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Technical Note

Evaluation of Coexisting Enhanced TCP Flows on the High-speed Internetworking Satellite (WINDS)

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Abstract: The Wideband InterNetworking engineering test and Demonstration Satellite (WINDS) has an ultra-high speed international Internet-based communication system. However, the characteristics (for example, transmission bit errors, large propagation delay) of its satellite communication markedly degrade the throughput of conventional TCP (TCP Reno). Therefore, the satellite communications should adopt an enhanced TCP which has been proposed for high-bandwidth and long-delay networks, and can utilize the resource of the satellite network at a maximum level.
In this study, we have compared the performance of ten TCPs (TCP Reno and nine enhanced TCPs) by building an experimental environment of the satellite communication over WINDS. The measurement results have shown that TCP Hybla achieves the best performance among all TCPs in terms of the throughput of communication over WINDS. Therefore, TCP Hybla could be the best solution to communications established on WIND's satellite network. However, the congestion control of one TCP Hybla flow has not only suppressed the transmission speed of other flows of TCP Reno, but also prevented the windows size of other TCP Hybla flows from reaching the stable state when multiple TCP flows coexist on the same satellite link. This should be taken into account when using TCP Hybla.

Keywords: WINDS, satellite network, enhanced TCP, performance comparison, fairness evaluation

1. Introduction

WINDS is a Wideband InterNetworking engineering test and Demonstration Satellite jointly developed by Japan Aerospace Exploration Agency (JAXA) and the National Institute of Information and Communications Technology (NICT) [1]. The WINDS was launched on February 23, 2008 from the Tanegashima Space Center to establish a broadband information and telecommunications network. The satellite communication system of WINDS aims at achieving a maximum speed of 155 [Mb/s] for general use and an ultra-high speed of 1.2 [Gb/s] for specific use such as a backbone patch, which is much faster than previous ones.

However, the communication link of WINDS randomly drops data packets even when the network is not congested, similar to existing internetworking satellites [2]. In addition, a large propagation delay is required for transmitting data between the earth and its orbit. These factors degrade performance of conventional TCPs (namely, TCP Reno) [3], [4]. This is because the congestion control halves the transmission speed when packet loss occurs, and takes a long time to recover the speed to former levels on a long delay link.

On the other hand, in order to maximize the data transmission performance on the network where conventional TCP degrades its performance, many enhanced versions of TCP have been proposed [5], [6], [7], [8], [9], [10], [11], [12], [13]. The enhanced TCPs are expected to improve the data transmission performance of WIND's satellite network.

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In this study, in order to determine the most appropriate TCP which achieves the best performance on the WINDS's satellite network, we evaluate and compare the data transmission performance between ten TCPs in detail. For the evaluation, an experimental environment is constructed by preparing a small antenna for HDR-VSAT (High Data Rate-Very Small Aperture Terminal) and a large antenna for LET (Large Earth Terminal). Furthermore, we clarify whether the use of the selected TCP affects the performance of other TCP flows which coexist on the same satellite link of WINDS. The performance of each TCP in terms of both the throughput and fairness have been presented in previous research [14]. This research deeply analyzes the measurement results in order to disclose an effect of the congestion control of the TCP on performance. As a result, we confirm the practicality of the selected enhanced TCP on realistic environments where many TCP connections are established simultaneously.

The rest of this paper is organized as follows. In Section 2, the major specifications of WINDS and related works about TCP communications over satellite network are described. Section 3 compares transmission performance among various TCPs on the WINDS's satellite network, and the practicality of the TCP with the best performance is clarified in Section 4. Finally, our conclusions are presented in Section 5.

2. Related Works

2.1 Specification of WINDS

This section presents a major specification of WINDS [15], [16]. As shown in **Table 1**, WINDS adopted Ka-band (uplink: 28 [GHz] bands, downlink: 18 [GHz] bands) in order to realize broadband satellite communications. In addition, two types of antennas were developed for WINDS to provide a wide coverage area. First, WINDS has two fixed antennas named Multi-Beam Antenna (MBA). One MBA covers Japan and the other covers cities in the Asia region. Second, a scanning spot antenna named Active Phased Array Antenna (APAA) is used for establishing high-speed communications over a wide area of the Asia-Pacific region.

In addition, WINDS is equipped with an on-board Asynchronous Transfer Mode (ATM) switch developed by NICT. Due to the ATM switch, WINDS can achieve faster (up to 155 [Mb/s]) communication and higher resource utilization than existing internetworking satellites. Furthermore, by using bent-pipe communication with a large-scale antenna, WINDS can construct ultra-high speed (up to 1.2 [Gb/s]) symmetrical communication link. These communication speeds have not been achieved by any existing satellite communication systems [17].

2.2 Existing Studies for Enhancement of TCP

Many existing studies have presented various communication characteristics of the satellite communications [3], [4], [17]. In these works, many problems which affect the performance of satellite communications have been clarified.

Bad atmospheric and/or space conditions (for example, rain, snow, etc.) markedly reduce signal strength on the satellite link, which can cause random bit errors in data communications. As a result, data packets are randomly dropped on the satellite link even when the network is not congested. In addition, due to the long distance between the earth and its orbit, the one-way propagation delay increases up to 250 [ms]. These problems degrade data transmission performance of conventional TCP (namely, TCP Reno) because the congestion control of the TCP halves the transmission speed when the packet loss occurs and cannot rapidly increase the speed on the long-delay link.

On the other hand, many enhanced versions of TCP, which achieve high-speed communication on situations where the TCP Reno does not work well, have been proposed so far.

For example, HighSpeed TCP makes a minor modification of the congestion control algorithm of TCP Reno and increases the windows size faster than that of Ref. [5]. BIC (Binary Increase Congestion control) has an optimized congestion control algorithm for long fat networks, and attempts to find an optimal window size for the network by using a binary search algorithm [6]. CUBIC is a derivative of BIC, in which the window size is derived from a cubic function of time [7]. Both BIC and CUBIC have been implemented in Linux kernels. TCP Vegas detects the congestions on the connection based on increasing RTT (Round Trip Time) instead of packet losses, in order to detect congestions before packet losses actually happen [8]. TCP Hybla determines the window size based on RTT just as TCP Vegas does, but it also increases the window size W_i at a higher rate when the RTT of the connection is larger, as shown in Eqs. (1) and (2), in order to achieve a high throughput on a long delay networks [9].

$$W_{i+1} = W_i + 2^{\rho} - 1 \quad \text{(Slow Start Mode)} \qquad (1)$$

$$W_{i+1} = W_i + \frac{\rho^2}{W_i} \quad \text{(Congestion Avoidance Mode)} \qquad (2)$$

where ρ indicates an RTT [ms] divided by the reference round trip time (25 [ms] in general).

In this research, in order to determine the most appropriate TCP for the WINDS's satellite network, the performances of these TCPs are evaluated in an experimental environment in detail.

Table 1 Major specification of WINDS.

Data Relay	ATM Baseband Switching Communication	Bent-pipe Communication
Frequency	Up-link: 27.5–28.6 GHz / Down-link 17.7–18.8 GHz	
Antenna Beams	Fixed beams (MBA) for Japan and cities in Asia region / Scanning Spot beams (APAA) for other Asia-Pacific region	
Data Rate	Up-link: 1.5, 6, 24, 51, 155 [Mb/s] Down-link 155 [Mb/s]	Symmetrical-Link: 622 [Mb/s], 1.2 [Gb/s]

3. Performance Comparison among Ten TCPs

3.1 Experimental Environment

We built the experimental environment of the WIND's satellite network in Kashima, Japan. As shown in **Fig. 1**, two desktop PCs were prepared for the sender/receiver terminals which are connected via the satellite link. The specifications of the two desktop PCs are summarized in **Table 2**.

In this measurement, a five-meter antenna for LET (Large Earth Terminal) and a 1.2-meter antenna for HDR-VSAT (High Data Rate-Very Small Aperture Terminal) were deployed on sender and receiver points, respectively. Here, the data rate (i.e., 155 [Mb/s] for ATM switching communication, 1.2 [Gb/s] for bent-pipe communication) of WINDS is shared by all users. Hence we could not set the data rate to the maximum. For the experimental evaluation, CBR (Constant Bit Rate) of 51 [Mb/s] or 24 [Mb/s] was adopted as the data rate of the satellite link between the points.

Table 3 shows measurement results of the Round-Trip-Time (RTT) and jitter of latency on the WINDS's satellite network between the sender and the receiver. RTT was measured by *ping* and jitter was obtained by generating UDP traffic with *Iperf*. As shown in this table, RTT was about 800 [ms]. RTT is calcu-

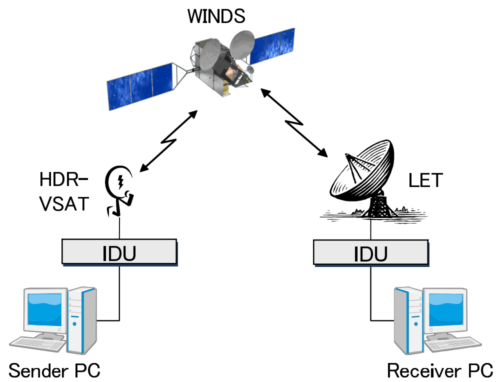

Fig. 1 Experimental environment for performance comparison.

Table 2 Major specifications of the sender/receiver PCs.

CPU	Intel Core2 Extreme CPU Q6850 3.00 GHz
Memory	4 GB
OS	Red Hat Enterprise Linux (64 bit) kernel 2.6.26.5

lated at 500 [ms] from a distance between the earth and the orbit of WINDS, hence an additional time of 150 [ms] is required for transmitting a data packet between two points through WINDS. This additional 150 [ms] is derived from IDU (InDoor Unit) for transforming Ethernet frames into WINDS's frames.

In the experimental environment of Fig. 1, the receiver PC is connected to a HTTP server program running on the sender PC and downloads a file using the *wget* program. In order to perform trials of many kinds of settings during the limited experiment time, a relatively small file (18.5 [MB]) has been utilized. Also, and one trial has been performed in each setting. During the download, the receiver PC obtained statistical data about TCP (for example, size of received data) by using *web100*, and derived a throughput of each TCP from the data [18].

3.2 Measurement Results

Figure 2 shows the change of throughput of each TCP during one downloading experiment, where the throughput is calculated every second. This figure presents the performances of four TCPs, because others show almost the same characteristics as Reno. As shown in this figure, TCP Hybla increases in throughput at a higher rate than other TCPs, and thereby finishes downloading very quickly.

In addition, **Table 4** presents average throughputs of ten TCPs during the downloading. As shown in this table, every TCP cannot utilize the transmission capacity of the WINDS's satellite link at the maximum, because the size of the data transmitted between PCs is very small. However, TCP Hybla achieves better performance on the satellite link than other TCPs.

Therefore, we can conclude that the TCP Hybla is the most appropriate TCP for WINDS's satellite network for all existing enhanced TCPs.

Table 3 Network characteristics of WINDS's satellite link.

	RTT	Jitter[ms]	
	[ms]	VSAT → LET	LET → VSAT
51 [Mb/s]	778	16.3	16.3
24 [Mb/s]	777	16.2	16.2

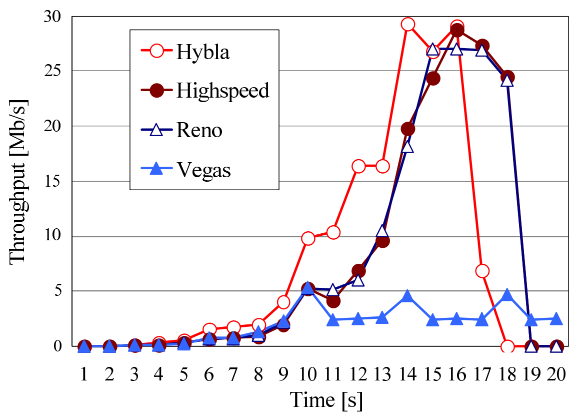

Fig. 2 Throughputs of TCPs.

Table 4 Average throughputs of ten TCPs **[Mb/s]**.

	BIC	CUBIC	Highspeed	H-TCP	Hybla
51 [Mb/s]	7.2	7.1	7.6	8.2	8.5
24 [Mb/s]	6.2	6.1	7.5	5.8	6.9

	Reno	Scalable	Vegas	Veno	Westwood
51 [Mb/s]	7.5	5.9	2.6	7.5	3.5
24 [Mb/s]	3.8	7.2	3.1	6.1	5.3

4. Fairness Evaluation of TCP Hybla

As mentioned in Section 3, TCP Hybla has outperformed other TCPs in terms of the transmission speed on the WINDS. In this section, in order to clarify the practicality of the TCP Hybla, we evaluate the performance under the condition where multiple TCP connections coexist on the same satellite link.

4.1 Experimental Environment

Figure 3 shows an overview of this experiment. In the evaluation, data traffic of TCP Reno and Hybla were generated by *Iperf* between VSAT and LET for two minutes and the average throughput was measured by *TCP Probe* [19]. In order to monitor performance of each kind of TCP separately, the flows of TCP Reno and that of TCP Hybla were generated by different PCs as shown in Fig. 3.

Furthermore, a CBR (Constant Bit Rate) of 51 [Mb/s] was set for the satellite link between VSAT and LET. Other settings are the same as the environment of Section 3.

4.2 Measurement Results

Figures 4 and **5** show the average throughput of each TCP flow when multiple flows of each TCP (Reno or Hybla) are generated on the WIND's satellite link. As shown in these figures, TCP Hybla outperforms TCP Reno in terms of the average throughput of each connection when two flows are transmitted simultaneously. However, when five TCP flows coexist on the satellite link, only few flows of TCP Hybla achieve higher throughput than the flows of TCP Reno.

Next, **Figs. 6** and **7** show the average throughput of each TCP connection in cases where the data flows of both TCP Reno and Hybla coexist on the same satellite link. Regardless of the number of flows of each TCP, the average throughput of TCP Hybla is much higher than that of TCP Reno. Furthermore, from Figs. 4, 5, 6 and 7, we can understand that the throughput of TCP Reno greatly decreases when the flows of TCP Reno are transmitted

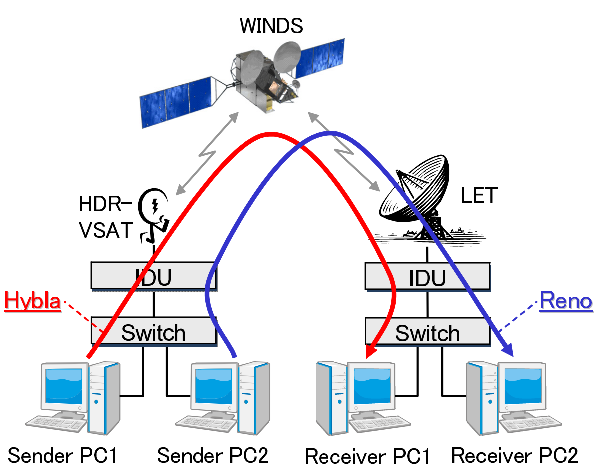

Fig. 3 Experimental environment for fairness evaluation.

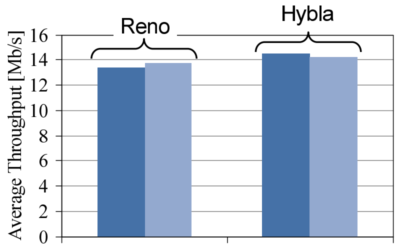

Fig. 4 Average throughputs of TCP flows: One kind of TCP (two flows).

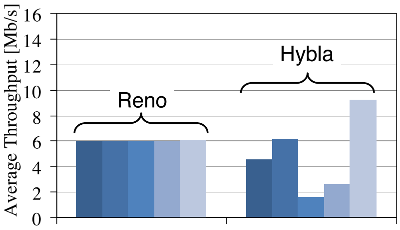

Fig. 5 Average throughputs of TCP flows: One kind of TCP (five flows).

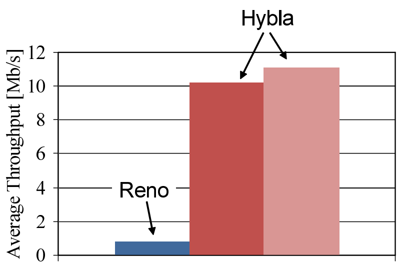

Fig. 6 Average throughputs of TCP flows: Different kinds of TCPs (Reno × 1 + Hybla × 2).

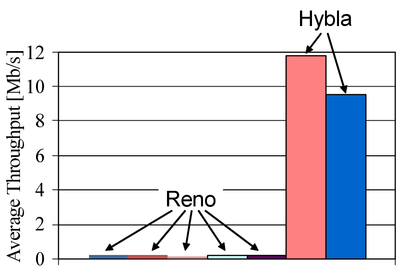

Fig. 7 Average throughputs of TCP flows: Different kinds of TCPs (Reno × 5 + Hybla × 2).

together with that of TCP Hybla.

In order to evaluate fairness of resource consumption between TCP flows, a fairness index of each case is calculated by using the following equation.

$$f = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2}, \tag{3}$$

where x_i indicates a throughput of the i-th TCP flow, and n indicates the total number of TCP flows on the satellite link. The index which is close to one means that the bandwidth of the satellite link is equally shared among TCP flows.

Table 5 shows the fairness index of each combination of TCP flows. As shown in this table, TCP Hybla achieves an excellent fairness index when the two TCP flows are transmitted at the same time. However, the index is very small when a large number of flows of TCP Hybla coexist on the satellite link and when the flows of both TCP Reno and Hybla are transmitted together.

Table 5 Fairness index of each combination of TCP flows.

Reno × 2	Reno × 5	Hybla × 2	Hybla × 5
1.00	1.00	1.00	0.76

Reno × 1 + Hybla × 2	Reno × 5 + Hybla × 2
0.72	0.31

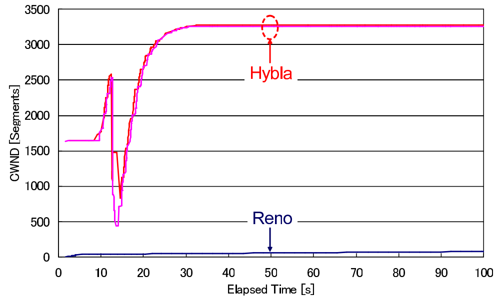

Fig. 8 CWND of each TCP flow: Reno × 1 + Hybla × 2.

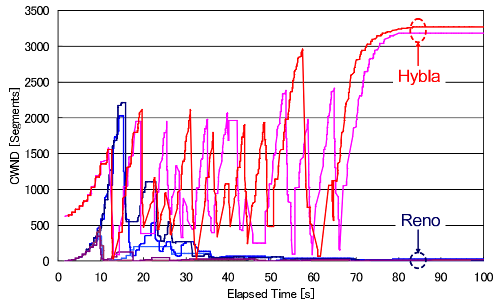

Fig. 9 CWND of each TCP flow: Reno × 5 + Hybla × 2.

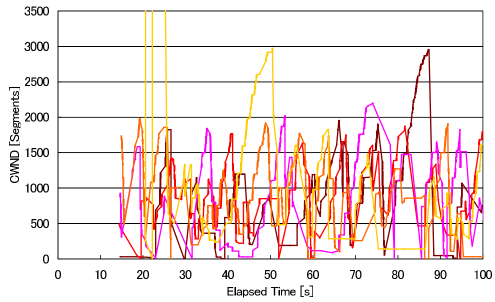

Fig. 10 CWND of each TCP flow: Hybla × 5.

This is because the rapid increase in the congestion window size of one flow of TCP Hybla shown in Eqs. (1) and (2) suppresses the congestion window size of other flows of not only TCP Reno but also Hybla.

4.3 Discussion of Fairness between TCP Connections

Figures 8 and **9** indicate the time variation of a congestion window size (CWND) of each TCP connection when the data flows of both TCP Reno and Hybla coexist on the same satellite link. As shown in these figures, the congestion window size of TCP Hybla rapidly increases, which suppress the congestion window size of other TCP flows as mentioned in Section 4.1. Furthermore, the congestion window size of TCP Hybla largely fluctuates with time, and needs a long time to reach the stable state when many TCP flows coexist in the same satellite link. This is because TCP Hybla sensitively reacts to the variation of the data transmission rate of other flows, rapidly changing the congestion window size.

In addition, **Fig. 10** shows a congestion window size when the five TCP Hybla connections are simultaneously established. With the increase in the number of TCP Hybla flows, the congestion window size of each flow fluctuates for a longer time. Therefore, in order to maximize the total throughput of TCP Hybla when multiple flows are simultaneously established, a synchronization method of the congestion window size between TCP Hybla connections needs to be considered.

5. Conclusions

It has been known that the High-Speed Internetworking Satellite, WINDS, achieves an ultra-high speed international Internet-based communication. But, an appropriate TCP which can achieve excellent data transmission performance on the long-fat network over WINDS has not been clarified yet.

In this study, we have established the experimental environment of the satellite communication through WINDS in order to compare the performance among various TCPs in detail. From the measurement results, we have clarified that TCP Hybla achieves higher throughput than others by increasing the window size on the WINDS's satellite link very quickly.

However, the rapid increase in the congestion windows size of TCP Hybla has not only suppressed the transmission speed of other flows of TCP Reno, but also prevented the windows size of other TCP Hybla flows from reaching the stable state when multiple TCP flows coexist on the same satellite link. Therefore, it is suggested by this study that when the satellite network is used for specific services where the users are pre-determined such as e-learning and telemedicine, TCP Hybla could be the best solution for all connections established on WINDS's satellite network. Moreover, data should be transmitted by a small number of connections. Furthermore, in order to maximize the total throughput of TCP Hybla, a synchronization method of the congestion window size between TCP Hybla connections should be considered.

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