TCP Performance Analysis on Asymmetric Networks Composed of Satellite and Terrestrial Links

Hiroyasu Obata
Graduate School of Information Sciences
Hiroshima City University
Hiroshima, Japan
obata@nets.ce.hiroshima-cu.ac.jp

Kenji Ishida, Junichi Funasaka, and Kitsutaro Amano
Department of Computer Engineering
Faculty of Information Sciences
Hiroshima City University
Hiroshima, Japan
{ishida, funa, amano}@ce.hiroshima-cu.ac.jp

Abstract

As the Internet users increase, asymmetric networks which provide asymmetric bandwidth or delay for uplink and downlink have become a great attraction. However, asymmetric networks which use both terrestrial and satellite links at the same time 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.

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 [5]. Such WWW service allows users to take advantage of asymmetric networks, by making requests for web content 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 standard transport level protocol that provides the reliable, full duplex, and stream service [13]. However, TCP has not been designed for asymmetric networks [2, 4, 12]. In the last few years, several articles have been devoted to the study of TCP performance on asymmetric networks[1, 4, 8]. 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 [8]. 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 the-

0-7695-0921-5/00 $10.00 © 2000 IEEE

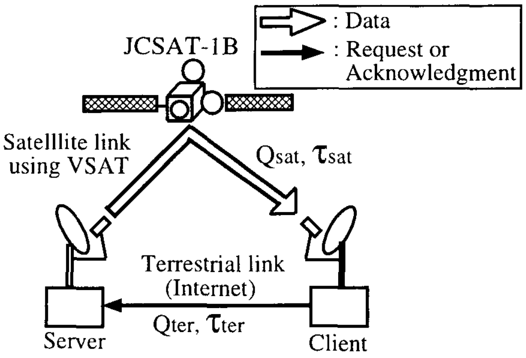


Figure 1. Asymmetric Network composed of VSAT satellite communication system and Internet

oretical formula in [4], (2) the outputs of simulation by NS (Network Simulator) [14], and (3) the experimental results using the VSAT satellite communication system for satellite links and the Internet for terrestrial links [7]. 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 Section 3. Numerical results and discussion are then presented in Section 4. Finally, Section 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 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 τ_{sat} and τ_{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 the data transmission two cases. One is large data case which means that data size to be transmitted is large. In this case, data transmission is not completed in Slow Start phase. Another is small case 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 are enough buffering in the client and the satellite link is error–resilient. This is a realistic assumption of satellite communications [1, 6, 11].

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, 6, 10, 11]. 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, 8]. Since [4] is an extension of the one in [8], 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 [7].

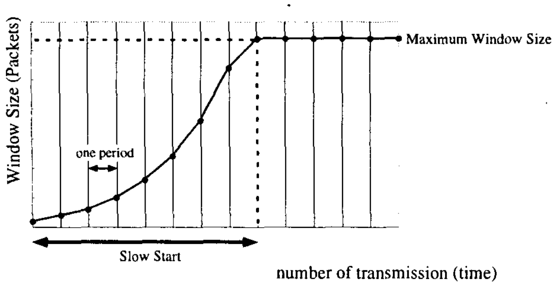


Figure 2. The Continuous Change of $w(n)$

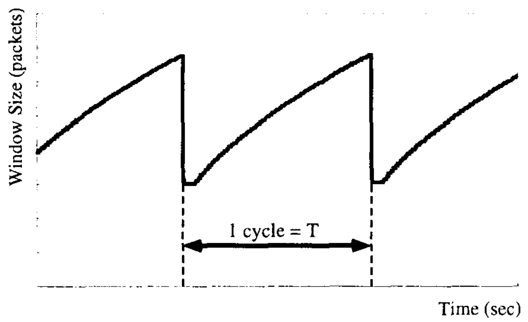


Figure 3. The Window Size with Steady Changes

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 period, i.e. the period from transmission at a certain window size to next transmission, 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 doesn't assume retransmission is that the new evaluation formula only covers the asymmetric networks composed of satellite and terrestrial links. Usually, satellite link rarely cause 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 [13]. Note that it is assumed that two data segments arrive at the same time. 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 the equation (1), where n is number of transmission, $w(0)$ equals to 1, and $\lceil a \rceil$ means the smallest integer in the range $[a, \infty)$.

$$w(n+1) = w(n) + \lceil \frac{w(n)}{2} \rceil \tag{1}$$

$w(n)$ 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.

$$t(n) = max(rtt, a(n), q(n-1)) \tag{2}$$

Fig.4 shows three cases of $t(n)$:

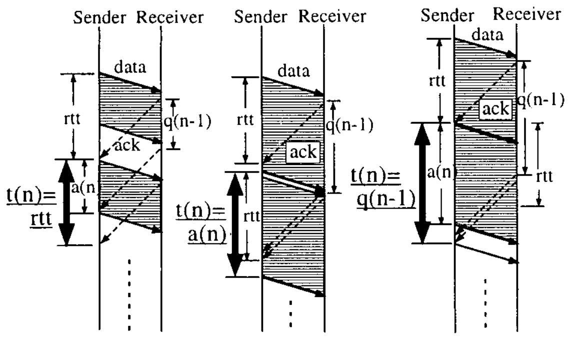
- case1: The throughput does not reach the bandwidth of downlink, because the window size $w(n)$ is small.
- case2: The throughput reaches the bandwidth of downlink, because the window size $w(n)$ is large.
- case3: The sender is waiting for ack segments from the receiver, because the bandwidth of uplink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

Taking Delayed Ack into account, the round trip time rtt is described as the equation (3) using $\tau = \tau_{sat} + \tau_{ter}$ as the round trip propagation delay. Packet size of data P is the sum of data segment size and headers of both TCP and IP. When $w(0) = 1$, rtt is described as the equation (4) since ack is delayed by a certain period d. TCP Reno adopts 200msec as d [13].

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

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

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



case1. rtt is maximum case2. a(n) is maximum case3. q(n-1) is maximum

Figure 4. Three Cases of $t(n)$

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

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

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 the equation (7). The transmission time in Slow Start phase (t_{slow}) is expressed as the sum of $t(n)$ up to $n = th$, similarly.

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

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

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 the equation (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 the equation (9), where m mod n means the rest of dividing m into n.

$$t_{rest} = \frac{F_{rest} \ \mathrm{mod} \ MWS}{Q_{sat}} + \tau_{sat} \tag{9}$$

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 the equation (10) from the equation (8) and the equation (9), where $t_{rest} = 0$ if F_{rest} can be divided by MWS without a remainder. A notation $\lfloor a \rfloor$ means the maximum integer involved in the range $(-\infty, a]$, here.

$$T = \lfloor \frac{F_{rest}}{MWS} \rfloor \cdot t_{max} + t_{slow} + t_{rest} \tag{10}$$

At last, the throughput can be obtained as file size F over total transmission time 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 the equation (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 the equation (11).

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

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

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

4. Numerical Examples

In this section, for the asymmetric network, we will show numerical examples based on the new formula presented in Section.3. The results of calculation are compared as follows. First, we compare the results with output by NS (Network Simulator) [14] in subsection 4.2.1. Second, in subsection 4.2.2, the results are compared with both the experimental data [7] 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

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

satellite communication systems and Internet [7] (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 [7]. In every case, the throughput is derived for various maximum window sizes.

In the simulations, the maximum window size is set as 4KByte, 8KByte, 16KByte, 32KByte, 64KByte, 128KByte, and 192KByte. The maximum window size when the throughput saturates is also set. It equals $w(n)$ when n satisfies $rtt = a(n)$. It can be obtained from the equations (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 [7]. The bandwidth of the satellite link is fixed as 64Kbps. The maximum window size is varied between 3KByte and 32KByte. The experimental data is estimated in above each case. We average five data obtained by DBS [9] for each independent TCP connection whose duration is 60 seconds.

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

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. Fig.5 shows the throughput by the proposed formula and the outputs from the simulation when the bandwidth of downlink is 2Mbps, the one of uplink is 64Kbps, and the propagation delay of uplink is set as 250msec, 125msec, and 30msec. Fig.6 shows the similar results when the propagation delay of downlink is 250msec, the one of uplink is 125msec, and the bandwidth of uplink is set as 64Kbps, 16Kbps, and 4Kbps. In these figures, each symbol shows the output of the simulation and each line shows the theoretical value by the proposed formula.

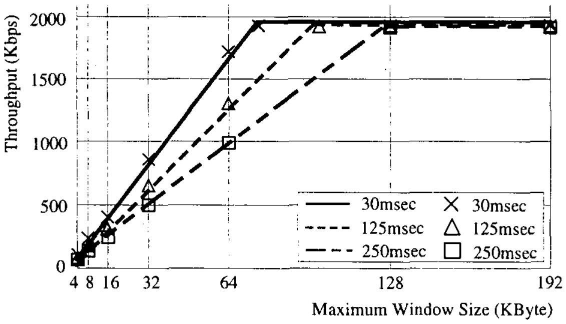


Figure 5. Comparison of the throughput by the proposed formula and the simulation results by NS, with various delay on Uplink

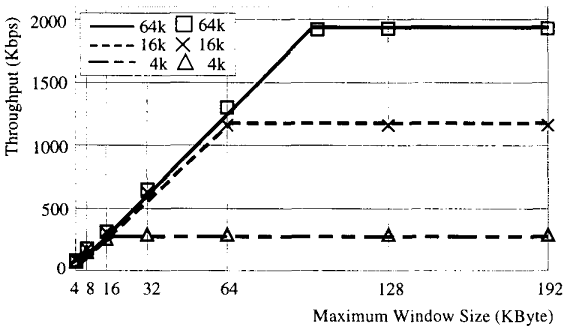


Figure 6. Comparison of the throughput by the proposed formula and the simulation results by NS, with various bandwidth on Uplink

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 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.

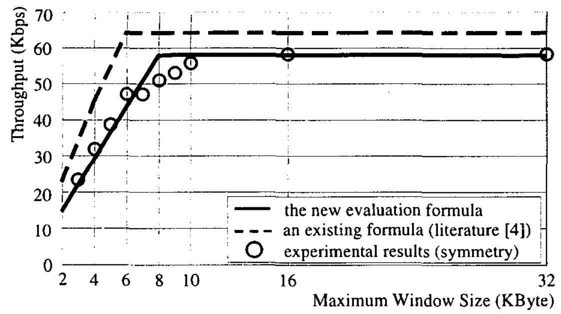


Figure 7. Comparative Results on the symmetric network (both downlink and uplink are satellite)

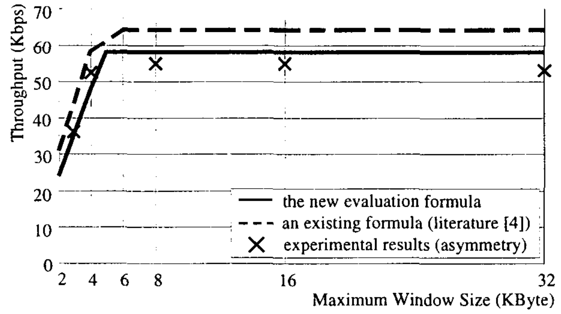


Figure 8. Comparative Results on the asymmetric network

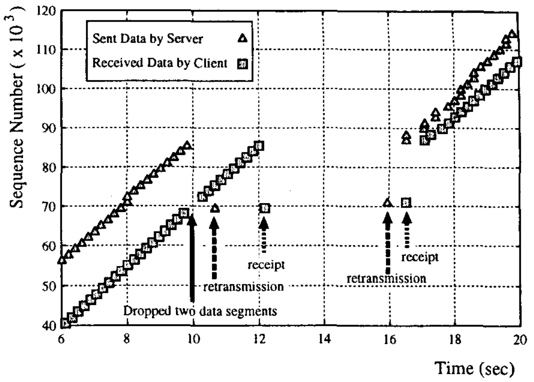


Figure 9. The change of the sequence number

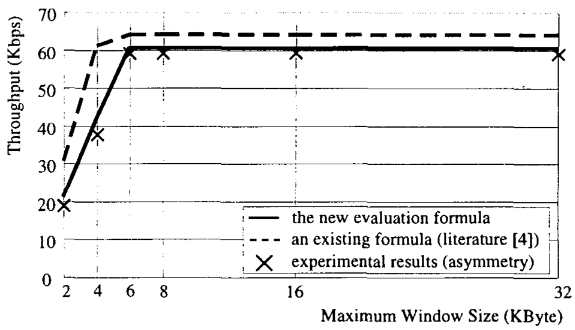


Figure 10. Comparative Results on the asymmetric network with another configuration

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 [7] 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. Fig.7 shows the result from a symmetric network whose propagation delay is 250msec and whose bandwidth is 64Kbps. Fig.8 shows the result from the asymmetric network which use satellite links (propagation delay is 250msec and bandwidth is 64Kbps) as downlink and the Internet (propagation delay is 25msec and bandwidth is 737Kbps) 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 the equation (5) is replaced with αP where α (redundancy coefficient) is 16/15. Therefore, we obtain the following equation (5'). The throughput in Fig.7, Fig.8, and Fig.10 is calculated based on the equation (5').

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

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

In Fig.8, the throughput deteriorates at 32Kbyte maximum window size. Fig.9 shows data sequence number of the server and the client when the maximum window size is 32Kbytes at Fig.8. From Fig.9, two data segments drop and are retransmitted on satellite links. And the server couldn't retransmit two packets in one round trip time because of the long round trip time. Therefore it takes long time for retransmitting lost data, and the server began to transmit the new data in Slow Start phase. As a result, the throughput from the asymmetric network deteriorates.

In order to confirm the above consideration, we construct an asymmetric network with another configuration. That is, while BSD/OS4.0 is installed on both the server and the client on previous configuration [7], FreeBSD3.3-RELEASE is now newly installed on them. Fig.10 depicts the experimental results using the new network configuration and the results by the proposed formula.

It is shown that when maximum window size is large, the theoretical throughput is consistent with the experimental value. It may be because the implementation of queue management or the queue size of BSD/OS4.0 have some problem on such asymmetric network.

From Fig.7, Fig.8, and Fig.10, 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 throughput 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 the equations (3) and (5). Therefore, we obtain an equation (13).

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

Based on the equation (13), the following observations are derived. Assumed that both the bandwidth and the propagation delay of satellite links are fixed, the window size at saturation (W_{th}) is proportional to the propagation delay of terrestrial links (τ_{ter}) and is inversely proportional to the bandwidth of terrestrial links (Q_{ter}). When using satellite links as downlink, since the bandwidth and the delay of satellite links can be assumed fixed, the throughput is mainly effected by the bandwidth and the delay of terrestrial links. From the above observation, there is good possibility that applying asymmetric networks will raise the throughput compared with symmetric networks which consist of satellite links only, except when terrestrial link is terribly congested. However, the throughput is dependent on the characteristics of the terrestrial links.

Second, 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] covers the global asymmetric networks. Therefore it will makes 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 overcome the existing formula when small data, such as contents of World Wide Web, are transferred.

For future study, we will compare the analytical results by the proposed formula with additional experimental results using the VSAT system. We also plan to extend current evaluation formula to the HTTP performance evaluation.

Acknowledgments

The authors thank Prof. Matsuichi Yamada of Tokyo Engineering University for providing us with the counter side of VSAT satellite communication system. This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B), 10450152, and a Hiroshima City University Grant for Special Academic Research.

References

[1] M. Allman et al., "Ongoing TCP Reseach Related to Satellites," RFC2760, February 2000.

[2] C. Barakat, E. Altman, and W. Dabbous, "On TCP Performance in a Heterogeneous Network: A Survey," IEEE Communications Magazine, Vol.38, No.1, pp.40-46, January 2000.

[3] DSL Forum, "General Introduction to Copper Access Technologies," http:// www.adsl.com/general_tutorial.html, 1999.

[4] G. Hasegawa, M. Murata, and H. Miyahara, "Performance Evaluation of HTTP/TCP on Asymmetric Networks," International Journal of Communication Systems, Vol.12, No.4, pp.281-296, July 1999.

[5] Hughes Network Systems, "DirecPC," http://www.direcpc.com/, 2000.

[6] T. Inoue, K. Ishida, K. Amano, T. Yamashita, Y. Katsumi, and M. Yamada, "Experiments for computer communications by VSAT systems," IEICE Technical Report, SAT99-11, May 1999. (in Japanese)

[7] T. Inoue, H. Obata, K. Ishida, K. Amano, Y. Katsumi, and M. Yamada, "Experimental evaluation of TCP performance on asymmetric links using VSAT satellite communication system," IEICE, Network Architecture Workshop, pp.122-129, February 2000. (in Japanese)

[8] T.V. Lakshman, U. Madhow, and B. Suter, "Window-based error recovery and flow control with a slow acknowledgement channel: a study of TCP/IP performance," Proc. INFOCOM'97, pp.1201-1211, April 1997.

[9] Y. Murayama and S. Yamaguchi, "DBS: a powerful tool for TCP performance evaluations," Performance and Control of Network Systems, Proc. SPIE, Vol.3231, November 1997.

[10] N. Nakayama, et al., "A satellite communication system for interactive multimedia networks," IEICE Trans. Commun., Vol. E80-B, No.1, January 1997.

[11] M. Ogawa, N. Imura, and F. Takahata, "Experimental study on performance evaluation of TCP through satellite communication link," IEICE Technical Report, SAT99-77, July 1999. (in Japanese)

[12] C. Partridge and T. Shepard, "TCP/IP Performance over Satellite Links," IEEE Network, Vol.11, No.5, pp.44-49, September 1997.

[13] W. Stevens, "TCP/IP Illustrated, Volume 1", Addison-Wesley, January 1994.

[14] UCB Multicast Network Research Group, "UCB/LBNL/VINT Network Simulator NS (ver.2)," http://www-mash.cs.berkeley.edu/ns/ns.html, 2000.