Haptic Data Reduction in Time-delayed Teleoperation Based on the Time Domain Passivity Approach

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***Abstract*— We propose a novel combination of haptic data reduction with the control architecture of the time domain passivity approach (TDPA) in teleoperation systems for dealing with time-varying delay. The sampling rate of haptic data is typically 1kHz for stability and transparency reasons. This high packet rate as well as the additional data overhead becomes a critical factor for data transmission in a packet-switched communication network. On the other hand, passivity-based control architecture needs to be employed to guarantee system stability, when communication delay exists. In this paper, we develop a TDPA-based haptic data reduction approach to reduce the packet rate over the communication network while preserving system stability in the presence of varying communication delays. Compared to the existing wave variable-based (WV-based) haptic data reduction approaches, our proposed scheme has smaller distortion in force signals and is flexible and robust to time-varying delays. Experiments show that our proposed approach can reduce the packet rate up to 80%, without introducing significant distortion. In addition, the proposed approach outperforms the existing WV-based approach in both packet rate reduction and subjective preference for delays up to $100ms \pm 30ms$.**

I. INTRODUCTION

A teleoperation system, also referred to as a bilateral teleoperation system with haptic feedback, allows human users to interact with a remote environment by means of slave and master devices, which exchange force and position/velocity information over a communication link [1]. The slave system is typically controlled by position/velocity commands, while the visual and haptic information sensed by the slave system during teleoperation are sent back to and displayed on the master system (Fig. 1).

Haptic signals on both the master and slave sides need to be sampled and packetized immediately with a rate of 1 kHz. This is necessary for stability and transparency reasons [2], [3]. Such a high packet rate as well as the additional data overhead due to the transmission of packet header information lead to inefficient communication in a packet-switched network [4]. Haptic data reduction based on human perceptual limitations, the so-called perceptual deadband coding approach (DB approach), is introduced in [4], [5], [6], [7]. The communication delay, however, is ignored.

For geographically distributed teleoperation systems, communication delay is a critical factor for system stability and is not negligible [8]. To enable stable teleoperation systems in the presence of significant communication delay, passivity-based control architectures, such as the wave-variable (WV) transformation (or WV architecture) [9], [10] and the time domain passivity approach (TDPA) [11], have been developed. The WV architecture ensures system stability for arbitrary large and constant delays. The TDPA, on the other hand, is able to deal with time-varying delay without knowing the network parameters. System passivity is guaranteed by using passivity observers and passivity controllers (see Sec. II-A for more details).

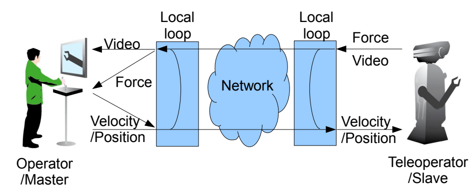

Fig. 1. Overview of a teleoperation system (adopted from [1]).

Haptic data reduction approaches for time-delayed teleoperation systems have been proposed in [12], [13], in which the wave-variable transformation is combined with the DB approach to enable data reduction and to ensure system stability. In the following of this paper, we call these methods as the WV-based haptic data reduction approaches, or WV-based approach. The authors of [12] apply the DB approach directly on the wave variables and find the perceptual threshold of the deadband parameter. In [13], the authors use the method called local computation of wave variables to enable the use of the DB approach in the time domain (in force and velocity signals), when the communication delay is known. The authors of [13] also show that their method outperforms the one proposed in [12]. Both the approaches, however, can only deal with constant delay, known [13] or unknown [12].

In this paper, we present a novel TDPA-based haptic data reduction approach (TDPA-based approach) for dealing with time-varying delay, without knowing the network parameters. Compared to the existing WV-based approaches, our proposed scheme has smaller distortion in force signals and is flexible and robust to time-varying delays. Experimental results show that the proposed TDPA-based approach outperforms the WV-based approach [13] in both packet rate reduction and subjective preference for communication delays up to $100ms \pm 30ms$.

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II. BACKGROUND

A. Time domain passivity approach (TDPA) for bilateral teleoperation control with communication delays

TDPA ensures the stability of teleoperation systems in the presence of arbitrary communication delays using passivity observers (PO) and passivity controllers (PC). The stability arguments are based on the passivity concept, which characterizes the energy exchange over a two-port network and provides a sufficient condition for the input/output stability. Compared to the WV control architecture, the TDPA is able to deal with time-varying delays and packet loss in a relatively simpler structure without knowing the parameters of the network. Although the WV architecture is extended to be available for time-varying delays [14], the change rate of the communication delay must be known, as it is one of the necessary parameters for computing the passivity condition. For these reasons, the TDPA architecture is adopted to guarantee system stability in our work.

1) **Passivity of a two-port network:** Data communication in a teleoperation system can be represented by a typical two-port network as illustrated in Fig. 2. The passivity condition for a two-port network requires a positive net energy output, which means that $E_{in}(k) \geq E_{out}(k)$ must be held at any sampling instant k (System initial energy is assumed to be zero). In [11], input and output energy flows on both the master and slave sides are separated to be $E^m_{in}(k)$, $E^m_{out}(k)$, $E^s_{in}(k)$ and $E^s_{out}(k)$. The computation of all the energy flows are as follows:

$$E^m_{in}(k) = \begin{cases} E^m_{in}(k-1) + \Delta T f_m v_m, & \text{if } f_m v_m > 0 \\ E^m_{in}(k-1), & \text{if } f_m v_m \leq 0 \end{cases} \quad (1)$$

$$E^m_{out}(k) = \begin{cases} E^m_{out}(k-1) - \Delta T f_m v_m, & \text{if } f_m v_m < 0 \\ E^m_{out}(k-1), & \text{if } f_m v_m \geq 0 \end{cases} \quad (2)$$

$$E^s_{in}(k) = \begin{cases} E^s_{in}(k-1) + \Delta T f_s v_s, & \text{if } f_s v_s > 0 \\ E^s_{in}(k-1), & \text{if } f_s v_s \leq 0 \end{cases} \quad (3)$$

$$E^s_{out}(k) = \begin{cases} E^s_{out}(k-1) - \Delta T f_s v_s, & \text{if } f_s v_s < 0 \\ E^s_{out}(k-1), & \text{if } f_s v_s \geq 0 \end{cases} \quad (4)$$

where ΔT is the sampling time. f_m and v_m denote the force and velocity signal on the master side, and f_s and v_s are the force and velocity signal on the slave side.

According to Eq. (1)-(4), all energy flows on both the master and slave sides are positive and monotonic increasing. The passivity condition for this two-port network proposed in [11] is:

$$E^m_{in}(k) + E^s_{in}(k) \geq E^m_{out}(k) + E^s_{out}(k), \qquad \forall k \geq 0 \quad (5)$$

A sufficient and more conservative condition is:

$$E^m_{in}(k) \geq E^s_{out}(k), \text{ and } \quad E^s_{in}(k) \geq E^m_{out}(k) \quad (6)$$

Note that $E^m_{in}(k)$ and $E^m_{out}(k)$ are computed on the master side, and $E^s_{in}(k)$ and E^s_{out} are on the slave side. In order to examine the system passivity according to Eq. (6), $E^m_{in}(k)$ must be sent to the slave side, and $E^s_{in}(k)$ must be sent to the master side. Due to the communication delay, the received E^m_{in} on the slave side and the received E^s_{in} on the master side at the sampling instant k are $E^m_{in}(k-T_1(k))$ and $E^s_{in}(k-T_2(k))$, where $T_1(k)$ and $T_2(k)$ denote the forward and backward communication delays at sampling instant k. Thanks to the monotonic increase of the input/output energy, it is sufficient to satisfy Eq. (7) in order to satisfy Eq. (6). Thus, Eq. (7) is the general and sufficient condition for system passivity of a two-port network with communication delays.

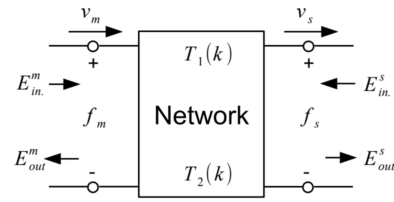

Fig. 2. Energy flow of a teleoperation system represented by a two-port network. The energy on the left (master) and right (slave) sides are further separated into input and output flows [11], [19]. $T_1(k)$ and $T_2(k)$ denote the forward and backward communication delays at sampling instant k.

$$\begin{aligned} E^m_{in}(k-T_1(k)) \geq E^s_{out}(k) \\ E^s_{in}(k-T_2(k)) \geq E^m_{out}(k) \end{aligned} \quad (7)$$

2) **Time domain passivity approach:** As illustrated in Fig. 3, the POs compute the input and output energy on both the master and slave sides. Meanwhile, they examine the passivity condition according to the locally computed output energy and the received input energy from the other side. If the passivity condition is satisfied, the received velocity or force signal is directly applied. If not, the PC is activated and the adaptive dampers α and β are computed to dissipate the output energy and thus to preserve the system passivity:

$$\begin{cases} v_s(k) = v_{sd}(k) + \beta(k) f_s(k) \\ f_m(k) = f_{md}(k) + \alpha(k) v_{mc}(k) \end{cases} \quad (8)$$

Considering the energy dissipation (E^m_{PC} and E^s_{PC}) due to the damping α and β on the master and slave sides, the general passivity condition described in Eq. (7) should be modified. The final passivity conditions based on Fig. 3 are given as:

$$\begin{aligned} W_m(k) = E^s_{in}(k-T_2(k)) - E^m_{out}(k) + E^m_{PC}(k-1) \geq 0 \\ W_s(k) = E^m_{in}(k-T_1(k)) - E^s_{out}(k) + E^s_{PC}(k-1) \geq 0 \end{aligned} \quad (9)$$

The computation of the dissipated energy and the damping α and β as suggested in [11] are given as:

$$\alpha(k) = \begin{cases} 0, & \text{if } W^m > 0 \\ -\frac{W^m(k)}{\Delta T v^2_{mc}(k)}, & \text{eles, if} |v_{mc}(k)| > 0 \end{cases} \quad (10)$$

$$\beta(k) = \begin{cases} 0, & \text{if } W^s > 0 \\ -\frac{W^s(k)}{\Delta T f^2_s(k)}, & \text{eles, if} |f_s(k)| > 0 \end{cases} \quad (11)$$

$$\begin{cases} E^m_{PC}(k) = \Delta T \sum_{j=0}^{k} \alpha(j) v^2_{mc}(j) \\ E^s_{PC}(k) = \Delta T \sum_{j=0}^{k} \beta(j) f^2_s(j) \end{cases} \quad (12)$$

In Fig. 3, the virtual mass and spring model is employed as a passive low-pass filter for the velocity and force signals. See [11] for more detail.

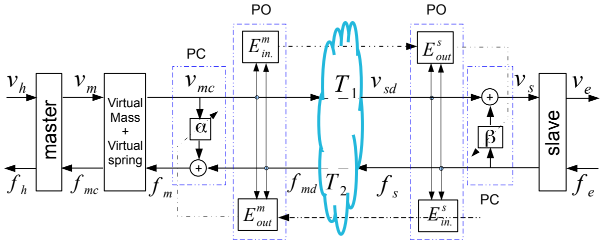

Fig. 3. A time-delayed teleoperation system with the TDPA and the virtual mass-spring filter (adopted from [11]).

B. Perceptual deadband-based haptic data reduction

Recent haptic data compression algorithms exploit mainly the characteristics and limitations of the human haptic perception system [4-7]. These approaches are inspired by Weber's law [15], which provides a mathematical model of human perception. It states that the minimum change in intensity perceivable between two stimuli ΔI, called just noticeable difference (JND), is a constant proportion of the starting intensity of a reference stimulus I [16]:

$$\Delta I / I = \epsilon \tag{13}$$

In Eq. (13), the JND (or difference threshold) is identified by psychophysical methods and the ratio ϵ (with its corresponding stimulus energy I) is called the Weber Fraction (WF) [16]. For haptic perception, the WF is constant and has been found to be in the range of 5% to 15%, depending on the type of stimulus and the limb/joint where it is applied [17].

Inspired from Weber's Law, small changes in the rendered force feedback signal are considered to be unperceivable samples. For a given force sample I, the deadband parameter (DBP) p defines a deadband (DB) zone $\Delta = 2pI$ (see Fig. 4). Samples that lie in the deadband zone can be dropped. When the difference between the recently sent sample and the current signal value violates the deadband zone, the current value is sent as a new update. At the receiver side, a basic upsampling method called zero-order hold (ZOH) strategy is utilized to interpolate the irregularly received signal samples to a high sampling rate that is required for the local control loops.

Fig. 4 shows the principle of the DB approach. Filled sample circles represents the update samples. The gray zones illustrate the deadband zone (perception thresholds) defined by the DBP. The samples inside the zone are interpolated by ZOH approach at the receiver side. The size of the applied deadband zone is increased directly proportional to the magnitude of the most recently transmitted haptic sample and the DBP p. If the signal violates expected deadband zone, then a signal update is sent over the network and the current deadband zone is also updated with this recent sample.

Note that the simple ZOH strategy is a non-passive reconstruction scheme [12], [13], which could jeopardize the system stability. To ensure a stable deadband reconstruction, the authors in [12], [13] have modified the simple ZOH scheme and proposed the passive ZOH reconstruction strategies. For example, in [13] the passive ZOH scheme on force is:

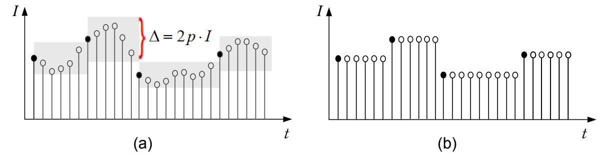

Fig. 4. 1-DoF deadband approach. The input signal (a) is downsampled and only the values represented with black filled circles are transmitted. In (b), the output signal is upsampled using the zero-order-hold method.

$$f(k) = f(k^*) - sign(v_s)\Delta_f \tag{14}$$

where $k^* < k$ is the time instant of the most recently received signal and $f(k^*)$ is the most recently received force signal. p is the deadband parameter. $\Delta_f = p \cdot f(k^*)$ denotes the DB zone with regard to the most recently received signal $f(k^*)$.

III. Haptic Data Reduction Using TDPA

In this section, we present a novel combination of haptic data reduction approach with TDPA control architecture to deal with time-varying communication delays. The deadband approach with the zero-order-hold (ZOH) method as proposed in [5] is employed for data reduction and reconstruction. As illustrated in Fig. 5, the blocks "deadband control", on both the master and slave sides, control the transmission rate of the velocity / force signals. If the change of the current signal with respect to the most recently sent signal is smaller than a DB zone defined by the DBP, the current signal will not be sent. Otherwise, the current velocity/force signal will be sent. At each sampling instant, if nothing is received, the block "deadband reconstruction" generates the same signal as the most recently received one for the subsequent computation. Compared to the original TDPA architecture, the computation of the energy in POs is now modified according to the deadband approach. The energy changes on both the master and slave sides at each time instant k can be described as follows:

$$\Delta E^m(k) = \begin{cases} v_{mc}(k) f_{md}^{recv}(k) \cdot \Delta T, & \text{if signal received} \\ v_{mc}(k) f_{md}(k^*) \cdot \Delta T, & \text{else} \end{cases} \tag{15}$$

$$\Delta E^s(k) = \begin{cases} v_{sd}^{recv}(k) f_s(k) \cdot \Delta T, & \text{if signal received} \\ v_{sd}(k^*) f_s(k) \cdot \Delta T, & \text{else} \end{cases} \tag{16}$$

where $k^* < k$ is the time instant of the most recently received signal. $v_{sd}(k^*)$ and $f_{md}(k^*)$ are the most recently received velocity and force signal. $v_{sd}^{recv}(k)$ and $f_{md}^{recv}(k)$ denote the currently received velocity and force signal. Based on the signs of the energy change, the input or output energy on both the master and slave sides can be computed according to Eq. (1)-(4).

Although the simple ZOH reconstruction scheme is non-passive, the POs and PCs ensure the passivity of the two-port network (marked by the blue dotted lines in Fig. 5) at each sampling instant. Thus, the simple ZOH method can be directly applied without any modification. Conversely,

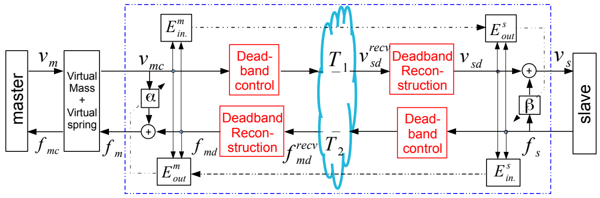

Fig. 5. Overview of the TDPA-based haptic data reduction approach in combination with the perceptual deadband coding scheme.

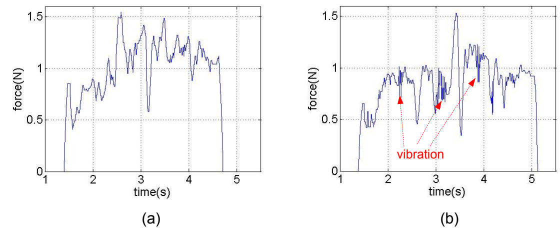

Fig. 7. Reconstructed force signal (amplitude) with the DBP of 10%. (a) Simple ZOH strategy. (b) passive ZOH scheme using Eq. (14). The force signal in (b) has more vibrations than that in (a). These vibrations are subjectively perceivable and disturb the user's interaction with the virtual object.

the WV-based approaches do not have such a passivity guarantee when the simple ZOH reconstruction scheme is applied. Therefore, passive ZOH reconstruction strategies are necessary.

Compared to the simple ZOH reconstruction method, the passive ZOH reconstruction strategies ([12], [13]), however, could lead to greater signal error between the real and reconstructed signal and to greater signal jumps when a new signal is received. Fig. 6(a) shows the input signal sequence in which the two black filled circles denote the transmitted signal. The reconstructed signal using the simple ZOH method is shown in Fig. 6(b), where the maximum signal error is half DB zone ($\Delta/2$) and the maximum signal jump is also about $\Delta/2$. Fig. 6(c) shows the reconstructed signal using the passive ZOH reconstruction strategies, where in the worst case the maximum signal error is Δ and the maximum signal jump is also about Δ. This greater signal error/jump due to the modification of the deadband reconstruction strategy could result in additional force distortion and perceivable vibration, when human user is involved in the haptic loop.

To verify this hypothesis, we have conducted a simple subjective test, in which 15 subjects are asked to interact with a virtual object using a real haptic device. During the interaction, subjects can switch between the simple ZOH scheme and the passive ZOH method. The DBP is set to be 10% and the delay is 0. A typical example of the force signals during the experiment is shown in Fig. 7. The force signal of the passive ZOH method (Fig. 7(b)) has more vibrations than that of the simple ZOH scheme (Fig. 7(a)). All subjects can perceive the disturbing from the high frequency vibrations. Thus, the simple ZOH reconstruction method in the TDPA-based approach introduces less distortion compared to the passive ZOH scheme in the WV-based approach.

In general, the advantages of our proposed TDPA-based haptic data reduction approach in comparison with the WV-based approaches are the flexibility in time-varying communication delays and the lower distortion in force signals. Tab. I simply contrasts these approaches.

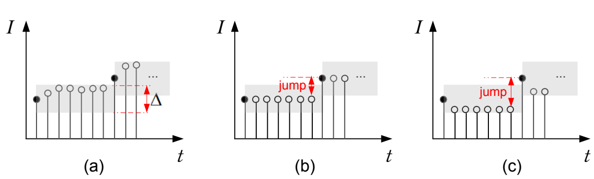

Fig. 6. The worst case of the data reconstruction using different deadband reconstruction schemes. (a) Input signal. (b) Reconstructed signal using the simple ZOH strategy. (c) Reconstructed signal using the passive ZOH strategies proposed in [12], [13]. The Y-axis denotes the signal intensity, either in the time domain (velocity/force) or in the wave domain.

TABLE I
COMPARISON OF DIFFERENT DEADBAND RECONSTRUCTION METHODS.

	comm. delay	max. error	max. jump
Method in [12]	constant	Δ	about Δ
Method in [13]	known & constant	Δ	about Δ
Proposed method	time-varying	$\Delta/2$	about $\Delta/2$

IV. EXPERIMENTAL EVALUATION

Generally, the low packet rate of haptic data and high system transparency are conflicting objectives in system design. Considering the limits of human haptic perception, however, a slightly distorted signal due to the deadband approach is not necessarily perceivable. With a proper DBP, low packet rate and high perceptual transparency can be thus achieved simultaneously.

We conduct subjective tests to evaluate the effect of the proposed TDPA-based approach on haptic data reduction in the presence of communication delays. In addition, the packet rate as well as the user preference in our approach are compared with those in the WV-based haptic data reduction approach proposed in [13].

The experiments are conducted in a virtual environment (VE) with a real haptic device (Geomagic Touch®) as illustrated in Fig. 8. The VE is developed based on the Chai3D library (www.chai3d.org). A 1-DoF rigid wall with the stiffness of 700N/m is placed in the middle of the VE as the remote object on the slave side. The dynamic of the virtual robot in the VE is designed based on the dynamic of the haptic device [18].

A. Experiment A

The first experiment is conducted to verify the feasibility of the proposed TDPA-based approach for constant and varying communication delays.

1) Setup and procedure

Three different round-trip communication delays are tested: 1) 10ms constant delay, 2) 100ms constant delay, and

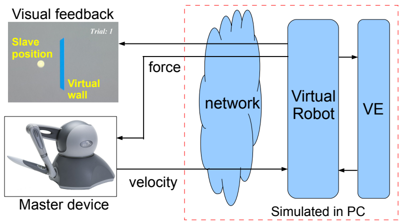

Fig. 8. Experimental setup. The network, the virtual robot, and the virtual environment (VE) are simulated in a PC based on the CHAI3D library.

3) varying delay with mean 100ms and jitter 30ms. For each delay, a series DBP values are tested: 0%, 2%, 5%, 8%, 10%, and 15%.

During the experiment, the subjects need to interact with the virtual wall by pressing it in and out at a rate about 0.5Hz. For each DBP value, subjects should give a rating from level 1 to 5 according to the quality of the displayed haptic sensations. 1) Level 5: no difference with respect to the reference. 2) Level 4: perceptible difference, but not disturbing. 3) Level 3: slightly disturbing. 4) Level 2: strongly disturbing. 5) Level 1: completely distorted. During the experiment, a reference (the same delay as the current trial with 0% DBP, designated level 5) can be called at any time to provide a high quality contrast for the subjects. The reason for not using the case of 0ms delay and 0% DBP as the reference is that we only investigate the effect of the DBP, but not the delay, on the subjective quality. For the same applied delay conditions to a set of DBPs, we consider level 5 to be when DBP is 0, as this is when the TDPA can provide the best force signal with communication delays.

15 subjects participated in the experiment, ranging in age from 25-45. The whole experiment is repeated twice for each subject. An anti-noise headset is provided to isolate the subjects from ambient noise.

2) Results

The packet rate / subjective rating vs. DBP for the three tested communication delays are shown in Fig. 9 and Fig. 10. In general, higher DBPs lead to lower packet rate and lower subjective rating. In Fig. 9, the packet rate curves of the three tested communication delays are very close to each other. The DBP, compared to communication delay, has significant and the dominating effect on the packet rate (two-way ANOVA: communication delay $p = 0.77$; DBP, $p < 0.0001$; interaction, $p = 0.62$). In addition, no significant difference can be found in the subjective ratings of the three tested communication delays at the same DBP in Fig. 10 (two-way ANOVA: communication delay, $p = 0.54$; DBP, $p < 0.0001$; interaction, $p > 0.99$). This indicates that the distortion on the force signal due to the DBP is independent of communication delays (up to $100ms \pm 30ms$).

The combined curves from Fig. 9 and Fig. 10 are shown in Fig. 11, which illustrates the relationship between the subjective quality and the packet rate (also called QR-curve). If a DBP of 5% is applied, the packet rate can be reduced up

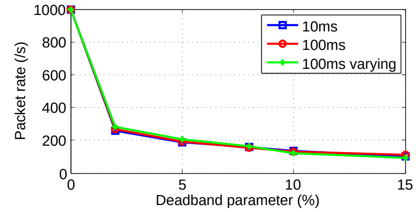

Fig. 9. Packet rate vs. deadband parameters for different delays.

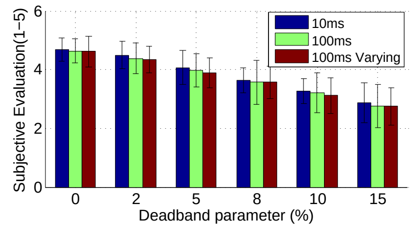

Fig. 10. Mean and standard deviation of the subjective ratings vs. DBP.

to 80% while the subjective quality remains sufficiently high (at about level 4). Thus, the TDPA-based approach achieves a high packet rate reduction without significantly degrading the subjective quality. In addition, the high similarity of the three curves in Fig. 11 implies again that the effect of the DBP on both the packet rate and subjective quality is independent of communication delays.

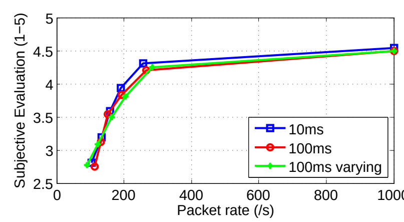

Fig. 11. Subjective quality vs. packet rate (QR-curve).

B. Experiment B

Compared to the WV-based haptic data reduction approaches, a known advantage of using the proposed TDPA-based approach is the ability to deal with varying delays. However, the efficiency of packet rate reduction and the quality on subjective experience between these approaches are still unknown. In this experiment, we compare the performance between our proposed method and the WV-based haptic data reduction approach proposed in [13] in both packet rate reduction and subjective preference. According to the discussion in Sec. III, high frequency vibrations introduced by the passive ZOH reconstruction scheme can result in perceivable force distortion. In addition, vibrations in force signal could also lead to dramatic force changes and thus results in a larger packet rate. Thus, a reasonable hypothesis is that "the packet rate of using the TDPA-based approach is smaller than the WV-based approach if the DBP is the same. Meanwhile, the subjects prefer the TDPA-based approach at high DBP values ($\geq 10\%$)."

In order to make an easier comparison for subjects on the quality between the TDPA-based and WV-based approaches, we adopt an indirect comparison by introducing a common reference for the two approaches. In the common reference case, the applied DBP value is the same as it in the other two approaches, but the delay is set to be zero and no passivity control architecture is applied. The common reference is considered to have a standard environment impedance with respect to the applied DBP. The comparisons are thus made between the common reference and the TDPA-based approach, and between the common reference and the WV-based approach. Actually, if there is no delay, the force signal in the common reference would not be distorted except by the applied DBP. If delay exists, in order to guarantee system stability, the DB approach must be combined with either the TDPA or the WV method, which introduces more distortion. In this experiment, we need to find which combination performs better for the tested DBPs.

1) Setup and procedure

The tested DBP values are the same as those in the first experiment: 0%, 2%, 5%, 8%, 10%, and 15%. Since the WV-based approach is not able to deal with varying delays, we set the round-trip communication delay in this experiment to be 100ms and constant. The experiment has six trials for the six randomly ordered DBPs. In each trial, subjects need to compare the two approaches (TDPA-based and WV-based) with the common reference during their interaction with the virtual wall. The subjects are the same as those in the first experiment. After each trial, the subjects need to answer the following two questions: 1) which approach shows a closer behavior (impedance) to the common reference? 2) which approach do you prefer?

2) Results

The result of the packet rate vs. the DBP is illustrated in Fig. 12. A significant lower packet rate can be observed when our proposed TDPA-based approach is applied (one-way ANOVA on packet rate: $p < 0.05$ for DBPs 5%-15%). For a DBP of 5%, the packet rate of the WV-based approach is about 250 packets/s, while the packet rate of the proposed TDPA-based approach is about 170 packets/s. An improvement of more than 30% in packet rate reduction is achieved.

For the subjective quality, the results of the two questionnaires are shown in Tab. II. For all the tested DBPs, most of the subjects believe the TDPA-based approach shows a closer behavior to the common reference. The TDPA-based approach is also preferred by the subjects compared to the WV-based one. Note that the results of the closeness and preference evaluations are very similar to each other, which implies that most of the subjects prefer the TDPA-based approach which introduces less modification on environmental impedance. If we look at the results at the DBP of 0%, where no data reduction exists and the distortions on the environment impedance are only from the control architectures. The

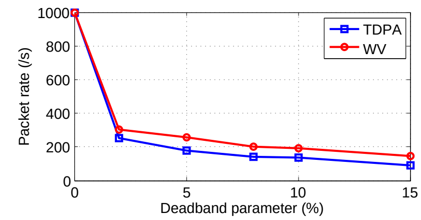

Fig. 12. Comparison of Packet rate reduction for two haptic data reduction approaches in delayed teleoperation systems.

TDPA architecture shows subjectively closer impedance to the original environment. This conforms to the conclusion in [11], where the authors suggest that the TDPA control architecture modifies the feedback force less than the WV architecture.

Thus, the hypothesis made at the beginning of this experiment is confirmed. In addition, the subjects prefer the TDPA-based approach also at lower DBP values for communication delays up to $100ms \pm 30ms$.

TABLE II

RESULTS OF THE FIRST QUESTIONNAIRE: SUBJECTIVE IMPEDANCE.

Question 1: impedance closeness						
DP (%)	0	2	5	8	10	15
TDPA-based	73%	80%	73%	80%	93%	100%
WV-based	27%	20%	27%	20%	7%	0%

Question 2: preference						
DP (%)	0	2	5	8	10	15
TDPA-based	73%	87%	80%	80%	93%	93%
WV-based	27%	13%	20%	20%	7%	7%

V. Discussion

A. *Deadband parameter vs. communication delay*

It is clear that increasing the DBP value leads to larger force distortion. In addition, the TDPA control architecture can also cause a different kind of force distortion. According to [11], dramatic force change could happen when the passivity controller increases the customized damping to dissipate the system energy. The strength of this distortion becomes larger along with the increase in communication delay. In our experiment, the tested delays are up to $100ms \pm 30ms$. At this level, the effect of the delay on system stability can be well compensated for without significant distortion. However, for larger delays, e.g. 2000ms, the force distortion introduced by the control architecture is not negligible [11]. With the increase of the communication delay, the force distortion from the control architecture becomes more dominating and thus the distortion from the DBP could be harder to be perceived. Therefore, subjective rating in the first experiment in the presence of large delays could be different from the current results. One hypothesis is that the ratings for difference DBPs in Fig. 10 becomes closer. More experiments regarding to this hypothesis will be conducted in our future work.

B. DB-based packet reduction vs. packet loss

According to the DB approach, if the change between the most recently sent sample and the current sample is sufficiently small, the current sample is not sent (dropped). This is a kind of packet loss. According to [11], packet loss introduces additional artifacts in force signal, since the master and slave cannot exchange the energy information and thus the passivity controller behaviors more conservative. Larger DBP value leads to higher packet rate reduction and thus results in more "packet loss". Therefore, the effect of the DBP on the force distortion is not only from the ZOH reconstruction scheme, but also from the packet loss-like (PLL) behavior due to the combination of the deadband approach and the TDPA architecture. The difference between the PLL behavior and the real packet loss is that in the former case the signal sender knows when the communication stops and when it recovers. Based on this knowledge, it is possible to design an energy predictor to enable less conservative control for the passivity controller.

C. TDPA vs. WV control architectures

According to [11], the TDPA architecture modifies the environment impedance (stiffness) less than the WV architecture. We also observe the similar results from the experiment B, where most of the subjects suggest that the WV-based approach shows a softer environment than the TDPA-based one. Although the displayed impedance can be increased to be closer to the original environment impedance by increasing the characteristic impedance b in the WV architecture, free space motion requires a very small value of b [12]. Typically, a compromise value is chosen. In our experiment, we set $b = 3.5Ns/m$.

On the other hand, subjects feel dramatic force changes in very short time occasionally when the TDPA-based approach is applied. Position drift is another issue of the TDPA architecture, but it can be compensated using an extended TDPA architecture [19]. With the delay of $100ms \pm 30ms$ and low frequency input in our experiment, however, these distortions are not sufficiently significant and the subjects prefer the TDPA-based approach. For larger delays, due to the increase of the force distortion from the TDPA control architecture, the subjective preference might change.

VI. CONCLUSIONS

In this paper, we present a control scheme different from the previous work and based on the TDPA architecture, which allows a reduction of haptic data using a simple ZOH deadband reconstruction approach, while preserving system stability in the presence of time-varying communication delays, without knowing the network parameters. The proposed approach can reduce the packet rate up to 80% without introducing significant distortion for communication delays up to $100ms \pm 30ms$. Compared to the WV-based approach, the system is subjectively more transparent when the TDPA-based approach is employed. In addition, the proposed approach has a higher efficiency in packet rate reduction.

Future work will focus on system performance for different delays in real network setup. In addition, the energy predictor mentioned in Sec. V-B can also be developed to reduce the force distortion from the passivity controller. Extending the WV-based approach to deal with time-varying delay according to [14] is also an interesting topic.

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