SUMMARY ‘Super Hi-Vision’ (SHV) is promising as a future form of television. It is an ultra-high-definition TV system that has 16 times the number of pixels of HDTV and employs a 22.2 multichannel sound system. It offers superior presence and gives the impression of reality. The information bitrates of the current prototypes range from 24 to 72 Gbit/s, and a fiber optic transmission system is needed to transfer even just one channel. This paper describes the optical transmission technologies that have been developed for SHV inter-equipment connects and links between outdoor sites and broadcasting stations.

key words: high definition television, digital broadcasting, optical transmission, digital interface

1. Introduction

Television broadcasting in Japan will have switched from analog broadcasting to digital broadcasting by 2011. The main digital broadcasting services offered by broadcasters are HDTV programming rather than standard-definition programs. Broadcasters begin to look into the feasibility of future broadcasting services beyond the level of HDTV. NHK is researching and developing ‘Super Hi-Vision’ (SHV). SHV is an ultra-high-definition TV (UHDTV) system with 16 times the number of pixels of HDTV and a 22.2 multichannel sound system, and its viewers will be able to watch images within a visual angle range of 100 degrees. Compared with HDTV, SHV will offer superior presence and convey a more convincing impression of reality.

Cameras, displays, and recorders are being developed for SHV [1]. To deliver SHV broadcasting to homes, compression, transmission, and home-reception equipment should be also developed. SHV test broadcasting via satellite is planned to begin in 2020.

The amount of information contained in the SHV signal is much larger than in the signals of current television systems. This means SHV requires the latest transmission technologies. This paper gives an overview of SHV and describes its optical transmission technologies.

Table 1 EHRI resolution in pixels.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Number of pixels (vertical, horizontal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EHRI-0</td>
<td>1920, 1080</td>
</tr>
<tr>
<td>EHRI-1</td>
<td>3840, 2160</td>
</tr>
<tr>
<td>EHRI-2</td>
<td>5760, 3240</td>
</tr>
<tr>
<td>EHRI-3</td>
<td>7680, 4320</td>
</tr>
</tbody>
</table>

Fig. 1 Comparison of spatio-temporal resolutions.
(7680 × 4320) pixels. The first camera and display prototypes used four 8-million-pixel imaging and display devices, respectively. Two imaging (display) devices were used for the green image, and one each was used for red and blue images. The diagonal-pixel-offset method [4] was used to process the green image. The resulting system is hence called the ‘Dual-Green imaging system’. At present, experimental SHV programs are being produced with the Dual-Green imaging system.

2.3 Sound Specifications of SHV

Digital broadcasting in Japan supports the 5.1 surround sound system. This system conveys a two-dimensional spatial impression to viewers. SHV features three-dimensional spatial sound from a 22.2-multichannel system [5] (Fig. 2). This system can reproduce an immersive and natural sound field, and it consists of upper, middle and lower layers having nine, ten, and three speakers, together with two low-frequency effect bass speakers.

In the rest of this paper, we shall mainly refer to video signal transmissions, because the bitrate of the sound signals is much lower than the bitrate of video signals.

2.4 Transmission of SHV

2.4.1 Bitrate of Transmission

This section shows how the transmission bitrate of SHV is calculated. Table 2 summarizes the calculation for full-resolution SHV. The ‘transmission’ bitrate includes the information about the pixels, audio signals and additional control signals.

The Super Hi-vision image has 7680 pixels horizontally and 4320 pixels vertically. Each pixel has red, green, and blue components, and each component represents its image information as a 12-bit value. The frame rate is 60 frames per second, and all told, the bitrate amounts to 72 Gbit/s. Table 2 also shows corresponding values for HDTV and Dual-Green SHV. Note that the frame scanning rate of HDTV is 30 frames/s interlaced, while SHV is 60 frames/s progressive.

2.4.2 A Variety of Transmission Distances

The transmission distances for program production vary from short haul to long haul, as shown in Fig. 3. The technologies required for developing equipment economically also vary depending on transmission distance; i.e., connections between camera and display would be short distance ones on the order of a meter, whereas production equipment connected through a network in a broadcasting station would require medium distance connections on the order of 1 km. Outdoor program productions would involve substantially longer transmission distances, as would interstation connections.

2.4.3 Required Quality of Video Transmission

The bit error rate (BER) is the most significant property of a digital transmission. Other important properties are the jitter of the recovered clock at the receiver and the latency caused by signal processing during transmission. Quality measurement methods have yet to be standardized for SHV,

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<table>
<thead>
<tr>
<th></th>
<th>HDTV</th>
<th>SHV</th>
<th>SHV (Dual-Green)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of pixels (vertical, horizontal)</strong></td>
<td>1920, 1080</td>
<td>7680, 4320</td>
<td>7680, 4320</td>
</tr>
<tr>
<td><strong>Frame rate/s</strong></td>
<td>30 (interlaced)</td>
<td>60 (progressive)</td>
<td>60 (progressive)</td>
</tr>
<tr>
<td><strong>Sampling frequency ratio</strong></td>
<td>(Y,Pₐ,Pₑ)=4:2:2</td>
<td>(R,G,B)=4:4:4</td>
<td>1(R), 2(G), and 1(B) samples in every 2 × 2 pixels</td>
</tr>
<tr>
<td><strong>Bit rate per component</strong></td>
<td>10</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td><strong>Bitrate [Gbit/s] (pixel information)</strong></td>
<td>1.244</td>
<td>71.66</td>
<td>19.90</td>
</tr>
<tr>
<td><strong>Bitrate [Gbit/s] (transmission)</strong></td>
<td>1.485</td>
<td>72</td>
<td>23.76</td>
</tr>
</tbody>
</table>
and the methods used to evaluate HDTV have had to be used instead. In fact, because the physical signal of SHV is composed of parallel signals in HDTV-like format, quality measurements based on HDTV methods are applicable in most situations.

Most quantitative measuring methods use color bar test signals [8]. These sorts of measurements can sufficiently simulate practical situations. For assessing marginal performance, a bit-serial digital check-field signal [9] (also known as ‘pathological pattern’) is occasionally used for testing signals that would be received under severe conditions.

The BER requirement of 10G-SDI is $10^{-12}$ or less when the received power is between $-13.5$ to $0.5$ dBm [10]. The BER of a color bar test signal cannot be directly measured, but it can be calculated from the error count of the Cyclic Redundancy Check Code in the test signal.

The spectrum of the jitter in a recovered clock contains a range of spectral components. For HD-SDI signals, spectral components above 100 kHz are classified as alignment jitter, and spectral components above 10 Hz are classified as timing jitter [7]. The alignment jitter is thus part of the timing jitter. The amplitudes of the alignment jitter and timing jitter have to be less than 0.2 UI (Unit Interval), and 1 UI, respectively.

Latency is an especially significant factor in live broadcasting. Although official specifications do not exist, latency should be much less than the period of the video frame (1/60th of a second for SHV). Long latencies during live programs, for example, tend to disturb newscasters in a studio and reporters far away from a broadcasting station when they talk to each other on camera.

3. Optical Interface for SHV Production Equipment

3.1 Existing Interface Standard for HDTV and UHDTV

SHV program production will need a standard interface to connect cameras, displays, and other production equipment. The HDTV interfaces of present-day digital broadcasting are standardized as HD-SDI (High-Definition Serial Digital Interface) also known as 1.5 Gbit/s SDI [7]. An HD-SDI can carry an HDTV video signal at 30 frames/s. There are also ‘dual link’ and 3G-SDI standards that have transmission rates of 3 Gbit/s. These standards can carry HDTV video signals at 60 frames/second. While a dual link is composed of a pair of HD-SDIs, a 3G-SDI is for a single 3-Gbit/s signal. 10G-SDI (10 Gbit/s Serial Digital Interface) is the most recent interface to be standardized [10]. It can carry a UHDTV signal having $3840 \times 2160$ pixels, and its total bitrate is 10.692 Gbit/s.

The SHV interface is now undergoing standardization. Equipment should be able to be connected by using a single cable up to 2 km long, as in the case of HD-SDI. Although a single 10G-SDI cannot be used to carry a full-resolution image signal (72 Gbit/s), a parallel 10G-SDI connection can be set up to do so.

The following sections describe the optical interface for connecting full-resolution SHV production equipment with eight 10G-SDIs and wavelength division multiplexing.

3.2 Block Diagram of Interface

Figure 4 shows the block diagram of the optical interface. The input side consists of thirty-two dual link interfaces. The inputs are separated into eight groups, and each group is converted to a 10G-SDI electrical signal. The eight 10G-SDI electrical signals are then converted into eight optical signals having different wavelengths by using XFPs (10 Gigabit small Form-factor Pluggable modules). The wavelengths range from 1547.72 to 1553.33 nm and are on 100-GHz (0.8 nm) spacing ITU grid channels to enable dense wave division multiplexing (DWDM).

The multiplexed optical signals are sent to the receiving interface of other equipment through a single-mode fiber. At the receiver, the optical signals are restored to thirty-two dual link signals.

Figure 5 shows the appearance of the prototype interface. The prototype is about 10 inches high, and it has a stack of eight DSP boards and 64 BNC connectors for the dual link signals on a back panel. The optical interface is an LC connector.

3.3 Measured Characteristics

3.3.1 BER

Figure 6 plots BER versus the O/E converter’s input power for the interface after transmission of color bar test signals (circles in figure) and PRBS-31 pattern signals (rhombuses in figure) over a distance of 2 km. Since the BER differences were negligibly small among all wavelengths, the values in the figure were the best among the eight wavelengths. The
BERs for the color bar test signals mostly coincided with the BERs for the PRBS-31 pattern. The BERs were less than $10^{-12}$ when the received power at the O/E module was more than $-19$ dBm, and they were less than $10^{-13}$ when the received power at the O/E module was between $-17$ and $+0.5$ dBm. The interface met the BER requirement. The loss tolerance between the transmitter and receiver was calculated to be 15 dB.

In a long-term measurement conducted for five days, no CRC error occurred when the O/E module input power was $-13.5$ dBm, which is the minimum input power prescribed in SMPTE435-3-2009 [10]. The BER was estimated to be $3 \times 10^{-15}$ or less. A latency of the whole signal processing from the transmitter to the receiver was 11 microseconds, which is much shorter than the duration of a video frame.

### 3.3.2 Jitter Characteristics

The jitters of 1.5 Gbit/s digital interface signals were measured. The alignment and timing jitters (respectively, 0.12 UI and 0.16 UI) met the jitter requirements. The jitters when the interfaces were connected in series were measured. Figure 7 shows the relation between jitter and the number of series connected interfaces. The alignment jitter hardly changed as the number of interfaces increased. Moreover, although the timing jitter increased by 0.04 UI when eight interfaces were connected, it remained much lower than the requirement.

### 3.3.3 Connection Test Using SHV Camera

We performed an experiment on the prototype interface and full-resolution SHV camera. The eight-hour experiment demonstrated that stable error-free full-resolution SHV video could be transmitted through the interface without interruption.

### 4. Long-Haul Optical Contribution Link

#### 4.1 16-Wavelength DWDM Link for Dual-Green SHV

#### 4.1.1 Live Transmission Experiment of Dual-Green SHV Signal

NHK conducted the first live relay transmission of Dual-Green SHV and 22.2 multichannel sound. The experiment was conducted over a distance of 260 km via an optical-fiber network. The transmission equipment for the experiment used a single fiber and DWDM technology.

Figure 8 shows the setup of the optical transmission experiment. The Dual-Green SHV signal was composed of 16 HD-SDI signals. The 16 input signals at the transmission site directly modulated the optical intensities of 16 laser diodes to be multiplexed with a 100-GHz (0.8 nm) frequency interval in the 1.55-micrometer wavelength band according to ITU-T Recommendation G.694.1. At the receiving site, the multiplexed optical signals were reconstructed into an SHV signal. Figure 9 shows the optical spectrum of the DWDM signal measured at the receiving site.

We used four erbium-doped fiber optical amplifiers (EDFAs) to transmit an SHV signal several hundred kilometers without any repeaters. Using optical amplifiers makes transmission systems simpler than ones relying on electrical recovery which need optical WDM filters and lots of O/E and E/O converters at every relay point. The EDFAs compensated the total optical-fiber loss of 63 dB over the 260 km. The fiber was an ordinary single mode fiber (SMF) designed to have no chromatic dispersion around the 1.3-micrometer wavelength. The 16 lightwaves were collectively amplified by cascaded EDFAs that were inserted in the optical transmission line, as shown in Fig. 8.

#### 4.1.2 Long-Haul Transmission Characteristics

We measured the BERs of two different HD-SDI test sig-
signals, an SMPTE color bar test signal [8], and a bit-serial digital check-field signal [9]. Figure 10 plots the measured BER with received optical power on the abscissa. The BERs of the bit-serial digital check-field signal were almost equal to those of the color bar test signal. The average optical power to the 16 optical receivers was $-23$ dBm for the whole live transmission. At that optical power level, no error was detected from any of the outputs of the O/E converters during approximately 14 hours of measurement.

During high-speed digital optical transmissions through an ordinary single mode fiber at non-zero dispersion wavelength, chromatic dispersion degrades jitter performance. Chromatic dispersion can be canceled by putting a dispersion compensation fiber (DCF) that has the opposite value of the chromatic dispersion coefficient in front of the optical receiver.

Figure 11 shows the eye diagrams of the received 1.485-Gbit/s stream after a 260-km single mode fiber transmission. The eye diagrams, (a) and (b), were measured with and without compensation by the DCF, respectively. The results showed that the received HD-SDI signal waveform could be reshaped by the DCF.

Figure 12 shows the jitter of the optical transmission system with residual chromatic dispersion after compensation by the DCF. The alignment jitter was 0.15 UI (unit in-
terval), and the timing jitter was 0.2 UI. These values are within the allowable limits. This experiment demonstrates that chromatic dispersion does not need to be compensated in a 1.485-Gbit/s DWDM transmission system using a single mode fiber shorter than 260 km.

The figure also shows the results for a bit-serial digital check-field signal. Although the alignment jitter was close to the allowable limit, it nonetheless exceeded the limit at all chromatic dispersion values. This suggests that the jitter performance may still have to be improved. The measured latency was 4 ms, which is shorter than the frame period.

### 4.1.3 SHV Live Transmission Experiment

On November 2nd, 2005, NHK conducted a live relay transmission of a Dual-Green SHV image and 22.2 multichannel sound signals. The experiment was conducted over a distance of 260 km via an optical-fiber network. Figure 13 shows the setup of the experiment. The transmitting site (Kamogawa, Chiba) switched between three different SHV video signals in real time, two from live cameras and one from a disk recorder. Multi-channel audio signals were digitized into the AES format and embedded in the HD-SDI signals without compression. Because a single HD-SDI signal can carry eight sound channels, we embedded 32 channels of sound in four of the 16 HD-SDI signals.

The audio signals were separated from the video signals at the receiving site (our laboratories in Tokyo). The video was shown on a 450-inch screen with a SHV projector, and the audio was played through a 22.2 sound system.

### 4.2 40-Gbit/s TDM Link for Dual-Green SHV

The technologies described in the above section mainly use dark fiber, wherein a specialized transmission format for video signals can be transparently transmitted. Since it would be better to use optical networks of telecommunications carriers (hereinafter called ‘lease lines’) for longhaul live-video links stretching over hundreds of kilometers, it would be more feasible to construct a hybrid link that utilizes both dark fiber and lease lines. However, the use of lease lines may be limited in terms of bitrate, frame structure, and other aspects. Then, we developed transmission technologies accommodating SHV signals in an Opti-
cal Transport Network (OTN), which is a standardized signal format used by communication networks.

OTN technology is commonly called digital wrapper technology [11]. The line rate of OTU3 (Optical Transport Unit-3) is 43 Gbit/s, which is high enough to transmit a 24-Gbit/s SHV signal together with RS (255, 239) parity bits.

#### 4.2.1 Conversion of 24-Gbit/s SHV Signal into OTU3 Signal

Figure 14 shows the procedure for converting an SHV signal into an OTU3 signal, the payload of which can accommodate up to four 9.95-Gbit/s signals. First, the 16 HD-SDI signals making up the SHV signal are converted into three 9.95-Gbit/s signals, each having an STM-64 (Synchronous Transport Module-64) frame structure [12]. Next, each 9.95-Gbit/s signal is converted into an ODU2 (Optical channel Data Unit-2) signal [11]. These three ODU2 signals together an ODU2 signal consisting of null data are then put into the payload of an OTU3 signal. RS (255, 239) codes are calculated for every sixteen bytes of the header and payload of the OTU3 signal. Finally, the OTU3 frame in Fig. 14 is generated in a 3.35 microsecond cycle and transmitted at a bitrate of 40 Gbit/s (at a line rate of 43 Gbit/s including a redundant RS code bitrate).

Our equipment uses an FPGA (Field Programmable Gate Array) to convert up to six HD-SDI signals into a 9.95-Gbit/s signal and a commercially supplied OTN framer LSI to convert the 9.95-Gbit/s signals into an OTU3 signal.

#### 4.2.2 Transmission of SHV Clock Signal

The SHV clock signal, equal to each HD-SDI clock signal, must be recovered from the OTU3 signal received at the receiver site, because the output video at the receiver should be synchronized with the input video at the transmitter. Since the SHV clock signal and OTU3 core/metro network clock signal differ in frequency, the link requires an accurate video clock recovery method. Our system uses the SRTS (Synchronous Residual Time Stamp) method [13] to transmit the SHV 74.25-MHz clock signal through an OTU3 network with a 77.76-MHz clock.
Figure 15 illustrates this clock recovery method. The transmitter counts the number of cycles of the 77.76-MHz clock signal \( f_s \) within N cycles of the SHV 74.25-MHz clock signal \( f_n \) and transmits this value to the receiver as a variable RTS (Residual Time Stamp). At the receiver, the counter circuit is driven at the cycle of the 77.76-MHz clock signal recovered from the received OTU3 signal. Short pulses are output only if the counter value is equal to the received RTS value. Since each interval between pulses is almost equal to N cycles of the SHV 74.25-MHz clock signal, the SHV 74.25-MHz clock signal is N times the frequency of the pulses. The RTS values are put into the header of each 9.95-Gbit/s signal, and N is set to 21.

4.2.3 BER Measurements

We evaluated the SRTS method by measuring the BER characteristics of the received SHV signal. Figure 16 shows BERs for equipment utilizing optical amplitude shift keying modulation, which is equivalent to on-off keying modulation. The wavelength and output optical power were 1.55 micrometers and 0 dBm, respectively. The equipment was capable of transmitting SHV over a distance of 5 km without error correction and 6 km with error correction.

Furthermore, the use of RZ-DQPSK modulation, two optical amplifiers, and a dispersion compensation fiber was found to be sufficient for 50-km transmissions without error correction.

Figure 16 BER characteristics of the received SHV signal.

4.2.4 Jitter

Jitter characteristics were measured in an indoor trial, in order to evaluate the suitability of the SRTS method for SHV clock signal transmissions. HD-SDI color bar test signals were converted into an asynchronous 40-Gbit/s OTU3 signal and transmitted over a 2-km single mode optical fiber. The alignment jitter and timing jitter of the received signal were respectively 0.12 UI and 0.20 UI, which met the jitter requirements.

4.2.5 Latency and SHV Video Transmission

The overall latency of the transmitting and receiving equipment was 245 microseconds, which is short compared with the duration of a video frame.

We demonstrated quasi error-free transmission of SHV video without interruption over the course of the experiment, which was about a day.

5. Conclusion

Super Hi-Vision is a promising form of future television. However, compared with the television systems of today, it is more complex and large-scale. Many challenging technical problems need to be overcome, and engineers from a broad range of fields will have to collaborate in its development. Moreover, the technologies that spring from its development will have to be internationally standardized so that Super Hi-Vision can spread throughout the world.

Acknowledgments

The research on the fiber-optic link was supported by the New Energy and Industrial Technology Development Organization, Japan, under a project titled “The Development of Next-generation High-efficiency Network Device Technology”.

The research on the broadcasting station network was done in collaboration with the National Institute of Advanced Industrial Science and Technology.
References


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