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SHD Digital Cinema Distribution over a Fast Long-Distance Network

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Abstract

We have developed a prototype super-high-definition (SHD) digital cinema distribution system that can store, transmit, and display eight-million-pixel motion pictures that have the image quality of a 35-mm film movie. The system contains a movie server, a real-time decoder, and an SHD projector. Using a Gigabit Ethernet link and TCP/IP, the server transmits JPEG2000 compressed motion picture data streams to the decoder at transmission speeds as high as 300 Mbps. The received data streams are decompressed by the decoder, and then projected onto a screen via the projector. By using an enlarged TCP window, multiple TCP streams, and a shaping function to control the data transmission quantity, we achieved real-time streaming of SHD movie data at about 300 Mbps between Chicago and Los Angeles, a distance of more than 3000 km. We also improved the decoder performance to show movies with image qualities of 450 Mbps or higher. Since UDP is more suitable than TCP for fast long-distance streaming, we have developed an SHD digital cinema UDP relay system, in which UDP is used for transmission over a fast long-distance network. By using four pairs of server-side-proxy and decoder-side-proxy, 450-Mbps movie data streams could be transmitted.

Keywords : Digital Cinema, Electronic Cinema, Super High Definition Image, Image Transmission, Contents Distribution

I. Introduction

Advances in computer and telecommunication technology and the growth of broadband networks have stimulated the development of applications that use high-quality image communications. In particular, precision color imaging systems are required for digital images to have a quality level demanded by professional users in fields as diverse as printing, medicine, and image archiving. The images produced by such systems, known as super high definition (SHD) images, are defined as having a resolution of at least 2k scanning lines with 24-bit color separation[1]. SHD images surpass the quality of 35-mm film in terms of spatial resolution and approach the quality of 60-mm film. In our early study on SHD images and their applications[2][3], we developed several types of frame buffer to display still images or short movies (1 to 16 seconds) for CRT monitors with 2048x2048 pixel resolution. SHD movies are very promising in many applications, especially in the commercial movie industry as a replacement for conventional 35-mm cinefilm works.

Digital cinema projection via the 1080/24p format applied to High Definition TV (HDTV) technology is making major commercial inroads. However, its limited resolution have prevented HD digital cinema from reproducing the image quality of film[4]. The spatial resolution of 35-mm (original negative) cinefilm exceeds 1k scanning lines[5]. Therefore, higher quality digital cinema systems are desired[6]. One approach to addressing this problem is to develop SHD systems.

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We have developed an SHD digital cinema system[7][8][9] that uses an eight-million (3840x2048) pixel image format with 30-bit color separation and 24 frame-per-second (fps) motion. The eight-million pixel level is the standard anticipated for the next generation of digital cinema systems. The resolution of the system is about four times that of the 1080/24p format (1920x1080 pixel), so that the picture quality surpasses that of the original 35-mm cinefilm, as shown in Fig. 1. While 35-mm cinefilm has been the standard for commercial movies, it is becoming increasingly costly to make many copies and distribute them to many locations around the world. Furthermore, the copies are inferior in quality compared to the original film. If the SHD digital cinema distribution system can be put to practical use, such cost will be reduced, and people throughout the world will be able to appreciate movies equivalent in quality to the originals.

Since LANs are generally constructed on IP-based networks, and WAN infrastructures are also shifting to IP networks using optical Gigabit Ethernet (GbE) subscriber lines, we use the TCP/IP protocol stack to transmit movie data in the SHD digital cinema system. The total bit rate of an SHD movie data is 5.6 Gbps (3840x2048 pixel, 24 fps, and 30-bit color mode). Therefore, the SHD movie data should be compressed to 10:1 or more in order to transmit them, and a high-speed network of GbE is required for their distribution. We have selected TCP for the connection protocol of the SHD movie data transmission. TCP is adequate for a stable connected transmission and is the best method to share the bandwidth of an IP router based network. Within a cinema complex, it is very easy to use, but for long-distance (large round-trip-time) networks, it is very difficult for its full performance to be exploited. In this paper, we describe how the SHD movie data can be transmitted over fast long-distance networks. In section 2, we briefly introduce our prototype SHD digital cinema distribution system. The results for SHD movie data transmission experiments using TCP and UDP are reviewed in sections 3 and 4, respectively. Section 5 offers conclusions and future study topics.

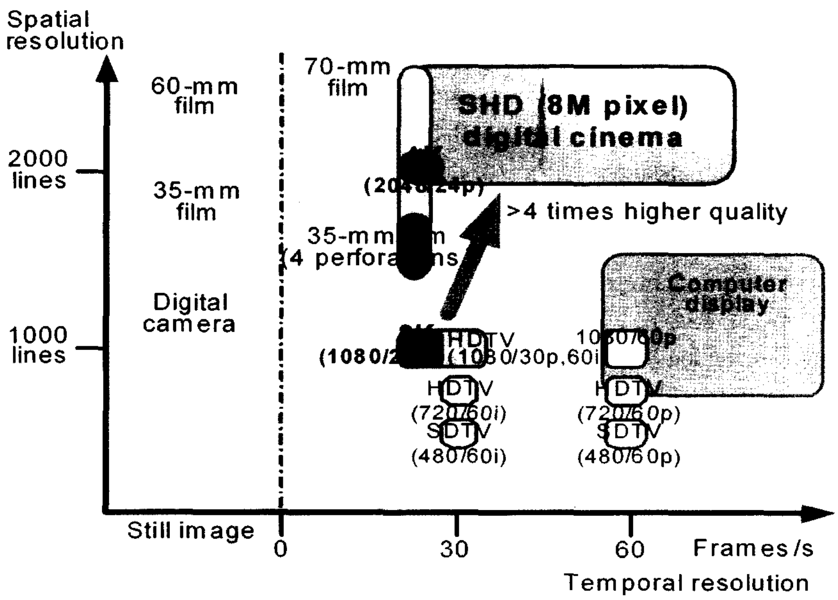

Fig. 1. Resolutions of different motion picture formats

Ⅱ. SHD Digital Cinema Distribution System

We have developed a prototype digital cinema system that can store, transmit, and display SHD digital cinema of eight million (3840x2048) pixel resolution by using the JPEG2000 coding algorithm [10]. The SHD digital cinema distribution system, shown in Fig. 2 and 3, provides the functionality of a

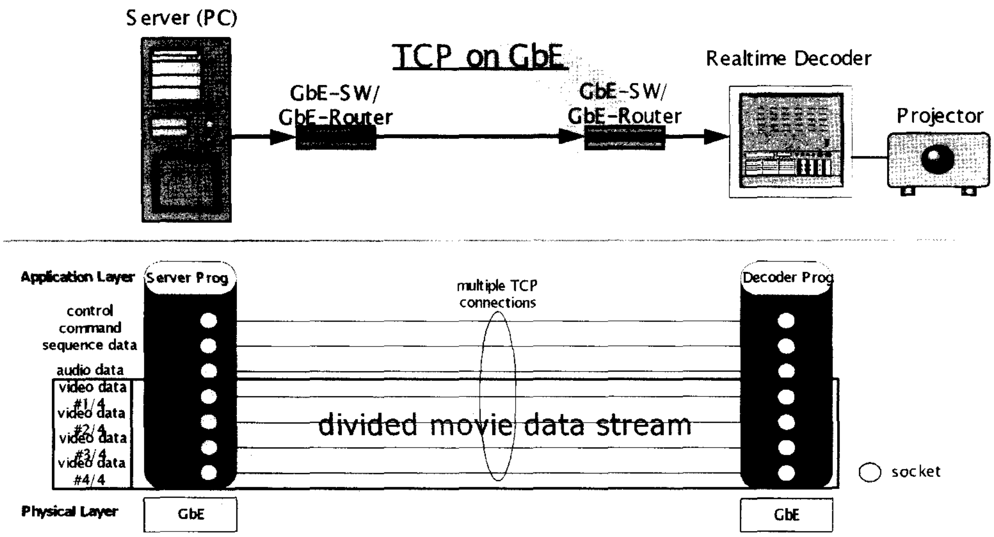

Fig. 2. System configuration of prototype SHD digital cinema distribution system

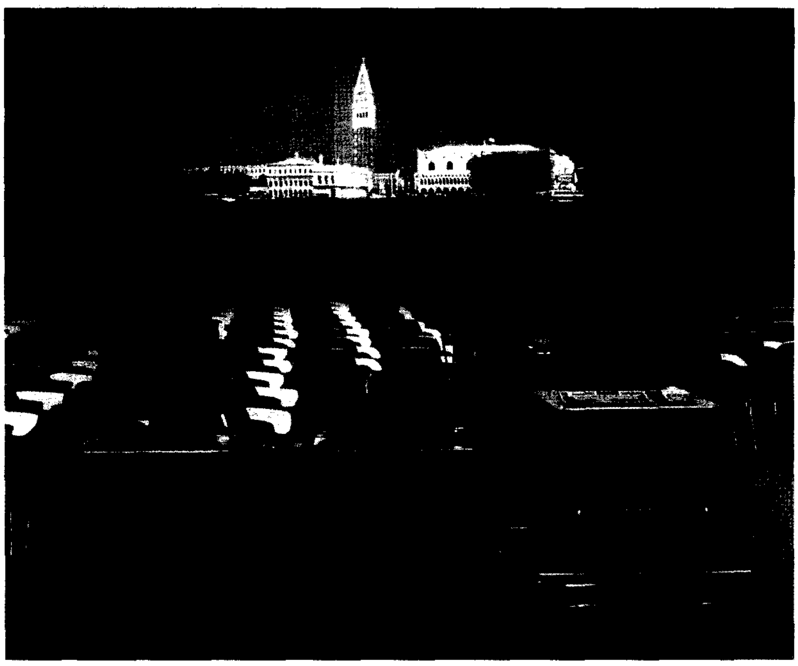

Fig. 3. Photograph of SHD digital cinema distribution system (From the left: server, GbE-switch, and real-time decoder; at the rear: projector)

video-on-demand service for movie contents. The system consists of three main devices: a real-time decoder, an SHD projector, and a movie server. While SHD movie cameras are not commercially available, we assume that the movie data have been compressed and stored in advance. The decoder decompresses the video streams transmitted from the server and outputs the digital video data to the projector.

1. JPEG2000 Real-Time Decoder

A JPEG2000 real-time decoder with an IA-32 based Linux PC has been developed. Four JPEG2000 decoder boards are installed on the 64-bit PCI-bus of the PC. Each board has 30 JPEG2000 processors (ADV-JP2000, Analog Devices Inc.) that process a quarter (1920x1024 pixel) of the whole image area. The decoder uses 120 JPEG2000 processors working in parallel and can perform real-time decompression at 48 frames per second on 3840x2048 pixel 30-bit color images (i.e. 400M pixels per second). The decoder program runs as an application that consists of two threads with dual CPUs (Pentium3-1.23GHz x2) that share the PC's main memory as a large data buffer. The decoder receives the JPEG2000-coded data stream with the GbE network interface from the movie server and decodes it quickly enough for real-time projection. To guard against network congestion, a large memory buffer of 200 to 400MB is used in the decoder's PC part. Therefore, the movies are played back progressively with a delay of only 5-10 seconds. Recently, we improved the decoder's performance in order to be able to show the movies with image qualities of 450 Mbps or higher with the color space RGB 4:4:4[11].

2. SHD D-ILA Projector

The SHD projector uses three units of the prototype eight megapixel (3840x2048 pixel) D-ILA device (a kind of reflective LCD panel) produced by JVC, one each for RGB 10-bit colors. By using a 1600-W Xenon lamp, its effective brightness exceeds 3000 ANSI lumens, which is bright enough to show images on 300-inch (diagonal) screens. We think thatthe horizontal resolution of 3840 pixels will cover almost all image applications and enable us to fully utilize the vertical resolution of 2048 pixels even if the movie has a wide aspect ratio. The 30-bit color depth eliminates pseudo edges that are perceived on the gradation pattern of CG-based images. A refresh rate of 96 Hz was chosen for the projectors. This high refresh rate thoroughly eliminates flicker, and is compatible with 24-fps movies. Each frame of the decoder output is displayed four times in the projector without any interpolation between adjacent frames.

3. Movie Server

The movie server is an IA-32-based Linux PC with dual CPUs (Pentium3-1.23GHz x2) and a high-performance RAID0 (striping mode) disk. The movie films were digitized (3840x2048 pixel, 8 bit or 10 bit RGB per pixel) from 35-mm film with a high-quality pin registered film scanner (ImagerXE, IMAGICA Corp.). The film-digitized movie data or computer generated movie data were (1) divided into 128x128 pixel image tiles/blocks, (2) compressed/encoded by a suitable data-format for the decoder, and (3) formed into one large file bringing 1000 frames together as one unit before being stored in the RAID of the server. A server program that receives a "Start (data transfer)"command reads the movie data from the RAID and writes them periodically to the GbE network interface.

Ⅲ. Digital Cinema TCP Transmission Trial

The fall 2002 Internet2 member meeting was held on Oct 28-29, 2002, at the University of Southern California. During this meeting, we performed an SHD digital cinema streaming experiment linking Chicago

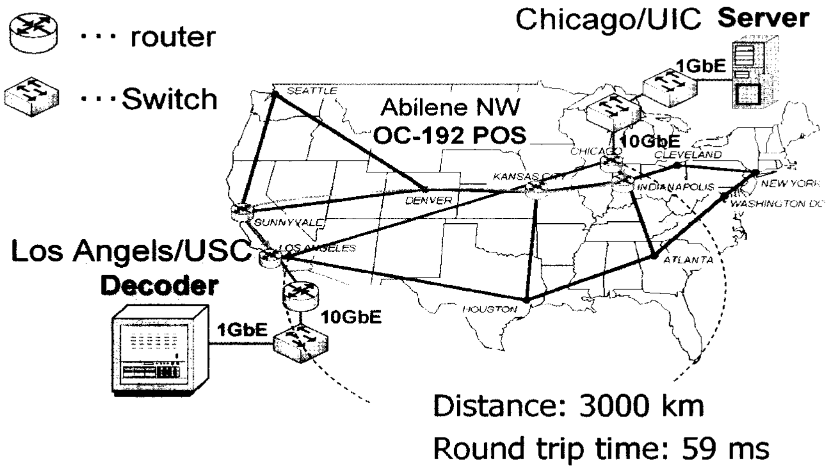

Fig. 4. Network configuration of long-distance TCP transmission experiment on Internet2

and Los Angeles via the Internet2 Abilene network [12]. The objectives were to assess the practicality of SHD digital cinema transmission over the next-generation Internet by using the TCP protocol and to make a comparison of the transmission qualities over a local distribution network.

1. Network Topology for SHD Digital Cinema over I2

Internet2 (I2) is a non-profit consortium led by over 200 universities working in partnership with industry and government to develop and deploy advanced IP network applications and technologies. I2 has a very high-performance backbone network, called "Abilene," that was developed by the University Corporation for Advanced Internet Development (UCAID).

We set up the server in the Electronic Visualization Laboratory (EVL) at the University of Illinois, Chicago (UIC). The decoder and the projector were installed at the Robert Zemeckis Center of School of Cinema-Television at the University of Southern California (USC), Los Angeles. UIC and USC were connected to the I2 network via two regional networks with Gigabit Ethernet links, i.e., the Metropolitan Research and Education Network (MREN) and California Research and Education Network-2 (CalREN-2). The network configuration is shown in Fig. 4. A bit stream of SHD movie-data, originating from the server at the EVL, was transmitted through the Abilene backbone network and projected at the Robert Zemeckis Center by utilizing a Gigabit Ethernet switch (OptiSwitch 4000 of MRV Communications, formerly Zuma Networks). The distance between the server and the decoder was more than 3000 km. The round trip time (RTT) of the network was measured to be 59 ms.

2. TCP Transmission Experiment

Here, let us review the lessons we learned from the trials of SHD digital cinema distribution over I2. To improve the throughput of the long-distance TCP transmission, we used (1) an enlarged TCP window, 4MB, (2) multiple TCP connections between the server and the decoder, and (3) a shaping control function that depended on the data transmission quantity. We achieved stable SHD digital cinema streaming despite the long delay (RTT: 59 ms) between Chicago and Los Angeles (distance: 3000 km)[13]. In the initial server configuration, where one movie data set of each compressed frame had been sent in one write operation to the GbE network

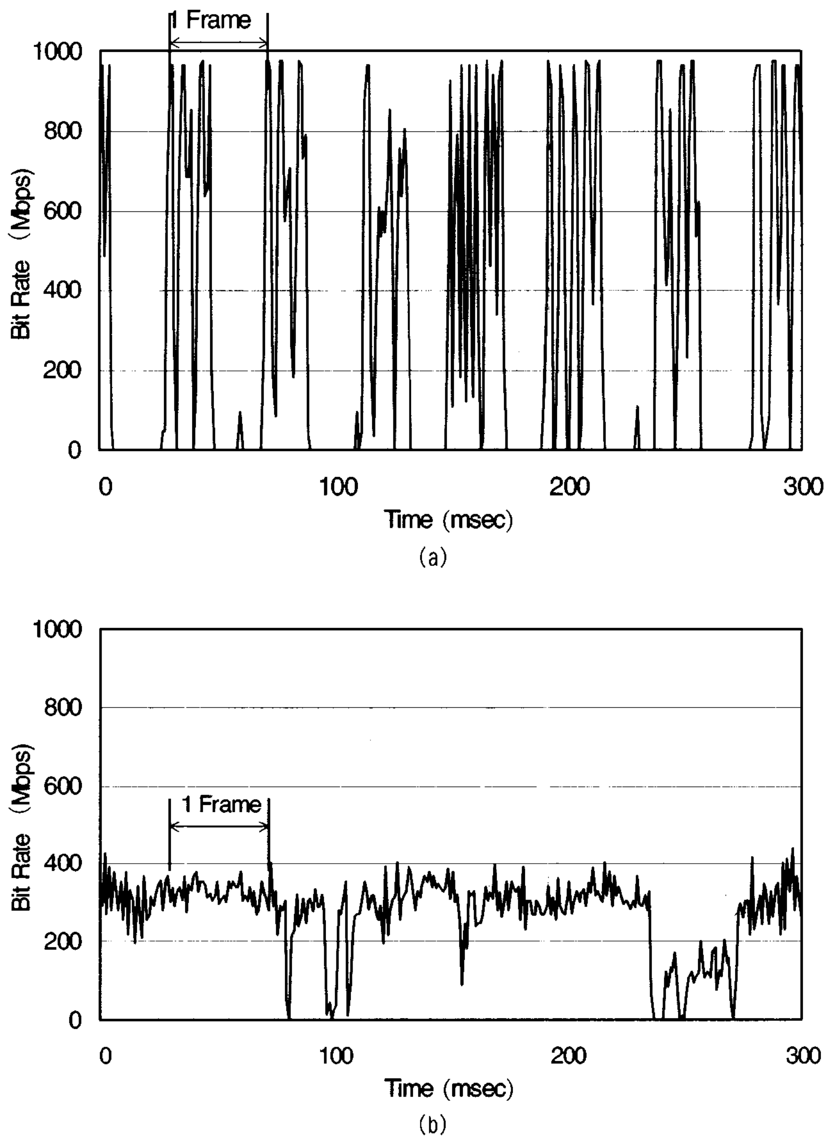

Fig. 5 Example of application traffic monitor outputs (a) without traffic shaping, (b) with traffic shaping

interface, the traffic was very intermittent as shown in Fig. 5 (a). The peak rate was over 800 Mbps, so the network routers were subjected to a heavy load if we used a data rate over 300 Mbps. The current

TCP transmission program reduces the peak rate by shaping/splitting each frame data to small packets while preserving the required average rate. A shaping control function was built into the socket writing process of the server application. The server application program divides the data of each frame into n equal segments and allocated them to each TCP connection with the decoder. Then the program divides each segment into r equal pieces and writes a piece into each TCP socket sequentially r times. A suitable waiting time follows each writing so frame data is sent in precisely 1/24 second. In this case, the waiting time is (1/24)/ nr second. We set nr to be 4096 in the experiment (i.e. when the number of TCP connections is 64, r is 64.). Therefore, the waiting time was 10 second. As a result, the traffic was smoothed as shown in Fig. 5 (b). Sending the packets by multiple TCP connections is particularly effective when the data rate decreases due to a large RTT caused by network delay.

Fig. 6 shows total throughput for different numbers of TCP connections. We transmitted the movie data streams while increasing the number of TCP connections between the server and the decoder. Throughput increased with the number of TCP connections, reaching a ceiling with 80 connections. A preliminary experiment of the UDP path bandwidth test showed that the packet loss didn't occur unless 800 Mbps was exceeded. Although the I2 network bandwidth was sufficient and 300-Mbps streaming proved to be possible with multiple TCP connections and data shaping, 450-Mbps streaming was impossibl (Table 1).

Table 1. Results of SHD digital cinema transmission

		Bit Rate [Mbps]						
		50	100	150	200	250	300	450
Number of TCP Connections	1	◎						
	4	–	◎					
	16	–	–	◎				
	64	–	–	–	◎	–	○	
	80	–	–	–	◎	–	○	
UDP Relay		–	–	–	–	–	–	○

○ transmission was completed without shaping function
◎ transmission was completed with shaping function

Ⅳ. Digital Cinema UDP Transmission Trial

Our previous SHD digital cinema distribution system used a TCP protocol/connection. TCP is not popular in real-time video streaming, because its retransmission scheme based error control is not suitable for real-time video streams and it is incompatible with multicasting.

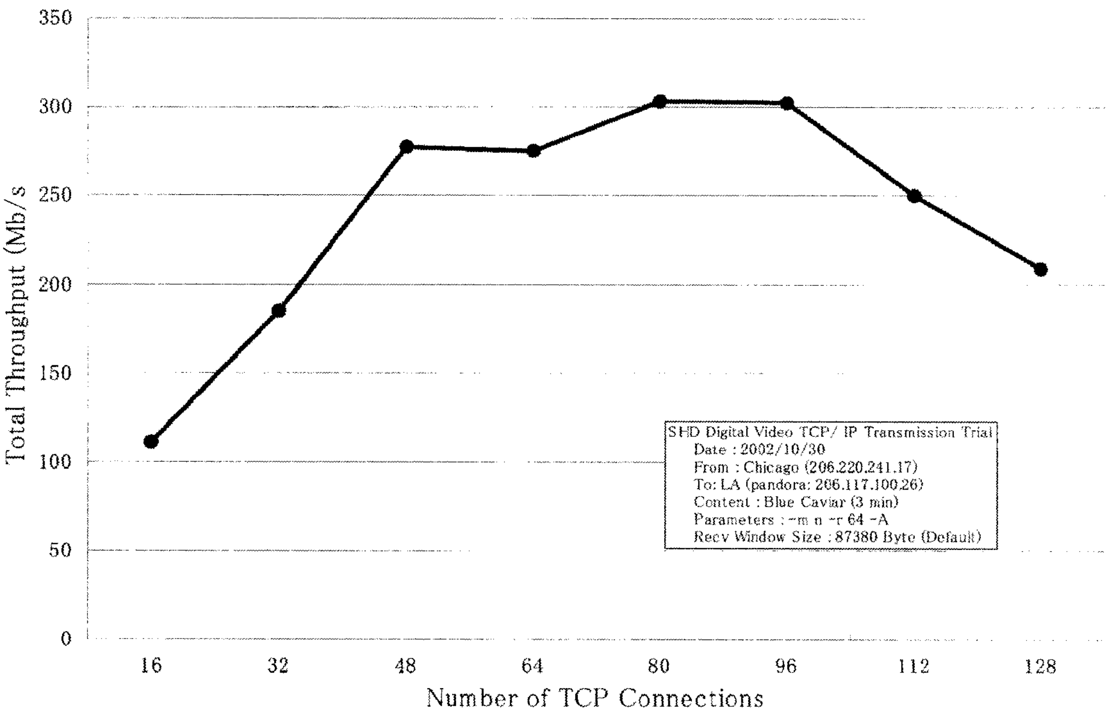

Fig. 6. Total throughput with multiple TCP connections

To transfer real-time video streams, the user datagram protocol (UDP) or the real-time transport protocol (RTP) have been widely used[14]. UDP is more suitable than TCP for fast long-distance streaming. To transmit SHD movie data using the UDP protocol, we developed a prototype UDP relay system for the SHD digital cinema distribution that works as a protocol transformer between TCP and UDP. The UDP relay system comprises four pairs of server-side proxy and decoder-side proxy installed in the network between the server and the decoder (see Fig. 7)[15]. The server-side proxies convert the data

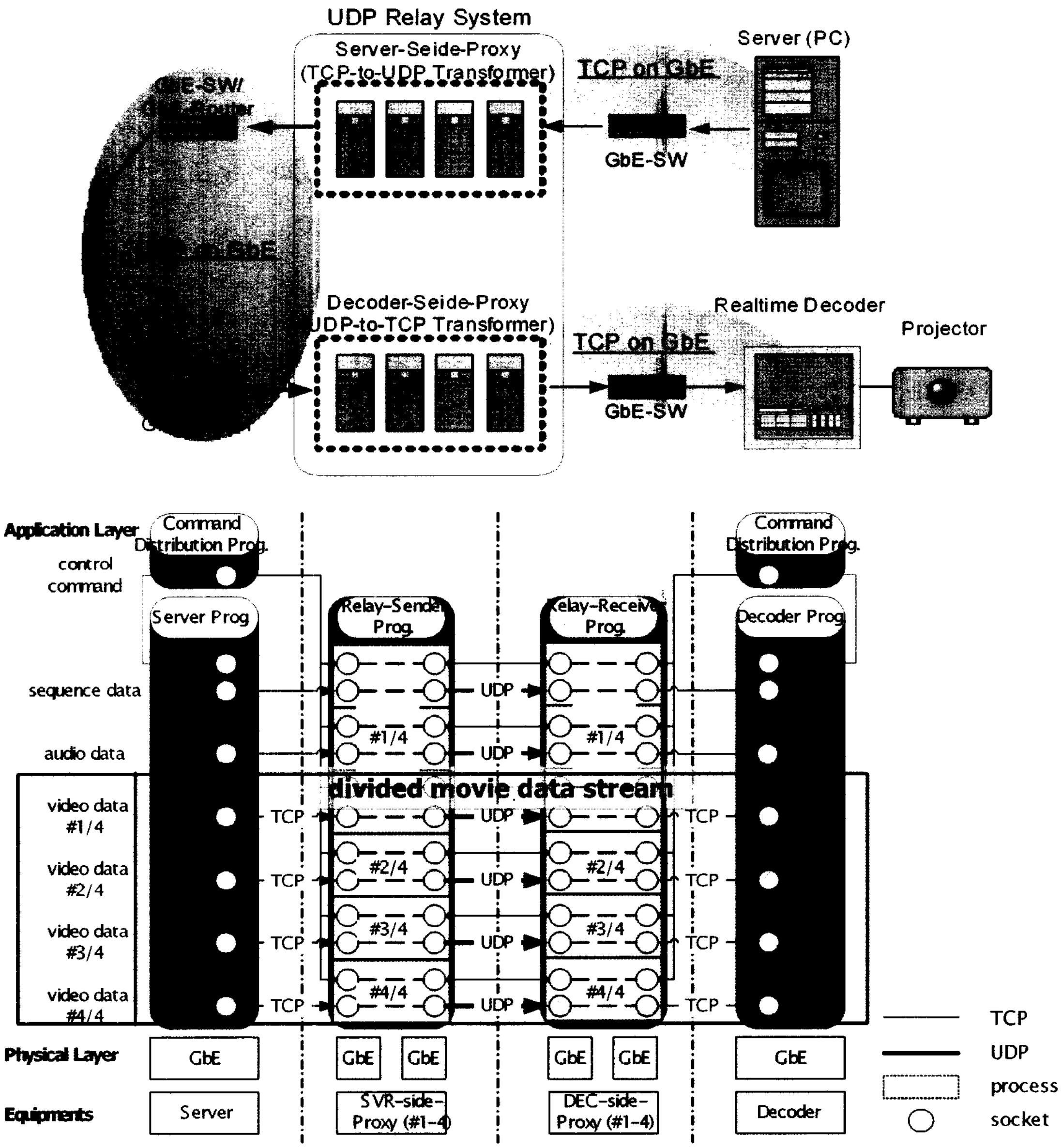

Fig. 7. System configuration of prototype SHD digital cinema UDP relay system

stream from TCP to UDP, and the decoder-side proxies convert it from UDP to TCP. Each proxy unit is an IA-32-based blade PC that consists of Linux running on dual CPUs (Pentium3-1.26GHz x2), 1-GB memory, and dual GbE network interfaces. Since a single proxy unit does not have sufficient processing capacity, movie data streams are divided into four segments and four proxy units do the TCP/UDP and UDP/TCP conversion processing for these segments.

1. SHD Digital Cinema UDP Relay System

The UDP relay system was designed for a contents delivery network (CDN) that provides SHD digital cinema streaming service of movie data at over 450 Mbps on a long-distance/global high-speed network.

In our previous SHD digital cinema distribution system, the server application program divides the movie data stream after making four or more TCP connections between the server and the decoder, and it writes the divided movie data segments into each socket as shown in Fig. 2. It might be possible to transmit movie data streams by a single or multiple UDP connection between the server and the decoder directly. In the performance of a single server and a single decoder, however, it is difficult to be going to build the TCP-like reliability on the UDP transmission additionally later. Because the UDP relay system composed of plural proxy units has an enough performance by their parallel processing, it will be able to implement the TCP-like UDP transport functions.

Fig. 7 (b) shows the connections of the application programs using the UDP relay system. The "Connect" command makes TCP connections in order to distribute the control command among the server, the decoder, and the UDP relay system. In a similar manner as with the previous server and the decoder, the server-program has four TCP connections for transmitting movie data via its four proxies, and the decoder-program also has four TCP connections with its four proxies. Through the command-distribution program of the server and the decoder, play-control commands like "Start (data transfer)" and "Stop (data transfer)" are transmitted/distributed to the server-side and decoder-side proxies with the TCP protocol.

According to the "Start" command, each server-side-proxy receives from the server block data (encoded unit, block size: 128x128 pixel) comprising one quarter of the video data in each movie frame. Each server-side proxy transmits the received block data to its decoder-side proxy with the UDP connection while adding the check sum. If the check sum is confirmed, i.e., the block data have accurately reached the decoder-side proxies, the proxies transmit the block data of the current frame to the decoder with a TCP connection. If they have not reached the proxies accurately (if the checksum is not confirmed), block data that have already been received are transmitted to the decoder to make up for the lost block data.

The audio data are transmitted through the primary server-side/decoder-side proxy in the same manner as with the video data. The audio data are divided into ten sets according to the movie frame segments. If any of divided data is lost, blank data are transmitted in place of the lost data.

The sequence data of the movie, such as stream length of each movie frame and byte length of block data distributed to each relay/proxy unit, are transmitted separately from the main (video and audio) data streams. This information enables the UDP relay system to receive/transmit large and variable- size (~2MB) code-blocks for each frame, and with one read operation, pass them to the GbE-NIF. This results in faster TCP/UDP protocol transformation and higher network throughput than is possible with small and fixed-size code-streams.

2. UDP Transmission Experiment

We made an experimental long-delay (equivalent to long-distance) and GbE network environment similar to the Interent2 network between Chicago and Los Angeles, by using a network emulator (Packet Sphere, Emprix). We set the constant latency at 30 ms so that the round trip time (RTT) was 60 ms.

When a 64-kB socket buffer was used at speeds of 500 Mbps or over, packet loss occurred. We succeeded in transmitting movie data of 300 Mbps on average. It initially appeared that it would be possible to transmit movie data streams of 450 Mbps on average. However, this could not be done without dropping block-data, which caused packet loss.

When the socket buffer was extended to 4MB, packet loss did not occur. Thus, we could confirm with our SHD digital cinema UDP relay system that it is possible to transmit an SHD digital cinema with picture quality of 450 Mbps or higher at the origin in a good network with little packet loss (Table 1). Furthermore, we were able to transmit the movie data of 450 Mbps at the origin in our emulated network environment even after extending the RTT to 1 ms.

V. Conclusions

We have developed a digital cinema distribution system offering SHD image quality (3840×2048pixel) that enables us to transmit digital cinema contents with the quality of the original 35-mm cinefilm by using TCP/IP protocol stack. The system requires high-quality connectivity between the server and the decoder that can provide sustainable bandwidth without significant packet loss or jitter. The trans- mission of SHD movie data from a remote server to a distant decoder without interruption can only be accomplished over a fast long-distance network with sufficiently high capacity and quality of service. We performed a long-distance (i.e. long delay) TCP transmission experiment that involved three measures designed to ensure stable TCP transmission, and with it successfully achieved stable TCP transmission of 300Mbps SHD digital cinema despite the long delay. The three measures were enlargement of the TCP window, multiple TCP connections, and the use of a shaping function to control the data transmission quantity.

We have also developed an SHD digital cinema UDP relay system and confirmed that it can be used to transmit 450-Mbps SHD digital cinema in a long-delay high-speed network. It also enables SHD digital cinema distribution to multiple locations by using a multicast address. The results we obtained give impetus to the idea that SHD digital cinemas can be distributed anywhere at any time. Conducting experiments in high-speed WAN environments, such as the I2 network, is one of the next subjects we intend to address in our future research. One problem is that under a heavy network load, a large quantity of block data of movie frames may be lost since the UDP protocol does not have any error recovery function. Since loss of too many packets may result in severe degradation of output image quality, it will be essential to use an error recovery technique for UDP transmission. If we can add a retransmission function that can also preserve the system's real-time property and/or the forward error correction (FEC) function, we can improve its performance. The implementation of such a function is another subjectfor future research. The next SHD digital cinema UDP relay system we develop should be able to use FEC to preserve image quality in networks that suffer from packet-loss problems.

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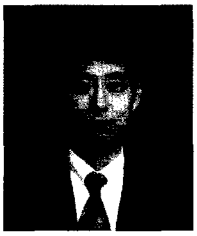

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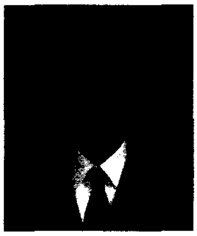

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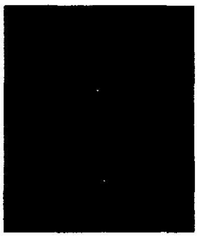

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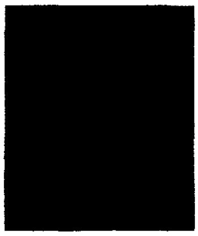

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