PAPER

A Flexible Video CODEC System for Super High Resolution Video

Takeshi YOSHITOME[†a)], **Ken NAKAMURA**[††], ***Nonmembers***, **Jiro NAGANUMA**[†], ***and*** **Yoshiyuki YASHIMA**[†], ***Members***

SUMMARY We propose a flexible video CODEC system for super-high-resolution videos such as those utilizing 4k × 2k pixel. It uses the spatially parallel encoding approach and has sufficient scalability for the target video resolution to be encoded. A video shift and padding function has been introduced to prevent the image quality from being degraded when different active line systems are connected. The switchable cascade multiplexing function of our system enables various super-high-resolutions to be encoded and super-high-resolution video streams to be recorded and played back using a conventional PC. A two-stage encoding method using the complexity of each divided image has been introduced to equalize encoding quality among multiple divided videos. System Time Clock (STC) sharing has also been implemented in this CODEC system to absorb the disparity in the times streams are received between channels. These functions enable highly-efficient, high-quality encoding for super-high-resolution video.

key words: *super high resolution video, CODEC, 4k × 2k*

1. Introduction

The number of video applications for super-high-resolution (SHR) images has been increasing in the past few years. SHR video images are 2 - 16 times larger than HDTV images, and they have 30 - 60 fps. Because of their high quality and the high level of realism they convey to the viewer, SHR systems [1]–[5] are expected to be platforms for many video applications, such as digital cinema, virtual museums, and public viewing of sports, concerts and other events. For SHR video applications, it is important to reduce the network bandwidth, because raw SHR video requires very high-speed transmission lines or high-speed disks that operate at 3 - 24 Giga bit/sec. SHR video compression schemes are thus needed to reduce the transmission and recording costs.

We have already developed a CODEC system [1] for SHR, it consists of multiple conventional MPEG-2 HDTV CODECs [6] and a frame synchronizer. The main benefit of this system is its ability to handle SHR video of various resolutions. This system can adapt to many kinds of SHR images by increasing or decreasing the number of encoders and decoders used. However, it is difficult to equalize the encoding quality among multiple encoders, and it is also difficult to record and playback the SHR stream because it consists of separated multiple HDTV streams.

In this paper, first, we describe the basic idea behind our CODEC system, which is spatial image division and multiple stream output. Section 3, we explain the video shift and padding function, which solves the boundary distortion problem caused by spatial image division. Section 4, we show switchable cascade multiplexing that enable to increase the flexibility of the combination of SHR video programs in multiplexing mode. Section 5, we show how to synchronize the multiple outputs in multiplexing mode and in non-multiplexing mode. Section 6, we explain the strategy of the adaptive bit-allocation in multiplexing mode. Sections 7 and 8 discuss our evaluations of the CODEC system. A few trails with transmission and recording using our system are described in Sect. 9. Section 10 is a brief conclusion.

2. Spatially Parallel CODEC System

This CODEC system adopts the spatial image division and multi-stream output approach. In spatial image division, the input image is divided into multiple sub-images and the encoder modules encode them in parallel, as shown in Fig. 1.

This approach is reasonable in terms of cost performance and scalability and has been used in some HDTV CODEC systems that use multiple SDTV CODEC's [6], [8]. We used it when we constructed the SHR CODEC system based on multiple MPEG-2 HDTV CODEC LSIs. Spatial image division can use a one-stream output system, in which the sub-streams generated by the encoder modules are re-

SHR images	Num. of Channel	Size	Target
Left / Right	2	2k x 1k	3D
1 2	1	4k x 1k	Wide View
1 2 3	1	6k x 1k	Sport
1 2 / 3 4	1	4k x 2k	Digital Cinema
1 .... 4 / .... / 12 16	1	8k x 4k	Future BS

Fig. 1 Examples of SHR images.

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[†]The authors are with NTT Cyber Space Laboratories, NTT Corporation, Yokosuka-shi, 239–0847 Japan.
[††]The author is with NTT Communication Corporation, Tokyo, 163–1421 Japan.
a) E-mail: yoshitome.takeshi@lab.ntt.co.jp

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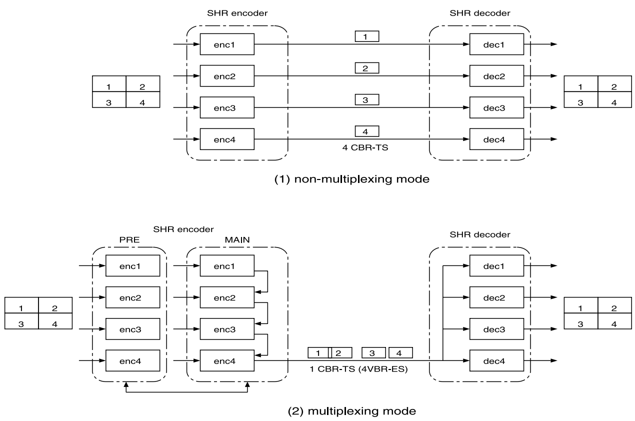

Fig. 2 Overview of SHR CODEC system.

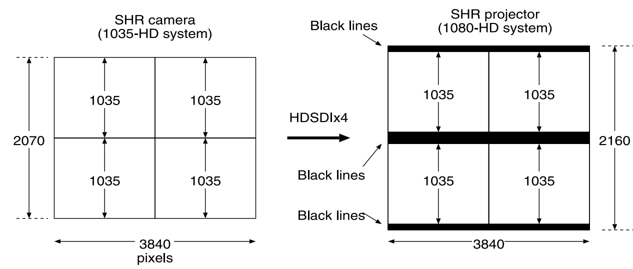

Fig. 3 Black line problem caused by mismatch between active lines.

constructed into one SHR elementary stream (ES), or it can use a multiple-stream output system, where several HDTV streams generated by the encoder modules are output directly in parallel or multiplexed into one transport stream (TS). We used the multiple stream output system for SHR communication applications, because conventional HDTV decoders can decode its output stream, whereas a one-stream SHR output system needs dedicated SHR decoders. There is an overview of our CODEC system in Fig. 2. The CODEC has two output modes, i.e., a multiplexing and a non-multiplexing mode. In the non-multiplexing mode, each encoder module outputs a constant bit rate (CBR) ES, and this is converted into CBR-TSs which are transmitted in parallel. In the multiplexing mode, the pre-encoder analyzes the input images and each encoder module in the main-encoder outputs a variable bitrate (VBR) ES, and these are multiplexed into one CBR TS. The multiplexing mode has the advantages of available transmitters and efficient coding. The other advantage of the multiplexing mode is that it is easy to record and playback the TS because the TS to be handled is single. However, it is difficult to record and playback in the non-multiplexing mode due to synchronization problems among multiple TSs.

3. Video Shift and Padding Function

Generally, SHR or over-HDTV image camera systems output divided images by using conventional HDTV video-signal interfaces, such as HD-SDI's. There are 1080 active lines in a conventional HDTV system [10]. Here, this system is called a 1080-HD in this paper. However, some SHR systems use the old HDTV signal system [11], where there are 1035 active lines, we call this the 1035-HD.

There are two problems in connecting SHR equipments that has a different number of active lines. The first is the black line problem. If 1035-HD system signals are received by a conventional 1080-HD system, the received image data do not fill the active line, e.g., 1920×1035 image data on 1920×1080, and the remaining lines are filled with black or zero data. A 3840×2160 projector, which uses the 1080-HD system, will display three horizontal black lines on the screen, as shown in Fig. 3, when the projector is connected to a 3840×2070 camera that uses a 1035-HD system. It seems that an effective solution is to vertically shift the SHR image data with the SHR projector to overcome this black-line problem; however, this solution is insufficient rectify to the second problem.

The second problem is distortion caused by mismatch between the image boundary and the DCT block boundary. Because MPEG-2 encoders transform 8×8 image blocks by using DCT and cut off high-frequency components, if the edge of the image and the DCT block boundary do not match, the border will not be sharp and the image data will be eroded by black data. Thus, coding distortion will be visible at the boundary of the divided images. Although this problem also occurs at the border of ordinary coded images, it is more visible in SHR systems because the boundaries of the divided images are positioned at their center.

The video shift and padding function modules in our encoder system are placed in front of the encoder modules to solve the mismatch problem. These modules can copy the top and bottom lines of image data onto non-image data areas. There is an example of a data flow that includes the video shift padding function in Fig. 4 (b). A data flow without the function is also shown in Fig. 4 (a). In both examples, the 1920×2060 pixel images of the SHR camera are output using two 1035-HDSDI signals that have five blank lines. In Fig. 4 (a), such 1080-HDSDI signals has been input to the encoding module directly without the video shift and padding function, causing boundary mismatch to occur between the edge of the image and the DCT block. These mismatches appear not only at the top of the active image and also at its bottom. In Fig. 4 (a), the hatched areas representing the output of the SHR projector mean that the lines degraded in the video quality. However, in Fig. 4 (b), our encoder has received a 1035-HD signal using the conventional 1080-HDSDI system, and has shifted and padded the input image to prevent the coding distortion mentioned above. In the example in Fig. 4 (b), the shift and padding function cannot prevent the two mismatches from occurring, which appear at the top and bottom of the active image at the same time. This is because "1030" is not a multiple of eight. To make the distortion noise caused by mismatch inconspicuous, the video shift size has been determined to prevent the mismatch border from being allocated to the center of SHR image, and to copy the top and bottom lines of the image data onto the non-image data area. The decoder system does nothing in regard to this operation because the copied data are aborted later. There are examples of output images with and without our function in Figs. 5 and 6. Figure 6 indicates that the video quality is not satisfactory because many viewers may recognize the horizontal center line caused by the mismatch of the image boundary and DCT block boundary as previously mentioned. However, it is difficult to find such a line in Fig. 5. These results demonstrate that video shift and padding prevent image quality from degrading around the center of the frame because the image border matches the DCT block.

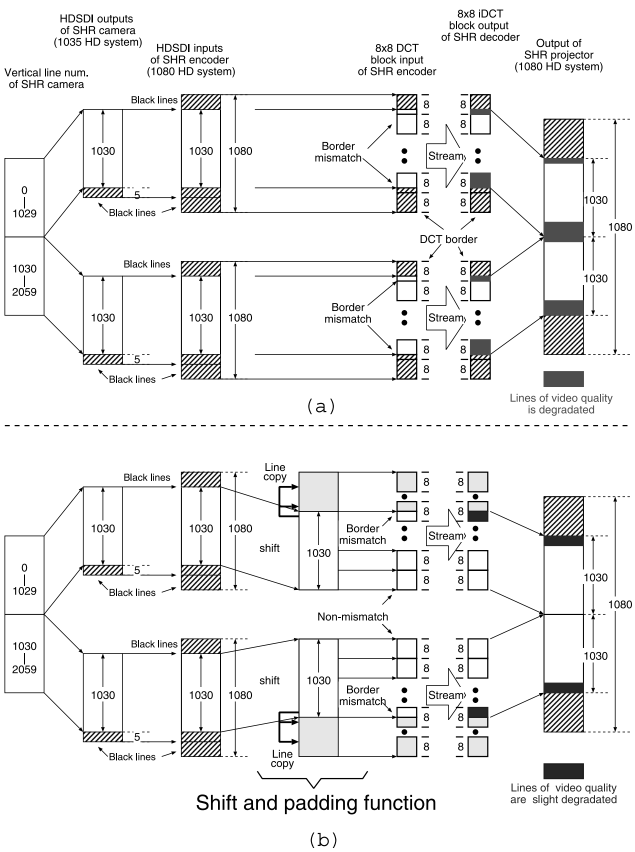

Fig. 4 Data flow from SHR camera to SHR projector with video shift and padding function.

4. Switchable Cascade Multiplexing Function

Our system is equipped with a switchable cascade multiplexing function to increase its flexibility in the multiplexing mode. This function of our encoder system is outlined in Fig. 7. The basic concept behind this function is to mix TS packets from two packet queues, i.e., internal and external queues. The internal queue stores the packets generated in the i-th encoder itself and the external one stores the packets transferred from the $(i-1)$th encoder through a high-speed serial cable. The packets in these two queues are mixed at the multiplexing circuit and the system packet inserter adds various system layer packets such as the Program Association Table (PAT), Program Map Table (PMT), Program Clock Reference (PCR), and NULL. The eliminator, which is located at the front of the external queue rejects unnecessary system-layer packets and outputs only video and audio packets to the external queue. Packets from the i-th and $(i-1)$th encoder's packets are the output of the i-th encoder. The cascade multiplexing function of each encoder is switchable to adapt to many types of SHR images, as shown in Fig. 1. Output of the i-th encoder is the packets from i-th and $(i-1)$th encoder's packets. There are some examples of cascade multiplexing switch settings listed in Table 1. The left of this table shows the relationship between all encoder inputs and the sub-image of the SHR video to be encoded. The center indicates the cascade multiplexing switch settings of all encoders and the right lists the SHR streams of all encoder outputs. We can see that the 6K × 1K stream is output to encoder #3 and the HD stream is output

Fig. 5 Output image using our shift and padding function.

Fig. 6 Output image without our shift and padding function.

Table 1 Examples of cascade multiplexing switch setting for many kinds of SHR video programs.

HDSDI input				Cascade sw setting			Stream output			
enc.1	enc.2	enc.3	enc.4	enc.1	enc.2	enc.3	enc.1	enc.2	enc.3	enc.4
$4k2k$				on	on	on	-	-	-	$4k2k$
$6k1k$			HD_1	on	on	on	-	-	$6k1k$	$6k1k+HD_1$
				on	on	off	-	-	$6k1k$	HD_1
$4k1k$		$2k2k$		on	on	on	-	$4k1k$	-	$4k1k+2k2k$
				on	off	on	-	$4k1k$	-	$2k2k$
		HD_1	HD_2	on	off	off	-	$4k1k$	HD_1	HD_2
				on	off	on	-	$4k1k$	HD_1	HD_1+HD_2
HD_1	HD_2	HD_3	HD_4	on	on	on	HD_1	HD_1+HD_2	$HD_1+HD_2+HD_3$	$HD_1+HD_2+HD_3+HD_4$
				off	off	off	HD_1	HD_2	HD_3	HD_4

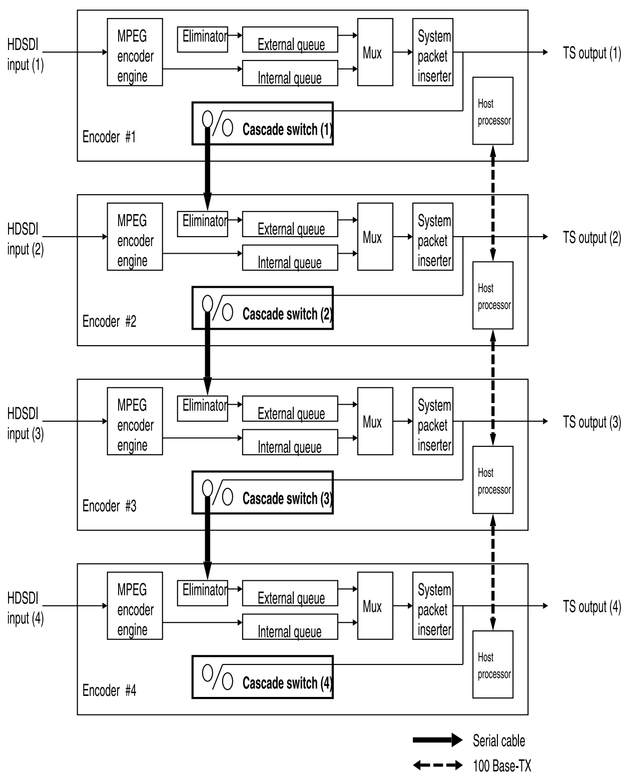

Fig. 7 Switchable cascade multiplexing in multiplexing mode.

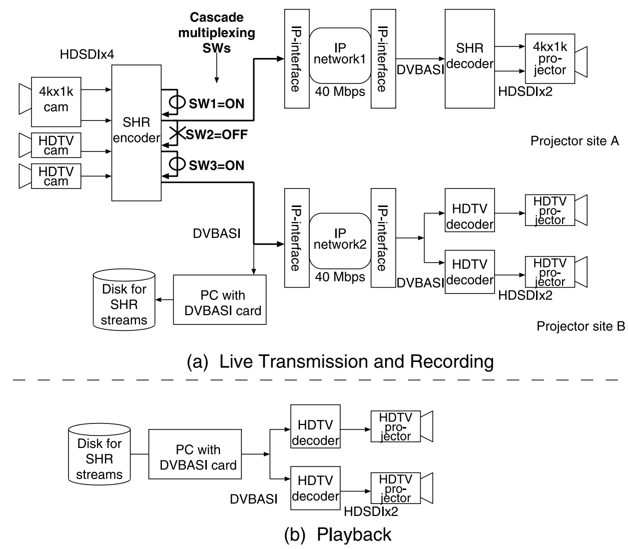

Fig. 8 SHR live transmission and local playback of $4k \times 1k$ program and two HDTV programs.

to encoder #4 when all multiplexing switches except the 3rd encoder's are turned on. The 4K × 2K stream is output to encoder #4 when the multiplexing switches of all encoders turn on. This means many SHR video sizes and many combinations of SHR video programs can be handled using this switchable cascade multiplexing. Also, every stream can be recorded and easily played back using a conventional PC with a DVB-ASI interface card because the stream of each encoder's output is a single TS consisting of several ESs.

There is a block diagram of SHR live transmission for two different sites and local playback using the switchable cascade multiplexing function in Fig. 8. By setting three multiplexing switches (Sw1, Sw2, and Sw3) (i.e., On, Off, and On), the 4K×1K TS can be transmitted from the camera side to the projector at site A, and a single TS that consists of two elementary HDTV streams can be transmitted to the projector at site B. If the setting of the switches is changed to (On, On, and On) and the bandwidth of IP network 2 can be increased to 80 Mbps, all streams including the two HDTV' streams and the single 4K × 1K stream can be transmitted to the projector at site B. In addition, a conventional PC can easily record and play back the transferred SHR stream at low cost.

5. Two Synchronization Schemes

Even if all decoders can input the same PCR packets using the cascade multiplexing function mentioned above, conventional decoders generate different STCs because each PLL of conventional decoders is made of different crystal. This indicates the possibility of sub-images of SHR decoders being displayed without synchronization. This CODEC system has two schemes to synchronize channels. The first is a multiplexing mode that shares a common STC, as seen in Fig. 9.

To synchronize all input video signals in the encoder system, a 27-MHz system clock and an STC value are generated from one of the input video signals and distributed to

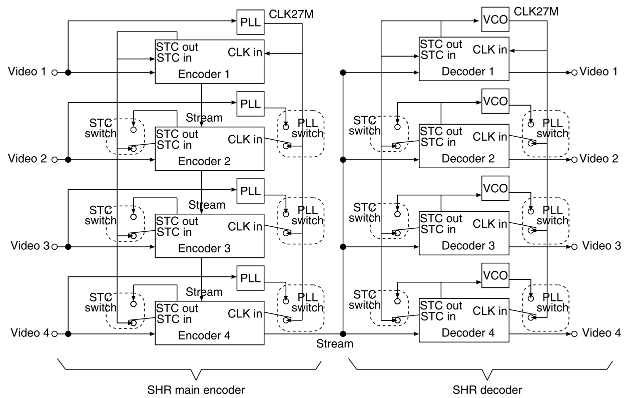

Fig. 9 Synchronization achieved by STC sharing in multiplexing mode.

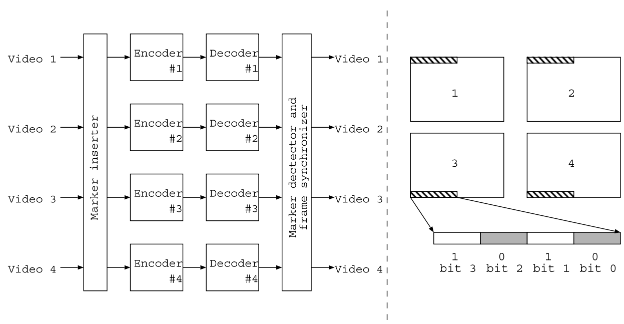

Fig. 10 Synchronization achieved by sync marker in non-multiplexing mode.

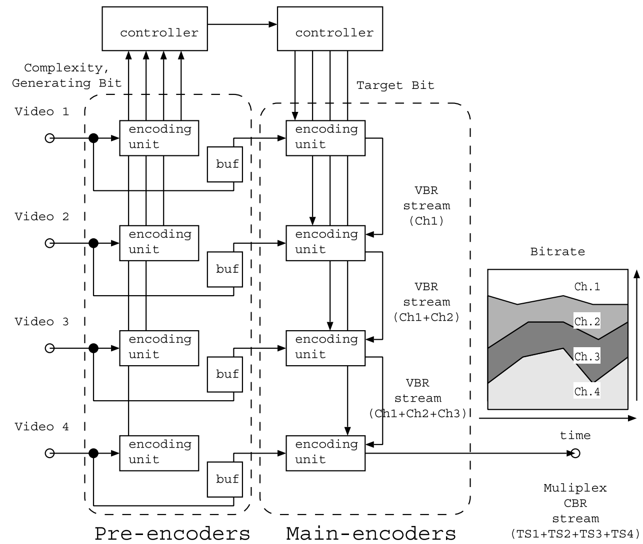

Fig. 11 Two-stage spatially parallel encoding in multiplexing mode.

the encoders. Each encoder generates a PCR and a Presenting Time Stamp/Decoding Time Stamp (PTS/DTS) based on the given system clock and STC value. The decoders consist of one master decoder and several slave decoders. The master decoder generates a 27-MHz system clock and an STC from the received PCRs and distributes the system clock and STC value to the slave decoders. To deal with deviations in the received timing and to avoid stream buffer underflow or overflow, the encoder system generates a PTS/DTS with an adequate timing margin.

The second synchronization method is the sync marker scheme, which is mainly useful with multiple conventional HDTV encoders and decoders in the non-multiplexing mode. Many conventional decoders do not have an STC sharing scheme and cannot deal with ancillary data, such as that in time code information. Our encoder places a sync marker on the top or bottom of the active line of each channel of the image, as shown in Fig. 10. The decoded images on the receiving side are synchronized with a multiple frame synchronizer that we have developed [1]. The benefit of this sync marker scheme is that the latest CODEC can be used for SHR video compression. We can replace the MPEG-2 CODEC with the latest H.264 CODEC without changing the construction of the SHR system.

6. Rate Control in Multiplexing Mode

We introduced a two-stage encoding system to equalize and improve the encoding quality of all partial frames. The system consists of pre-encoders, main-encoders, and a controller, as outlined in Fig. 11. The pre-encoder encodes and analyzes the input partial frame, and sends encoding parameters such as image complexity and the number of encoded bits to the controller. All pre- and main-encoders operate in parallel by receiving a common signal from the controller. Because of the time delay generated by the frame buffer in front of the main-encoder, the four main-encoders encode the $(N + 1)$-th frame when the four pre-encoders encode the first frame (N is GOP size).

The details of this rate control flow are given in Fig. 12 and it consists of five stages. First, the i-th frame is input to the pre-encoders, and the $(i - N)$-th frame is also input to the main-encoders in Stage 1. The reason the main-encoders input a delayed frame is to improve their own encoding quality. It is well known that scene changes degrade the encoding quality. If the encoders can detect future alterations of the image complexity such as scene changes, they can better distribute target bits to all frames, and minimize the degradation in encoding quality. Large delay increases encoding quality and the latency of the CODEC. However, small delay decreases them. The value of frame delay is determined by a trade off between the encoding quality and the delay of the CODEC system. We selected one GOP delay as a good trade-off point. In Stage 2, the pre- and main-encoders encode all partial frames. After the i-th frame is encoded by the pre-encoders, the controller obtains complexity $Xp_{i,k}$ and generated bits $S_{i,k}$ of partial frame (i,k) from the k-th pre-encoder in Stage 3. Then, in Stage 4, the function of "Future_X_based_STEP1()" calculates the target bits, TAm_j, of the $(i-N)$-th non-separated frame by taking the complexity of the next N frames into consideration. In other words, this complexity information on the next N frame enables the controller to determine a precise value for the target bits of the main-encoder, and the encoding quality of the main-

```
Two_Stage_Rate_Control ( ) {
  N = GOPSIZE;
  for ( all frame(i) ){

  // Stage.1 : Set parameter for encoder
    i = frame_number;
    for( all encoder(k) ) {
        F(i,k) = Partial_Frame( Frame(i), k );
        set_pre_encode(input:F(i,k),Tp(i,k));
        if ( ( j = i − N ) >  0 )
          set_main_encode(input:F(j,k),Tm(j,k));
    }

    // Stage.2 : Execute encoding
    exec_pre_encode();
    if (  j > 0  ) exec_main_encode();

    /* Stage.3 : Read output parameter from encoder  */
    read_pre_encode (output:Sp(i,k),Xp(i,k));
    if (  j > 0  ) read_main_encode(output:Sm(j,k));

    // Stage.4 : Calculate target bits for pre−encoder
    for( all pre_encoder(k) )
        Tp(i+1,k) = tm5_like_STEP1(input: Sp(i,k));

    // Stage.5 : Calculate target bits for main−encoder
    XAp(i) =  ∑k Xp(i,k);
    SAm(i) =  ∑k Sm(i,k);
    if (  j > 0  ) {
      // calculate target bits using next N frame's complexity
      TAm(j+1) = Future_X_based_STEP1(input:
                         XAp(i),XAp(i-1), .., XAp(i-N),
                         SAm(i),SAm(i-1), .., SAm(i-N));
      for( all main_encoder(k) )
        Tm(j+1,k) = TAm(j+1) * Xp(j+1,k) / ∑k Xp(j+1,k);
  }
}
//Frame(i):The i-th frame of SHR video sequence
//Tp(i,k): Target bits for PartialFrame(i,k) in pre-enc(k)
//Tm(i,k): Target bits for PartialFrame(i,k) in main-enc(k)
//Sp(i,k): Generated bits for PartialFrame(i,k) in pre-enc(k)
//Sm(i,k):Generated bits for PartialFrame(i,k) in main-enc(k)
//Xp(i,k): Complexity for PartialFrame(i,k) in main-enc(k)
```

Fig. 12 Rate control flow in multiplexing mode.

encoder will thus be superior to that of the pre-encoder. This is why we allocated an N frame buffer in front of the main-encoder.

The output VBR ES of the main encoders are multiplexed into one CBR TS through coordinating the multiplex modules in the encoder LSIs. The output bitrates of the main-encoders are changed at the same timing, while the bitrate of the multiplexed TS is held constant. This bit-allocation process enables the overall picture quality to be kept almost constant, because it updates the rate-distortion models of all frame parts by using the coding information from all encoders in every frame.

7. Evaluation

This section discusses the results of several simulations that compared the proposed bit-allocation method with the fixed bit-allocation method. In these simulations, 1920×1080 video sequences were divided into four video sequences (960×540 pixels each); the total bitrate was 20 Mbps; the coding structure was $M = 3$(IBBP); and 120 frames were encoded.

Table 2 Bitstream characteristics with conventional method and proposed method.

Partial frame position	Average partial frame bits (kbit)	Average Quantizing parameter	Average PSNR (dB)
conventional method			
upper left	166.2	58.53	25.80
upper right	165.9	57.45	25.87
lower left	165.4	24.13	30.55
lower right	165.3	24.73	30.36
Average	165.7	41.06	28.19
proposed method			
upper left	225.7	38.94	27.14
upper right	227.0	38.86	27.13
lower left	96.4	36.50	29.84
lower right	98.5	36.52	29.75
Average	161.3	37.70	28.48

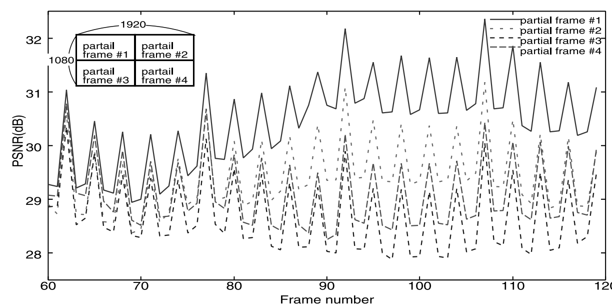

Fig. 13 PSNR of partial frames with conventional method. (sequence: "Church")

First, we compared the bitstreams generated by the two bit-allocation methods: fixed allocation and the proposed method. The video sequence "Soccer Action" was used for both simulations. Table 2 shows the average frame bits are almost the same in number for the fixed allocation method and the proposed method. In the conventional method, the PSNR of the partial frames in the upper parts is 5 dB less than that of lower parts. In the proposed method, the number of frame bits in each partial frame in the upper part are almost double the frame bits of the partial frames in the lower parts, because the proposed method distributes the target bits proportionally according to the complexity of each partial frames. The proposed method reduced the difference in PSNR between partial frames to 1.7 dB.

The disparity in PSNR among the four partial frames for the two bit-allocation methods are depicted in Figs. 13 and 14. The x-axis means the frame number and the y-axis means the PSNR (dB) in these figures. During frames 90-120, the PSNR of partial frame #3 is about 2.5 dB lower than that of #1 with the conventional method. In contrast, the disparity in PSNR among the divided frames decreases to 1.0 dB with the proposed method.

Table 3 lists the average PSNR and disparity in PSNR for the proposed method and the fixed bit-allocation method for five standard video sequences. The PSNR disparity (*DSNR*) is defined by

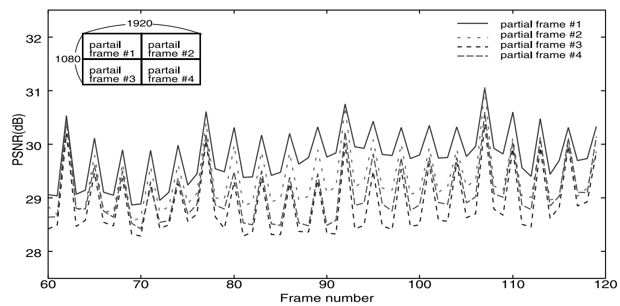

Fig. 14 PSNR of partial frames with proposed method. (sequence: "Church")

Table 3 Average PSNR and disparity PSNR with conventional method and proposed method.

Average of PSNR (dB)			
original frame size	1920 × 1080		
num of encoder	4	4	1
method	proposed	convent.	convent.
Church	29.43	29.47	29.57
Whale Show	28.15	27.85	28.41
Soccer Action	28.48	28.19	28.52
Sprinkling	26.00	25.47	26.53
Horse Race	33.40	33.30	33.41
Average	29.09	28.85	29.28
Disparity of PSNR (dB)			
method	proposed	convent.	convent.
Church	0.74	1.61	0.80
Whale Show	2.07	5.17	1.91
Soccer Action	2.87	4.86	2.77
Sprinkling	4.71	8.66	4.15
Horse Race	0.79	1.52	0.81
Average	2.23	4.26	2.08

$$DSNR = max(PSNR_{k=0..3}) - min(PSNR_{k=0..3}), \quad (1)$$

where $PSNR_k$ is the PSNR of partial frame k. The results for a single encoder using the conventional method have also been listed for reference. Table 3 shows that the average PSNR with the proposed method is 0.24 dB higher than that with the fixed bit-allocation method. The PSNR disparity with the proposed method is 2 dB lower than that with the conventional method and this is nearly that of the single encoder.

8. Experimental System

We developed an experimental SHR CODEC system [9] based on the system we have just described. Its specifications are listed in Table 4.

The encoder for this CODEC system consists of the pre-encoder unit and the main-encoder unit shown in the photograph in Fig. 15; these units were built with the same hardware, and only the firmware is different. Both units comply with the 1U (44 × 482 × 437 mm) rack size, and includes an audio encoder and a multiplexer, and each has four encoding units that use the new multiple-chip-enhanced 422P@HL MPEG-2 video encoding LSI [7]. There is a photo of the inside of the encoder in Fig. 16.

Table 4 Specifications of experimental CODEC system.

Video format	1080i (60/59.94i) × 4 720p (60/59.94p) × 4
Video interface	HDSDI × 4
Stream interface	DVB-ASI × 4
Compression	MPEG-2 422P@HL MP@HL
Bit rate	60 - 160 Mbps
Bitrate control	CBR for TS VBR for ES
Power	AC 100 - 240 V
Size (mm)	460 (W) × 440 (D) × 44 (H) × 2

Fig. 15 Photograph of SHR encoding system.

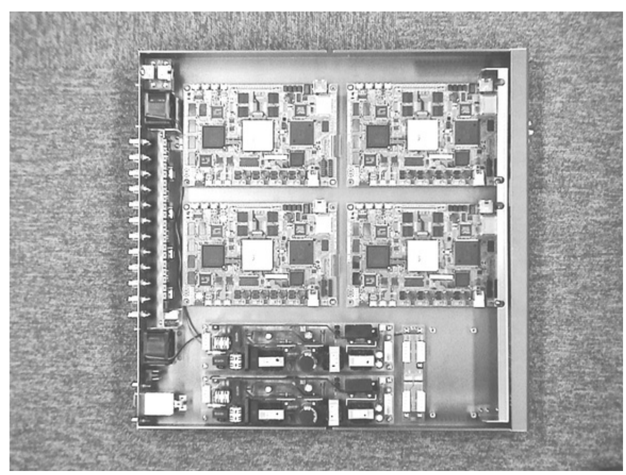

Fig. 16 Inside of SHR encoder.

We used 100 Base-TX for communication between these encoder units. The host processor in the pre-encoder unit performed calculations with the bit-allocation method described in Sect. 6, without requiring the use of any external equipment. The SHR decoder consisted of four HDTV decoders, and embodies the STC sharing. The CODEC system can be adapted to many SHR frame sizes by increasing or decreasing the number of CODEC modules instead of having to design and manufacture a new SHR encoder and decoder that can only handle one SHR image resolution.

9. Trail

We carried out live transmission of the 2007 Toyota Cup Soccer Tournament [13] from the Yokohama International

Fig. 17 4K × 2K camera for SKF2004.

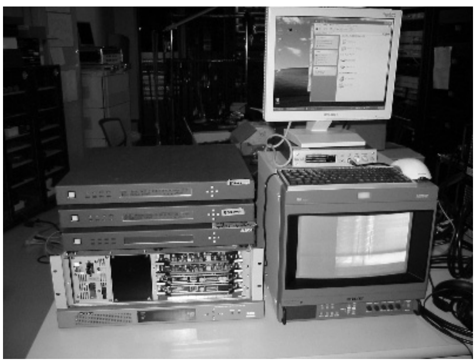

Fig. 18 SHR codec and local monitor for SKF2004.

Stadium to a movie theater in Kawasaki City using this system. A 6K × 1K camera [3] and our SHR encoder and decoder were used for this transmisson. A second example where we used our system was an SHR image recording of an orchestral concert at the Saito Kinen Festival 2004 [12].

The SHR image was taken with a 4K × 2K camera [4], as shown in Fig. 17, and was recorded with our SHR encoder. Four-channel audio streams were recorded without any compression to maintain high audio quality. There is a photograph of the system, which consisted of our SHR encoder and the stream recorder, in Fig. 18. The results obtained demonstrate that the proposed system architecture makes it possible to create high-quality video encoding systems that have scalability in terms of target video resolution.

10. Conclusion

We propose a multi-channel CODEC system for super-high-resolution video. It uses the spatially parallel encoding approach and has sufficient scalability for the target video resolution to be encoded. The switchable cascade multiplexing function of our system enables various super-high-resolutions to be encoded and super-high-resolution-video streams to be recorded and played back using a conventional PC. STC sharing absorbs the disparity in the times streams are received between channels. Two-stage encoding has the ability to equalize the encoding quality of all partial frames. These functions enable highly-efficient, high-quality encoding for super-high-resolution videos. In the future, we intend to change the MPEG-2 coding LSI of the CODEC system to an H.264 LSI.

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Takeshi Yoshitome received his B.S. and M.S. in computer science, from Tsukuba University, Japan, in 1982 and 1984. In 1984, he joined the Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan, where he has been engaged in research and development of image processing system. He is currently a Senior Research Engineer with the Visual Media Communications Project at NTT Cyber Space Laboratories, Kanagawa in Japan.

Ken Nakamura received his B.E. and M.E. degrees from Keio University in 1995, 1997, respectively. In 1997 he joined the NTT Laboratories, Nippon Telegraph and Telephon (NTT) Corporation, Kanagawa, Japan, where he has been engaged in research and development of digital video coding system. Since 2005, he has worked at the NTT Communications Corporation Tokyo, Japan.

Jiro Naganuma received the B.S. degree in electrical engineering from Tokushima University, Tokusima, Japan, in 1981, and the Ph.D. degree in information science from Kyoto University, Kyoto, Japan, in 1995. In 1981, he joined Musashino Electrical Communication Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan. He currently a senior research engineer at Media Communication Project of NTT Cyber Space Laboratories, Kanagawa, Japan. He engaged in the research of high-level VLSI architectures and design methodologies for multimedia embedded system LSIs. Dr. Naganuma is a member of the Information Processing Society of Japan (IPSJ), and the IEEE Computer Society.

Yoshiyuki Yashima received the B.E., M.E. and Ph.D. degrees from Nagoya University, Nagoya, Japan, in 1981, 1983 and 1998, respectively. In 1983 he joined the Electrical Communications Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan, where he has been engaged in the research and development of high quality HDTV signal compression, MPEG video coding algorithm, and lossless image coding system. His research interests also include pre- and post-processing for video coding, processing of compressed video, compressed video quality metrics and image analysis for video communication system. He is currently a Senior Research Engineer, Supervisor, of the Visual Media Communications Project in NTT Cyber Space Laboratories. He has been also a visiting professor of Tokyo Institute of Technology since 2004. He was awarded the Takayanagi Memorial Technology Prize in 2005. Dr. Yashima is a member of the IEEE Signal Processing Society, the Information Processing Society of Japan (IPSJ), and the Institute of Image Information and Television Engineers of Japan (ITE).