HoIP: A Point-to-Point Haptic Data Communication Protocol and Its Evaluation

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***Abstract*—Telehaptics applications are usually characterized by a strict imposition of a round trip haptic data latency of less than 30 ms. In this paper, we present Haptics over Internet Protocol (HoIP) - a low latency application layer protocol that enables haptic, audio and video data transmission over a network between two remotely connected nodes. The evaluation of the protocol is carried out through a set of three experiments, each with distinct objectives. First, a haptic-audio-visual (HAV) interactive application, involving two remotely located human personnel communicating via haptic, auditory and visual media, to evaluate the Quality of Service (QoS) violation due to the protocol. Second, a haptic sawing experiment with the goal of assessing the impact of HoIP and network delays in telehaptics applications, by taking the example of a typical telesurgical activity. Third, a telepottery system to determine the protocol's ability in reproducing a real-time interactive user experience with a remote virtual object, in presence of perceptual data compression and reconstruction techniques. Our experiments reveal that the transmission scheduling of multimedia packets performs well in terms of maintaining the latencies well under the QoS thresholds.**

***Keywords* -** *HoIP, telehaptics, fragmentation, augmentation, latency, multiplex*

I. Introduction

Haptics deals with the branch of science concerned with the sense of physical touch. Haptic technology utilizes the force-feedback mechanism to deliver an enriched interactive user experience with virtual/remote objects by making them palpable. The various applications that exploit the haptic feedback mechanism include teleoperation [1], telementoring and collaborative surgical simulations [2], cultural heritage museum [3], entertainment and gaming [4], social networking for an immersive interaction, etc. These applications could also involve other multimedia types alongside haptics. Each media type comes with its own set of QoS requirements, to be agreed upon by the network to ensure a glitch-free display of the continuous media. The violation of QoS parameters causes a poor perception of media units by the end user. The maximum allowable one-way delay and jitter (both in ms) for different media, according to [5], is respectively as follows: Haptic: 30 and 10, audio: 150 and 30, video: 400 and 30. Hence, in a multimedia application there is a need for the design of a QoS aware multiplexer, which at any point in time forwards only one of the competing media channels towards the communication link, so that all QoS needs are satisfied.

In an attempt to haptically perform a distant task, as in telehaptics applications, researchers have been looking at different possibilities for efficient haptic data communication between interacting agents. A typical telehaptics application runs at a haptic data sampling rate of 1 kHz. One of the foremost challenges in such communication include maintaining an overall round trip latency of less than 60 ms [6], otherwise there arise issues related to haptic perception and stability of the global control loop. To circumvent these, a conventional technique is to carry out packetization at the haptic sampling rate, thereby injecting 1000 packets/sec into the network. The option of merging multiple haptic samples in a single packet is also ruled out, due to latency issues. Hence the haptic protocols carry the tremendous responsibility of delivering data at very low delay ranges, and also curtailing the packet rates by a large amount, without introducing any noticeable degradation in perception.

Several protocols (not specifically designed for haptics) have been shown to be not appropriate for their usage in telehaptics applications. The Synchronous Collaboration Transport Protocol (SCTP) [7] and the Light TCP [8] adopt the concept of reliable packet delivery of key updates and unreliable delivery of normal updates. This reliability mechanism results in the increased overall latency in the communication system. The Real Time Protocol for Interactive Applications (RTP/I) [9], an application layer protocol for remote interactive applications, adds a header of length 28 bytes to every haptic sample. For a typical haptic sampling rate of 1 kHz, this protocol injects a huge overhead into the network. Certain protocols have been specifically designed for haptic applications. The Application Layer Protocol for Haptic Networking (ALPHAN) [10] does not consider the possibility of reducing the packet rate generated by the application. The Perception based Adaptive Haptic Communication Protocol (PAHCP) [11] employs Weber's law to adaptively sample the data without considering the temporal variation in Just Noticeable Difference (JND) of human haptic perception. Further, the above mentioned haptic protocols do not carry out a detailed analysis of sender and receiver module processing delays. In our previous work, we introduced Haptics over Internet Protocol (HoIP) [12] to address the aforementioned challenges in telehaptics applications. However, it renders support only for communicating haptic data.

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Figure 1: Existing HoIP frame structure

In this paper, we present an advanced version of HoIP, that enables multimodal data transmission by appropriately multiplexing haptic, audio and video data into hybrid application layer messages. We also discuss the simulation of a telehaptics environment by applying a proportional-derivative (PD) controller at the teleoperator. We present three experiments with distinct objectives, developed for performance evaluation of the protocol. The HAV interactive experiment between two users measures the extent of QoS adherence of HoIP, even when the network bandwidth is at least equal to the application data rate. The haptic sawing experiment is designed with the objective of measuring the overall influence of the delays due to the network and the protocol, by simulating a typical telesurgical task of cutting a hard object without damaging the softer tissues underneath it. The telepottery system investigates the protocol's ability in reproducing the interactive experience to the user, in presence of packet reduction schemes, discussed in [12]. In the HAV experiment, the possibility of a deteriorated experience due to mutual incompatibility between users is ruled out by measuring only the media frame delays at the receiver, and not asking for the subjective rating. In the telepottery experiment, the focus is more on the interaction with a virtual object based on haptic-visual feedback.

The remainder of the paper is organized as follows: Section II gives a brief overview of the existing architecture of HoIP. Section III describes the proposed transmission framework. Section IV describes the procedure followed for simulating a telehaptic environment. In Section V, we describe the three experiments designed for the protocol evaluation. and we provide the constituents of the overall application data rate. In Section VI we present and analyze the various findings of the experiments. Section VII summarizes the conclusions of our work and points few directions for future research.

II. Haptics over Internet Protocol - HoIP

HoIP being an application layer protocol, employs UDP and IP implementations to communicate data over the network. HoIP is characterized by a fixed packet header format, shown in Figure 1, of length 12 bytes, out of which 3 bytes are reserved for future enhancements of the protocol. Adaptive sampling techniques, such as Weber sampler and level crossings, discussed in [13], have been employed to curtail the packet rate, without causing any disturbance to the human sensory mechanism. However, we also provide the option of packet transmission at the default haptic loop rate. In order to take advantages of the dynamics of the human perception [14], the sampling thresholds (the field *Threshold* in Figure 1) are periodically communicated, as a part of the header, so that the other node can refrain from sending unnecessary packets. At the receiver, continuous haptic data is reconstructed (in case of adaptive sampling) from the non uniform, discretely arriving samples by employing extrapolators like sample-hold and linear extrapolators. The system administrator has the flexibility to choose various protocol parameters like the sampling mechanism (bit *A*), type of sampler (field *S*), extrapolator, etc to suit to the telehaptic application, and the communication network load capacity. Another feature of HoIP is the periodic transmission of haptic data to prevent error propagation due to UDP packet losses. The field *Sequence number* is used for tracking out-of-order, and undelivered packets. *Inter sample time* can be used for adjusting the rendering time of individual samples, and also for estimating the communication network parameters like the latency, traffic, etc. HoIP also simplifies the connection with the haptic interface through the usage of a data pipe [15]. HoIP is developed in C++, and follows a multithreaded library architecture to minimize the data processing delays, the details of which can be found in [12].

III. Proposed HoIP Transmission Framework

We now define a few terms, which will be referred frequently in the remainder of the paper.
Winning media: the multimedia type that is assigned the highest transmission priority, in case of multiple competing media types.
Fragmentation: division of a large media frame into smaller units for efficient transmission over the communication channel.
Augmentation: consolidation of heterogeneous media data into a single packet.

The transmission framework holds the responsibility of selectively determining the winning media, fragmenting the winning media frame, augmenting it with the earliest unsent haptic sample, carrying out the media-specific HoIP message packetization, and sending the message to UDP layer as shown in Figure 2. The multiplexing of multimedia is added to have a priority-based transmission of media frames. Fragmentation of media frames is vital in avoiding clogging of the communication link, caused due to transmission of large size frames. For example, transmission of an unfragmented video frame of size 2000 bytes results in a latency of 16 ms on a 1 Mbps channel. Hence, the subsequent media frames experience this large delay even before their transmission begins.

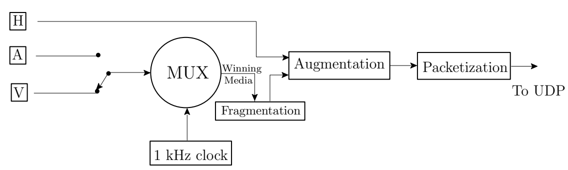


Figure 2 : Block diagram of the proposed HoIP transmission framework.

Let M denote the size of the haptic sample, N denote the fixed maximum payload size after augmentation, P denote the size of pending fragment of the winning media to be transmitted. N, M and P are expressed in bytes. Figure 3 illustrates the working of fragmentation and augmentation modules. The winning media payload size is a variable quantity, with a maximum value of $N - M$. If $P < N - M$, the case in the third mux cycle, the entire pending fragment of winning media frame, denoted by S, is augmented with the haptic sample. It can be noted from the figure that $S < N - M$. If $P \geq N - M$, a winning media fragment of size $N - M$ is augmented with the haptic sample. The segment labelled *H* refers to the haptic sample.

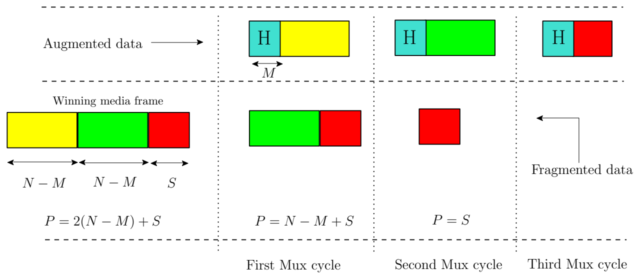


Figure 3 : Illustration of payload fragmentation and augmentation.

The QoS aware *multiplexer* module of HoIP appropriately selects the winning media amongst the competing multimedia data to be transmitted, along with haptic data, based on the frame generation times, so that none of the media violates its respective QoS conditions. The current multiplexer design considers a specific case where the haptic data transmission is carried out at default sampling rate of 1 kHz. The multiplexer clock is set to 1 kHz, so that it is in synchronization with haptic sample generation. At every tick of the multiplexer clock, a fragment of the winning media frame (if available) is augmented with the leading haptic sample. The term *leading* refers to the earliest frame in the media buffer to be transmitted. The *multiplexer* runs the *transmission scheduler* algorithm, shown in Algorithm 1, to select a fragment from the winning media frame, which is augmented with the earliest unsent haptic sample. If both audio and video buffers are empty, then only the haptic payload is transmitted. If either of them is non-empty, then a fragment of a pre-defined length is extracted from the media frame, and is appended to the haptic payload. If both buffers are non-empty, then the conflict is resolved based on a first-come-first-serve (FCFS) scheme, according to which the earliest generated leading media frame gets the highest priority in terms of transmission. This strategy minimizes the risk of media QoS violation and avoids a scenario wherein a later frame gets a higher priority than a previously generated frame. If the generation times of leading frames of multiple media are identical, then the media with the most strict QoS bounds, in our case audio, gets a preference, since it has a higher likelihood of violating them in a shorter time span. Finally, the augmented media data is loaded into transmission buffer, from which it is extracted for packetization.

N plays a crucial role in governing the overall delay, jitter. A large value results in higher delay on the haptic media, and a small value results in improper utilization of the channel, resulting in increased delays on audio and video.

In order to accommodate multimodal data in a message, we made suitable changes to the existing HoIP message structure, and are shown in Table 1. Other relevant header information in the first byte in Figure 1 is fixed for an entire session, and hence is shared between the interacting agents during the session initiation. The message headers are followed by the corresponding media payloads.

Haptic	Media Type (1 byte), Haptic Timestamp (4 bytes)
Haptic-Audio	Media Type (1 byte), Haptic Timestamp (4 bytes), Audio Timestamp (4 bytes), Audio Sequence Number (2 bytes), Payload Length (2 bytes)
Haptic-Video	Media Type (1 byte), Haptic Timestamp (4 bytes), Video Timestamp (4 bytes), Video Frame Number (2 bytes), Video Fragment Number (2 bytes) Payload Length (2 bytes).

Table 1: Proposed HoIP header contents.

IV. Telehaptics Simulation

In certain telehaptic applications, such as telesurgery, the two remote nodes share a master-slave relationship, wherein the master (operator or OP) sends commands to the slave (teleoperator or TOP) to mimic its actions as accurately as possible, without compromising on the response time. To accomplish this task, we employed a proportional-derivative (PD) controller at TOP, whose response is proportional to the rate of change of error between the OP and TOP positions. Hence the PD controller drives the TOP along the path followed by the OP. The PD controller was chosen over other controllers for achieving a swift TOP response. Let $\bar{P}_n$ and $\bar{V}_n$ be latest received position and velocity co-ordinates of OP, respectively, and the current TOP position and velocity be denoted as P_n and V_n. The force X_{n+1} to be rendered at TOP during the next time instant is calculated as

$$X_{n+1} = K_p * (\bar{P}_n - P_n) + K_v * (\bar{V}_n - V_n) \qquad (1)$$

where K_p and K_v are the position and velocity gains of the PD controller, respectively. K_p is set to 25 N/m and K_v to 2 Ns/m empirically. Haptic sawing and telepottery experiments described in Section V-B and V-C, respectively employ PD controller to control the TOP.

V. Design of Experiments

A. Haptic-Audio-Visual Interaction

Typically a HAV interactive system consists of multiple distantly located communicating systems which share local haptic device position, velocity, audio and visual information with each others. All along the teleconferencing session if any of the media involved violates its respective QoS conditions, the end users can perceive the disturbance and hence the overall experience deteriorates. We designed a virtual interactive teleconferencing system to test the effectiveness of multiplexing scheme of HoIP, wherein two users can interact with each other through touch, speech and visual senses. An environment was created in which the users virtually shake hand through the haptic device and move between pre-defined points while maintaining the contact. During the interaction, the users could also communicate verbally and visually to aide in the completion of the activity. The visual and auditory capturing and display devices were also provided for the interaction. During the course of interaction, the receivers at both ends constantly measure the delay that individual

Algorithm 1 Transmission Scheduler Algorithm

if audio and video buffers are empty **then**
  transmit leading haptic sample
else if only audio buffer is non-empty **then**
  while leading audio frame transmission is incomplete **do**
    augment leading haptic sample and a fragment of leading audio frame
    transmit augmented data
  end while
else if only video buffer is non-empty **then**
  while leading video frame transmission is incomplete **do**
    augment leading haptic sample and a fragment of leading video frame
    transmit augmented data
  end while
else
  resolve conflict on FCFS basis
  while winning media frame transmission is incomplete **do**
    augment leading haptic sample and a fragment of leading frame of winning media
    transmit augmented data
  end while
end if

media frame experiences. For this experiment, we chose haptic data transmission at default sampling rate (1 kHz). The HAV interaction makes use of the transmission scheduling scheme described in Section III.

B. Haptic Sawing

In telesurgery, there could be a bone that needs to be cut, without damaging the underlying soft tissues. Any delay, due to the processing of haptic data or the communication link, results in a lag in the feedback, the consequence of which could be the surgeon sawing more than what is necessary. In order to investigate the effects of HoIP processing delay, in terms of the extra penetration into an object, we simulated a telehaptic scenario wherein a hard object is positioned over a soft object in a haptic environment governed by the equation below.

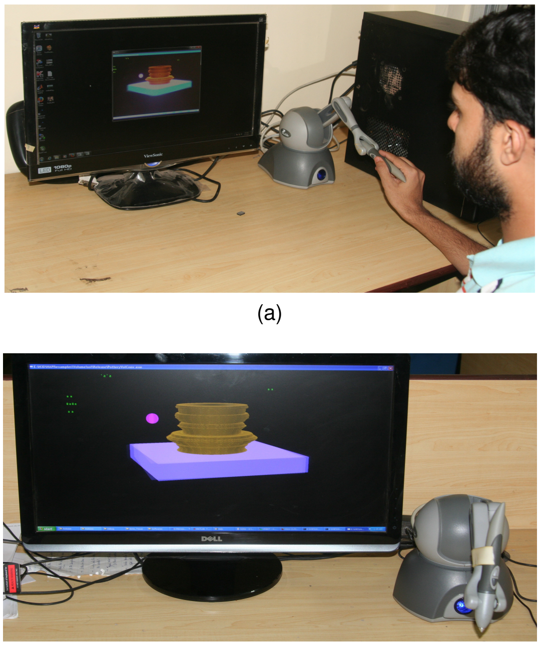
$$X(P_y) = \begin{cases} 0, & \text{if } P_y > 0 \\ 2.3N, & \text{if } P_y < -0.05m \\ 3N, & \text{otherwise} \end{cases} \tag{2}$$

where X(P_y) and P_y refer to the current force rendered and the current position of the haptic device stylus in the vertical axis at the OP, respectively.
The hard and soft forces were carefully chosen to ensure that their difference is larger than the human JND, and also the user experiences a minimal physical jerk at the hard-soft object interface, which is a case if the force gradient is not very high at that point. Since the perception of forces due to hard and soft objects is not easily differentiable at the OP (due to haptic device limitation), we resort to piece-wise constant model of force, defined by Equation (2). The user moves the haptic device stylus vertically downwards, as in sawing the hard object, and stops when the softer forces are perceived. In order to avoid any bias on the experiment due to visual feedback, we disabled the visual modality of HoIP. This also highlights the role of haptic modality alone in telesurgery. We measure the additional penetration depth before the arrival of softer forces as an indication of the effects of delays. The additional penetration depth, δ can be measured as

$$\delta = |P_{y(ideal)} - P_{y(exp)}| \tag{3}$$

where $P_{y(ideal)}$ and $P_{y(exp)}$ are the haptic device stylus positions at the onset of softer forces at OP under ideal (zero delay) and experimental conditions, respectively.

C. Telepottery System



(a)

(b)

Figure 4 : A demonstration of telepottery experiment: (a) Operator end showing the user interaction through the master haptic device. (b) Teleoperator end showing the rendered virtual clay and the slave haptic device.

An important measure in the evaluation of HoIP is its fidelity in terms of reproducing the interactive experience of a

5	No perceivable impairment
4	Slight impairment, but no disturbance
3	Perceivable impairment, slight disturbance
2	Significant impairment, disturbing
1	Extremely disturbing

Table 2: Subject rating scheme

virtual environment, when the participating nodes are distantly located from each others. In addition to this, an assessment of the packet rate reduction, and the perceptual similarity of the reconstructed data to the original are also essential. For this purpose, we adopted a volume conserving haptic pottery system from [16], wherein the user interacts with a cylindrical virtual clay model through the haptic device, in an attempt to transform it into a nice looking pot. We designed a telepottery system in which the operator, based on haptic and visual feedback, manipulates the virtual clay model rendered on a distant setup, using the PD controller explained in Section IV. Figure 4 shows a typical teleoperation scenario, using the example of telepottery, at both ends. The packet rate reduction is based on Weber's law of JND [17]. The subjects initially performed the experiment on a standalone system, wherein the locations of the subject and the rendered object are the same, following which they were moved to a telehaptic setup. Towards the end of experiment, the subjects were asked to rate the interactive telehaptic experience on a scale of 5, relative to the standalone setup, based on the subject rating scheme as shown in Table 2. Since adaptive sampling mechanism is involved, the transmission scheduling schemes cannot be applied. The haptic and video information is transmitted as and when generated with fragmentation, but without augmentation.

D. Overall Data Rate

In our experiments, we used G.711 audio coding at the rate of 64 kbps, and H.264 video coding at the rate 400 kbps. The data rate of different components of the application are as follows.
Payload: Haptic - 192 kbps (24 bytes/second), Audio - 64 kbps, Video - 400 kbps.
Headers: Haptic + Audio + Video + UDP + IP + Ethernet $\approx$ 472 kbps.
Hence the overall data rate $\approx$ 1.2 Mbps.

VI. Experimental Results

A. Experimental Setup

The haptic devices used were Phantom Omni, with six input degrees of freedom (DOF) and three output DOF. Both PCs, employed were equipped with 4 GB RAM, connected on a network emulator with bandwidth set to 1.2 Mbps. This value of bandwidth was specifically chosen to equal the overall data rate of the HAV application. Video data was captured using a generic web camera from Microsoft, and communicated at a standard rate of 25 fps. The propagation delay of the network was configured to 15ms for the HAV interaction and telepottery experiment, and 5ms for the haptic sawing experiment. For haptic sawing experiment, we trained three users to perform the experiment with an average velocity of 5 cm/s, since very fast movements are least likely to occur in telesurgery. A total of ten subjects, seven males and three females, each belonging to the age group of 25 to 35, participated in the telepottery experiment. Out of the ten participants, two were regular haptic users, and the other eight were novice users. Prior to the experimentation, the users were given ample time for familiarization with the telehaptic system and the experimental procedure. For brevity, we present results for a single user and five users for haptic sawing and telepottery experiments, respectively. For measurement of the latency, the system clock of the computers were synchronized using Network Time Protocol (NTP). For our experiments, N is set to 82 bytes empirically.

B. Quality of Service Verification

Figure 5 shows the plots of individual media delays measured against the generation time of the media frames. Apparently, the delays measured stay well within the acceptable limits and hence none of the media QoS conditions are violated. Haptic media suffers the minimum delay since audio and video frames span multiple packets. The periodicity of the delay is due to the periodicity of the frame generation process. Our aim here is to show that FCFS scheme for multiplexing along with fragmentation works without clogging the network. Transmitting the audio/video frames without fragmentation would result in increase in haptic data latency, and hence a higher possibility of QoS violation due to stricter requirement. For networks with very high bandwidth, the QoS conditions could be met even without fragmenting, but we are targeting low capacity networks in which the available bandwidth is just sufficient to support the data rate of the application. Table 3 provides a comparison between the QoS delay and jitter, and the observed delay and jitter for every media. The transmission of a video frame prior to an audio frame causes high, yet acceptable jitter in the auditory media. Apparently, QoS needs of all competing media are satisfied, with just sufficient bandwidth available for the application.

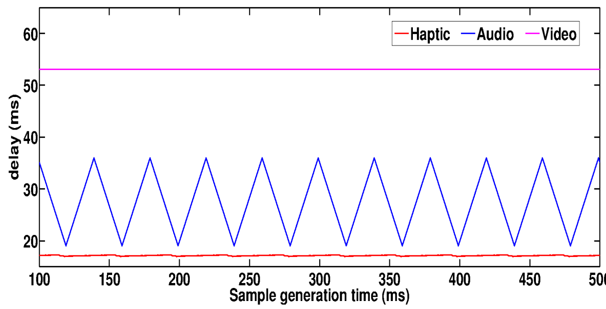


Figure 5 : Delay plots of haptic, audio and visual data.

	Delay (ms)		Jitter (ms)	
	QoS	Observed(max)	QoS	Observed(max)
Haptic	30	16	10	0.1
Audio	150	36	30	17
Video	400	53	30	0

Table 3: Comparison of observed delay and jitter with QoS

C. Additional Penetration Depth

Figure 6 shows the variation of the received forces over haptic device stylus positions in vertical axis at OP, in the ideal case as well as based on the experimental data for haptic sawing experiment. It shows that $P_{y(ideal)}$ is -0.0500254 m, and $P_{y(exp)}$ is -0.0500785 m. Hence the additional penetration depth, using Equation (3) is measured to be 0.0531 mm, whereas the numbers in the figure are in m, which is extremely

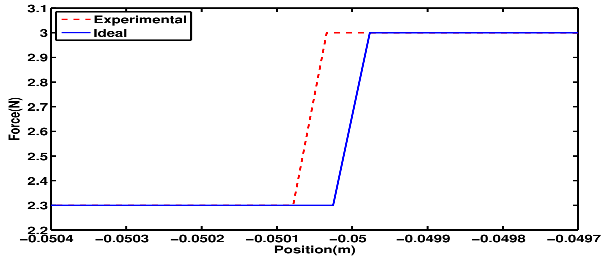


Figure 6 : Plot of received force vs haptic device position in vertical axis at the OP.

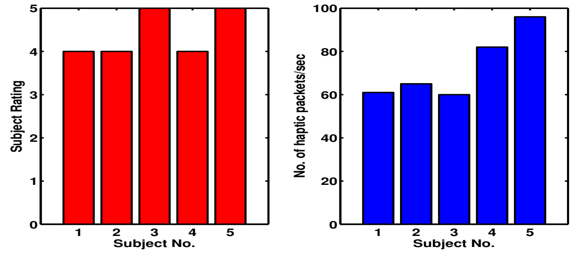


Figure 7 : Plot of subject rating and number of haptic packets/sec for various subjects.

negligible. δ is measured without compensating for the network delay, which means that the effect of HoIP alone on the additional penetration depth is much lower than δ. This suggests that HoIP processing delays are substantially low. However, one needs to analyze the impact of the additional penetration depth with respect to the application. The penetration depth due to HoIP alone is a function of the HoIP sender and receiver processing delays, and is independent of the network delay.

D. Subjective Rating and Haptic Packet Rate Reduction

Figure 7 shows the subjective rating of the telepottery experience, relative to standalone pottery, and the generated haptic packet rates for different subjects for the telepottery experiment. The plot of subject rating reveals that the users experienced no noticeable impairment in spite of the reduced packet rates, and the increased physical separation between the interacting systems. The graph of packet rates shows that HoIP is indeed very successful in cutting down the packet rate by more than 90%, relative to the default sampling rate packetization. The variation in packet rates is due to different speeds with which the users manipulated the object.

VII. Conclusions and Future Work

In this paper, we described HoIP - a simple, low latency application layer protocol, that can efficiently handle multimodal data communication between distant agents. HoIP carefully schedules the transmission of media fragments ensuring no media suffers unnecessary delays, and hence satisfying the QoS requirements. The haptic sawing experiment revealed the low latency data processing ability of HoIP, which is crucial for a telehaptic application. The telepottery experiment showed that HoIP curtails the packet generation rate of a telehaptic application by a significant quantity, without causing any perceivable impairment to the human senses. The multimodal data handling feature of HoIP creates a simple platform for the telehaptic application developers to add future enhancements. HoIP also provides researchers with a ready-to-use networked haptic, audio and video environment to carry out a wide range of experiments. These properties make HoIP a very suitable candidate for telesurgery and other telehaptic applications.

As a direction for future research, we would like to investigate the performance of HoIP on a real-world network which is prone to irregular fluctuations in the available bandwidth, and devise a network state aware transmission scheduler. Also, we would further like to study friendliness of HoIP packet transmission to other TCP based packet sources. Also, we would like to devise techniques for lossless compression of multimedia packets during conditions when the available bandwidth is less than the default packetization rate of the application.

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