PAPER

DRoF-Based Optical Video Re-Transmission System with Adaptive Combination Compression for Rain Attenuated Satellite Broadcast Signals

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SUMMARY   In order to further reduce the transmission rate of multi-channel satellite broadcast signals, whose carrier-to-noise ratio (CNR fluctuates due to rainfall attenuation, we propose a novel digitized radio-over-fiber (DRoF) -based optical re-transmission system based on adaptive combination compression for ultra-high definition (UHD) broadcasting satellite (BS)/communications satellite (CS) broadcast signals. The proposed system reduces the optical re-transmission rate of BS/CS signals as much as possible while handling input CNR fluctuations. Therefore, the transmission rate of communication signals in time-division multiplexing (TDM) transmission is ensured, and network sharing of communication signals and broadcast signals via passive optical network (PON) is realized. Based on the ITU-R P.618-13 prediction model, an experimental evaluation is performed using estimates of the long-term statistics of attenuation due to rainfall. The attenuation is evaluated as a percentage of the time that long-term re-transmission service is available. It is shown that the proposed system is able to accommodate a wide range of rainfall attenuation and achieve a 99.988% time percentage for the duration of service provision. In order to show the rate reduction effect of the proposed system, the quantization bit reduction effect as a function of the input CNR, which depends on rainfall attenuation, is experimentally confirmed. Experiments show that service operation time of 99.978% can be achieved by 3-bit transmission. This means a 62.5% reduction in transmission rate is realized compared to conventional fixed quantization. Furthermore, the average quantization bit number in our system for service operation times is 3.000, indicating that most service operation times are covered by just 3-bit transmission.
key words: digitized radio-over-fiber, optical re-transmission, broadcasting signal, ultra-high definition satellite broadcasting

1. Introduction

In recent years, with the development of fiber-to-the-home (FTTH), triple play services that provide data communication, audio, and video have been realized by telecommunication carriers [1]. In addition to telecommunication signals, optical re-transmission of broadcast signals for video distribution has been recognized as one of the major sources of revenue for telecommunication carriers [2]. In optical re-transmission of broadcast signals, telecommunications carriers receive digital terrestrial television (DTT) signal and broadcasting satellite (BS)/communications satellite (CS)

signals via radio waves, convert them into optical signals, multiplex them with communication signals, and finally distribute them to customers.

For the optical re-transmission of broadcast signals, subcarrier multiplexing (SCM) is widely used [3]. SCM is a technology that directly converts frequency-multiplexed (FDM) signals into optical signals and transmits them. One of the beneficial features of SCM is that it offers a coaxial interface at the end-to-end of the network. This is expected to reduce the service entry barriers experienced by cable television (CATV) operators who do not have FTTH network.

However, SCM has some technical problems caused by its use of analog optical transmission. Since SCM transmits an optically intensity-modulated RF signal, it is difficult to expand the transmission range of the access network [4]. This transmission distance limitation forces telecommunication carriers to deploy a large number of re-transmission facilities in the access network. In addition, packet-based digital communication signals as used in the passive optical network (PON) cannot be multiplexed in the time domain with SCM broadcast signals. Hence, it is necessary to operate the access network on the premise of wavelength multiplexing, which requires dedicated wavelength multiplexing facilities and raises equipment costs [5].

To solve these problems faced by existing systems, we have proposed a novel optical video re-transmission system that applies the concept of digitized radio-over-fiber (DRoF) [6], [7]. The radio frequency (RF) signal received as a ra-
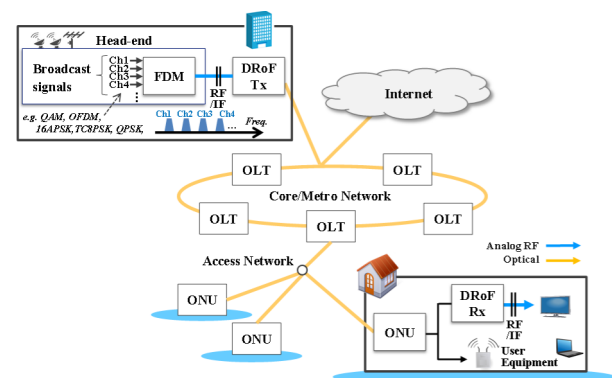
Fig. 1   Optical video re-transmission architecture applying digitized radio-over-fiber.

dio wave or an intermediate frequency (IF) signal (yielded by head-end frequency conversion) are converted into digital signals, then framed and optically re-transmitted. In the optical section, the signal is time-division multiplexed with the communication signal and transmitted through the common network. This allows the existing PON facilities owned by telecommunication carriers to also be used for optical re-transmission of broadcast signals. In addition, multiplexing in the time domain enables low-cost optical re-transmission without the need set dedicated optical wavelength equipment for the distribution of just broadcast signals.

However, one of the critical issues in DRoF-based transmission systems is the increase in transmission rate. For example, base band unit (BBU) and remote radio head (RRH) of mobile network communicate via common public radio interface (CPRI) for DRoF [8], [9]. The required quantization bit size in CPRI is 15-bits, and the transmission rate is 19.7 Gbps (corresponds to two CPRI option 7 channels), which is a drastic increase compared to the original data [9]. On the other hand, in the optical re-transmission of broadcast signals, broadcast signals of multiple channels including DTT and BS/CS are optically re-transmitted. Broadcast signals have a much wider total channel bandwidth than CPRI signals. Therefore, reducing transmission rates becomes a more difficult technical problem. In particular, our system assumes the PON is shared by communication signals and broadcasting signals by time division multiplexing (TDM). Therefore, in order to assure the transmission rate of the communication system as much as possible, the transmission rate of the optical re-transmission should be minimized as much as possible.

Our system is expected to accommodate, in addition to DTT in the ultra-high frequency (UHF) band, BS/CS for satellite broadcasting in the super-high frequency (SHF) band [6], [7]. In particular, in Japan, 4K/8K ultra-high definition (UHD) BS/CS broadcasting services has been underway since 2018 and is currently in the process of spreading [10]. These UHD BS/CS signals are received via satellite channels at the RF frequency of the 12 GHz band, down-converted to IF in the head-end, and delivered to the user's side [11]. Here, as the IF, the frequency band from 1.032 to 2.070 GHz is used for right hand circularly polarized (RHCP) signals, and the frequency band from 2.224 to 3.223 GHz is used for left hand circularly polarized (LHCP) signals. Therefore, a higher frequency band is used in the wireless section compared with DTT. In general, the attenuation in the wireless section due to weather conditions can be significant depending on the frequency band [12]. UHD BS/CS using the 12 GHz band has a larger attenuation than DTT. Therefore, the carrier-to-noise ratio (CNR), which is an important quality index of the signal received at the head-end, fluctuates depending on the weather conditions. When the CNR of received signal changes, the acceptable CNR margin in the network section also changes. Since there is a trade-off between the signal compression ratio and the signal quality at the network, it is necessary to relax the compression ratio by assuming the worst case of the received signal

at the headend in order to satisfy the required CNR at the receiver. Our previous system simply assumed the fixed case of the received signal CNR at the head-end and assigned a fixed compression parameter at the DRoF-transmitter (Tx).

To reduce the transmission rate of optical re-transmission of BS/CS broadcast signals as much as possible in the face of fluctuations in CNR due to rain attenuation, this paper proposes a DRoF-based adaptive optical re-transmission system based on combination compression. The proposed system reduces the transmission rate for more broadcast signals by dynamically assigning compression parameters that take into account actual fluctuations in the input CNR to the DRoF-Tx due to rainfall attenuation. As a result, PON sharing in the time domain by the communication signal and the broadcast signal is realized. An experimental evaluation based on the prediction model of ITU-R P.618-13 is conducted to confirm that the proposed system is able to accommodate the wide range of rainfall attenuation values that can occur in the field [13]. Furthermore, the transmission rate realized by our proposal is experimentally investigated for various DRoF-Tx inputs.

2. Related Works

Our research is related to research on system level design including quantization in DRoF technology.

A typical system for DRoF is the common public radio interface (CPRI) in the mobile fronthaul [8], [9]. CPRI has been introduced as a fronthaul interface that connects the base band unit (BBU) to remote radio heads (RRHs). The radio signal waveform generated in the BBU is analog-to-digital (A/D) converted, and the radio signal waveform is regenerated by digital-to-analog (D/A) conversion in each RRH. CPRI uses the fixed quantization number of 15-bits to ensure signal quality [8], [9]. Similar to CPRI, in hybrid fiber-coaxial (HFC), DRoF is applied in baseband digital forward or return (BDF/BDR). BDF/BDR is defined as an interface for connecting fiber nodes of the HFC network and cable modems [14], [15]. BDF/BDR provides a simple, service-transparent digitized interface. The BDF/BDR digitization process uses the fixed quantization number of 12-bits [14], [15]. As mentioned above, some commercial systems basically perform very simple uniform fixed quantization. In uniform quantization, quantization partitioning is uniform regardless of the distribution characteristics of the signal amplitude. Therefore, large quantization bit numbers are essential to reduce CNR degradation. As a result, higher transmission rates are required.

To suppress the increase in transmission rate, the use of non-uniform quantization has been proposed. In non-uniform quantization, quantization partitioning is determined non-linearly with respect to the scalar and vector of the signal. Scalar quantization is realized by the mu-law codecs for audio signal processing such as voice over internet protocol (VoIP) [16], [17]. It is also listed as an option set in CPRI. In [18], a method that combines non-linear quantization and differential PCM is used. In [19],

the clustering-based k-means method is applied. In vector quantization, multiple vectors are generated from the input samples, and clustering is performed on the vectors. For example, [20] uses an extended multidimensional k-means method. In [21], two-dimensional vector quantization using vector linear prediction is applied. Non-uniform quantization reduces the quantization degradation compared to uniform quantization. In general, the transmission rate in DRoF system is defined by the product of the number of quantization bits and the sampling frequency in the ADC of the transmitter. For example, if the sampling frequency is fixed, the transmission rate is proportional to the number of quantization bits. Therefore, the CNR margin is increased because non-linearization allows reductions in the quantization bit number, and thus the transmission rate. However, conservative system level design determines the quantization bit and parameters assuming the minimum signal quality of the system input. That is, even when the input CNR is relatively high, the quantization bit associated with the minimum input CNR is applied. As a result, the transmission rate is fixed according to the minimum input CNR. From the viewpoint of enhancing system economy, the application of the above-mentioned advanced non-uniform quantization does not provide sufficient enhancement. This is because the quantization bit reduction effect is bound to the lowest input CNR.

Therefore, in order to realize further transmission rate reduction and improve spectral efficiency for a signal whose quality fluctuates over time, the adaptive allocation of the quantization bit has been proposed, [22] proposes adaptive non-linear distortion where feedback is used to set parameters for the input signal. [23] proposes an adaptive quantization and channel coding scheme for pulse amplitude modulation (PAM) 4 optical links. However, as far as is known, these adaptive compression studies targeted mobile signals. Since there is just one channel in the mobile fronthaul, some adaptive some compression methods suitable for single channel used are adopted in [22], [23]. On the other hand, in our system, it is assumed that compression is applied to a bulk signal containing a large number of channels that are frequency-multiplexed to reduce equipment cost. Furthermore, it should be noted that [22], [23] did not carry out quantitative evaluations including level design to handle changes in signal quality (e.g. CNR) due to weather events such as rainfall. Unlike conventional research in which only mobile service signals occupy the network, our system shares the network between broadcast signals and communication signals in the time domain. Therefore, it is necessary to perform a level design that carefully considers compression against input signal quality fluctuation due to rainfall attenuation. These points make it infeasible to apply existing research to our system.
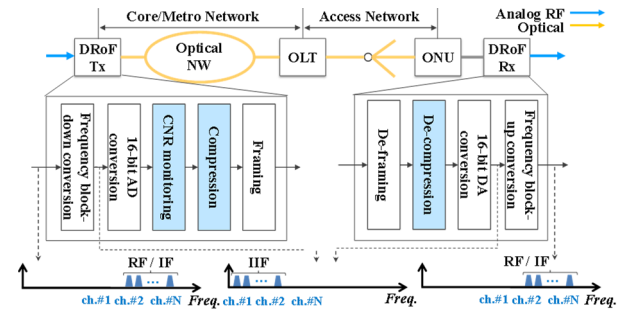
Fig. 2 Processing scheme in the proposed DRoF-based adaptive optical video re-transmission system.

3. Proposals

### 3.1 DRoF-Based Adaptive Optical Video Re-Transmission System

Our adaptive optical video re-transmission system offers coexistence with communication systems. Our proposal changes the compression rate applied in RF/IF signal processing to suit the input CNR in order to minimize, as much as possible, the transmission rate decreases of the communication system.

Figure 2 shows the processing flow of the proposed system. The proposed system deploys DRoF-Tx and DRoF-receiver (Rx) at both ends of the network. Frequency multiplexed multi-channel RF/IF broadcast signals are input to DRoF-Tx. The RF/IF signal is block down-converted to the internal intermediate frequency (IIF). The frequency-converted signal is input to a 16-bit analog-to-digital converter (ADC), and is quantized for processing in the digital domain. After analog-to-digital (A/D) conversion, the CNR of the quantized signal is monitored to detect the channel with the lowest CNR. The compression parameters are determined according to the channel with the lowest CNR. Signal compression is performed in the time domain based on the determined compression parameters. Details of compression scheme are described later. After the compressed signal is framed, it is transmitted through the optical network composed of core/metro network and access network. In the access network, the signal is transmitted through a PON consisting of an optical line terminal (OLT) and optical network units (ONUs) [24]. At the receiver side, the electrical signal output from the ONU is input to the DRoF-Rx, where it is de-framed and de-compressed. The decompressed signal is digital-to-analog (D/A) converted by a high bit digital to analog converter (DAC). Since the bandwidth of the signal output from the DAC is IIF, it is collectively frequency converted from IIF to RF/IF. The frequency converted multi-channel RF/IF signals are output from the DRoF-Rx.

As described above, the existing communication networks are utilized, and the multi-channel broadcasting signals are optically re-transmitted.
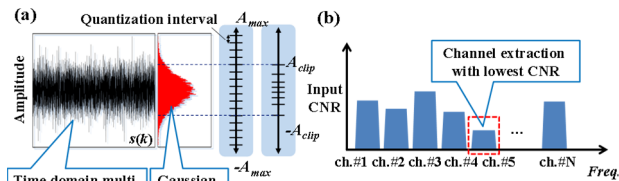
Fig. 3 Graphical understanding of signal processing in compression schemes. (a) is the graphical description of a schema that selects the channel with the lowest CNR from the input channels. (b) is the graphical description of compression process combining signal clipping and nonlinear transformation.
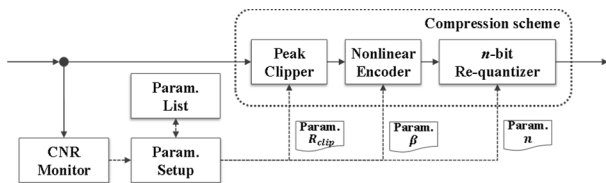
Fig. 4 Signal processing details of the compression scheme.

3.2 Adaptive Signal Compression Scheme

The DRoF-Rx in our system is deployed at the user' side. From the perspective of cost, the devices deployed must be implemented as simply as possible. In addition, in order to realize network sharing while assuring the transmission bandwidth of communication signals, a method that can achieve a high compression rate is required. Hence, we utilize a simple and highly effective nonlinear compression scheme that combines signal peak clipping and nonlinear transformation in the time domain.

Figure 3(a) visualizes the compression scheme. The time waveform of the multiplexed multi-channel RF/IF signal has a Gaussian-like probability density function (PDF). Therefore, our proposal first clips the less informative amplitude part away from the center. Next, we reduce the quantization error of the signal by nonlinear quantization according to the amplitude distribution of the clipped signal. The CNR margin obtained by reducing the quantization error is used to reduce the quantization number. The dotted line in Fig. 4 shows the signal processing flow of the compression scheme. It consists of Peak Clipper, Nonlinear Encoder, and n-bit Re-quantizer. First, the Peak Clipper clips the time domain signal at a certain clipping depth. The following equation shows input signal $s(k)$ clipped at the clipping amplitude of A_{clip}.

$$
s_{clip}(k) = \begin{cases} s(k) & for \ |s(k)| < A_{clip} \\ A_{clip} & for \ |s(k)| \geq A_{clip} \end{cases} \tag{1}
$$

where s_{clip} is the clipped signal and k is the k-th sample. Also, the clipping ratio R_{clip} is defined as the ratio of clipping amplitude A_{clip} and the root mean square (RMS) value of the signal as indicated by the following equation.

$$
R_{clip} = 20 \log_{10} \left(\frac{A_{clip}}{\sigma_{RMS}} \right) \tag{2}
$$

Here, σ_{RMS} represents the RMS value of the signal. While clipping the signal reduces the quantization interval, clipping noise increases with clipping depth. As a result, the CNR of the signal is degraded. Therefore, peak clipping at the optimal clipping ratio is required. In the Nonlinear Encoder, the clipped signal is nonlinearly transformed by the following equation.

$$
u = A_{clip} sgn \left(s_{clip} \right) \frac{log \left(1 + \beta \left| s_{clip} \right| / A_{clip} \right)}{log(1 + \beta)} \tag{3}
$$

where u is the nonlinear transformed signal and β represents a nonlinear parameter. This nonlinear parameter adjusts the nonlinearity of the signal. The n-bit Re-quantizer re-quantizes the transformed signal by n-bit by subtracting the quantization bit number from 16-bits. This combination of signal clipping, nonlinear transformation, and re-quantization, offers effective and significant reductions in the transmission rate.

It is obvious that setting the optimal compression parameters is critical in achieving high compression ratios while suppressing signal CNR degradation. There is a trade-off between the compression ratio of the transmission rate and the degradation of the signal CNR. In other words, increasing the compression ratio degrades the signal CNR. In addition, the input CNR to DRoF-Tx varies depending on weather conditions. Therefore, depending on the input CNR, it is necessary to determine the compression parameters that yield acceptable compression ratios. In our proposal, the compression parameters are dynamically assigned to the Peak Clipper, Nonlinear Encoder, and n-bit Re-quantizer of the compression scheme as shown in Fig. 4. As shown in Fig. 3(b), the input signal has different CNR for each channel. Therefore, the CNR of each channel is monitored. The channel with the lowest CNR is extracted by monitoring, and Param.Setup determines the compression parameters according to that channel. Here, the compression parameters are determined in advance and listed in Param.List; they are referenced regularly. Clipping depth R_{clip}, nonlinear parameter β, and re-quantization bit n are assigned to the Peak Clipper, Nonlinear Encoder, and n-bit Re-quantizer, respectively. Signal compression is performed using these parameters.

The compression parameters described in Param.List are determined in advance by the optimization scheme. As shown in Fig. 5, the difference signal between the input signal s to the Compressor and the output signal s'_n from the De-compressor is obtained. Here, s'_n means a signal re-quantized by n-bits. The difference signal is expressed by the following equation.

$$
\Delta s_n \left(k, R_{clip}, \beta \right) = s(k) - s'_n \left(k, R_{clip}, \beta \right) \tag{4}
$$

Where k indicates k-th sampling. The error power defined by Eq. (5) is calculated using the difference signal.
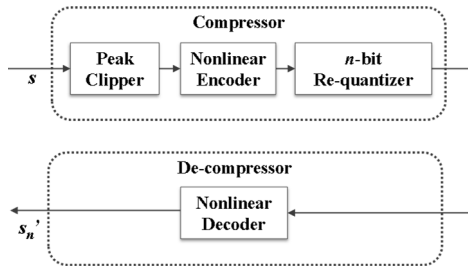
Fig. 5 Configuration diagram of signal processing in the optimization scheme.

$$\Delta e_n\left(R_{clip},\beta\right) = \sum_{k=0}^{k=N} \Delta s_n^2/N \qquad (5)$$

Here, N indicates the total number of samples. R_{clip} and β that minimize the error power in the case of the quantization number n-bit are calculated by the following equations.

$$^\forall\beta > 0, ^\forall R_{clip} > 0, minimize\left\{\Delta e_n\left(R_{clip},\beta\right)\right\} \qquad (6)$$

Based on Eq. (6), R_{clip} and β are calculated according to each quantization number. This above process is carried out under each CNR condition by varying the input signal CNR range from 35 dB to 14.5 dB in 0.5 dB intervals, and the values of R_{clip}, β, and n that attain the required CNR at the receiver side are determined.

4. Evaluation

4.1 System Level Design Assuming Rainfall Attenuation; Modeling of DRoF-Tx Input

Channel state fluctuations in satellite broadcasting are a significant determiner of the CNR of the signal input to the DRoF-Tx. The main cause of the decrease in CNR is rainfall [25]. At frequencies above 10 GHz, rainfall attenuation often results in lower CNR. Therefore, we calculated the signal CNR received at the antenna site on the ground via the satellite channel and modeled the CNR of the DRoF-Tx input. First, to permit statistical analysis, the rainfall attenuation was calculated using the rainfall attenuation prediction model of ITU-R P. 618-13 [13], and used to calculate the DRoF-Tx input CNR.

In calculating the rainfall attenuation, the prediction model shown in ITU-R P. 618-13 was used [13]. With this model, the rainfall attenuation for some percentage of time p is calculated by inputting the point rainfall rate for the location for 0.01% of an average year. Rainfall attenuation A_p with percentage of time p is expressed by the following equation.

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta)} \qquad (7)$$

Here, β is expressed by the following equation.

Table 1 Parameters used in rainfall attenuation analysis.

Parameters	Abbreviation	Set value
Point rainfall rate for the location for 0.01 % of an average year [mm/h]	$R_{0.01}$	69
Height above mean sea level of the earth station [km]	h_s	0.03
Elevation angle [degrees]	θ	46
Latitude of the earth station [degrees]	φ	35.64
The predicted attenuation exceeded for 0.01% of an average year	$A_{0.01}$	10.31
Frequency [GHz]	f	12.130

$$\beta = -0.005(|\varphi| - 36) \qquad (8)$$

The parameters used in the analysis are listed in Table 1. The parameters were set based on the values in reference [26].

On the other hand, the received CNR in satellite communication is determined by Eq. (9) using effective isotropic radiation power (*EIRP*) and parameter G/T [27]. Rainfall attenuation A_p included in the term of Eq. (9) is defined by Eqs. (7) and (8) as a function of the percentage of time p. Therefore, the received CNR (i.e. input CNR to DRoF-Tx) is also expressed as a function of percentage of time p. Parameter *EIRP* represents the transmission power intensity in the antenna directivity direction. Parameter G/T is generally called the *figure of merit* [28].

$$CNR = EIRP - L_s - A_p + G/T - 10\log kB \qquad (9)$$

Here, L_s represents free space propagation loss, while k and B indicate Boltzmann's constant and signal bandwidth, respectively. Parameter G/T in Eq. (10) is given by the following equation.

$$G/T = G_r - 10\log T_s \qquad (10)$$

Parameter G_r is antenna gain, and indicates the equivalent total noise temperature of the receiving system. Here, G_r is given by aperture efficiency η of a parabolic antenna, antenna diameter δ, and wavelength λ [29].

$$G_r = \eta\left(\frac{2\pi\delta}{\lambda}\right)^2 \qquad (11)$$

Also, T_s of Eq. (10) is represented by antenna noise temperature T_a, reference temperature T_0, and receiver noise temperature T_r.

$$T_s = T_a + (L_F - 1)T_0 + L_F T_r \qquad (12)$$

Here, L_F represents the feed line loss. The antenna noise temperature T_a of Eq. (12) is refined by the following equation.

$$T_a = T_m\left(1 - 10^{-(A/10)}\right) \qquad (13)$$

Here, T_m represents the average propagation temperature.

Further, T_r of Eq. (12) is expressed by the following equation using receiver noise figure NF.

$$T_r = (NF - 1)T_0 \tag{14}$$

The input CNR to DRoF-Tx is calculated using Eqs. (7) to (14). Here, the parameters used in the CNR calculation are given in Table 2. The parameters were determined based on the typical receiving facilities at the head-end. Parameter A_p, the statistical rainfall attenuation value calculated from ITU-R P. 618-13, was used to calculate the input CNR to DRoF-Tx.

Table 2 Signal parameters used in received CNR calculation.

Parameters	Abbreviation	Set value
Equivalent isotropic radiated power [dBW]	$EIRP$	60
Free space propagation loss [dB]	L_s	205.8
Boltzmann constant	k	1.38×10^{-23}
Bandwidth [MHz]	B	33.7561
Wavelength [m]	λ	0.024
Antenna diameter [m]	δ	1.2
Aperture efficiency	η	0.6
Feed line loss [dB]	L_f	0.5
Receiver noise figure [dB]	NF	0.8
Reference temperature [K]	T_0	290
Average propagation temperature [K]	T_m	273

4.2 Experimental Setup

In order to investigate the dependency of the transmission rate on the fluctuating input CNR, we experimentally confirmed the required quantization bit number corresponding to the DRoF-Tx input CNR as determined in 4.1.

Figure 6 shows the experimental setup for the transmission of UHD BS signals. The inset photo in Fig. 6 shows our actual experimental setup. The 11ch frequency-multiplexed integrated services digital broadcast signals for satellite 3rd generation (ISDB-S3) were output from a signal generator (SG) [30]. The detailed parameters of the ISDB-S3 signals used in the experiment are shown in Table 3. They were generated by employing 16-amplitude and phase shift keying (APSK) [30]. The 11ch output signal was generated as an IF signal with frequency range from 2224.41 MHz to 2642.51 MHz. In this experiment, due to the limitations of experimental equipment, a total of 11 channels (2224.41 to 2642.51 MHz) were utilized as transmission signals in the BS IF band of LHCP, excluding the highest frequency channel with a center frequency of 2663.62 MHz. These IF signals simulate the signals after frequency conversion from the 12 GHz RF band used in the satellite broadcasting. The FDM signal was block-down converted directly from IF to IIF using a 2209.41 MHz local oscillator (LO). The high frequency band of the converted signal was cut by a low pass filter (LPF). The signal after passing through the LPF was amplified by the amplifier. The amplified signal was input to the 16-bit ADC and digitized. Part of the digitized signal was branched and the CNR of each channel was moni-
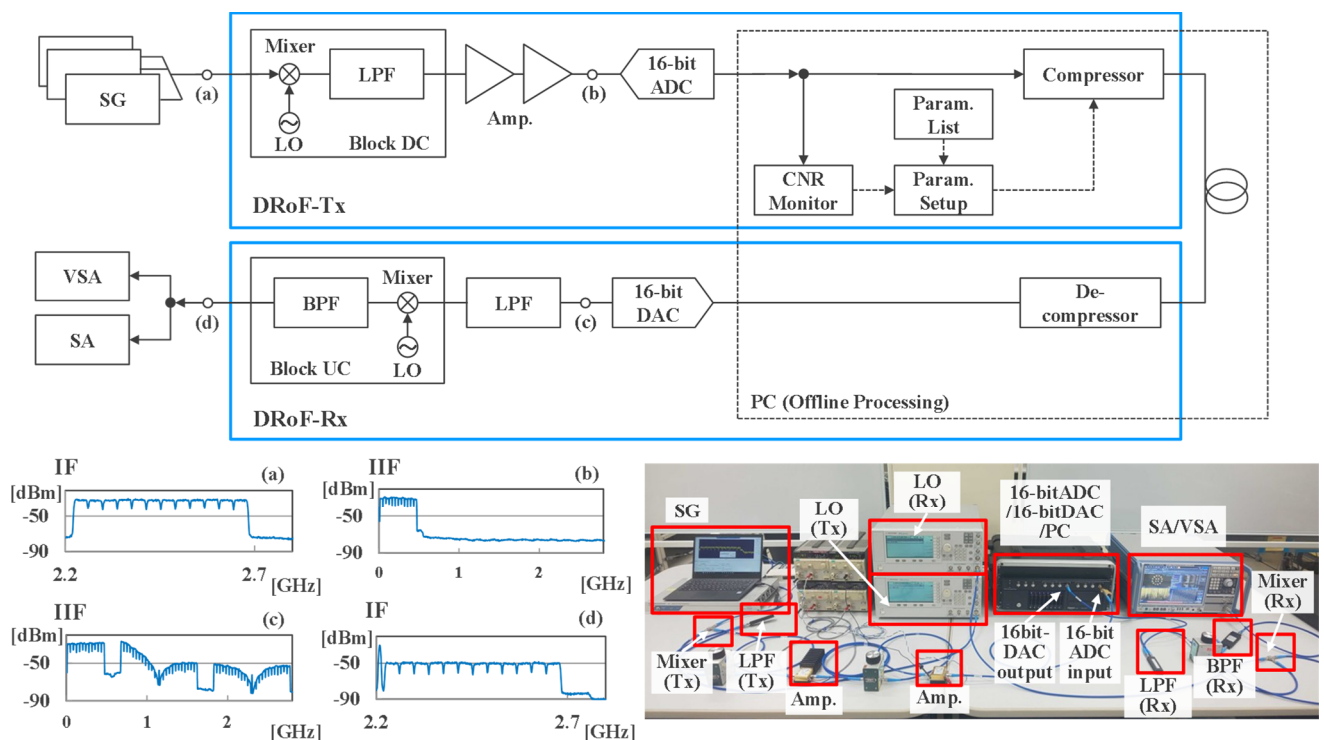
Fig. 6 Experimental setup for UHD BS signal transmission using proposed system.

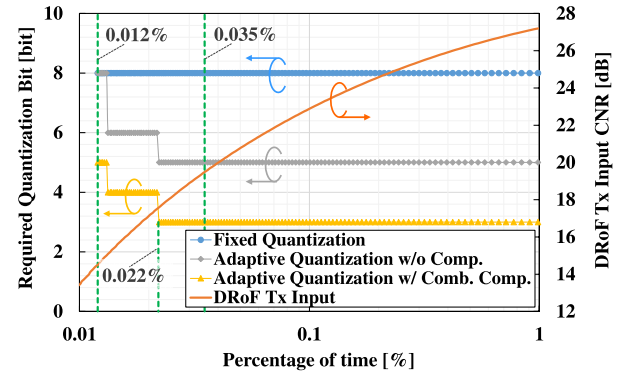**Table 3** Signal parameters used in the experiment.

Parameters		Set value
Channel number		11
Occupied bandwidth [MHz]		34.5
Channel bandwidth [MHz]		38.36
Modulation scheme		16APSK
Forward error correction	Inner code	LDPC code (Code length: 44880)
	Coding rate	7/9
	Outer code	BCH (65535, 65343) Shortened code
Roll off factor		0.03
Symbol rate [Mbaud]		33.7561

Fig. 7 Required quantization bit and input CNR for percentage of time.

tored by the CNR Monitor. Monitoring detected the channel with the lowest CNR, which was used in determining the compression parameters. The compression parameters were referenced from the pre-determined Param.List and applied by the Compressor to compress the signal. The compressed signal was transmitted from the DRoF-transmitter to the DRoF-receiver. On the other hand, on the DRoF Receiver side, the transmitted signal was decompressed by the De-compressor and converted into an analog signal by 16-bit DAC. The DAC output was input to the LPF, and the harmonic components generated by the DAC were cut off. The signal output by the LPF was directly block-up converted by the 2209.41 MHz local oscillator. The out-of-band component was cut by the band pass filter (BPF) and output from the DRoF-receiver. The signal quality of the output signal was measured by using a vector signal analyzer (VSA) and signal analyzer (SA).

5. Results and Discussion

The transmission rate of the proposed system varies with the state of the satellite broadcasting. This is because the minimum quantization bit needed for DRoF-Tx may change depending on the input CNR. Therefore, the required quantization bit was experimentally evaluated in order to investigate the transmission rate according to the input CNR assuming it was varied due to rainfall attenuation. Here, the minimum quantization bit number that allowed the output signal CNR from DRoF-Rx to satisfy the required value (CNR≥14 dB) is defined as the required quantization bit number [31].

Figure 7 shows the required quantization bit number and the input CNR to DRoF-Tx for the percentage of time p. An experimental evaluation was performed using estimates of long-term statistics of rainfall attenuation based on the ITU-R P.618-13 prediction model. That is, the attenuation was evaluated based on the percentage of time in which service operation is available. Service operation time means the time during which the long-term re-transmission service is provided. Three cases were compared; 1) Fixed quantization, 2) Adaptive quantization w/o compression, and 3) Adaptive quantization w/ combination compression (i.e.

Proposal). 1) Fixed quantization; At the minimum allowable input CNR (i.e. 14.5 dB) without quantization bit reduction, the minimum quantization bit that satisfies the required CNR was set. 2) Adaptive quantization w/o compression; For each input CNR, the minimum number of quantization bits was assigned under the condition that no compression scheme was applied. 3) Adaptive quantization w/ combination compression (i.e. Proposal); While the combination compression scheme was applied, the smallest number of quantization bits that met the required CNR on the receiving side was dynamically assigned. The vertical axis on the left plots the required quantization bit number, and the vertical axis on the right plots the DRoF-Tx input CNR. The horizontal axis plots the percentage of time p. From Fig. 7, it can be seen that 8-bits are required for the case of fixed quantization. On the other hand, in adaptive quantization w/o compression and adaptive quantization w/ combination compression, the required quantization bit number increases as the percentage of time p decreases. This is because the input CNR decreases as the percentage of time p decreases, i.e. rainfall attenuation worsens. Focusing on the percentage of time 0.035%, which indicates the service availability of existing satellite broadcast services, adaptive quantization w/o compression requires 5-bits [26]. On the other hand, the proposed method can reduce the quantization bit number to 3-bits. In addition, the results attained by the proposal show that transmission is possible with 3-bits even at p=0.022. This means that 99.978% is attained with just 3-bits.

Furthermore, it was experimentally confirmed in that the requirements for DRoF-Rx output were met even when the percentage of time p was 0.012%. When the percentage of time p was 0.012%, the quantization bit number required for adaptive quantization w/o compression was 8-bits. On the other hand, we confirmed that our proposal can satisfy the required CNR using only 5-bits. Furthermore, the average quantization bit number was investigated in the range of $p \geq 0.012\%$ to statistically evaluate adaptive compression. The average quantization bit number for fixed quantization and adaptive quantization w/o compression were 8.000 and 5.000, respectively. With the proposal, on the other hand, the average quantization bit number for adaptive quantiza-
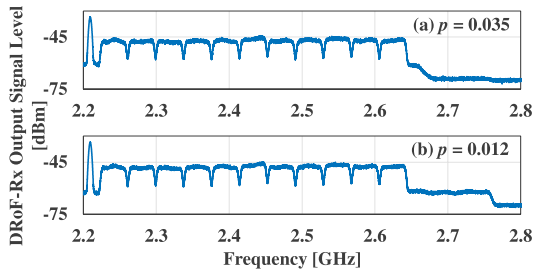
Fig. 8 Spectral result of output signal from DRoF-Rx. (a) shows the output signal from DRoF-Rx under the condition of $p = 0.035$. (b) shows the output signal from DRoF-Rx under the condition of $p = 0.012$.
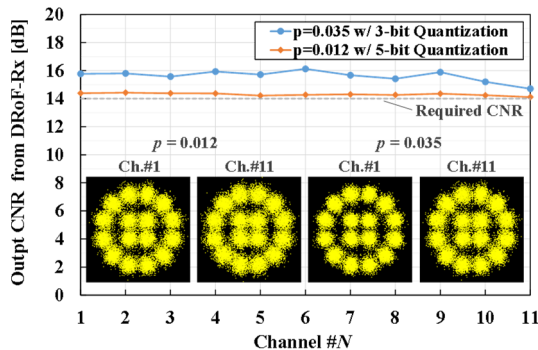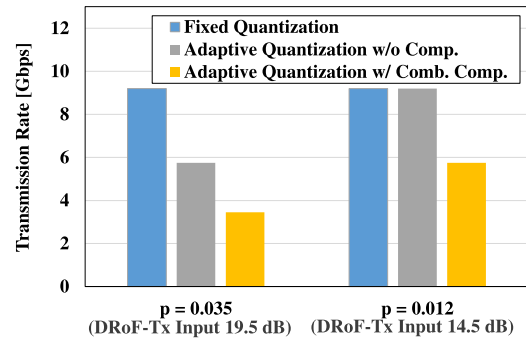

Fig. 9 All channel CNR measurement of output signals from DRoF-Rx. The inset shows a screenshot of the constellation diagram under the conditions $p = 0.035$ and $p = 0.012$.

Fig. 10 Transmission rate results for percentage of time. The transmission rate results under the conditions of percentage of time 0.035 and 0.012 are shown. Three transmission methods are compared: 1) Fixed quantization, 2) Adaptive quantization w/o compression and 3) Adaptive quantization w/ combination compression.

tion was 3.000. This indicates that for most of the time, the adaptive compression scheme yields successful transmission with just 3-bits.

To confirm that all channels met the required quality against the percentage of time p, we scanned all the channels under the conditions of $p = 0.035\%$ and $p = 0.012\%$. Based on the optimization process, $(R_{clip}, \beta, n) = (5, 1, 3)$ at $p = 0.035\%$ and $(R_{clip}, \beta, n) = (9.5, 2, 5)$ at $p = 0.012\%$ were applied as the calculated compression parameters. Figure 8 shows the captured signal spectrum. Snapshots for the case of $p = 0.035\%$ and $p = 0.012\%$ are shown. Figure 9 shows the CNR measurement results of all transmitted channels. Adequate channel CNR was achieved under the conditions of $p = 0.035\%$ and $p = 0.012\%$. From the output CNR results, it is clearly understood that the required CNR of all channels was satisfied for 0.035% and 0.012%. The inset in Fig. 9 shows Ch.#1 and Ch.#11 constellations for 0.035% and 0.012%. These constellation plots confirm that signal reception was realized while maintaining the signal quality even in Ch.#1 and Ch.#11, which are weak against the negative effects of frequency conversion and filtering.

All these results clearly show that our proposal achieved signal transmission and reception with fewer quantization bits at various input CNR values while satisfying the required CNRs in all channels.

Figure 10 shows the transmission rate results for the percentage of time p. Transmission rates for the percentages of time $p = 0.035$ and $p = 0.012$ are shown. Three

transmission methods were compared: 1) Fixed quantization, 2) Adaptive quantization w/o comp. and 3) Adaptive quantization w/ combination compression. In fixed quantization, the quantization bit was fixed at 8-bits, so the transmission rate was also fixed regardless of the input CNR. On the other hand, in adaptive quantization, the minimum quantization bit was assigned according to the input CNR. Therefore, the transmission rate was reduced compared to fixed quantization. However, when the compression is not applied, the effect of reducing the transmission rate is limited due to quality deterioration triggered by quantization error. On the other hand, it is understood that the transmission rate can be dramatically reduced by using the proposal. At $p = 0.035$, a reduction of 62.5% was achieved compared to Fixed quantization. In addition, 40% reduction was obtained compared to Adaptive quantization w/o comp. At the transmission limit of $p = 0.012$, no transmission rate reduction effect was obtained in the case of Adaptive quantization w/o comp. However, by using the proposal, a 25% transmission rate reduction could be achieved.

From these results, our system can achieve a high transmission rate reduction of 62.5% compared to Fixed quantization and 40% reduction compared to Adaptive quantization w/o compression within 99.978% service operation time ($p \geq 0.022$). This means that it covers most of the service operating time. More notably, our system was able to cover 99.988% ($p \geq 0.012$) of the service operating time with the transmission rate reduction effect of 25%.

6. Conclusion

We have proposed the adaptive optical re-transmission system; it applies combination compression with non-linear conversion and peak clipping to UHD BS/CS satellite broadcast signals whose input CNR to DRoF-Tx fluctuates significantly due to rainfall attenuation. Our system dynamically assigns compression parameters according to the input CNR to the DRoF-Tx to achieve the highest possible compression ratio while satisfying the required quality on the receiver side. By reducing the transmission rate as much as possi-

ble according to the input to the DRoF-Tx, the transmission rate of the communication signal shared over PON can be maximized as much as possible. The applicable service operation range of our proposed system was experimentally investigated using the prediction model of ITU-R P.618-13. The proposed system achieved to cover 99.988% of service operating time. Furthermore, we investigated the quantization bit number required for the input CNR values created by the rainfall attenuation range, and showed its impact on the transmission rate. Experiments showed that the service operation time of 99.978% can be achieved with 3-bit quantization. This means our system can reduce the transmission rate by 62.5% compared to conventional fixed quantization. In addition, the average quantization bit number for service operation times ($p \geq 0.012$) was investigated. The average quantization bit number in our system was 3.000. Most of the service operation times are covered by just 3-bit transmission; this is a significant transmission rate reduction effect compared to conventional approaches.

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