

# Evaluation of TCP Performance on Asymmetric Networks Using Satellite and Terrestrial Links

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**SUMMARY** By the growth of the Internet, the client's access to the Internet have been increasing. In order to meet those demands, asymmetric networks have become a great attraction. However, asymmetric networks composed of satellite and terrestrial links have not been enough investigated. Therefore, this paper proposes a new formula for TCP performance evaluation for the asymmetric networks. Using this evaluation formula, we calculate the throughput of TCP Reno over the asymmetric networks taking Slow Start into account. The calculation results are compared with the following: (1) the value based on an existing theoretical formula, (2) the outputs of simulation by NS (Network Simulator), and (3) the experimental results using VSAT (Very Small Aperture Terminal) satellite communication system for satellite links and the Internet for terrestrial links. As a result, it is shown that the new formula is more precise than the one already proposed.

**key words:** *TCP performance, asymmetric networks, satellite links, terrestrial links, Internet*

## 1. Introduction

Recently, asymmetric networks which provide asymmetric bandwidth or delay for uplink and downlink have become a great attraction. The main reason is that the client's access to the Internet is essentially asymmetric. In order to meet those demands, new network technologies are emerging. Examples of these are ADSL (Asymmetric Digital Subscriber Line) [3] and cable modem. A particular WWW service is also realized by using both satellite links and terrestrial links. This service is operated by several techniques, such as UDLR (Uni-Directional Link Routing) system [5], [6], NTT system [7], [8], and DirecPC system [9]. These WWW services allow users to take advantage of asymmetric networks, by making requests for web contents from the Internet via a terrestrial (land) line such as a modem, and receiving that information via a high speed, error-resilient satellite link. Moreover, it is pointed out that satellite-terrestrial networks have a potential ability to support multicast services efficiently.

TCP (Transmission Control Protocol) is the stan-

dard transport level protocol that provides the reliable, full duplex, and stream service [19]. However, TCP has not been designed for asymmetric networks [2], [4], [18]. In the last few years, several articles have been devoted to the study of TCP performance on asymmetric networks [1], [4], [14]. In a recent paper [4], the authors propose a new excellent analysis formula for asymmetric networks. The obtained formula in [4] is an extension of the one in [14]. However, in [4], the authors focus on the mean throughput of TCP with regular relatively long period. Therefore, the formula tends to overestimate the throughput of TCP, when transmission data size is small such as several web data transfer.

So far, asymmetric networks which are composed of the terrestrial and satellite links have not been enough investigated. Therefore, this paper proposes the new formula for the TCP performance evaluation for the asymmetric networks. In order to get more precise formula, we deal with Slow Start phase of TCP in detail. Using this evaluation formula, we calculate the throughput of TCP Reno over the asymmetric networks. The result of calculation is compared with the following: (1) the value based on an existing theoretical formula in [4], (2) the outputs of simulation by NS (Network Simulator) [20], and (3) the experimental results using the VSAT satellite communication system for satellite links and the Internet for terrestrial links [11]. As a result, it is shown that the new evaluation formula is more precise than the one already proposed.

The rest of this paper is organized as follows. Section 2 gives the network model that we will use in the analysis and the simulation. Next, for the asymmetric networks, we show the new formula which estimates TCP throughput in Sect. 3. Numerical results and discussion are then presented in Sect. 4. Finally, Sect. 5 concludes this paper.

## 2. Network Model

The network model that we will use in the analysis and the evaluation is depicted in Fig. 1.

The model consists of a server, a client, and two links (see Fig. 1); downlink (satellite link) from the server to the client and uplink (terrestrial link) from the client to the server. The downlink and the uplink

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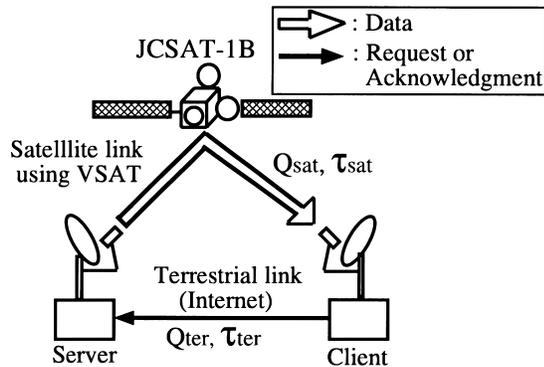


Fig. 1 Asymmetric network composed of a VSAT satellite communication system and Internet.

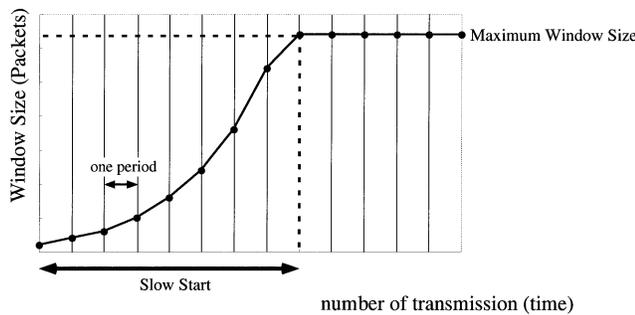


Fig. 2 The continuous change of  $w(n)$ .

have asymmetric bandwidth and delay. Bandwidths of the downlink and the uplink are denoted as  $Q_{sat}$  and  $Q_{ter}$ , respectively. Propagation delays of the downlink and the uplink are denoted as  $\tau_{sat}$  and  $\tau_{ter}$ , respectively. Data segment size and ack segment size are represented by  $d_{seg}$  and  $d_{ack}$ , respectively. The sum of TCP and IP header size is denoted as  $d_{head}$ .

### 3. Proposed Formula

In order to get new precise formula, we will consider two cases of the data transmission. One is case with large data size which means that data size to be transmitted is large. In this case, data transmission is not completed in Slow Start phase. Another is case with small data size which means that data size to be transmitted is small. In this case, data transmission is completed in Slow Start phase. Note that the new formula consists of Slow Start phase and Maximum Window Size phase (see Fig. 2). An existing formula in [4] hardly seems to estimate TCP throughput for a period such that data transmission is completed in Slow Start phase. This is the reason why the new formula is able to estimate TCP throughput more precisely.

In this paper, the throughput of TCP is defined as (transmission data size without IP and TCP headers)/(data transmission time). It is assumed that retransmission of data does not occur, meaning that there

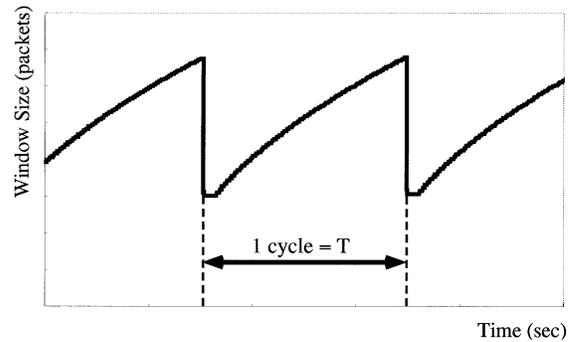


Fig. 3 The window size with steady changes.

are enough buffering in the client and the satellite link is error-resilient. This is a realistic assumption of satellite communications [1], [10], [17].

Section 3.1 gives explanation of related works. Section 3.2 shows the new formula when the transferred data is assumed to be large. Section 3.3 shows the new formula when the transferred data is assumed to be small.

#### 3.1 Related Works

Several researchers have studied the performance of satellite links [1], [2], [10], [16], [17]. However, asymmetric networks which use both terrestrial and satellite links at the same time are not enough investigated.

Analytical results of the mean throughput of TCP are presented for asymmetric networks [4], [14]. Since [4] is an extension of the one in [14], we briefly explain the formula in [4].

In the formula [4], firstly the time dependent behavior of the window size is obtained. The time dependent behavior means that the length  $T$  of the window size cycle and the variance of the window size per time  $t$  (see Fig. 3). Secondly, the instantaneous throughput  $\rho(t)$  at time  $t$  is obtained. The  $\rho(t)$  is defined as (the window size at time  $t$ )/(the round trip time). Finally, the throughput is obtained as  $\frac{1}{T} \int_0^T \rho(t) dt$ .

The authors in [4] focus on the mean throughput of one regular cycle. Therefore, it is expected that the formula in [4] tends to overestimate of the throughput, when transmission data size is relatively small.

#### 3.2 Large Data Size

In order to overcome the issue, as mentioned above, we will focus on not the regular state but the starting point (Slow Start phase) of data transfer. As a result, in case of both the steady state and the starting state, we can get more precise throughput estimation close to the actual value in [11].

In TCP, the transmission of data is based on window control. In each transmission, the window size may be individual. Thus, we assume that the sending pe-

riod, i.e. the period from transmission at a certain window size to transmission at next window size, is a function of the number of transmission (see Fig. 2). This is a new idea of our formula. The total transmission time is the sum of sending period for every transmission from start to end. Note that no retransmission is assumed to occur. The reason why we don't assume retransmission is that the new evaluation formula only covers the asymmetric networks composed of satellite and terrestrial links. Usually, satellite links rarely causes the packet loss in fine weather. Therefore the new evaluation formula will be able to calculate precisely to some extent without assuming retransmission.

Basically, the window size in Slow Start phase increases by 1 segment when 1 ack segment is received. When  $w(n)$ , i.e. the number of data segments at  $n$ -th transmission, is transmitted by sender, the sender will receive  $w(n)$  ack segments. TCP Reno, however, adopts Delayed Ack: the receiver sends an ack segment after receiving two data segments [19]. Note that it is assumed that two data segments arrive in serial order. Taking Delayed Ack into account,  $\lceil \frac{w(n)}{2} \rceil$  ack segments will come to the sender. The window size at  $n$ -th transmission is expressed in Eq. (1), where  $n$  is number of transmission,  $w(0)$  equals to 1, and  $\lceil a \rceil$  means the smallest integer in the range  $[a, \infty)$ .

$$w(n+1) = w(n) + \left\lceil \frac{w(n)}{2} \right\rceil \quad (1)$$

$w(n)$  behaves like Fig. 2: it increases up to the maximum window size which is advertised from the receiver, and stays in fixed value.

Here, sending period  $t(n)$  is defined as the time between the transmission whose window size is  $w(n)$  and the next transmission whose window size is  $w(n+1)$ .  $t(n)$  is a function of

- $rtt$ : round trip time,
- $a(n)$ : transmission time required for sending data segments whose window size is  $w(n)$ , and
- $q(n-1)$ : transmission time required for sending ack segments corresponding to the  $n-1$ -th transmission.

Thus,  $t(n)$  is to be the maximum of  $rtt$ ,  $a(n)$ , and  $q(n-1)$ . Using the maximum function  $max$ , it is described as follows.

$$t(n) = \max(rtt, a(n), q(n-1)) \quad (2)$$

Figure 4 shows three cases of  $t(n)$ :

- case1: The throughput does not reach the bandwidth of downlink, because the window size  $w(n)$  is small.
- case2: The throughput reaches the bandwidth of downlink, because the window size  $w(n)$  is large.
- case3: The sender is waiting for ack segments from the receiver, because the bandwidth of uplink is extremely narrow.

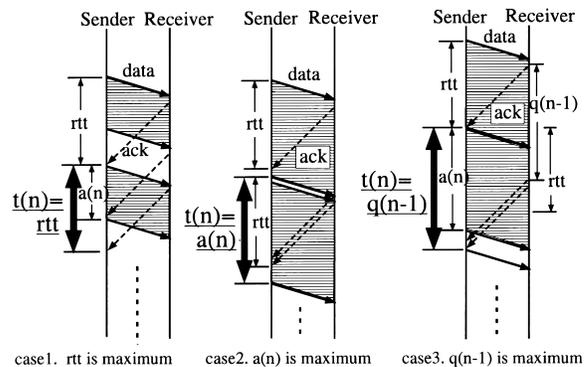


Fig. 4 Three cases of  $t(n)$ .

The receiver sends an ack segment after receiving two data segments, because TCP Reno adopts Delayed Ack [19]. Therefore, the round trip time  $rtt$  is the sum of the time required to transmit two data segments and one ack segment, and the propagation delay of the downlink and uplink. Thus, the round trip time  $rtt$  is described as Eq. (3) using  $\tau = \tau_{sat} + \tau_{ter}$  as the round trip propagation delay. Here, packet size of data  $P$  is the sum of data segment size and headers of both TCP and IP. In case of  $w(0) = 1$ , the ack is delayed by a certain period  $d$ . Therefore,  $rtt$  is the sum of the time required to transmit one data segment and one ack segment and  $d$ , and the propagation delay of the downlink and uplink. Thus,  $rtt$  is described as Eq. (4) when  $w(0) = 1$ . Here, TCP Reno adopts 200 msec as  $d$  [19].

$$rtt = \tau + \frac{2 \cdot P}{Q_{sat}} + \frac{d_{ack}}{Q_{ter}} \quad (3)$$

$$rtt = \tau + \frac{P}{Q_{sat}} + \frac{d_{ack}}{Q_{ter}} + d \quad (4)$$

$a(n)$  and  $q(n)$  are described as Eqs. (5) and (6), respectively.

$$a(n) = \frac{P \cdot w(n)}{Q_{sat}} \quad (5)$$

$$q(n) = \frac{d_{ack} \cdot \lceil \frac{w(n)}{2} \rceil}{Q_{ter}} \quad (6)$$

The data transmitted in Slow Start phase ( $F_{slow}$ ) is obtained as the sum of  $w(n)$  just before  $w(n)$  becomes the maximum window size advertised by receiver. Threshold  $th$  is defined as the number of transmission at this moment, then  $F_{slow}$  is described as Eq. (7). The transmission time in Slow Start phase ( $t_{slow}$ ) is expressed as the sum of  $t(n)$  up to  $n = th$ , similarly.

$$F_{slow} = \sum_{k=0}^{th} \{w(k) \cdot d_{seg}\} \quad (7)$$

$$t_{slow} = \sum_{k=0}^{th} t(k) \quad (8)$$

Now, the rest of transferred data,  $F_{rest}$  is described as  $F_{rest} = F - F_{slow}$ , where the size of transferred file is  $F$  ( $F \gg F_{slow}$  since large data size is assumed). Here, we describe the maximum window size as  $MWS$ . We can derive the time required for transmitting the rest of transferred data from sending period  $t(n)$  multiplied by the number of transmission whose window size is  $MWS$ : how many times the rest of data is larger than  $MWS$ . As the transmission period  $t(n)$  is fixed, it can be described as a constant,  $t_{max}$ .  $t_{max}$  is obtained from Eq. (2) by applying  $w(n) = MWS/d_{seg}$ .

In some cases, data which is smaller than the maximum window size is left. The time required to send this rest data,  $t_{rest}$ , is described as Eq. (9), where  $(m) \bmod (n)$  means the residue of  $m$  divided by  $n$ .

$$t_{rest} = \frac{(F_{rest}) \bmod (MWS)}{Q_{sat}} + \tau_{sat} \quad (9)$$

The time  $T$  required for transmitting the file whose size equals to  $F$  is the sum of the time spent in Slow Start phase and the time required to transmit data segments in the maximum window size. Thus,  $T$  is described as Eq. (10) from Eq. (8) and Eq. (9), where  $t_{rest} = 0$  if  $F_{rest}$  can be divided by  $MWS$  without a remainder. A notation  $[a]$  means the maximum integer in the range  $(-\infty, a]$ , here.

$$T = \left\lfloor \frac{F_{rest}}{MWS} \right\rfloor \cdot t_{max} + t_{slow} + t_{rest} \quad (10)$$

The throughput can be obtained as file size  $F$  over total transmission time  $T$ . Therefore, the throughput is defined as  $\frac{F}{T}$ .

### 3.3 Small Data Size

In this section, the transferred data is assumed to be small. In other words, the transmission is completed in Slow Start phase. Such phenomenon may be often observed in World Wide Web data transfer. In the following, the transmission time  $T$  in such case is derived.

First, the maximum of transmitting time  $th'$  which satisfies  $F \geq F_{slow}$  is obtained from Eq. (7).

Next, the transmission time  $T$  is the sum of sending period  $t(n)$  up to  $n = th'$ . At the final transmission, the data which is smaller than the window size is transmitted in some cases. The time required to transmit it,  $t'_{rest}$ , is described as Eq. (11).

$$t'_{rest} = \frac{F - F_{slow}}{Q_{sat}} + \tau_{sat} \quad (11)$$

Finally, the total transmission time  $T$  is described as Eq. (12), where  $t'_{rest} = 0$  if all data are transmitted in the same size as the window size.

**Table 1** Network parameters.

File Size (kByte)	1024
Data Segment Size (Byte)	1448
Ack Segment Size (Byte)	52
Downlink Bandwidth (kbps)	2048, 64
Uplink Bandwidth (kbps)	64, 16, 4
Downlink Delay (msec)	250
Uplink Delay (msec)	250, 125, 25
Header Size (Byte)	52

$$T = \sum_{k=0}^{th'} t(k) + t'_{rest} \quad (12)$$

## 4. Numerical Examples

In this section, for the asymmetric network, we will show numerical examples based on the new formula presented in Sect. 3. The results of calculation are compared as follows. First, we compare the results with output by NS (Network Simulator) [20] in Sect. 4.2.1. Second, in Sect. 4.2.2, the results are compared with both the experimental data [11] and the formula in [4].

### 4.1 Parameters of Asymmetric Network

Table 1 shows a set of parameters of the asymmetric network. The asymmetric network is composed of the VSAT satellite communication systems and Internet [11] (see Fig. 1).

### 4.2 Evaluation

In this section, the value derived from the proposed theoretical formula is compared with the outputs of simulation by NS, the value derived from [4], and experimental data [11]–[13]. In every case, the throughput is derived for various maximum window sizes.

In the simulations, the maximum window size is set as 4 kByte, 8 kByte, 16 kByte, 32 kByte, 64 kByte, 128 kByte, and 192 kByte. The maximum window size when the throughput saturates is also set. It equals  $w(n)$  when  $n$  satisfies  $r_{tt} = a(n)$ . It can be obtained from Eqs. (3) and (5).

In the experiments, the VSAT system is used as satellite links. We have constructed a symmetric network in 1998 and an asymmetric one in 1999, and both involve the VSAT system [11]. The bandwidth of the satellite link is fixed as 64 kbps. The maximum window size is varied between 2 kByte and 128 kByte. The experimental data is obtained from above each case. We average five data obtained by DBS [15] for each independent TCP connection whose duration is 60 seconds.

In the theoretical evaluation, the propagation delay of terrestrial link is set as 25 msec referring observed value.

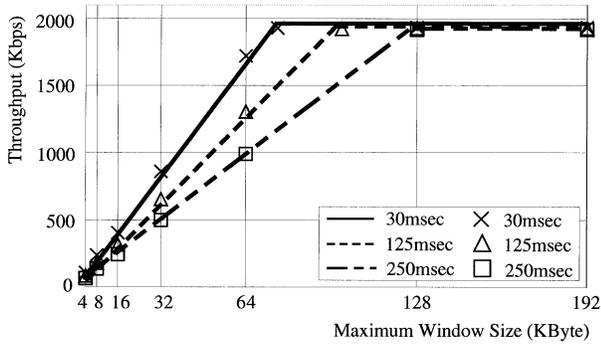


Fig. 5 Comparison of the throughput by the proposed formula and the simulation results by NS, with various delay on Uplink.

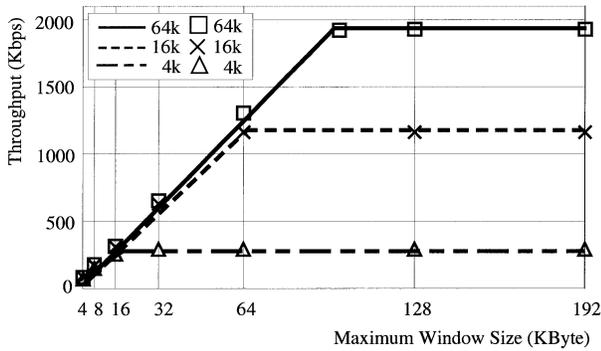


Fig. 6 Comparison of the throughput by the proposed formula and the simulation results by NS, with various bandwidth on Uplink.

#### 4.2.1 Comparison of the Throughput by the Proposed Formula and the One by NS

The value derived from the proposed formula is compared with the outputs of simulation applying the parameters in Table 1. Figure 5 shows the throughput by the proposed formula and the outputs from the simulation when the bandwidth of downlink is 2 Mbps, the one of uplink is 64 kbps, and the propagation delay of uplink is set as 250 msec, 125 msec, and 30 msec. Figure 6 shows the similar results when the propagation delay of downlink is 250 msec, the one of uplink is 125 msec, and the bandwidth of uplink is set as 64 kbps, 16 kbps, and 4 kbps. In these figures, each symbol shows the output of the simulation and each line shows the theoretical value by the proposed formula.

From Fig. 5, it is observed that the throughput increases as the delay of uplink decreases. It is because the faster an ack arrives, the maximum window size when the throughput saturates becomes small. From Fig. 6, it is shown that the throughput deteriorates when the bandwidth of uplink is extremely narrow. It is because the number of ack decreases.

From these figures, it is obvious that the value by the proposed formula is completely consistent with

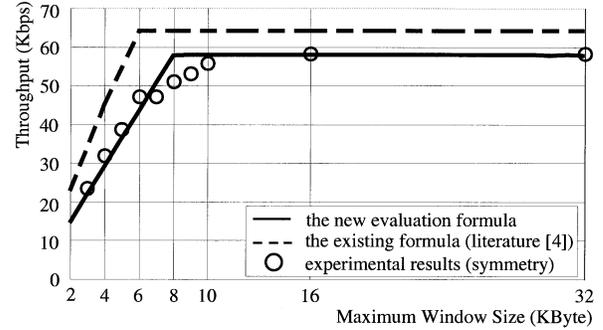


Fig. 7 Comparative results on the symmetric network (both downlink and uplink are satellite).

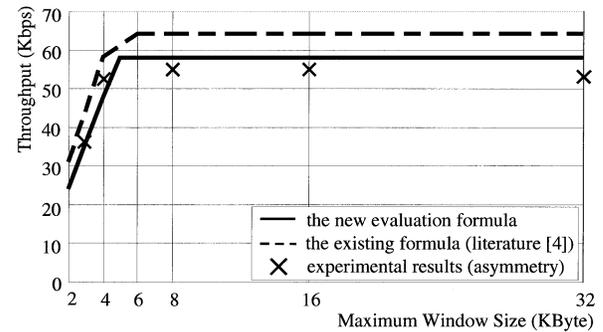


Fig. 8 Comparative results on the asymmetric network.

the outputs of the simulation. Thus, it is confirmed that the proposed formula can accurately derive the throughput of network whose bandwidth or propagation delay are asymmetric.

#### 4.2.2 Comparison of the Proposed Formula and the Existing One

We compare the value derived from the proposed theoretical formula with both the observed data [11] and the value derived from the existing formula [4]. We also show the results from symmetric networks and asymmetric networks in order to clarify the characteristic of the asymmetric networks. Figure 7 shows the result from a symmetric network whose propagation delay is 250 msec and whose bandwidth is 64 kbps. Figure 8 shows the result from the asymmetric network which use satellite links (propagation delay is 250 msec and bandwidth is 64 kbps) as downlink and the Internet (propagation delay is 25 msec and bandwidth is 737 kbps) as uplink.

The VSAT satellite system adds one redundant bit per 15 bits to data at IDU (In Door Unit) when the data are transmitted by the satellite channel. Taking this overhead into account,  $P$  in Eq. (5) is replaced with  $\alpha P$  where  $\alpha$  (redundancy coefficient) is 16/15. Therefore, we obtain the following Eq. (5'). The throughput in Fig. 7, Fig. 8, Fig. 10, and Fig. 11 is calculated based on Eq. (5').

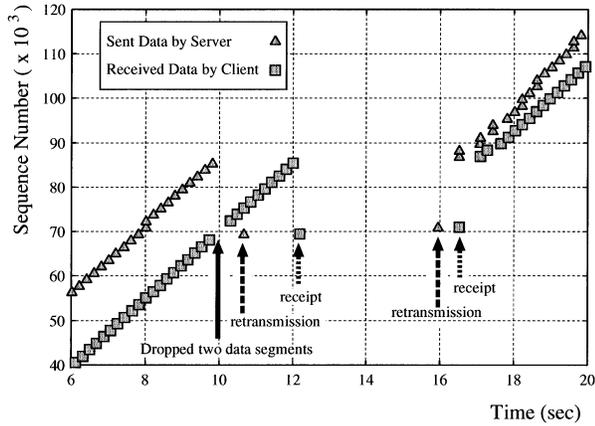


Fig. 9 The change of the sequence number.

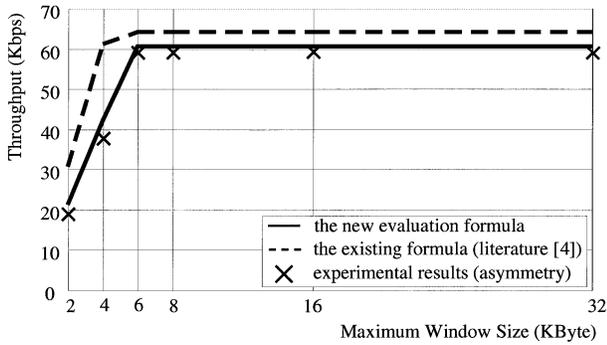


Fig. 10 Comparative results on the asymmetric network with another configuration (The bandwidth of downlink is 64 kbps).

$$a(n) = \frac{\alpha \cdot P \cdot w(n)}{Q_{sat}} \quad (5')$$

From Fig. 7 and Fig. 8, for small window size (2 kByte, 4 kByte, 6 kByte in the experiments), the asymmetric network tends to outperform the symmetric network.

In Fig. 8, the throughput deteriorates at 32 kByte maximum window size. Figure 9 shows data sequence number of the server and the client when the maximum window size is 32 kBytes at Fig. 8. Here, the result of Fig. 9 is obtained by the outputs of *tcpdump* command in the server (see Fig. 1). From Fig. 9, two data segments are dropped and are retransmitted on satellite links. And the server began to transmit the new data in Slow Start phase after retransmitting the lost data. As a result, the throughput on the asymmetric network deteriorates.

In order to confirm the above consideration, we construct an asymmetric network with another configuration [13]. That is, while BSD/OS4.0 is installed on both the server and the client on previous configuration [11], FreeBSD3.3-RELEASE is now newly installed on them. Figure 10 depicts the experimental results using the new network configuration and the results by the proposed formula.

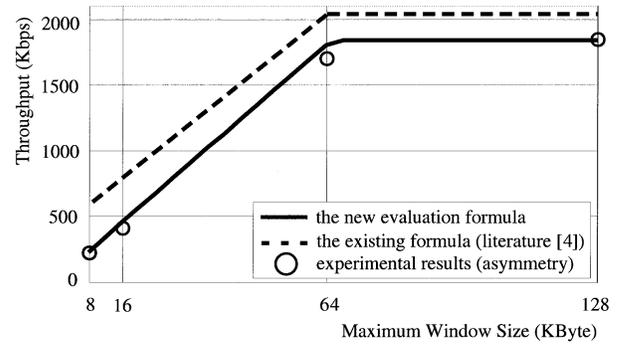


Fig. 11 Comparative results on the asymmetric network with another configuration (The bandwidth of downlink is 2 Mbps).

It is shown that when maximum window size is large, the theoretical throughput is consistent with the experimental value. It may be because the implementations of queue management or the queue size of BSD/OS4.0 have some problem on such asymmetric network. The reasons are as follows. We observed the sequence number in Fig. 9 by using *tcpdump* command at the server in Fig. 1. The server is the behind of the outgoing satellite communication line. Packet losses in Fig. 9 occur before transmitting the packet on the satellite interface. Therefore, we assume that it is caused by the implementations of queue management or the queue size of BSD/OS4.0.

So far, the bandwidth of downlink in Fig. 7, Fig. 8, and Fig. 10 is smaller than the bandwidth of uplink. To make the discussion deeper, we will show the case that the bandwidth of downlink is larger than the bandwidth of uplink. Figure 11 shows the experimental results using the new network configuration and the results by the proposed formula. (the bandwidth of downlink is 2 Mbps, the propagation delay of uplink is 19 msec, and the bandwidth of uplink is 872 kbps. )

From Fig. 7, Fig. 8, Fig. 10, and Fig. 11, it is obvious that our proposed formula is more precise than the one proposed in [4] on both the symmetric and the asymmetric networks.

### 4.3 Discussion

First, we discuss the window size on the asymmetric network. It is observed from Fig. 5 and Fig. 6 that the throughput saturates when the maximum window size becomes larger than a certain size. When the throughput saturates, the round trip time equals to the time which is required to transmit the amount of data corresponding to the maximum window size. In this case, the window size  $W_{th}$  is derived from Eqs. (3) and (5). Therefore, we obtain an Eq. (13).

$$W_{th} = 2 + \frac{Q_{sat}}{P} \cdot \left( \tau_{sat} + \tau_{ter} + \frac{d_{ack}}{Q_{ter}} \right) \quad (13)$$

In Eq. (13),  $Q_{sat}$ ,  $Q_{ter}$ ,  $\tau_{sat}$ ,  $\tau_{ter}$ ,  $P$ ,  $d_{ack}$  denote

the bandwidth of satellite link, the bandwidth of terrestrial link, the propagation delay of satellite link, the propagation delay of terrestrial link, packet size of data, and ack segment size, respectively. Based on Eq. (13), the following observations are derived. Assumed that both the bandwidth and the propagation delay of satellite links are constant, the window size at saturation ( $W_{th}$ ) is proportional to the propagation delay of terrestrial links ( $\tau_{ter}$ ) and is inversely proportional to the bandwidth of terrestrial links ( $Q_{ter}$ ).

Next, let us consider the cases when the bandwidth of downlink is set as 64kbps and 2Mbps. Figure 10 shows that the bandwidth of downlink is 64kbps. Figure 11 indicates that the bandwidth of downlink is 2Mbps. It is observed that the throughput in Fig. 11 is larger than that of Fig. 10 at the same maximum window size. However, in case of the throughput saturation, a bandwidth utilization of downlink in Fig. 11 (89.6%) is lower than the one in Fig. 10 (94.4%). Here, this bandwidth utilization is defined as  $\frac{\text{the throughput}}{Q_{sat}} \cdot 100$ .

We examine the accuracy of the proposed theoretical formula. It is observed that the value derived from the formula in [4] differs from observed one, because the previous formula always averages the throughput of one regular cycle. This averaging will lead to overestimating of the throughput. On the other hand, our proposed formula is precise because the throughput is derived based on the duration which is required to transmit each data taking the window size into account. Our proposed formula also consider the window size which is advertised from the receiver. Therefore our proposed formula is precise more than the previous formula considering only the congestion window size with steady changes (see Fig. 3).

The proposed formula covers only the asymmetric networks composed of satellite and terrestrial links among a variety of asymmetric networks. However, the existing formula [4] is able to cover more general asymmetric networks. Therefore it will make the difference in accuracy between the proposed formula and the previous formula.

## 5. Conclusion

In this paper, we theoretically studied the throughput of TCP Reno on the asymmetric networks composed of satellite and terrestrial links. This formula can derive the throughput on the asymmetric networks more precisely than the one already proposed. It especially tends to improve the existing formula when small data, such as contents of World Wide Web, are transferred.

For future study, we will plan to extend current evaluation formula to the HTTP performance evaluation.

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