet streams at a common link. Each sender transmits a packet stream at a transmission rate that is equal to the route available bandwidth. Next, each sender calculates the PCT and PDT metrics and sends the values to the control server. If the packet streams are synchronized, proceed to Step 4. Otherwise, there is no common link or the link available bandwidth of the common link does not affect the simultaneous available bandwidth. Terminate.

Step 4: Determine the state of packet stream synchronization at the common link. If the state is non synchronization, the control server adjusts the next transmission time of the adjusted packet stream with a predetermined adjustment width. If the state is partial synchronization, the control server tweaks the next transmission time of an adjusted packet stream to yield full synchronization as the next state. If the state is full synchronization, proceed to Step 5.

Step 5: Estimate the link available bandwidth of the common link by using Pathload.

Step 6: Check whether the packet streams are full synchronized. If they are full synchronized, update estimation results and proceed to Step 7. Otherwise, revoke the last estimation result and return to Step 4.

Step 7: Check whether the termination condition of Pathload is satisfied. If satisfied, terminate. Otherwise, return to Step 5.

If packet streams are fully synchronized at the common link, the link available bandwidth of the common link is estimated by using Pathload.

C. *Approach for finding optimal adjustment width*

When a target synchronization ratio is given, the *optimal* adjustment width can be obtained. In this case, the *optimal* adjustment width represents the width that is assured of yielding full synchronization as quickly as possible.

Let x be the synchronization ratio that is a fraction of packet stream duration V; the range of x is $0 \le x \le 1$, and let x *synchronization* represent the overlap of packet streams by more than or equal to x. $x = 0$ implies that no part of a packet stream overlaps the other while $x = 1$ implies that both packet streams overlap completely with no omission.

Let α be the target synchronization ratio. When $x \ge \alpha$, x synchronization is termed α synchronization. There are two types of α synchronization as shown in Figure 6.

The number of adjustments depends on adjustment width W, which is used for altering the transmission time of the adjusted packet stream. Adjustment width W is expressed as rV, where r is a coefficient. If r is large, the next non-adjusted packet stream that is expected to be synchronized may be passed through without realizing α synchronization. If r is small enough, an adjusted packet stream does not meet the next non-adjusted

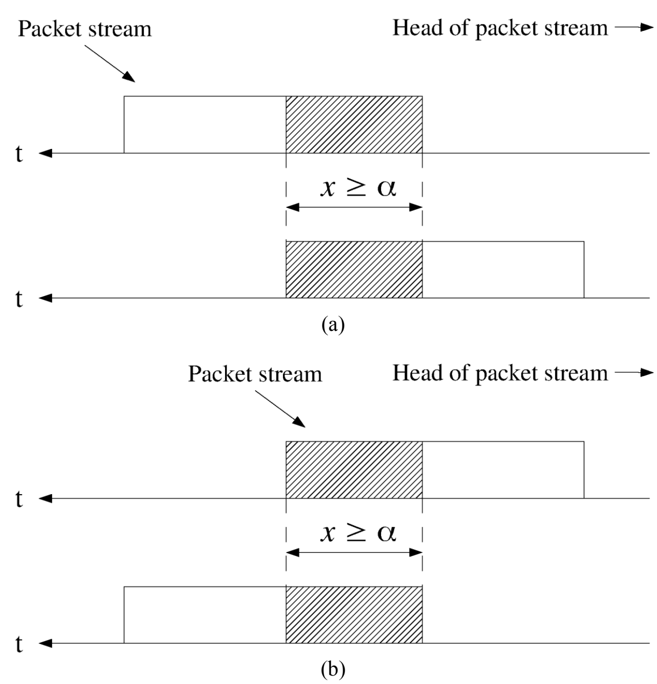

Fig. 6. Two types of x synchronization

packet stream. Thus, α synchronization with the next non-adjusted packet stream is achieved by iterative adjustments. However, a number of adjustments may be required to synchronize.

The following theorem holds.

Theorem 1 *When the transmission time of the adjusted packet stream is adjusted with adjustment width $W = rV$ for α synchronization against the non-adjusted packet stream, satisfying the following condition between r and α ensures synchronize with the non-adjusted packet stream.*

$$r \leq 2(1-\alpha) \tag{5}$$

<u>*Proof*</u> Assume the adjusted packet stream is x synchronized with the non-adjusted packet stream after the k th adjustment, where $0 < x < \alpha$ .Consider the condition to achieve α synchronization with the non-adjusted packet stream after the $k+1$ th adjustment. There are two cases of r. One is $r < 1$ and the other is $r \geq 1$:

1) $r < 1$
2) $r \geq 1$

Figures 7 and 8 show respectively these cases. In case 1), the ratio of the synchronized portion with the non-adjusted packet stream after the $k+1$ th adjustment is, as a function of x, $r_s(x)$, given by

$$r_s(x) = (1-x) + (1-r). \tag{6}$$

To achieve α synchronization with the non-adjusted packet stream after the $k+1$ th adjustment, $r_s(x)$ must be more than or equal to α .

$$r_s(x) \geq \alpha \tag{7}$$

$r_s(x)$ is a monotonically decreasing function because $\frac{dr_s(x)}{dx} = -1 < 0$ Figure 9 plots $r_s(x)$ as a function of x. Because $r_s(x)$ monotonically decreases in $(0, \alpha)$, the condition that $r_s(x) \geq \alpha$ holds for any x such that its range is $0 < x < \alpha$ is the condition that $r_s(x) \geq \alpha$ holds when $x \to \alpha$. Thus,

$$\lim_{x \to \alpha} r_s(x) \geq \alpha .$$

By using $r_s(x) = (1-x) + (1-r)$,

$$\lim_{x \to \alpha} (1-x) + (1-r) \geq \alpha$$

$$\therefore r \leq 2(1-\alpha).$$

In case 2), $r_s(x)$ is expressed by

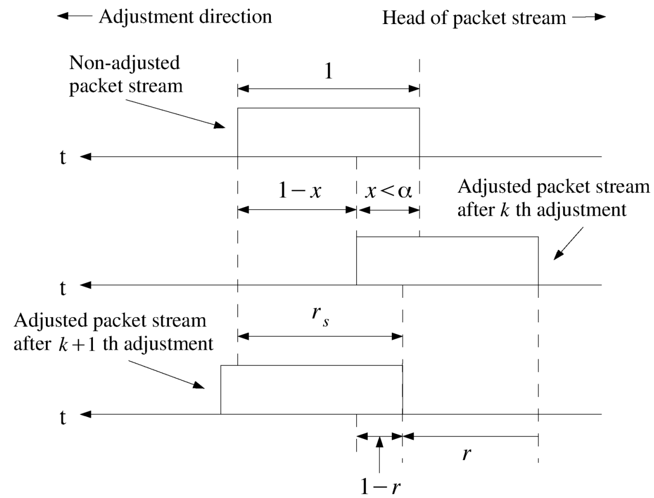

Fig. 7. 1) $r < 1$

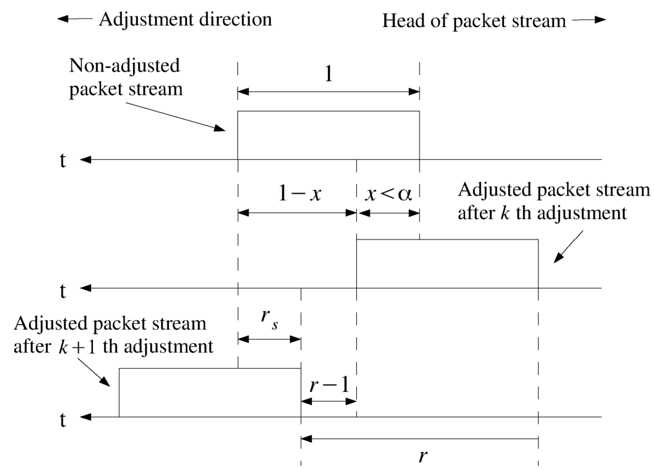

Fig. 8. 2) $r \geq 1$

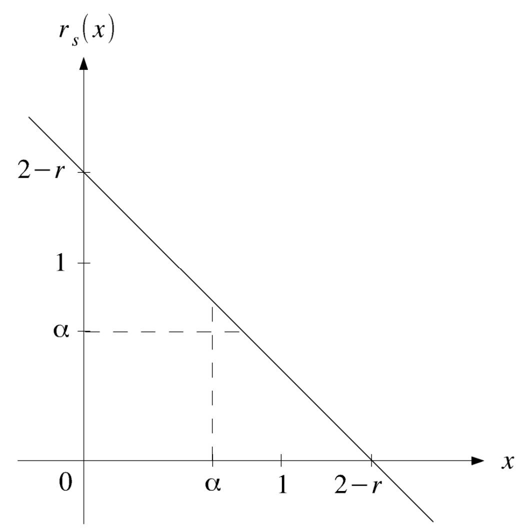

Fig. 9. $r_s(x) = (1-x) + (1-r)$

$$r_s(x) = (1-x) - (r-1). \tag{8}$$

In a manner similar to the case of 1), it is only necessary to evaluate the condition that $r_s(x) \geq \alpha$ holds when $x \to \alpha$. Thus,

$$\lim_{x \to \alpha} r_s(x) \geq \alpha .$$

By using $r_s(x) = (1-x) - (r-1)$,

$$\lim_{x \to \alpha} (1-x) - (r-1) \geq \alpha$$

$$\therefore r \leq 2(1-\alpha).$$

Both cases reach the same inequality. Consequently the condition to achieve α synchronization with the non-adjusted packet stream after the $k+1$ th adjustment is expressed by

$$r \leq 2(1-\alpha). \qquad \blacksquare$$

The following theorem holds. Let *P* be the period of the packet streams.

Theorem 2 *When the transmission time of the adjusted packet stream is altered via adjustment width W = rV for α synchronization with the next non-adjusted packet stream, the worst case number of adjustments for α synchronization,* n_w*, and the average number of adjustments for α synchronization,* n_a*, satisfy the following inequalities.*

$$n_w < \frac{P}{rV} \tag{9}$$

$$\frac{P - 2(1-\alpha)V}{2rV} \leq n_a \leq \frac{P + 2(1-\alpha)V}{2rV} \tag{10}$$

Proof The worst case for α synchronization is when the head of the adjusted packet stream is located at slightly less than α of *V* of the non-adjusted packet stream. Thus the ratio *x* of the overlapped portion of *V* is represented as $x = \alpha - \delta$, where δ is a minimal positive value. Figure 10 represents the worst case. The upper limit of the time distance that is adjusted by *W* to yield α synchronization with the non-adjusted packet stream is $P - (1-x)V + (1-\alpha)V$, then

$$n_w \leq \frac{P - (1-x)V + (1-\alpha)V}{W} .$$

By using *W* = *rV*,

$$n_w \leq \frac{P - (\alpha - x)V}{rV} .$$

By using $\alpha - x > 0$,

$$n_w < \frac{P}{rV} .$$

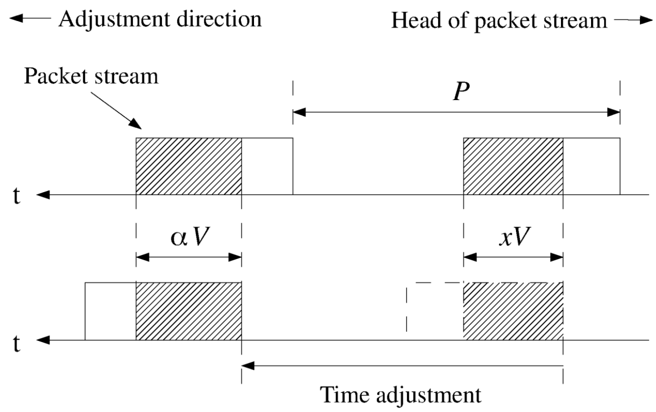

Fig. 10. Worst case for α synchronization

The average case for α synchronization is when the head of the adjusted packet stream is located at $\frac{P}{2}$. In this case, the lower limit of the time distance that is adjusted by *W* the yield α synchronization with the non-adjusted packet stream is $\frac{P}{2} - (1-\alpha)V$, then

$$n_a \geq \frac{\frac{P}{2} - (1-\alpha)V}{W} .$$

By using *W* = *rV*,

$$n_a \geq \frac{P - 2(1-\alpha)V}{2rV} . \tag{a}$$

The upper limit of the time distance is $\frac{P}{2} + (1-\alpha)V$,

$$n_a \leq \frac{\frac{P}{2} + (1-\alpha)V}{W} .$$

By using *W* = *rV*,

$$n_a \leq \frac{P + 2(1-\alpha)V}{2rV} . \tag{b}$$

By using (a) and (b), the following inequality is derived.

$$\frac{P - 2(1-\alpha)V}{2rV} \leq n_a \leq \frac{P + 2(1-\alpha)V}{2rV} \qquad \blacksquare$$

From Theorem 1, α synchronization inevitably succeeds if $r \leq 2(1-\alpha)$. From Theorem 2, the worst number of adjustments, n_w, is inversely proportional to *r*. Therefore the optimal adjustment width *W* for α synchronization is $W = 2(1-\alpha)V$.

VI. EXPERIMENT

Synchronization probability depends on the adjustment width. The probability, p_s, is defined by

$$p_s = \frac{N_s}{N_t}, \qquad (11)$$

where N_s is the number of successful α synchronizations with the non-adjusted packet stream and N_t is the number of trials. The dependency of the synchronization probability on adjustment width is examined via simulations. Parameters used in the simulation are shown in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Packets in packet stream K	100
Packet interval T	80 μ sec
Packet stream duration V	8 msec
Packet stream period P	72 msec
Number of trials n_t	10^6

Figures 11 and 12 plot the synchronization probabilities when α is respectively set to 0.6 and 0.8. Figures 11 and 12 indicate that α synchronization with the non-adjusted packet stream is successful if the adjustment width W is respectively less than or equal to 6.4 msec and 3.2 msec, which is equal to the optimal adjustment width, $W = 2(1-\alpha)V$, derived from Theorems 1 and 2.

Figure 13 shows the number of adjustments needed to realize α synchronization when α is set to 0.6. Figure 13 indicates that the number of adjustments is minimal when the adjustment width is 6.4 msec.

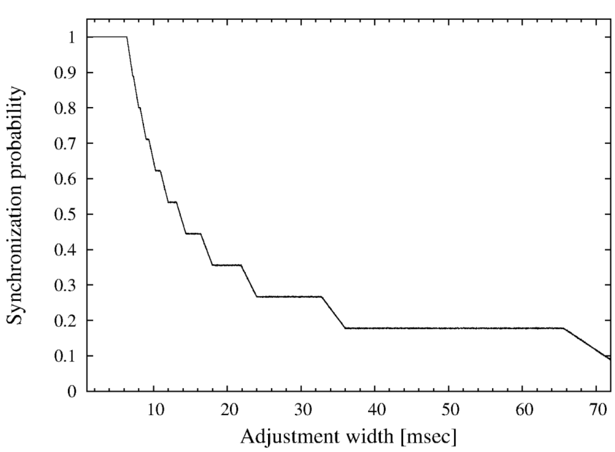

Fig. 11. Synchronization probability (α = 0.6)

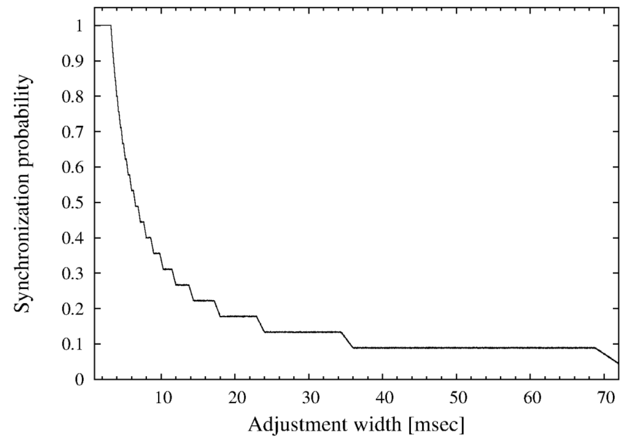

Fig. 12. Synchronization probability (α = 0.8)

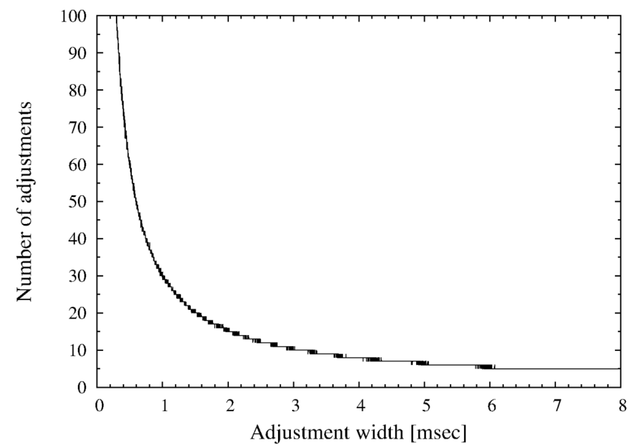

Fig. 13. Numbers of adjustments (α = 0.6)

VII. CONCLUSIONS

This paper has proposed a scheme for the simultaneous available bandwidth estimation in multiple-pair connections. To achieve this, the proposed scheme estimates the link available bandwidth of the common link, which may limit the simultaneous available bandwidth, by synchronizing packet streams at the common link if any common link exists. The state of packet stream synchronization can be observed by using the PCT and PDT metrics and then controlled appropriately. Full synchronization of packet streams for estimating the link available bandwidth of a common link is achieved by adjusting the transmission time via the adjustment width. We have formulated the optimal adjustment width when the target synchronization ratio is given. This paper provided the detail analysis and theorems on the adjustment width with proofs.

For a further study, grid scheduling should be investigated considering available bandwidth constraints in simultaneous multiple-pair connections.

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