3-9 Experiment of Non-Linear Compensation on Satellite Channel

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JAXA plans to use the Ka band (communication system) in order to increase the amount of data transmission between low earth orbit satellites and ground stations. In this paper, we report on the experimental result that the transmission characteristic can be improved by removing the nonlinearity existing in the satellite communication path by Digital Pre-Distortion (DPD) technology based on satellite installation. Moreover, by applying the DPD technique, we report the result that the difference between the degradation amount of the return channel in the ground station during 1.8 Gbps transmission and the degradation amount of the satellite return channel in the 28 GHz band can be reduced to about 0.4 dB. As a result of these experiments, we show that it is possible to estimate the distortion characteristics on the communication path from the receiving constellation and to correct the DPD parameters.

1 Introduction

Nowadays, Earth observation satellites which observe climate change, land-surface change, and so on are required to transmit high-capacity observation data in a short time in addition to expanding the observation area and enhancing the observation resolution, because immediate emergency observation has come to be considered important when natural disasters occur. JAXA plans to apply the frequency of the Ka band to a transmission system between Earth observation satellites and ground stations to fulfill the demand for high-capacity data transmission[1]. The allocable bandwidth of Ka band (25.5-27 GHz) is four times wider than that of X band (8.025-8.4 GHz), which has never been used in the JAXA Earth observation satellites, and the Ka band can be expected to improve transmission speed dramatically. However, the Ka band radio waves largely decay due to rainfall. Therefore, it is required to improve satellite transmission performance (Effective Isotropically Radiated Power: EIRP) to always keep the RF link quality. On the other hand, the Earth observation satellite needs to control the antenna pointing direction to the ground station as time advances, so it is hard to adopt a large antenna which improves the EIRP, because antenna pointing control is restricted by simultaneous data transmission. For this reason, it is essential to adopt a high-power amplifier which contributes to the EIRP improvement. However, the power consumption and heating value of on-board devices are strictly limited, so the devices must operate in a non-linear region with high power efficiency. Therefore, if using the higher-order modulation scheme which has high spectral efficiency, the transmission quality may deteriorate. Accordingly, we have studied the application of a signal distortion compensation technique which linearizes the non-linearity of the amplifier in advance on the satellite side.

This paper reports the experimental confirmatory result that the signal distortion compensation technique on the premise of satellite on-board can control the non-linearity existing in a satellite communication path and improve the transmission quality.

2 Types of non-linear compensation circuits

The distortion compensation methods are divided into two main groups: feedback systems and feedforward system. Feedback systems are not suitable for Ka band communication systems handling a wideband signal, because the operating bandwidth is limited due to the effect of the group delay characteristic for the feedback loop. On the other hand, feedforward systems have superior wideband performance. To materialize a feedforward system by analog circuits has the disadvantages that the amplifier for compensation requires linear operation to avoid degradation of transmission characteristics due to the distortion compensation amplifier itself, and the whole power efficiency of the power amplifier becomes low. It also has the disadvantages that the distortion compensation characteristics are required to be optimized depending on changes of the amplifier subject to compensation and the characteristics of the compensation amplifier itself, and to maintain the good transmission characteristic is difficult.

The digital pre-distortion technique is a method to digitally compensate non-linearity with the feedforward system. The Digital Pre-Distortion (DPD) is a technique that in advance obtains the non-linearity of the amplifier which is subject to compensation by measuring, etc., and removes the distortion component from the output signal of the amplifier by giving the amplifier the reverse non-linearity of the input signal. The advantages of the DPD are that a voluntary distortion compensation characteristic can be easily expressed only by multiplying the transmitting signal, digitally created, by a corrective coefficient, that the DPD is invariable to time, and that the distortion characteristics can be readily corrected, as necessary, by the method of writing the distortion compensation characteristic data in recording elements. These features can stably maintain the optimal characteristics even after launching the satellite. The expression of the corrective coefficient for the DPD has the approximation by a polynomial and the method of referencing the LUT (Look-up Table). Generically, the handling complexity depends on the amplifier characteristics and the distortion compensation performance to be materialized. If the frequency dependence of the amplifier is sufficiently small, it is promising as a distortion

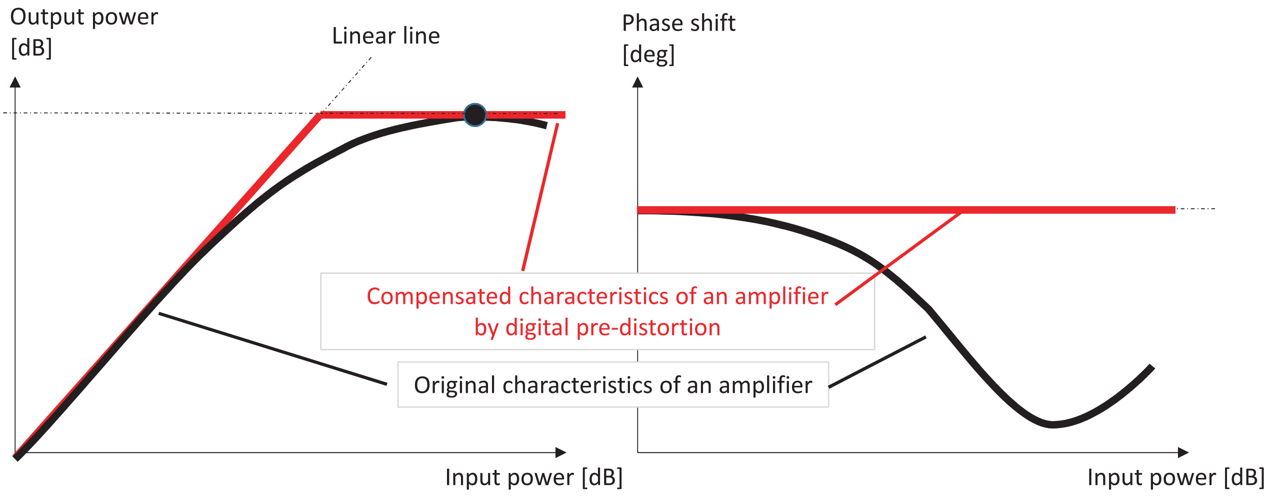


Fig. 1 Linearization concept diagram of amplifier by the DPD

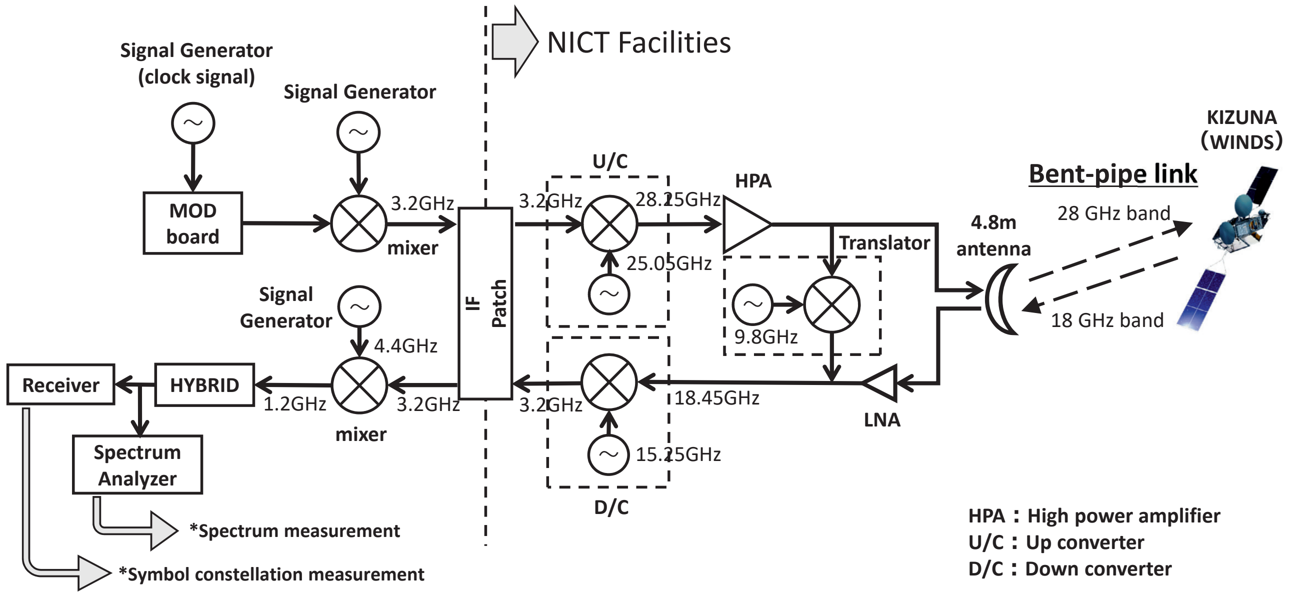


Fig. 2 WINDS experiment system diagram

compensation technique for the satellite, because relatively little computation can sufficiently compensate the distortion[2]. Figure 1 shows a conceptual diagram of the distortion compensation by the DPD. On the one hand, the compensation for the wideband signal requires high-speed operation because the compensable signal bandwidth by the DPD depends on the operation clock of the device, and in fact, it is difficult to remove all distortion components (spectrum re-growth) generated in the range out of the bandwidth. Accordingly, it is necessary not only to remove the distortion components due to the DPD but also to attenuate the radiation component out of the bandwidth by the band-pass filter (BPF), etc. located between the amplifier and the antenna.

3 Communication experiment configuration and overview

To confirm the performance of the non-linear distortion compensation with the DPD circuit, we experimented with the use of the bent pipe link, which uses the multi-beam antenna (MBA) of the wideband internetworking engineering test and demonstration satellite “KIZUNA” (hereinafter called WINDS), as the satellite link of the same Ka band — different from the frequency band allocated to the Earth observation satellite. Figure 2 shows the experiment system diagram at the time. In addition, Fig. 3 shows a photo of the breadboard for the modulation with the DPD function.

The modulated signal output from the breadboard for the modulation is up-converted to a signal of the 3 GHz band, and connects to the input port of the IF patch in the ground station of the NICT Kashima Space Technology Center[3] (hereinafter called Kashima station), Kashima city, Ibaraki prefecture. The Kashima station up-converts the signal of the 3 GHz band to the 28 GHz band, the high-power amplifier (HPA) amplifies the signal, and then the signal is sent from the antenna to the satellite. The WINDS converts the received signal frequency of the 28 GHz band to the frequency of the 18 GHz band, amplifies the signal power, and then sends the signal back to the Kashima station of NICT. The Kashima station down-converts the signal of the 18 GHz band received from the WINDS to the 3 GHZ band, and outputs it from the IF patch. In addition, the Kashima station has a frequency translator (hereinafter called “translator”) path as the path without using the satellite. The translator path is one to down-convert the up-converted signal of the 28 GHz band to the 18 GHz band and to connect to a reception path. The WINDS and translator paths can be changed by a switch. To observe the difference of the signals passing two different paths can evaluate the effect of the satellite communication path.

The received signal of the 3 GHz band is input to a receiver after being converted to 1.2 GHz frequency. The receiver used the cortex high data rate receiver, made by Zodiac Data Systems, available as a receiver for the Earth observation satellite[4]. The non-linear compensation performance by the DPD circuit was evaluated by BER (Bit Error Rate) at the demodulator. The high-power amplifiers respectively exist in the Kashima station and the satellite in the WINDS path, and the operating point of these amplifiers changes by radio attenuation due to clouds, etc. Therefore, the non-linearity of the satellite communication path cannot be identified in advance. For these reasons, we decided to estimate the non-linearity of the satellite communication path by the received constellation distribution to fix the corrective coefficient of the DPD. We set the data sequence to be sent to the 15-stage pseudo-random noise (PRN 15) which does not include an error-correcting code, and measured the BER after the receiver bit-synchronized to reset the bit error counter to zero (zero-reset). At the time, the ratio of signal power per bit vs. noise power

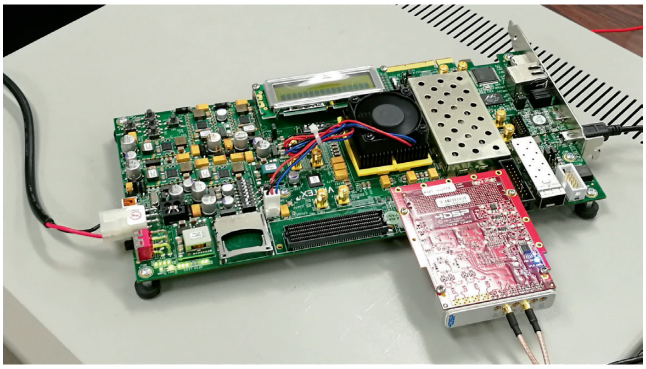


Fig. 3 Appearance of trial-product board equipped with non-linear distortion compensation circuit

Table 1 Main experiment parameters

Parameter	Value	Remarks
Symbol rate	340, 450 Msps	Selectable
Data pattern	PRN (Pseudo-Random Noise)	15-stage
Roll-off rate	0.4	Root-raised-cosine filter common to sending and receiving
Modulation scheme	16 QAM	

density (Eb/No) was calculated by the signal power and the noise power density measured with a spectrum analyzer after distributing the signal at the input port of the receiver by the directional coupler. As the satellite loopback system cannot freely control the noise amount, this experiment obtained the BER characteristics while varying Eb/No by changing the output power of HPA. The main parameters for this experiment are shown in Table 1. The MBA link of WINDS has 1.1 GHz bandwidth and has a sufficiently wide bandwidth for this experiment.

4 Experimental results

4.1 BER characterization by the DPD

To confirm the BER improvement effect by the DPD, we obtained BER in implementing the DPD on the 350 Msps symbol rate (data rate: 1.36 Gbps) that can most clearly confirm the non-linearity at a transmission rate exceeding 1 Gbps. In the satellite loopback communication path, as the non-linearities of the amplifier in the ground station and the amplifier mounted on the satellite are reflected in the whole non-linearity, we set a proper satellite repeater gain and conducted the test so that the BER characteristics can be confirmed in the widest dynamic range. Figure 4 shows the experimental results. The measured result of the translator loopback path shows that BER is improved as Eb/No becomes large (Fig. 4: green solid line). In addition, the required Eb/No seems to increase as BER becomes small. The error floor seems to appear around the point where the output power of the HPA in the ground station exceeds 47.2 dBm. This result tells us that for the translator path, the non-linear effect of the HPA of the ground station happens when the output power is around 47 dBm.

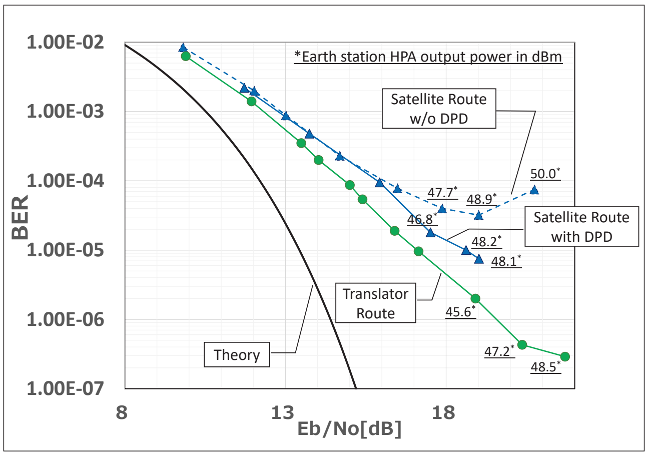


Fig. 4 BER characteristic change by the DPD

Next, the result measured in the satellite loopback path (Fig. 4: blue dashed line) tells us that, like the translator path, the BER seems to degrade as Eb/No becomes large. The error floor appears around the point where Eb/No exceeds 18 dB, and then BER rises as Eb/No rises. This is consistent with the trend that the signal distorts due to the saturation characteristic of the amplifier and the bit error determinately starts to arise. As compared to the result of the translator path, the degradation of BER is more noticeable. Therefore, it can be presumed that the effects by the non-linearities of not only the HPA in the ground station but also the satellite's on-board amplifier are added. We enabled the DPD to control the effect of these non-linearities (Fig. 4: blue solid line). As the I/O characteristics of the satellite's on-board amplifier are unknown, the LUT coefficient of DPD adjusted to that BER becomes the minimum. However, Subsection **4.2** will conduct evaluation of the effect on BER by the inconsistency of the non-linearity of the communication path with the distortion compensation characteristic. As a result of measurement, without the DPD, the best value of BER was 3.2×10^{-5} (Eb/No=19 dB), but it became 7.5×10^{-6} (Eb/No=19 dB) with the DPD, and even if increasing the output of HPA, BER did not degrade. In the range that Eb/No was 16 dB or less, BER did not show significant change regardless of the DPD. Therefore, it was estimated that the bit error by the Gaussian noise was dominant.

4.2 The Effect of inconsistency of amplifier characteristics and distortion compensation quantity on BER

For the satellite's on-board DPD which we suggest, it is required that the signal including inverse distortion made by the LUT is consistent with the non-linearity of the amplifier, because the LUT compensates the non-linearity of the amplifier. If the variation in the input level to the amplifier or the gain variation of the amplifier arises due to aging degradation, etc., the lowering effect of the DPD is expected since the distortion characteristic is not consistent with the compensation characteristic. Thus, we confirmed the BER degradation when increasing or decreasing the LUT 0.5 dB from the optimal operating point at a time. Figure 5 shows the DPD sensitivity measured result (Fig. 5: red solid line). The variation of the received power, or the variation of Eb/No, when decreasing or increasing the input power only by 0.5 dB, was -0.18 dB or +0.51 dB, respectively. The output power did not change linearly in response to the change in input power because the output power depends on the amplifying characteristics of the communication path. As compared to BER when implementing the optimal DPD for each Eb/No, BER when changing the LUT by 0.5 dB from the optimal operating condition deteriorates. Therefore, it was observed that the increasing case and the decreasing case for the input power were different. It is assumed that not only the change of the input power but also the difference of non-linearities between the input and output characteristics of the amplifiers which are not compensated arise as the difference of the degradation quantity. From these findings, we found it necessary to evaluate BER in consideration of the signal at the input point of the amplifier and the stability of the amplifier characteristics in actual operation.

4.3 BER characteristic improvement by the DPD on 1.8 Gbps transmission system

Finally, the measurement of BER by the satellite loopback system was made using a 450 Msps symbol rate, 0.4 roll-off rate and the 16 QAM signal to confirm the improvement effect of BER by the DPD at 1.8 Gbps data transmission speed which is expected to be realized for the next-generation Earth observation satellite. From the experimental result in Subsection **4.1**, the BER degradation due to the transmission path characteristics other than the non-linearity also exists and becomes large as the transmission rate increases. For these reasons, the BER degradation quantity of the whole experiment system was reduced by reducing the transmission loss due to cables, etc. before this measurement. Figure 6 shows the experimental result of the BER measurement. The BER characteristics of the translator loopback path (Fig. 6: solid lines) as reference are improved over the time of the experiment. In addition, Figure 6 tells us that the result obtains very close characteristics compared to the prediction result for the BER characteristic of the translator path calculated by the characteristics of the device used in the ground station, and that the experimental system is able to be constructed as expected. The comparison of the result (Fig. 6: blue dashed line) before applying the DPD, obtained in the satellite loopback path, and the result after applying the DPD (Fig. 6: blue solid line) allows the confirmation of the highest dissolution of the error floor, which arises due to the non-linearity of the amplifier, by applying the DPD.

In addition, Figures 7 and 8 show the received spectrum and constellation before and after applying the DPD when

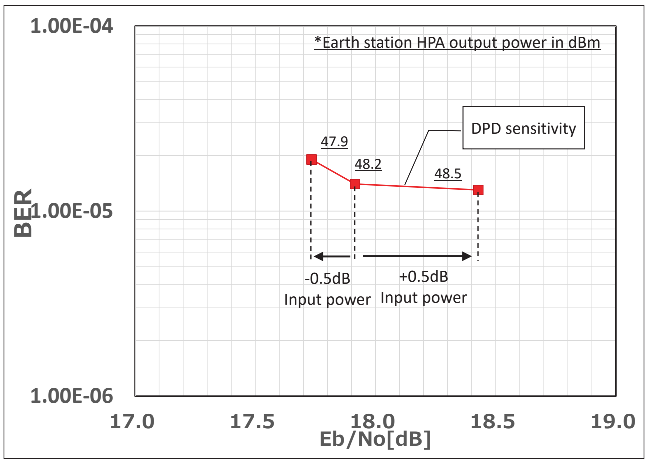


Fig. 5 Compensation sensitivity verification for the DPD

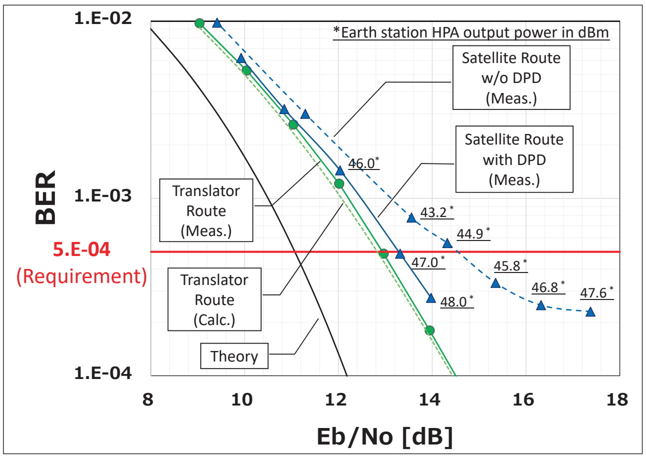
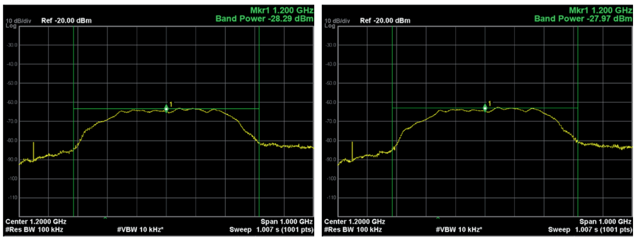
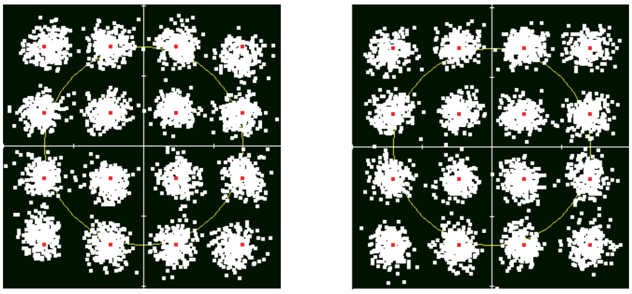


Fig. 6 Effect of DPD at 1.8 Gbps transmission



(a) DPD=OFF (b) DPD=ON

Fig. 7 Spectrum when applying DPD at 1.8 Gbps transmission



(a) DPD=OFF (b) DPD=ON

Fig. 8 Constellation when applying DPD at 1.8 Gbps transmission the output power of the HPA in the ground station is 48.0 dBm. The received spectrum does not show significant change due to the DPD. This is because the re-growth component reduced by the DPD is covered by thermal noise. On the other hand, the received constellation allows the confirmation of the effect dissolution of the power compression and the phase rotation in the communication path by the DPD. The comparison of the result (Fig. 6: blue solid line) after applying the DPD, obtained in the satellite loopback path, and the result of the translator loopback (Fig. 6: green solid line) gave the result that the difference from the required Eb/No at the BER requirement of 5×10^{-4} before decoding the error-correcting required by the satellite system is small, about 0.4 dB, and that the DPD application allows the transmission loss in the satellite communication path to become smaller.

5 Summary

In this experiment, we intended to improve the degradation of the transmission characteristics which arise due to the non-linear distortion of the power amplifier existing in the satellite communication path with the DPD technology assuming the satellite on-board. As the experimental result, we could experimentally confirm that the DPD using one LUT effectively compensated the non-linearity existing in the satellite communication path and that the transmission characteristics could be improved. Furthermore, we clarified that the consideration of the degradation of the transmission characteristics due to the power variation of the transmitter and the variation of the amplifier could reduce the frequency of update of the LUT, and that only correcting the LUT to give the received constellation an optimal allocation allowed the LUT to be easily updated. Therefore, this is practically a powerful method.

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