Dynamic Network Adaptation Scheme Employing Haptic Event Priority for Collaborative Virtual Environments

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ABSTRACT

In this paper, a dynamic network adaptation scheme employing haptic event priority is proposed based on stability and transparency analysis for haptic-based CVEs (collaborative virtual environments). For consistency, a client-server architecture is adopted, which includes a consistency server managing virtual object updates. Moreover, in this haptic-based CVE, position data (i.e., haptic interaction pointer and virtual object) between clients and the server is exchanged instead of force data for the stability. According to the transparency analysis, this haptic-based CVE has a maximum allowable delay bound for the transparent haptic interactions. Therefore, the proposed scheme adapts transmission rate and buffering time according to current network state within the end-to-end delay criterion. From experimental results, the network adaptation scheme of haptic events can guarantee better haptic interaction quality than the existing transport schemes over time-varying network.

Keywords

Collaborative virtual environments, stability, transparency, haptic interactions, network QoS, network adaptive transport, and prioritization.

1. INTRODUCTION

In the last few years, implementation of SVEs (shared virtual environments) has been particularly active. The SVEs have been implemented for training, education, concurrent engineering, and entertainment by sharing audio, video, and 3D graphics among participants remotely located around the world [1]. CVE (collaborative virtual environment) is a class of SVEs, which supports for users to simultaneously modify a same virtual object[1]. Recently haptic-based interactions are added to provide the participants haptic feeling of virtual objects as a feedback media. This haptic interaction in the CVEs is known to dramatically enhance the effectiveness of most VR (virtual reality) applications.

Realization of haptic-based CVEs must deal with consistency (concurrency), stability, transparency, and efficient transport. For the consistency and the stability of peer-to-peer haptic CVEs, Cheong [2] and Sankaranarayanan [3] proposed synchronization and consistency schemes. In teleoperation area[2], passivity concept has been applied for the stability under network delay and loss [4, 5]. Moreover, Hirche studied the transparency criterion of the teleoperation and proposed a transmission control scheme based on deadband control approach [4].

There are several existing papers on the efficient transport including STRON (supermedia transport for teleoperations over overlay networks) [6] and smoothed SCTP (synchronous collaboration transport protocol) [7]. Ishibashi [8, 9] and Hikichi [10] used client-server architecture for the consistency and proposed efficient haptic event transport components such as buffering, packetization, and transmission control. However, the stability and the transparency issues of client-server haptic-based CVEs have not been focused in their studies. Additionally, little attention has given to various network situations such as error-prone and time-varying channels.

In this paper, the stability and transparency analysis of the client-server haptic CVEs is described, and then a dynamic network adaptation scheme employing haptic event priority is proposed to efficiently transport the haptic data over Internet. According to the analysis, the haptic CVEs that exchange HIP (haptic interaction pointer) and virtual object position data between clients and a consistency server are stable regardless network delay. However, the transparency depends on the round trip delay, spring, and damping coefficients. Therefore, maximum allowable delay bound can be defined based on maximum allowable force difference. From experimental results, the network adaptation scheme can guarantee better haptic interaction quality with small playout delay and transmission rate.

The paper is organized as follows. In Section 2, the stability and transparency analysis of haptic CVEs with a consistency server is described. In Section 3 and 4, the haptic prioritization and dynamic network adaptation schemes are proposed and verified through the experimental results. Section 5 concludes the paper and explains future work.

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[1] To quote Hannaford et al. [1], “cooperative SVE”.

[2] The term “VE”, in this paper, is used in a broad sense including the teleoperation.

2. HAPTIC-BASED CVEs WITH A CONSISTENCY SERVER

2.1 System Description

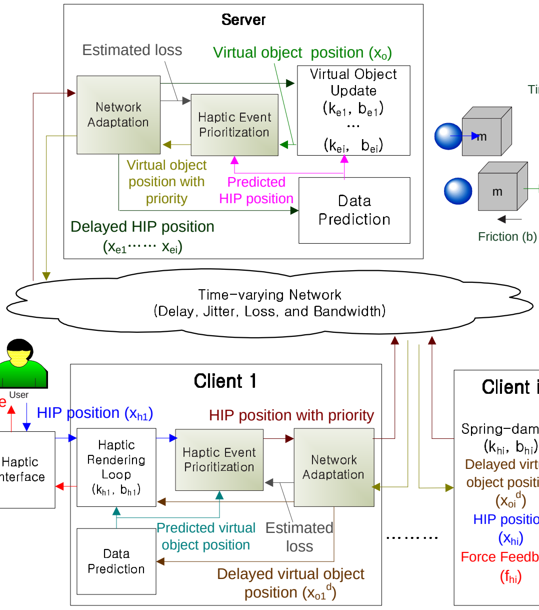

Figure 1. Overview of haptic-based CVEs.

In this paper, haptic-based CVEs between a server and multiple clients are considered for consistent updates of virtual objects (see Fig. 1). Two kinds of haptic events are communicated between the server and the clients: virtual object data (from the server to the clients) and HIP data (from the clients to the server). It is important to note that although force feedback itself is transmitted in some applications such as teleoperation systems [6], here it is assumed that the computation of force feedback is achieved at each client based on the communicated movement data. Moreover, it is assumed that the haptic events include many linear motions. Therefore, the data prediction in Fig. 1 can estimate lost and late-arrival haptic events [11].

The server maintains the consistency of a virtual object manipulated by clients. After collecting the HIP movement data of all clients, the server calculates the force feedback (f_{ei}) for the virtual object movement by using spring-damper model. Then, it decides the position of the affected virtual object by using known physical dynamics such that

$$m\ddot{x}_o(t) + b\dot{x}_o(t) = \sum_{n=1}^{i} f_{ei},$$

$$x_{ei}(t) = x_{hi}(t - T_i^{out}),$$

$$f_{ei} \;=\; -\left\{k_{ei}(x_o(t) - x_{ei}(t)) + b_{ei}(\dot{x}_o(t) - \dot{x}_{ei}(t))\right\},$$

where x_{hi}, x_{ei}, k_{ei}, b_{ei}, and T_i^{out} denote HIP position, delayed HIP position, spring-damper coefficients, and outgoing path delay of the i^{th} client, respectively. m and b are mass and damping resistance coefficient of the object. The updated virtual object information (x_o) will be sent back to the clients.

Haptic rendering loop in each client side detects collision between a virtual object and HIP. Then, it calculates the force in order to provide a user with the force feedback (with coefficients k_h and b_h), as follows:

$$x_{oi}^d(t) = x_o(t - T_i^{in}),$$

$$f_{hi}(t) \;=\; k_{hi}(x_{oi}^d(t) - x_{hi}(t)) + b_{hi}(\dot{x}_{oi}^d(t) - \dot{x}_{hi}(t)),$$

where f_{hi}, x_{oi}^d, and T_1^{in} denote force feedback, delayed virtual object position, and incoming path delay of the i^{th} client, respectively.

This study is concerned with time-varying and limited bandwidth problems of the Internet, and with how they affect haptic interactions. Solutions are sought in the application and transport layers of haptic-based CVEs systems. The following properties concerning a simulated underlying network are assumed. First, the network delay and loss vary during the simulation time more than the network requirements of haptic interactions (i.e., delay range: about $0 \sim 40ms$, loss range: about $0 \sim 30\%$). Next, a minimum T1 ($1.5Mbps$) connection between sites is assumed, and $500Kbps$ is defined as the target maximum bandwidth for haptic events.

In order to improve the haptic interaction quality over the assumed time-varying network, the haptic event prioritization and adaptive transport schemes are proposed, as shown in Fig. 1. The proposed schemes focus on three challenges for haptic-based CVEs, as follows: haptic event classification, transmission control, and network compensation schemes with a stable and low playout delay. As long as the quality degradation of haptic interactions does not annoy users, the transmission rate and network effects should be minimized. For this reason, a network adaptation scheme is applied to the proposed schemes.

2.2 Stability and Transparency Analysis

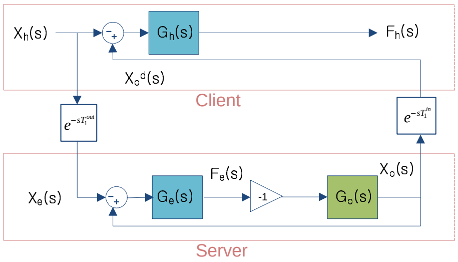

Figure 2. Block diagram of position/position hatpic CVEs with a consistency server and a client.

In order to analyze the stability and transparency of haptic CVEs with a consistency server and a client, impedances[3] of a operator hand (Z_h) and virtual environment (Z_e) are used in the Laplace domain. The models for the virtual object (G_o) and force feedback (G_h and G_e) dynamics in Fig. 2 are approximated by simple mass-damper and spring, as follows:

$$G_h(s) \;=\; G_e(s) = k \quad (k = k_h = k_e),$$

$$G_o(s) \;=\; \frac{1}{ms^2 + bs},$$

$$R \;=\; T_1^{out} + T_1^{in},$$

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[3] Mechanical impedance is usually defined as $Z = F/V$, where F is applied force and V is velocity. It can characterize the telehaptic system [12].

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where R denotes round trip delay. In order to simplify the analysis, here, the delay elements are approximated by a first order Padé series

$$e^{-sT} \approx \frac{1-\frac{T}{2}s}{1+\frac{T}{2}s}.$$

From above equations, the impedances of the operator hand and virtual environment are given by

$$\begin{aligned} Z_h(s) &= \frac{F_h(s)}{\dot{X}_h(s)} \\ &= \frac{-kRms^2-(kRb+2km)s-(2kb+2k^2R)}{Rms^3+(bR+2m)s^2+(2b+Rk)s+2k}, \\ Z_e(s) &= \frac{F_e(s)}{\dot{X}_e(s)} = \frac{-kms-kb}{ms^2+bs+k}, \end{aligned}$$

where F and X denote the Laplace transforms of f and x, and the subscript has the same meaning to that in Section 2.1.

From characteristic function of Z_h ($\varphi(s) = Rms^3 + (bR+2m)s^2 + (2b+Rk)s + 2k$), the haptic interaction through a consistency server is stable, if the passive human operator and virtual environments are assumed. It can be deduced from poles of $\varphi(s)$. All poles of $\varphi(s)$ are located on the left side of s-plane regardless of network delay.

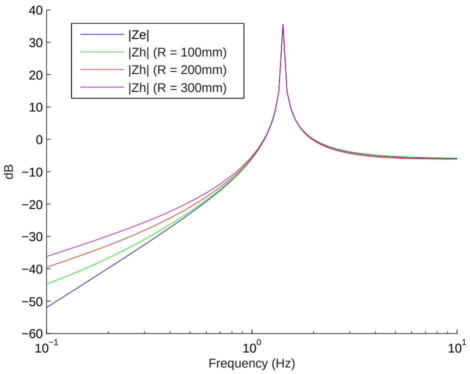

Figure 3. Magnitude responses of Z_e and Z_h.

According to a transparency criterion ($Z_h(s) = Z_e(s)$) [4], the haptic interaction through a consistency server over network delay is not transparent. Fig. 3 shows the change of magnitude response $|Z_h(s)|$ as the network delay is increasing. If there is no network delay, $|Z_h(s)|$ is equal to $|Z_e(s)|$ but otherwise it is larger than $|Z_e(s)|$ in the low frequency area. If there is network delay while a user manipulates a virtual object in the CVE, the virtual object does not move immediately. During that time period, penetration depth between the virtual object and HIP position increases, and the force feedback also increases eventually.

To obtain maximum allowable delay bound (R_{max}) for a certain transparency level, it is assumed that human input frequency rage is within 10^{-6}~$10^{3}Hz$. Then, Z_h and Z_e are approximated in the low frequency area in which the difference between Z_h and Z_e is maximum (see Fig. 3), as follows:

$$\begin{aligned} Z_h(s) &\approx -b+kR, \\ Z_e(s) &\approx -b. \end{aligned}$$

If maximum allowable force difference ratio[4] (F_{max}) is defined empirically, then R_{max} is calculated, as follows:

$$\begin{aligned} F_{\max} &= \frac{allowable\ force\ difference}{initial\ force}, \\ R_{\max} &\leq F_{\max} \times \frac{b}{k}. \end{aligned}$$

As a consequence, the client-server haptic-based CVEs are stable regardless network delay but not transparent. The transparency of the haptic CVEs depends on the round trip delay, spring, and damping coefficients, and can be used to obtain a maximum allowable delay bound based on a maximum allowable force difference. Therefore, network transport schemes such as transmission control, error control, and buffering should process haptic events within the maximum end-to-end delay for better haptic interaction quality.

3. PROPOSED SCHEMES

3.1 Haptic Event Prioritization

The haptic event priority assignment should reflect the influence of each haptic event to the end-to-end quality. Among three key parameters for QoS (rate, error, and delay), it is important to associate priority for loss and delay. Therefore, two indices are defined: HDI (haptic event delay index) and HLI (haptic event loss index).

For a delay, classification of n^{th} haptic event depends on the distance between the HIP position and the virtual object ($D_{hv}(n)$), as it is not necessary to satisfy the stringent QoS requirements of haptic events if there is no collision between a HIP and a virtual object. However, as it is difficult to predict whether or not a user will touch a virtual object or not, a sufficiently small distance threshold (TH_{hv}) is used, as follows: if $D_{hv}(n)$ is smaller than or equal to TH_{hv}, the HIP and virtual object are predicted to collide; HDI is defined as 1, otherwise HDI is defined as 0. TH_{hv} depends on the size and logical coordinate of the virtual environments[5] and is set to 0.1 empirically in this paper. The haptic events with $HDI(n) = 0$ can wait in network adaptation modules for a more efficient network transport, while the haptic events with $HDI(n) = 1$ are sent as soon as possible for the better haptic interaction quality.

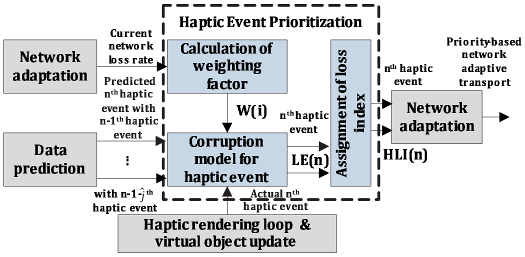

Figure 4. Diagram for haptic event prioritization according to loss.

In order to assign priority to each haptic event according to its loss, the quality degradation caused by the lost haptic

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[4] Weber fraction [4] can be used according to applications.

[5] We implement a virtual space with the viewport measuring 800 × 800 $pixels$ and logical coordinates from −3 to 3.

event should be predicted. The purpose of the corruption model of a haptic event is to estimate the impact of packet loss (see Fig. 4). Here, it is assumed that if the haptic event includes a linear motion, quality degradation will be small as it can be predicted correctly on the receiver side. However, if the haptic event includes a random motion, the quality degradation will be large. This indicates that the receiver will guess incorrectly if the haptic event is not sent. Quality degradation can be more severe over error-prone channels, as the receiver should predict the current haptic event without the latest information when the last haptic events are lost.

In order to formulate quality degradation, the loss effect ($LE(n)$) of the n^{th} haptic event is defined based on the current network loss rate (l) and the difference between the actual and predicted positions ($D_{ap}(n,i)$), as follows:

$$\begin{aligned} LE(n) &= \sum_{i=0}^{\hat{j}} W(i) \times D_{ap}(n,i), \qquad (1) \\ D_{ap}(n,i) &= |P_a(n) - P_p(n, n-i-1)|, \end{aligned}$$

$$W(i) = \begin{array}{ll} l^i, & (if \quad i \neq 0) \\ 1-l, & (otherwise) \end{array}$$

$$\hat{j} = \begin{array}{ll} argmin_{j \in N}(l^j - \alpha)^2, & (if \quad l \neq 0) \\ 0, & (otherwise) \end{array} \qquad (2)$$

where $W(i)$ and $\hat{j}$ are the weighting factor and the estimation period according to l, respectively. $P_a(n)$ and $P_p(n, n-i)$ denote the actual and predicted positions, respectively, of n^{th} haptic event, where $P_p(n, n-i)$ is predicted with $n-i^{th}$ haptic event. In this paper, a third-order predictive algorithm[6] is used, as follows:

$$\begin{aligned} P_p(n, n-i) = P_a(n-i) + T(n, n-i) \cdot P_a'(n-i) \\ + \frac{T(n,n-i)^2}{2!} \cdot P_a''(n-i) \\ + \frac{T(n,n-i)^3}{3!} \cdot P_a'''(n-i), \end{aligned}$$

where $T(n, n-i)$ is the elapsed time between the n^{th} and $n-i^{th}$ haptic events. The constant α in Eq. (2) is decided empirically. In this paper, α is set to 0.03, indicating that a network loss rate of lower than 3% is considered negligible.. If no network loss exists, Eq. (1) follows the method proposed by Ishibashi [9] in order to minimize the transmission rate.

Haptic events with different loss effects should be assigned to a finite number set category, which is required for network adaptive transport, as shown in Fig. 4. In this paper, three levels of HLI are simply defined, and two threshold values (TH_0 and TH_1) are used for the assignments of HLI. If the loss effect is less than or equal to TH_0, HLI of the haptic event is set to 0. If it is larger than TH_0 but less than TH_1, HLI of the haptic event is set to 1. Otherwise, HLI of a haptic event is set to 2, which indicates that loss of the haptic event can cause severe deterioration in the haptic interaction quality. The loss effect value signifies the distance between two positions in the virtual environments. Therefore, the assignment of the HLI according to the loss effects depends on the size of the virtual environments. Here, TH_0 and TH_1 are set to 0.01 and 0.011, respectively, which were derived empirically.

3.2 Network Adaptation

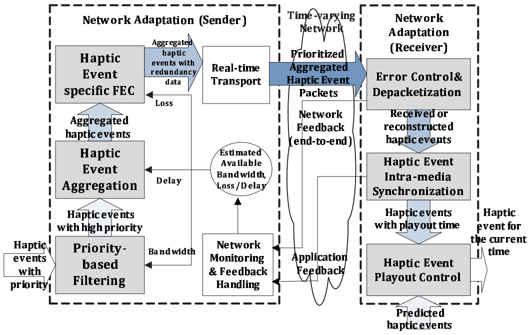

Figure 5. Haptic event adaptation scheme.

Following the target constraints on the bandwidth and priority, priority-based filtering in Fig. 5 module manipulates the transmission rate. The haptic event with $HDI(n) = 0$ does not need to satisfy the haptic event update rate of $1kHz$, as it only associated with the user's visual effect. Therefore, the haptic events with $HDI(n) = 0$ can wait in the module for $30ms$ in order to support the graphic rendering frequency of $30Hz$ or until a haptic event with $HDI(n) = 1$ is input into the module. If no haptic event with $HDI(n) = 1$ is input for $30ms$, the other haptic events are discarded with the exception of the haptic event with the largest LE and with $HLI(n) = 1$ or 2. Otherwise, all haptic events with $HDI(n) = 0$ are filtered. For a haptic event with $HDI(n) = 1$, whether it is discarded is decided immediately. Haptic events with $HLI(n) = 0$ are discarded as they can be predicted by the compensation module in the receiver application without the actual transmission of the haptic event. If the network bandwidth is sufficient for remote haptic interactions, all haptic events with $HLI(n) = 1$ and 2 go to the network-adaptive aggregation module in order to be integrated into a packet. Otherwise, the haptic events with $HLI(n) = 1$ can also be dropped based on TFRC.

Network-adaptive aggregation in Fig. 5 integrates a number of haptic events into a packet in order to reduce the transmission rate of the haptic events. However, if the transmission rate is too greatly reduced, the delay requirement of the haptic event will not be satisfied. Therefore, the correct aggregation interval must be determined while meeting the rate and delay requirements. Ishibashi et al. provide experimental results that show that an interval of $8ms$ is most viable [8]. However, because various network environments including loss and delay jitter are considered here, a range of $1ms$ to $8ms$ is decided as the aggregation interval keeping within the maximum allowable delay (R_{max}) (see Section 2.2).

The haptic event-specific FEC module in Fig. 5 satisfies the loss requirement by adopting media-specific FEC in order to take the advantage of low latency. The module generates redundant data for a haptic event with $HLI(n) = 2$. The redundant data for n^{th} packet are transmitted as $n+1$, $\cdots$, $n+k$ packets . Differential coding and quantization is adopted for the redundant data. In the differential coding, the difference in the position between the first haptic event in each packet and the event with $HLI(n) = 2$ is obtained.

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[6] It is the best up to approximately $80ms$ [11].

The parameter k changes from 1 to 4 according to the current network loss. Please refer [13] for the details of haptic event specific FEC.

Haptic event intra-media synchronization in Fig. 5 offsets network delay jitter effect by adaptively changing the playout time of the haptic event. The enhanced VTR algorithm [9] with an additional virtual-time expansion rule that prevents fluctuation of the playout delay caused by a network delay increment in a short period of time is employed. A_n, x_n, and t_n denote the arrival time, ideal target output time, and target output time of the n^{th} haptic event, respectively [9]. The haptic event received at A_n waits in the buffer during the estimate of the maximum network delay jitter and is then outputted at x_n. However, if the network delay jitter becomes larger than what was estimated, it continues to wait until t_n that is calculated by adding the total slide time (S_n) to x_n. If $A_n - t_n > 5$, S_n is increased in order to postpone t_n. If the delay between consecutive packets at the receiver is larger than the delay spike threshold[7], the slide time and the total slide time are set as $\triangle S_n = A_n - t_n$ and $S_n = S_{n-1} + \triangle S_n$, respectively, in order to achieve a lower rate of lost packets. Otherwise, S_n is set using the moving average, as follows:

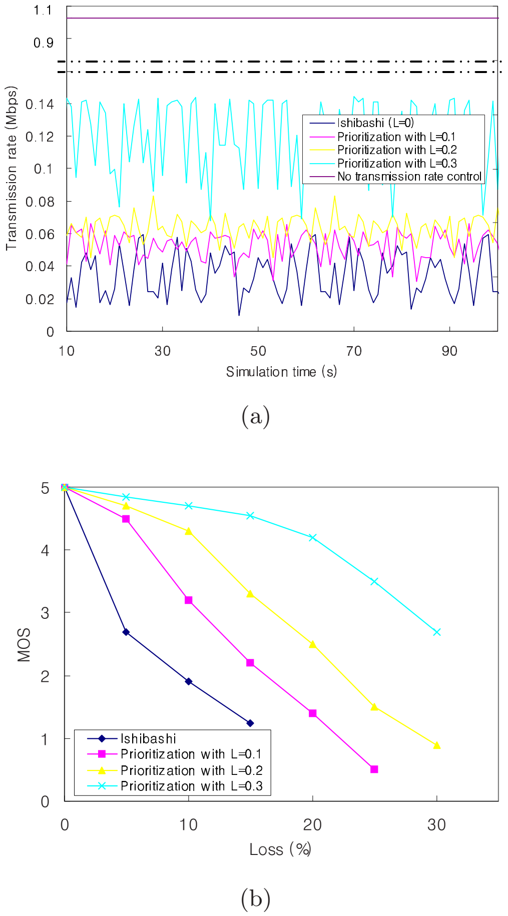
$$S_n = 0.125 \times (S_{n-1} + (A_n - t_n)) + 0.875 \times S_{n-1}.$$

The haptic event playout control module in Fig. 5 checks whether there is a haptic event in the buffer for the current time. If no such event exists, the module uses the predicted haptic event. When virtual time expansion occurs in the intra-media synchronization module, the playout control module should pause bringing the predicted data from the prediction module for $\triangle S_n$, as the output time of a haptic event for the current time is delayed for $\triangle S_n$ in order to guarantee sufficient buffering time.

4. EXPERIMENTAL RESULTS

To carry out realistic experiment-based evaluations on the impact of haptic transport schemes, we realize the networked haptic CVE testbed that consists of two clients, a server, and a network emulator. Each client node has a haptic interface device, PHANToM Omni, and participates in the haptic-based collaboration. The haptic event communication between the server and clients are going through the network emulator. On top of the testbed, a simple collaboration application, known as haptic-based room rearrangement, is run. When a HIP makes contact with the surface of a object, a force is generated according to the penetration depth of the HIP into the object. By using the HIPs, two participants can push the object side by side move it upward. The users can rearrange the objects in the virtual space through cooperative work.

The prioritization-based filtering scheme is compared with traffic control scheme proposed by Ishibashi [9], in order to verify the effectiveness of the proposed haptic prioritization scheme. As the performance measures, transmission rate and subjective assessment are employed. MOS (mean opinion score) evaluation with 10 subjects is used for the subjective assessment. We use the following 5 degree rating scheme: (1) very annoying, (2) annoying, (3) slightly annoying, (4) perceptible but not annoying, and (5) imperceptible [14].



(a)

(b)

Figure 6. Haptic event prioritization scheme: (a) transmission rate and (b) subjective assessment.

Fig. 6 shows that the proposed haptic event prioritization scheme provides better haptic interaction quality with the small transmission rate over error-prone network. The traffic control scheme [9] also discards haptic events with large prediction error but does not consider the current network loss rate. Therefore, it can support minimum transmission rate[8] but causes more severe deterioration of haptic interaction under network loss 30 %. If any traffic control scheme is not used, the transmission rate of haptic event is about $1Mbps$. However, we can reduce the transmission rate to about $0.8Mbps$[9].

In order to test the validity and usefulness of the proposed transport scheme, the proposed transport scheme and four combinations of transport components denoted by transport scheme #1∼#4[10] are tested over lossy network. Transport scheme #1 consists of Reed-Solomon FEC error control

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[7] Although the threshold is computed by adding a large value ($60ms$) to network delay variation, it is necessary to make a more efficient formula.

[8] The proposed prioritization scheme follows the traffic control [9] over no network loss ($L = 0$).

[9] It depends on linearity of the virtual object movement and current loss rate.

[10] Although it is desirable to evaluate existing transport protocols such as STRON and smoothed SCTP, it is not easy to re-invent them only with publicly available descriptions.

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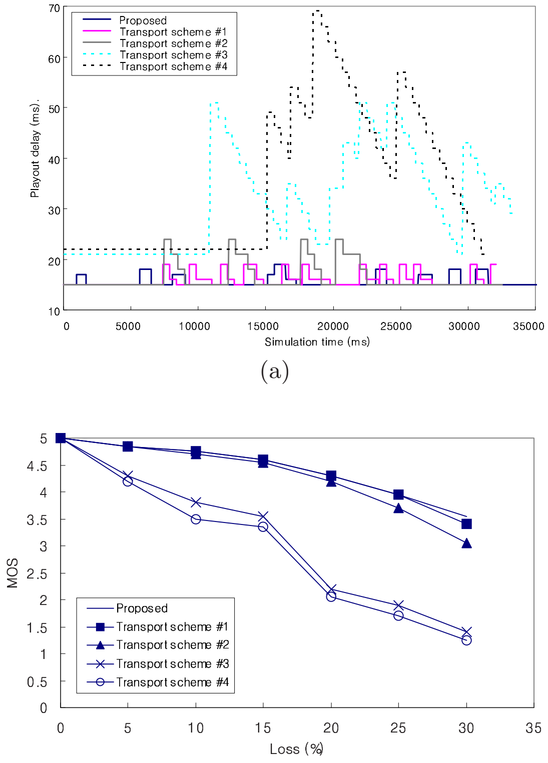

(a)

(b)

Figure 7. Haptic event network adaptation scheme: (a) playout delay and (b) subjective assessment.

and TFRC-like congestion control to reflect the features of STRON. Transport scheme #2 includes selective ARQ error control and congestion control similar to smoothed SCTP. Additionally, transport schemes #3 and #4 add aggregation schemes, as suggested in [8], to transport schemes #1 and #2, respectively. Moreover, they employ the VTR synchronization algorithm [9]. Here, as the performance measures, we employ the playout delay and the subjective assessment. For the playout delay evaluation, we change network loss for 30 seconds, as follows: (0 $\sim$ 5 s) 0 %, (5 $\sim$ 10 s) 10 %, (10 $\sim$ 15 s) 15 %, (15 $\sim$ 20 s) 20 %, (20 $\sim$ 25 s) 10 %, and (25 $\sim$ 30 s) 0 %.

Although the proposed transport scheme reduce the end-to-end delay, it provides better haptic interaction quality than the other transports when the network loss increases by 30 % (see Fig. 7. As shown in Fig. 7(a), the aggregation scheme, when combined with the error control schemes such as Reed-Solomon codes and ARQ, causes larger playout delay for the haptic interactions. Fig. 7(b) also shows that the transport scheme #3 and #4 have severe deterioration of haptic interaction quality according to the loss increase, because the aggregation scheme causes the burst loss of haptic event and playout delay increase.

5. CONCLUSIONS AND FUTURE WORK

In this paper, a dynamic network adaptation scheme employing haptic event priority was proposed on the basis of stability and transparency analysis of client-server haptic CVEs. According to the experimental results, it could provide better haptic interaction quality with the small playout delay and transmission rate than those of the previous transports. In order to reduce the network propagation delay, further direction of this study will be peer-to-peer haptic CVEs that is very similar to a teleoperator system. In the architecture, consistency issue will be more focused.

6. ACKNOWLEDGMENTS

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