Evaluation of Transmission Performance for Streaming CGH Video based on Computer Holography and Electro-Holography

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***Abstract*—Holography is an ideal three-dimensional display technology, and it can reconstruct natural-looking three-dimensional objects with sufficient depth. In this paper, we propose a system model that uses computer holography and electro holography to stream holographic videos. The holographic video is generated by synthesizing computer-generated holograms calculated by using light waves from a virtual object designed on a computer. The holographic video is streamed from a transmitter to a receiver with display devices via networks, and three-dimensional objects are optically reconstructed by using electro-holography with a spatial light modulator. The transmission performances of streaming holographic video over wired LAN (1000BASE-T), wireless LAN (IEEE 802.11ax), and local 5G network were evaluated.**

***Index Terms*—computer holography, electro-holography, streaming system, transmission performance**

I. Introduction

Three-dimensional display technologies are being increasingly applied to various fields. Holography is one such technology, and it uses interference of light waves to record and reconstruct light waves having three-dimensional information from an object [1]. Holography is suitable for the physiological functions of the human eye, such as focus adjustment, convergence, and binocular disparity, without causing fatigue or disorientation, making it ideal for three-dimensional display. Thus, holography-based three-dimensional displays are expected to be put into practical use in the future.

In holography, a hologram refers to the fringe pattern recorded as the interference of light waves from an object and a light source. When the hologram is illuminated by the same light source, the hologram diffracts the illuminating light waves and reconstructs the light waves of the recorded object. As a result, the light waves of the recorded object reach the viewer's eye; that is, viewers can see the the recorded object.

Computer holography is a technique based on the optical recording process in holography for generating interference fringes by computer numerical simulation [2], [3]. Holograms generated by computer holography are called computer-generated holograms (CGHs). The advantage of CGHs is that they does not require an optical system for recording and can record virtual objects created by a computer; however, it is crucial to reduce the amount of computation and increase the computation speed for the physical phenomena of light waves such as reflection, propagation, diffraction, etc.. The technology used to display CGHs on a special display such as a spatial light modulator (SLM) is called electro-holography [4], [5]. Electro-holography makes it possible to display three-dimensional moving objects by switching the displayed electronic CGH data; however, there are many challenges in practical application, such as a narrow viewing zone and viewing area. Moreover, compression and transmission methods for CGH data have not yet been established. Just as two-dimensional images and videos can be easily distributed, compression and transmission technologies should be considered for three-dimensional videos as well.

In this paper, we have developed a streaming system for CGHs data via networks in consideration of recent high-speed developments in wired and wireless communication technologies. In this system, CGH videos are generated by synthesizing CGHs data on a timeline, and the generated CGH videos are transmitted to the SLM as a display device. By using electro-holography, the CGH videos streamed via networks were outputted on the SLM, and the recorded moving object was optically reconstructed by illuminating displayed CGHs with a light emitting diode (LED). The CGH videos without any data compression of data were streamed, and we verified that the image quality pf CGH data and streamed data did not degrade as a result of compression or transmission errors. Using the system, we compared the transmission performance and image quality of the reconstructed objects when streaming over various network environments. The three network environments used for streaming were a general wired/wireless (Wi-Fi) LAN and a local 5G environment owned by the university.

II. Streaming System for CGH Videos

In recent years, multimedia data are easily transmitted and/or received via the Internet by used wired and/or wireless

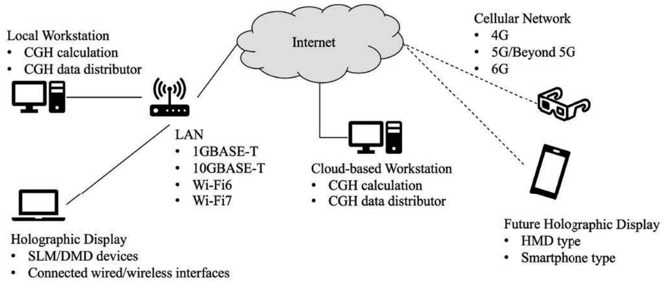


Fig. 1. Concept of the viewing system for CGH videos.

communication systems. It has become common for users to watch two-dimensional videos, whether they are shot in the real world or created by computer graphics, by downloading or streaming. For distributors, the data rate and the delay of the communication environment are important considerations when distributing videos. The data rate and delay determine the quality of the video and audio, and appropriate encoding/decoding methods are also necessary. When distributing three-dimensional videos, the data rate and delay of the communication environment must be considered as well.

Figure 1 shows a concept for distributing CGHs. The system should ideally enable users to view three-dimensional videos using devices with holographic display, just as they can view and distribute two-dimensional videos via various networks. To create such a system, it is necessary to consider how to compute, compress, send and receive CGHs data, and how to reconstruct objects from CGHs. This paper focuses on the transmission of CGH videos based on computer holography via networks, and we introduce an overview of the streaming system for CGH videos with electro-holography.

A. Related Works

Studies have reported the transmission of CGH data of real objects using digital holography via Internet [6], and the streaming of CGH data over LAN [7]. However, compression and evaluation methods of CGH image quality have not been established yet, and the relationship between the CGH transmission method depending on the communication environment and the degradation of image quality caused by transmission errors needs to be evaluated. Xu et al. proposed a system for transmitting CGHs [8] and described the bandwidth requirements for transmitting CGHs data to SLMs with various resolution and size specifications.

In these prior studies, the effect of transmission or compression errors on the image quality of reconstructed objects was not sufficiently evaluated. In the compression/transmission of CGHs data in particular, if CGHs are compressed using general compression techniques such as MPEG-4, the image quality of the reconstructed object may degrade due to loss of data [9], [10]. In [9], CGH videos were streamed with the MPEG-4 algorithm, and the contrast and noise were found to degrade in the reconstructed images with respect to the encoding rate of compression. In the wireless transmission of CGH videos [10], in addition to a decrease in brightness of the reconstructed image due to the encoding, a decrease in frame rate and loss of the reconstructed image with respect to the quality of the transmission path were also observed. From these studies, it is expected that compression and transmission technologies that does not affect the reconstructed object will be established in the future. Given the improvements in communication speed due to advancements in network technology, in this study we have developed a system for streaming uncompressed CGH videos via networks with no data degradation.

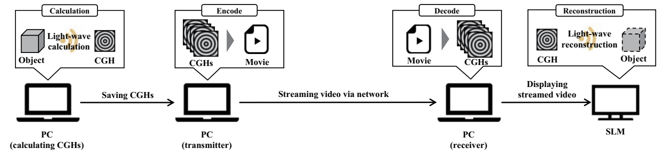


Fig. 2. Overview of the streaming system for CGH videos.

B. Overview of Streaming System

In this study, we developed a system for streaming CGH videos in uncompressed and with lossless compression via a network. Figure 2 shows an overview of the system, and each procedure will be described in the following sections.

1) Calculating CGHs: To calculate CGH data, we used the point cloud-based method, which treats the three-dimensional object to be displayed as a set of many point light sources. Assuming that the three-dimensional coordinate system comprising the object to be displayed is (x, y, z) and the two-dimensional coordinate system on the hologram plane to be recorded is (x_h, y_h), the complex amplitude $u(x_h, y_h)$ of the light wave on the hologram plane from an object can be calculated as [3]

$$u(x_h, y_h) = \sum_{j=1}^{M} \frac{A_j}{r_j} \exp\left[ikr_j\right] \quad , \tag{1}$$

where M is the number of point light sources which make up the object, A_j is the amplitude value of the jth point light source, the imaginary unit $i = \sqrt{-1}$, and the wavenumber k is $k = 2\pi/\lambda$. r_j is the distance between the jth point light source and the coordinates (x_h, y_h) on the hologram plane, and is given by

$$r_j = \sqrt{(x_h - x_j)^2 + (y_h - y_j)^2 + z_j^2} \quad . \tag{2}$$

The light waves propagating from the object, i.e., the object light, is calculated using the above equations. CGH data can then be generated by calculating the interference between the object light and the reference light. When generating a moving image, the above calculations for CGH data are performed for the required number of frames, and each frame is merged with the timeline.

2) Compression and Transmission of CGHs: When CGHs data are compressed with lossless codecs, the CGH data is encoded in the same way as in general video distribution. In the encoding process for compression, an uncompression

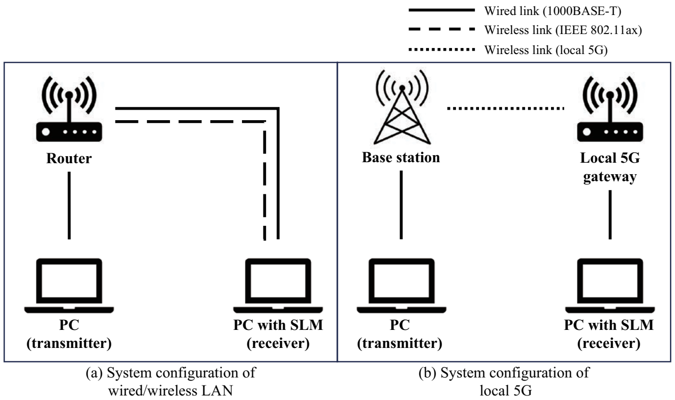


Fig. 3. Experimental setup.

or lossless codec is used to avoid losing data caused by compressing CGH data. In this study, we used the FFmpeg software [11], which can encode and decode data of video and audio data, to transmit uncompressed/lossless compressed CGH data streaming to a PC for displaying CGH data using the Secure Reliable Transport (SRT) protocol [12].

3) Receiving and Displaying CGHs: The CGH data transmitted in the above step was received by using the SRT protocol of the FFmpeg software in the PC. The received CGH data is decoded and displayed on the connected SLM, and three-dimensional moving object is optically reconstructed by illuminating the LEDs. Users can observe the reconstructed moving object with the streamed CGH video.

III. Experiments of Streaming Holographic Video

To evaluate the proposed system, the transmission performance and image quality of the reconstructed images were compared with CGH videos streamed via networks. The following sections will describe the experiments in detail.

A. Setup

The experimental setup shown in Fig. 3 consists of two PCs for transmitting CGH videos and displaying received CGH videos on SLM via networks. In LAN environments, the PC for the transmitter has a wired connection (1000BASE-T) to a router. The PC for receiver has a wired (1000BASE-T) or wireless (IEEE 802.11ax) connection to the router. In the experiments over wired/wireless LAN shown in Fig. 3(a), the CGH videos were streamed via the wired or wireless connection from the transmitter to the receiver.

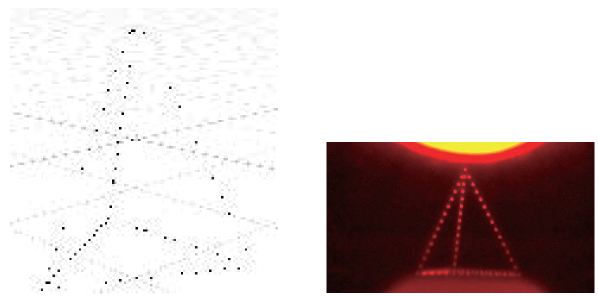
In the local 5G environment, the PC for the transmitter is connected directly under the base station of the local 5G, and the wireless communication based on the local 5G is carried out from the base station to the local 5G gateway. The PC for the receiver and local 5G gateway are connected by a wired connection (1000BASE-T). Under each network environment, CGH videos uncompressed or compressed with an arbitrary codec were streamed. As codecs for compression, uncompression (rawvideo) or lossless codecs such as ffv1, utvideo, and H.265 with lossless mode were used.

TABLE I
Parameters for calculating CGHs

Parameters	Values
Number of pixels	1920 × 1080 pixels
Pixel pitches	8.0 × 8.0 μm
Color level	8 bit grey level
Wavelength	632 nm
Number of frames	360 frames

TABLE II
Specification of SLM

Parameters	Values
Manufacturer	HOLOEYE Photonics AG
Part no.	HED 6001
Number of pixels	1920 × 1080 pixels
Pixel pitches	8.0 × 8.0 μm
Color level	8 bit grey level
Refresh rate	60 Hz



(a) Virtual object. (b) Reconstructed object.

Fig. 4. Virtual and reconstructed objects. (a) CGHs calculated with a virtual object. (b) Example of a reconstructed object captured by a digital camera in (b).

Tables I and II list the parameters for calculating CGHs and the SLM specifications, respectively. CGH videos with a resolution of full-HD, greyscale color mode, and 1 to 30 fps were prepared. Prior to the streaming experiment, the maximum throughputs were measured under each network environment. The throughputs in wired/wireless LAN were about 1 Gbps and that in the local 5G was about 480 Mbps. The procedures for streaming the CGH videos is as follows.

1) 1 to 30 fps CGH videos were created by merging 360 CGH images of the triangular pyramid consisting of 84 points shown in Fig 4(a), which were rotated by 1 degree for each image, into a timeline.
2) The generated CGHs were converted to videos with uncompression or lossless compression and streamed from a PC for transmitter to a PC for receiver via a network by using the SRT protocol.
3) The received CGH video was streamed and displayed on the SLM, and optical reconstruction was performed using LEDs. An example of a reconstructed object captured by a digital camera is shown in Fig. 4(b). Note that the received CGH video was also captured and the peak signal-to-noise ratio (PSNR) was obtained to determine whether data has been lost due to compression and/or

TABLE III
THROUGHPUT PERFORMANCE

Codec	Average throughput
rawvideo	540 Mbps
ffv1	310 Mbps
utvideo	397 Mbps
H.265	375 Mbps

TABLE IV
ROUND-TRIP TIME

Codec	Average round-trip time		
	Wired	*Wireless (Wi-Fi 6)*	*Wireless (Local 5G)*
rawvideo	0.4 ms	3.5 ms	58.4 ms
ffv1	0.3 ms	2.7 ms	50.5 ms
utvideo	0.5 ms	2.8 ms	50.4 ms
H.265	0.3 ms	3.0 ms	42.4 ms

transmission. At this time, statistics for transmission with the SRT protocol were also recorded.

IV. EXPERIMENTAL RESULTS

A. Uncompression/Lossless compression

Table III shows the results of the measured average throughput when the CGH videos, which were in full-HD resolution, greyscale color mode, 30 fps, were streamed via networks. Here, no significant differences in measured throughputs were observed between the networks. The required bit rate of the CGH video without compression is about

$$1920 \times 1080[\text{pixels}] \times 8[\text{bit}] \times 30[\text{fps}] = 497[\text{Mbps}] \quad .$$

Since headers and other data for transmission are added in addition to the above bit rates, the throughput of rawvideo was approximately as expected. In the transmission using lossless compression (ffv1, utvideo, H.265), we found that the compression ratio was not as high, but the throughput was lower than that of the uncompressed transmission. In the case of wireless transmission (IEEE 802.11ax, local 5G), when communication conditions were favorable, the results were almost the same for both uncompression and lossless compression as for transmission with a wired connection. In addition, the evaluation of CGH video quality after transmission by PSNR showed that the data before and after transmission were identical in all codecs. This indicates that, in transmission with uncompressed/lossless compressed codecs, no data loss occurs as a result of compression or transmission when communication conditions are favorable.

Table IV shows the results of the measured average round-trip time (RTT) under each environment. The RTT for wired connection is less than 1 ms, 2 to 3 ms in the wireless (IEEE 802.11ax) connection, and around 50 ms in the local 5G connection. In the local 5G environment, packet loss tended to occur when the RTT reached over 100 ms, and this was accompanied by dropped frames and degradation of video quality caused by distortion.

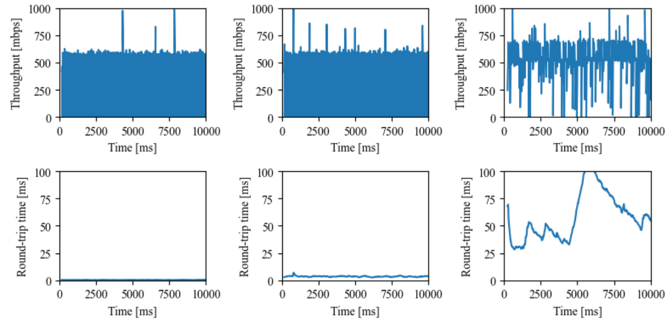


Fig. 5. Comparison of results of throughputs (top) and RTTs (bottom) in wired LAN (left), in wireless LAN (center), in local 5G network (right). The codec for streaming CGH video is uncompression (rawvideo).

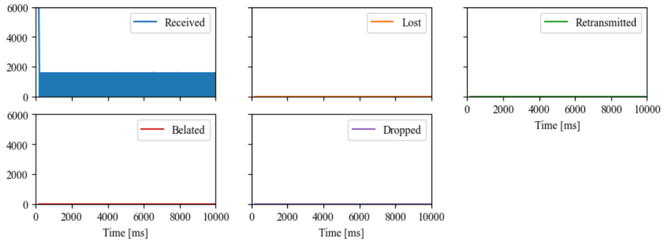
TABLE V
THROUGHPUT AND PSNR WITH LOSSY COMPRESSION

qp	Average throughput	PSNR
1	286.1 Mbps	56.7 dB
11	185.5 Mbps	46.3 dB
21	98.4 Mbps	38.6 dB
31	36.7 Mbps	31.6 dB
41	7.4 Mbps	25.4 dB
51	0.1 Mbps	22.4 dB

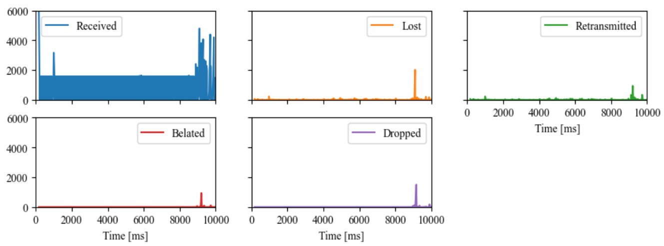
Figure 6 shows the results over each network, which includes the throughput and RTT per time for transmission with uncompressed CGH video (rawvideo). The throughputs had almost the same distribution but was highly variable in local 5G, and RTT had the greatest fluctuation in local 5G as well. Since this may be the cause of the dropped frames, it is necessary to adjust the frame rate and improve the transmission protocol to ensure stable transmission even in unstable communication environments in the future.

B. Lossy Compression

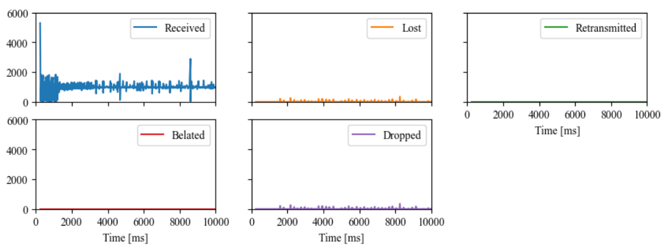
Table V shows the results of the average throughput and PSNR of CGH video after transmission with H.265 codec in lossy mode. In H.265, the quality of compressed video can be controlled by the parameters (qp=1 to 51). A video with qp=1 denotes a low compression quality and that with qp=51 denotes a high compression quality. In table V, the PSNR is about 56 for the low compression ratio with qp=1, and the PSNR value decreases as the compression ratio increases due to increased data loss. The results indicate a trade-off between compression ratio and CGH video quality, which is the same with two-dimensional video. In this study, uncompression and lossless compression were used for transmission as a compression method that does not degrade the quality of the reconstructed objects. However, in anticipation of future increases in transmission volume, such as 4K/8K videos and colorization, it will be necessary to consider a method that allows data loss to the extent that no image degradation is perceived in the reconstructed objects.



(a) Wired LAN (no drop).



(b) Wireless LAN.



(c) Local 5G network.

Fig. 6. Comparison of results for packet drop in (a) wired LAN, (b) wireless LAN, and (c) local 5G network. The codec for streaming holographic video is uncompression (rawvideo).

C. *Packet Drop in SRT Protocol*

SRT is an open source video transport protocol which aims to enable the delivery of high quality and low latency video via Internet. As mentioned previously, uncompressed and lossless compressed CGH videos with high bit rate were actually streamed via networks by using the SRT protocol; however, dropped frames were observed in some cases under unstable wireless communication environments.

Figure 6 shows examples of the number of packets versus time at the receiver side during transmission. In the figure, "Received" denotes the number of received DATA packets, "Lost" denotes the number of SRT DATA packets detected as presently missing, "Retransmitted" denotes the number of retransmitted packets registered at the receiver side, "Belated" denotes the number of packets that were received but ignored because they arrived too late, and "Dropped" denotes the number of packets dropped by the SRT receiver and, as a result, not delivered to the upstream application DATA packets.

When CGH videos were streamed over wireless LAN and local 5G network, some packets were lost, retransmitted, belated, or dropped. In such cases, the throughput is unstable, so high throughput is temporarily required. If the communication bandwidth is sufficient, the streaming is only minimally affected; but when the link speed fluctuates greatly, such as during wireless communications, it may be necessary to optimize the streaming.

In [13], [14], the image quality of light waves and reconstructed objects from CGHs with transmission errors were evaluated. These studies indicated that even if transmission errors occur to some extent, they do not affect the degradation of image quality of the reconstructed objects. Therefore, it is necessary to optimize the streaming of CGH video in the future, taking into account the tolerance for transmission errors.

V. Conclusion

We have proposed the streaming of uncompressed or lossless compressed CGH video to SLM in electro-holography under wired/wireless (Wi-Fi, 5G local) networks. CGH was generated by using computer holography, and CGH video synthesizing the generated CGHs was displayed on SLM. The CGH video was streamed to the SLM via wired/wireless LAN and local 5G networks. We compared the transmission performances of uncompressed and lossless compressed CGH video in the networks. When communication conditions were favorable, there was no significant difference in throughput between the wired and wireless environments, and no data loss resulting from compression and transmission was observed. We verified that the transmission of uncompressed/lossless compressed CGH video was possible in all environments. In the future, we aim to investigate the transmission of 4K CGH video and transmission via a public 5G network.

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