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INVITED PAPER Special Section on Electronic Displays

Development of Network Streaming System for CGH Video in Wired/Wireless Communications

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SUMMARY Holography is a three-dimensional (3D) technology that enables natural stereoscopic viewing with deep depth and expected for practical use in the future. Based on the recording process of holography, the electronic data generated through numerical simulation in a computer are called computer-generated holograms (CGHs). Displaying the generated CGH on a spatial light modulator and reconstructing a 3D object by illuminating it with light is called electro-holography. One of the issues in the development of 3DTV using electro-holography is the compression and transmission of a CGH. Because of the data loss caused by compression in a CGH, the quality of the reconstructed image may be affected, unlike normal 2D images. In wireless transmission of a CGH, not only data loss due to compression but also retransmissions and drops of data due to unstable network environments occur. These may degrade the quality of the reconstructed image, cause frame drops, and decrease the frame rate. In this paper, we developed a system for streaming CGH videos for reconstructing 3D objects using electro-holography. CGH videos were generated by merging multiple CGHs into a timeline, and the uncompressed or lossless compressed CGH videos were streamed via a network such as wired and wireless local area networks, a local 5G network, and mobile network. The performance of the network and quality of the CGH videos and reconstructed images were evaluated. Optically reconstructed images were obtained from the uncompressed CGH videos streamed via the networks. It was also confirmed that the required bit rate could be reduced without degrading the quality of the reconstructed image by using lossless compression. In some cases of wireless transmission, even when packet loss or retransmission occurs, there was no degradation in the reconstructed image quality.
key words: *holographic display, computer-generated hologram, electro-holography, wired/wireless transmission, performance evaluation*

1. Introduction

Three-dimensional (3D) display technologies have been researched and developed in various fields, and 3D displays that satisfy the physiological functions of the human eye are desired so that humans can view objects the same as they do in real space. These functions enable humans to view 3D objects naturally without fatigue or discomfort, even for long periods [1]. Therefore, practical 3D displays and technologies, such as holography, that have similar functions to those of the human eye are necessary.

Holography [2]–[4] is a 3D display technology that can record optical information from an object into a hologram by using the interference and diffraction of light waves. A hologram refers to the fringe pattern recorded as the interference of light waves from the object and a light source, which is called reference light. If the hologram is irradiated with the same light source, which is called reconstruction light, the hologram diffracts the illuminating light waves, and the light waves from the recorded object are faithfully reconstructed. Therefore, holography is known to be the ultimate 3D imaging technology that enables natural and deep depth perception due to the light waves of the recorded object reaching the viewer's eye, that is, viewers can see the recorded object.

Computer holography [5], [6] is based on the optical recording process in holography for generating interference fringes through computer numerical simulation. Holograms generated with computer holography are called computer-generated holograms (CGHs). The advantage of CGHs is that they do not require an optical system for recording and can record virtual objects created with a computer. However, it is crucial to reduce the amount of computation and increase the computation speed to enable the physical phenomena of light waves such as reflection, propagation, and diffraction.

Electro-holography [6]–[10] is used to reconstruct a 3D object from CGHs by outputting CGHs on a special display such as a spatial light modulator (SLM). Electro-holography makes it possible to display 3D moving objects by switching the displayed electronic CGHs; however, there are many challenges to practical application such as a narrow viewing zone and viewing area.

Multimedia data are easily transmitted and/or received via the Internet by using wired and/or wireless communication systems. It has become common for users to watch 2D videos, whether they are shot in the real world or created using computer graphics, by downloading or streaming. For distributors, the data rate and 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 and decoding methods are necessary [11].

When distributing 3D videos, the data rate and delay of the communication environment must also be considered. A streaming system should ideally enable users to view 3D videos using devices with holographic displays, just as they can view and distribute 2D videos via various networks [12]. To create such a system, it is necessary to consider how to compute, compress, send, and receive CGHs and reconstruct objects from the CGHs.

In this paper, we focused on transmitting CGHs and

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developed a system for streaming and reconstructing CGH videos. If a CGH video is compressed using common compression methods, the quality of the reconstructed image may be affected by the loss of CGHs due to compression. Therefore, there is a need for compression and transmission techniques specialized for holograms. With our system, 3D objects are optically reconstructed while streaming uncompressed or lossless compressed CGH video, which is possible with the recent development of transmission techniques. We also compared the transmission performance and image quality of the reconstructed images in uncompressed or lossless compressed CGH videos streamed via wired and wireless connections.

2. Streaming System for CGHs

2.1 Related Work

Studies have reported the transmission of CGHs of real objects using digital holography via the Internet [13] and the streaming of CGHs via local area networks (LANs) [14]. However, compression and evaluation methods of the image quality of CGHs had not been established, and the relationship between the transmission method for CGHs depending on the communication environment and degradation of image quality caused by transmission errors needs to be evaluated.

There have also been studies on the compression and transmission of CGHs [15], [16]. One involved an experiment on on-demand transmission of CGH videos using network-streaming technology [15]. In that study, noise and degradation in the image quality of reconstructed images were observed depending on the encoding rate of the videos. The cause is assumed to be that the CGH data were compressed using the MPEG-4 algorithm, which is a lossy compression method. Takao et al. [16] transmitted CGH videos compressed with H.264 encoding using Bluetooth and wireless LAN. They confirmed that not only the image quality degraded with the transmission speed but also the frame rate of the videos dropped, so the reconstructed images were defective due to the unstable wireless transmission environment. The results from these studies indicate that if CGH data compressed with lossy compression are wirelessly transmitted, not only defective CGH data due to compression but also data loss due to transmission are assumed to occur. These data losses could reduce frame rates and degrade image quality in the reconstructed images. Xu et al. proposed a system for transmitting CGHs [17] and described the bandwidth requirements for transmitting CGH data to SLMs with various resolution and size specifications. Future research is expected to establish compression and transmission techniques suitable for CGHs.

Since the effect of transmission or compression errors on the image quality of reconstructed objects was not sufficiently evaluated in those previous studies, compression and transmission technologies that do not affect the reconstructed object should be developed. Given the improvements in communication speed due to advancements in network technology, our system streams uncompressed CGH videos via networks with no data degradation.

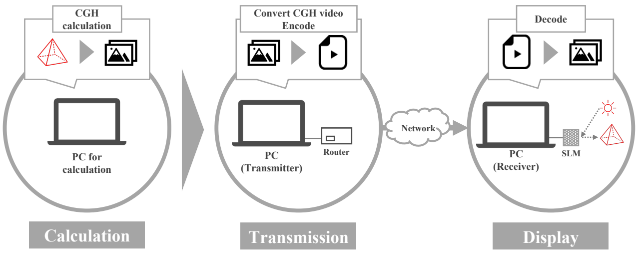


Fig. 1: Overview of developed streaming system for CGH video

2.2 Overview of Developed Streaming System

Our system streams CGH video through a network with no compression or lossless compression to avoid losing information due to the compression of CGHs. Figure 1 shows an overview of the system. The system consists of PCs for generating and displaying CGH videos that are connected to wired/wireless networks with network components.

2.2.1 Generation of CGH video

A CGH is calculated on the basis of point clouds [6]. The point-cloud approach expresses a 3D object as an aggregation of point-light sources. Assuming that the 3D coordinate system comprising the object to be displayed is (x, y, z) and the 2D 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

$$u(x_h, y_h) = \sum_{n=1}^{N} \frac{A_n}{r_n} \exp\left(ikr_n\right) \quad , \tag{1}$$

where N is the number of point-light sources constituting the object, A_n is the amplitude of the nth point-light sources, i is an imaginary unit, and $k = 2\pi/\lambda$ is the wavenumber. The notation r_n denotes the distance between the nth point-light source and coordinates (x_h, y_h) on the hologram and is obtained as

$$r_n = \sqrt{(x_h - x_n)^2 + (y_h - y_n)^2 + {z_n}^2} \quad . \tag{2}$$

By calculating the above equations, the light waves propagating from the object, called object light, are calculated. A CGH can be generated by calculating the interference with the object light and reference light. To create a video, the above equations are calculated for the required number of frames of the video, and each frame is combined in accordance with a timeline.

2.2.2 Compression and Transmission of CGH Video

When a CGH video is compressed with lossless codecs, the

Table 1: Parameters for calculating CGHs

	4K	full HD
Number of pixels	3840×2160	1920×1080
Pixel pitches	3.74×3.74 µm	8.0×8.0 µm
Size	14.4×8.1 mm	15.3×8.6 mm
Color mode	8-bit greyscale	
Wavelength	632 nm	
Number of frames	360 frames	

video is encoded in the same way as in general 2D video broadcasting. In the encoding process for compression, an uncompressed or lossless codec is used to avoid losing data caused by compressing CGH videos. We used the FFmpeg software [18], which can encode and decode data of video and audio data, to transmit uncompressed or lossless compressed CGH videos to a PC for displaying CGH data using the Secure Reliable Transport (SRT) protocol [19].

2.2.3 Display of CGH Video

The CGH video transmitted in the above step was received using the SRT protocol of the FFmpeg software in the PC. The received CGH video was decoded and displayed on the connected SLM, and a 3D moving object was optically reconstructed by illuminating the SLM with light-emitting diodes (LEDs). A human could observe the reconstructed moving object with the streamed CGH video. Note that the displaying of CGH video on an SLM is designed to capture the received CGH video. Therefore, we evaluated the loss of information due to transmission and compression by comparing the CGH videos before and after transmission.

3. Experimental Setup for Streaming CGH Video

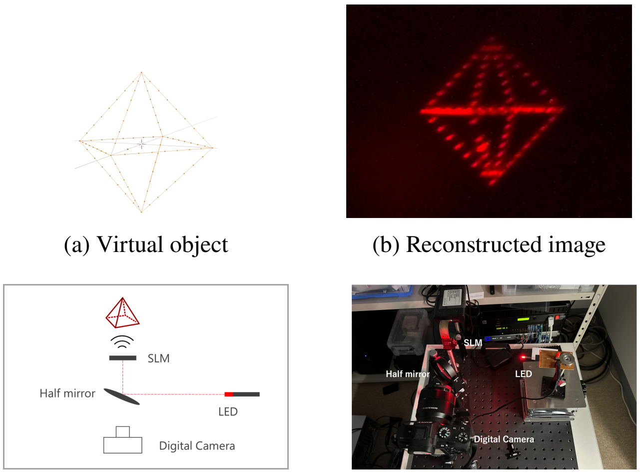
To evaluate our system, the transmission performance and image quality of the reconstructed images were compared with CGH videos streamed via networks. The following sections describe the experiments in detail.

The experimental setup shown in Fig. 1 consisted of two PCs for transmitting CGH videos and displaying received CGH videos on the SLM via networks and network components. Tables 1 and 2 list the parameters for calculating CGH and SLM specifications, respectively. CGH videos with a resolution of 4K or full HD, greyscale color mode, and 1 to 30 fps were prepared. Prior to the streaming experiment, the maximum throughputs were measured in each network environment. The throughputs in the wired and wireless LANs were about 6.8 and 2.9 Gbps, respectively, and that in the local 5G network was about 400 Mbps. The throughputs in the mobile network were under 100 Mbps. The procedures for streaming the CGH videos is as follows.

1. The 360 CGHs of the regular octahedron consisting of 93 points shown in Fig 2(a), which were rotated 1 degree for each image, were calculated with the parameters listed in Table 1.
2. The generated CGHs were converted to videos with no compression or lossless compression. CGH videos of 1

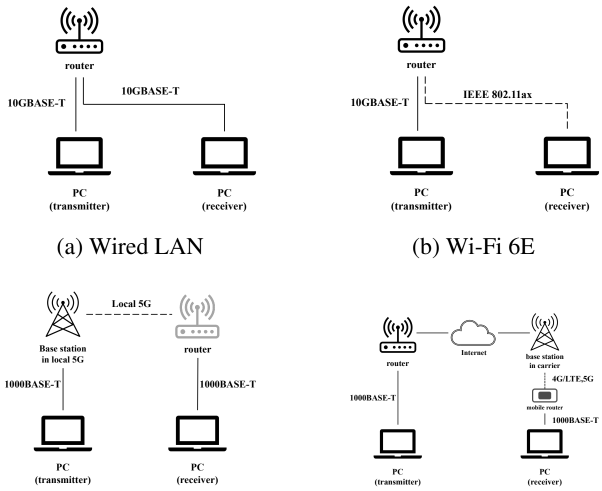
Table 2: Specifications of SLMs

	4K	full HD
Manufacturer	HOLOEYE Photonics AG	
Part no.	GAEA-2	HED 6001
Display Type	Reflective LCOS (Phase)	Reflective LCOS (Amplitude)
Number of pixels	3840×2160	1920×1080
Pixel pitches	3.74×3.74 µm	8.0×8.0 µm
Size	14.4×8.1 mm	15.3×8.6 mm
Color mode	8-bit greyscale	
Refresh rate	60 Hz	



(a) Virtual object (b) Reconstructed image
(c) Overview (d) Photo

Fig. 2: Optical system for reconstruction



(a) Wired LAN (b) Wi-Fi 6E
(c) Local 5G (d) Mobile

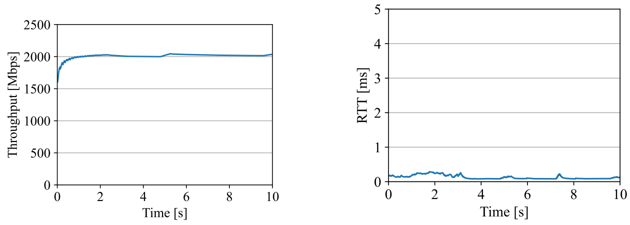
Fig. 3: Network connections in each network

to 30 fps were created by merging the 360 CGHs generated in the above step into a timeline and streamed from the PC for the transmitter to the PC for the receiver via a network by using the SRT protocol. The CGH videos were streamed in wired and wireless LANs, a local 5G network [20], and mobile network. In the LAN environments shown in Figs. 3(a) and (b), the PC for the transmitter has a wired connection (10GBASE-T) to a router. The PC for the receiver has a wired (10GBASE-T) or wireless (Wi-Fi 6E: IEEE 802.11ax [21]) connection to the router. In the local 5G environment shown in Fig. 3(c), the PC for the transmitter is connected directly with a wired connection (1000BASE-T) under the base station of the local 5G, and 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 via wired connection (1000BASE-T). In the mobile network shown in Fig. 3(d), the PC for the receiver is connected to a mobile router via wired connection (1000BASE-T). Wireless communication is carried out between the router and mobile router via the Internet through a base station of 5G or 4G/LTE constructed in the public carrier network. In each network environment, CGH videos uncompressed or compressed with an arbitrary codec were streamed. No compression (rawvideo) or lossless codecs, such as ffv1, utvideo, and H.265 [22] with lossless mode, were used as codecs for compression.

3. The received CGH video was streamed and displayed on the SLM, and optical reconstruction was carried out using an LED. An example of a reconstructed object captured with a digital camera is shown in Fig. 2(b), and an overview and photo of the optical system for reconstruction are shown in Figs. 2(c) and (d). Note that the received CGH video was also captured, and the peak signal-to-noise ratio (PSNR) was obtained to determine whether data had been lost due to compression and/or transmission. The statistics for transmission with the SRT protocol were also recorded for analysis.

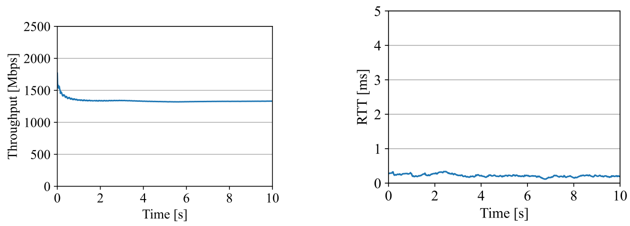
Note that CGH-video transmission, “uncompression” denotes no compression of data of CGH video, and “lossless compression” denotes data compression that allows the original data to be perfectly decoded from the compressed data. The data size of CGH videos with lossless compression will be smaller than that of uncompressed CGH videos, but the compression ratio will be lower than that of lossy compression. “Lossy compression” denotes data compression that uses inexact approximations and partial-data discarding to represent the content, and the data size will be reduced in accordance with the required data quality.

We describe the configurations of each network. Since uncompressed CGH video with 4K resolution and 30 fps is expected to have a bit rate of 1 Gbps or higher, a link speed of 10 Gbps is used for wired connection. Wi-Fi 6E is used for wireless connections, and a link speed over 1 Gbps is expected. In local 5G and mobile networks, the throughput is expected to be less than 1 Gbps. For transmitting CGH videos for future mobile communication and the performance verification for the current mobile communication, we developed a system for each network.



(a) Throughput (b) RTT

Fig. 4: Network performance with no compression via wired connection



(a) Throughput (b) RTT

Fig. 5: Network performance with lossless compression (H.265) via wired connection

4. Experimental Results

4.1 Wired Connection

To avoid the degradation of CGH video due to compression, uncompressed a CGH video was streamed via a wired LAN. The required bit rate of the CGH video without compression, which was in 4K resolution, greyscale color mode, and 30 fps, is about

$$3840 \times 2160[\text{pixels}] \times 8[\text{bit}] \times 30[\text{fps}] \approx 1991[\text{Mbps}] \ .$$

Figure 4 shows the throughput in (a) and round-trip time (RTT) in (b) for instantaneous time. The average throughput and RTT were about 2000 Mbps and 0.1 ms, respectively. Since headers and other data for transmission were added in addition to the above bit rates, the throughput of rawvideo was approximately as expected. There was no degradation of the CGH video by comparing the PSNRs between the CGH videos before and after transmission.

It was confirmed that uncompressed CGH video was streamed and an image was optically reconstructed from the streamed CGH video via wired connection without any data loss of the CGH video.

As mentioned above, uncompressed CGH video was streamed via network, and an image was optically reconstructed from the video. By using lossless compression,

Table 3: Network performance with uncompression or lossless compression via wired connection

Codec	Throughput [Mbps]	RTT [ms]
rawvideo	2013	0.12
H.265 (lossless)	1339	0.21
ffv1	1120	0.24
utvideo	1380	0.32

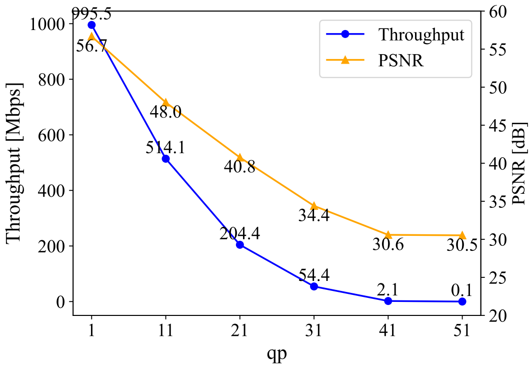


Fig. 6: Throughput and PSNR with lossy compression (H.265)

throughput will decrease without any data loss.

Figure 5 shows the throughput in (a) and RTT in (b) for instantaneous time with H.265 codec of lossless mode, respectively. Table 3 shows the results of the average throughput and RTT when the uncompressed or lossless compressed CGH videos, which were in 4K resolution, greyscale color mode, and 30 fps, were streamed via wired connection. There were no significant differences in distributions between other codecs. In the transmission using lossless compression (H.265, ffv1, utvideo), we confirmed that the compression ratio was not as high, but the throughput was lower than that of the uncompressed transmission. That is, throughput for the CGH video streaming decreased using lossless compression in wired transmissions.

In 2D video streaming, lossy compressed multimedia data are generally streamed with high efficiency via networks due to the compression ratio . The throughput and PSNR are shown in Fig. 6 for CGH videos streaming with lossy compression using H.265. In H.265, the quality of the compressed videos can be controlled by changing the parameter qp. As shown in the figure, lossy compression reduced the amount of data; however, the PSNR decreased, and the image quality degraded. Figure 7 shows the reconstructed images when the image quality was changed. This degraded image quality of CGHs may affect the image quality of the reconstructed image. Therefore, uncompression or lossless compression is considered effective for compressing and transmitting CGHs without any loss of quality of the reconstructed image.

4.2 Wireless Connection

In wireless transmission, when communication conditions were favorable, the results were almost the same for both no compression and lossless compression as for the transmission with wired connection. The evaluation of the image quality of CGH video after transmission in terms of the PSNR also showed that the data before and after transmission were identical in all codecs. This indicates that, in transmission with uncompressed or lossless compressed codec, no data loss occurs due to compression or transmission when communication conditions are favorable. In wireless communications, the RTT of wireless communication may be larger than that of wired communication and communication quality may not be stable. Therefore, data loss due to wireless transmission may occur in accordance with the communication quality.

In the following sections, we describe the results of transmission via wireless communication such as Wi-Fi 6E, a local 5G network, and mobile network.

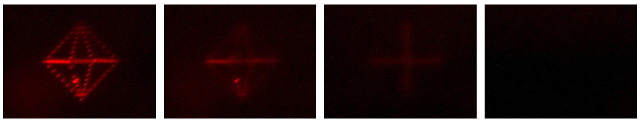

(a) qp = 21 (b) qp = 31 (c) qp = 41 (d) qp = 51

Fig. 7: Reconstructed images with lossy compression (H.265)

4.2.1 Wi-Fi 6E

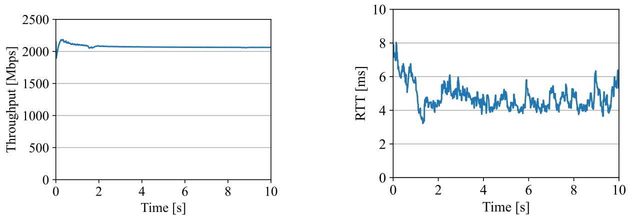
In Wi-Fi 6E, the wireless link speed between the router and PC for the receiver shown in Fig. 3(b) was about 4800 Mbps. The same CGH video with 4K resolution as in the wired LAN was streamed via Wi-Fi 6E.

Figure 8 shows the throughput in (a) and RTT in (b) for instantaneous time. The throughput and RTT were approximately 2100 Mbps and 4~8 ms. There were no significant differences in throughput between Wi-Fi 6E and wired LAN with uncompressed transmission. The results indicate that the RTT for Wi-Fi 6E was longer than that for wired connections shown in Fig. 4, and the RTT was not stable. The RTT is used to calculate or estimate the throughput per second in the SRT protocol. If the RTT is not stable, the throughput temporarily decreases, which may cause retransmissions or transmission errors.

4.2.2 Local 5G and Mobile Networks

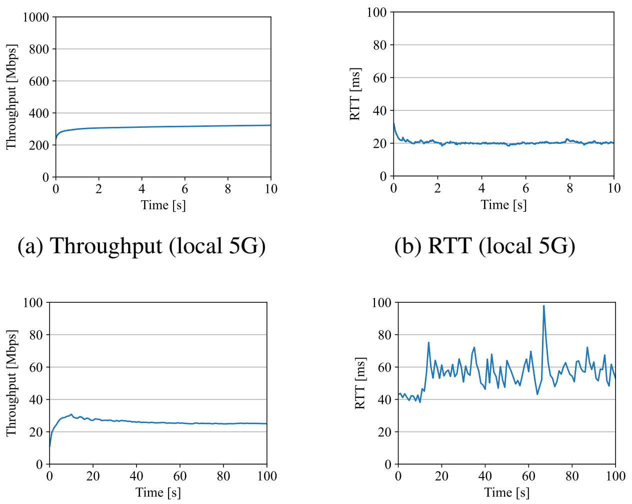
A local 5G network is a self-employed 5G service that enables local governments and companies to deploy a 5G system as spot services [20], [23], [24]. By using the local 5G network operated by our university, we evaluated the network performance for streaming a CGH video with occupying 5G wireless resources [25]. To verify the feasibility of streaming CGH video in the current public 5G or 4G/LTE mobile network, we also carried out streaming a CGH video via a mobile network.

The wireless link speed between the base station and



(a) Throughput (b) RTT

Fig. 8: Network performance with no compression via Wi-Fi 6E



(a) Throughput (local 5G) (b) RTT (local 5G)

(c) Throughput (mobile) (d) RTT (mobile)

Fig. 9: Network performance with no compression via local 5G and mobile networks

local 5G gateway shown in Fig. 3(c) was about 400 Mbps, and the CGH video with 4K resolution and 5 fps was streamed. The wireless link speed between the base station in the carrier and mobile router shown in Fig. 3(d) was under 100 Mbps, and the CGH video with full HD resolution and 1 fps was streamed.

Table 4 lists the results of the measured average throughput when the CGH videos, which were in 4K and full HD resolution, greyscale color mode, and 5, 1, and 2 fps, were streamed via the local 5G and mobile networks. Because it was expected that the throughput in the mobile network would be smaller than the wired LAN, Wi-Fi 6E, and local 5G network, CGH videos with 1 or 2 fps was streamed in the mobile network. The required bit rates of the CGH videos without compression were about

$$3840 \times 2160[\text{pixels}] \times 8[\text{bit}] \times 5[\text{fps}] \approx 334[\text{Mbps}] \ ,$$
$$1920 \times 1080[\text{pixels}] \times 8[\text{bit}] \times 1[\text{fps}] \approx 16.6[\text{Mbps}] \ ,$$
$$1920 \times 1080[\text{pixels}] \times 8[\text{bit}] \times 2[\text{fps}] \approx 33.2[\text{Mbps}] \ .$$

Figure 9 shows the throughput in (a) and RTT in (b) via the local 5G network and throughput in (c) and RTT in (d) via a mobile network for instantaneous time. The

Table 4: Network performance with no compression via wireless connection

Network	Video	Throughput [Mbps]	RTT [ms]
Wi-Fi 6E	4K, 30 fps	2073	4.8
Local 5G	4K, 5 fps	334	20.1
Mobile	full HD, 1 fps	26	57.1
Mobile	full HD, 2 fps	54	56.2

throughput was approximately 26 Mbps with uncompressed transmission (rawvideo) via the mobile network, while it decreased to approximately 11 Mbps with lossless compression (H.265). The RTT was 40~80 ms for the mobile network, indicating that the RTT for the mobile network was also not stable.

The measured throughput during uncompressed transmission was approximately 26 Mbps, which is slightly higher than the theoretical value. This is because the RTT was large (approximately 60 ms) and transmission environment was unstable, resulting in a temporary decrease in throughput and data retransmissions. However, in accordance with the PSNR using the CGH videos before and after the transmission, no data loss occurred due to the transmission. Therefore, no data drop is considered to have occurred, although retransmission control due to a temporary drop in throughput did occur. When the frame rate was increased from 2 to 3 fps, both uncompressed and lossless transmission was possible without data loss at 2 fps, but at 3 fps, data drop occurred during uncompressed transmission. This confirmed that uncompressed streaming transmission is possible at around 2 fps with current mobile communications. With the deployment of 5G technology, CGH video transmission with even higher frame rates will be possible, depending on the communication environment.

5. Discussion

As described in the above section, CGH videos were transmitted without any data loss due to compression and transmission in each network as comparing the PSNR of the videos before and after transmission. Although the resolution and fps of the CGH videos decreased in accordance with the throughput in each network shown in Tables 3 and 4, the videos could be transmitted and optically reconstructed images could be obtained. In future mobile communications, when higher speeds can be achieved, CGH videos with higher resolution and frame rates are expected to be transmitted.

There are cases in which the network becomes crowded due to increased packet loss and RTT with wireless transmission. Network traffic causes frame drops and delays, causing image disturbances and reduced frame rates. As mentioned previously, uncompressed and lossless compressed CGH videos with high bit rates were streamed via networks by using the SRT protocol; however, dropped frames were observed in some cases under unstable wireless communication environments. The SRT protocol is an open-source video-transport protocol to enable the delivery of high quality and low latency video via the Internet.

Figure 10 shows examples of the cumulative number of packets versus time at the receiver side during transmission. “Received” denotes the number of received DATA packets, “Lost” denotes the number of SRT DATA packets detected as currently 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, thus not delivered to the upstream application DATA packets.

When CGH videos were streamed with wireless communications, it was confirmed that 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 previous studies [26]–[28], 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 degrade the image quality of the reconstructed objects. Therefore, it is necessary to optimize the streaming of CGH video, considering the tolerance for transmission errors.

For unstable RTTs or huge fluctuations in the transmission rate, such as in wireless transmission, it is therefore desirable to consider optimizing the transmission protocol [29], [30].

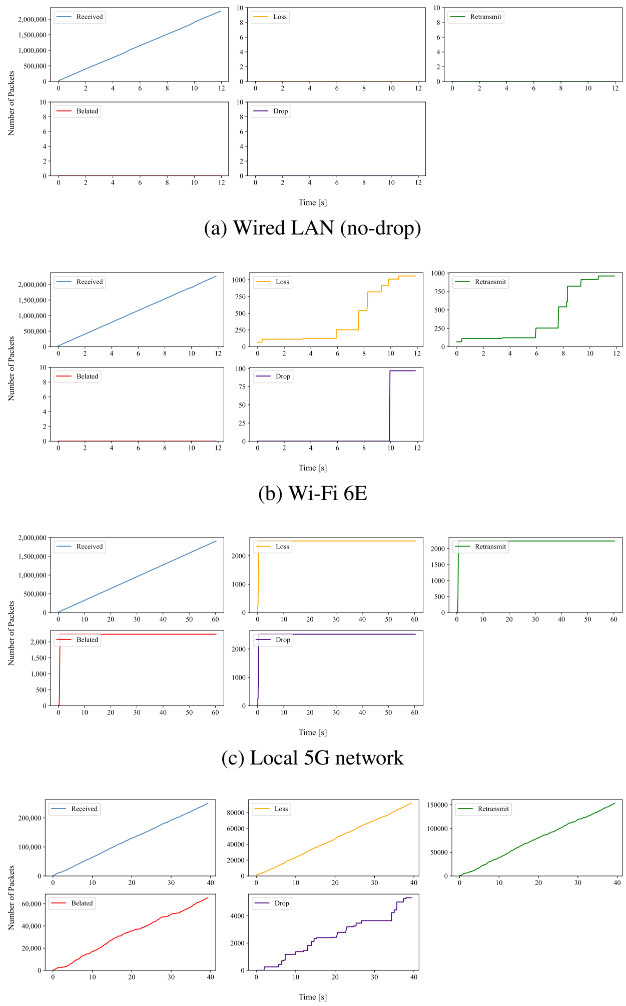
For practical use, a lossy compression method suitable for CGH transmission will be necessary, as in the case of 2D image transmission. The data size of full-color CGH videos are expected to be three times that of monochrome CGH videos. In uncompressed or lossless compression, the frame rate would decrease to transmit CGH videos. Therefore, lossy compression suitable for CGH videos, which can greatly reduce the data size, is necessary.

Another possible method is to transmit data of a 3D model or object light instead of transmitting data of CGHs. These transmission methods require the receiver to compute the CGHs, which will increase the computational load on the receiver. However, the possibility of flexible optical systems and reduced data size of transmission will make it necessary to consider these methods.

6. Conclusion

In this paper, we developed a system for streaming and reconstructing CGH videos with uncompression or lossless compression. CGH videos were streamed via a wired or wireless connection with uncompression or lossless compression, and 3D images were optically reconstructed by outputting the streamed CGH videos on an SLM. In the experiments, uncompressed or compressed CGH videos were streamed via networks, and the network performances were measured. As a result, the reconstructed images without any degradation due to compression and transmission were obtained by streaming uncompressed and lossless compressed CGH videos, although the frame rate and resolution had to be reduced depending on the throughput on each network. There was also no significant difference in throughput when streaming CGH videos via wired and wireless connections. We examined the degradation in CGH-video quality due to compression and transmission of the videos. Thus, we objectively evaluated the image-quality degradation of CGH videos due to compression and transmission in terms of the PSNR. The CGH videos after compression and transmission were completely restored to before transmission without degradation in image quality due to compression and transmission.

The outlook for future research is to improve the transmission protocol to ensure stable transmission via wireless connections and transmit the data to multiple streams at the same time.



(a) Wired LAN (no-drop)

(b) Wi-Fi 6E

(c) Local 5G network

(d) Mobile network

Fig. 10: Examples of packets for streaming CGH video via each network

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