Self-Interference Cancellation for Shared Band Transmission in Nonlinear Satellite Communication Channels

Sooyeob Jung, Joon Gyu Ryu, Deock-Gil Oh, and Heejung Yu

For efficient spectral utilization of satellite channels, a shared band transmission technique is introduced in this paper. A satellite transmits multiple received signals from a gateway and terminal in the common frequency band by superimposing the signals. To improve the power efficiency as well as the spectral efficiency, a travelling wave tube amplifier in the satellite should operate near the saturation level. This causes a nonlinear distortion of the superimposed transmit signal. Without mitigating this nonlinear effect, the self-interference cannot be properly cancelled and the desired signal cannot be demodulated. Therefore, an adaptive compensation scheme for nonlinearity is herein proposed with the proper operation scenario. It is shown through simulations that the proposed shared band transmission approach with nonlinear compensation and self-interference cancellation can achieve an acceptable system performance in nonlinear satellite channels.

Keywords: Nonlinear effect, Nonlinearity compensation, Satellite communication, Self-interference cancellation, Shared band transmission.

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I. Introduction

Based on the increasing demands for broadband multimedia services, the efficient spectrum utilization has become the most significant performance measure in satellite communication systems. To improve spectrum efficiency, the concept of a *shared band transmission* has been introduced. It can be regarded as an analog network coding scheme and a carrier super-positioning method. For example, two sources, such as a gateway and terminal, exchange their own data with each other through an intermediate node, such as a satellite in a frequency division duplex manner. Uplink signals from two different sources are transmitted in different frequency bands. However, downlink signals from the satellite to both the gateway and terminal are sent in the common frequency band. These two downlink signals are superimposed, that is, added, and one signal is then considered interference to the other signal. Owing to the network topology, the interference in the downlink signal, which is the sum of two signals from two different sources, is the returned version of the transmitted signal. Therefore, this interference is called *self-interference* or an *echo*. Under ideal channel conditions without a nonlinear effect and synchronization errors, self-interference is perfectly cancelled out using a replica of the transmitted signal with adjustments in the time and gain. Compared with a conventional satellite transmission scheme, the shared band transmission scheme can improve the spectral efficiency by sharing the downlink frequency band in the forward and return links.

In practice, the nonlinear effect in satellite channels cannot be avoided because of the use of a travelling wave tube amplifier (TWTA), which has a nonlinear property, for signal retransmission. To effectively cancel out any self-interference, the nonlinearity should be eliminated. When the exact parameters in the nonlinear model are unavailable, or the parameters vary over time owing to aging or temperature effects, the residual interference—caused by an imperfect cancellation—significantly degrades the system performance. Additionally, synchronization processes for the returned signal and signal regeneration are required with a consideration of the synchronization and signal power matching before the interference cancellation.

Shared band transmission techniques for satellite communication systems have been previously studied [1]–[6]. However, the nonlinear effects of satellite channels have been minimally investigated. For instance, the inverse function of the Saleh nonlinear model has been employed for compensation of the nonlinear effect of a TWTA in a satellite [4]. However, it is infeasible to use this inverse function for real implementation because of the restriction of the filter length. In [5], an interference cancellation method for shared band transmission was proposed by using the linear adaptive filter without consideration of nonlinear effects. The authors of [6] considered nonlinearity in a shared band transmission and suggested two different approaches to address self-interference cancellation. The first approach is to compensate the nonlinearity effect in the received composite signal. The other is to add the nonlinear effect on the reference signal and then cancel out the nonlinear self-interference. However, details on a nonlinearity estimation method were not mentioned in [6].

In in-band full-duplex communication, in which a communication node transmits and receives signals simultaneously with the same frequency band, the self-interference cancellation has been considered to obtain the desired data after cancelling out the transmitted signal [7], [8]. The authors of [8] proposed an adaptive nonlinear interference cancellation based on the memory polynomial model and a least mean squares (LMS) algorithm. In this case, the source of nonlinearity, that is, a power amplifier, is located in the same node and the nonlinearity can be directly estimated. With the estimated nonlinear coefficients, the distorted reference signal, specifically the replica of the transmit signal with nonlinear effects, can be generated and used for self-interference cancellation. In cases of satellite channels, the nonlinearity of a TWTA at a remote satellite should be considered. Accordingly, the existing approaches for in-band full-duplex radios cannot be directly applied for shared band transmission in a satellite channel.

In [9] and [10], the authors suggested equalization methods for the nonlinear satellite channel, such as LMS and the echo state network (ESN). Emerging from artificial neural networks, ESN shows a performance similar to that of the LMS approach. However, these studies have not included the interference cancellation for shared band transmission.

In this paper, an adaptive nonlinearity compensation scheme using a recursive least squares (RLS) algorithm [11] is adopted to compensate the unknown and time-varying nonlinearity of satellite channels. Although the dominant characteristics of nonlinearity have been previously known in general terms, they can be changed depending on the used satellite and other environment factors, such as aging and temperature effects. In the proposed operation scenario, a gateway first transmits its signal, and terminals then respond to the received signal. Initially, the gateway conducts the training of an adaptive nonlinearity compensator. After this initial phase is performed to train the adaptive algorithm, the nonlinearity of a TWTA is compensated and the desired signal with negligible residual interference can be obtained. It was shown through computer simulations that the proposed approach had < 1 dB of bit error performance loss at a 1% bit error probability under various conditions.

We herein employ standard notations. Vectors and matrices are written in boldface lowercase and uppercase characters, respectively. All vectors are column vectors. For matrix $\mathbf{A}$, $\mathbf{A}^T$ and $\mathbf{A}^H$ indicate the transpose and Hermitian transpose of $\mathbf{A}$, respectively. Finally, $E\{\cdot\}$ denotes the expectation of a random variable.

The remainder of this paper is organized as follows. Section II describes the presented system model and the proposed operation scenario. Sections III and IV illustrate the nonlinearity compensation using an RLS algorithm, the synchronization issues, and self-interference cancellation. The numerical results under various system configurations are presented in Section V, and concluding remarks are given in Section VI.

II. System Model

For the presented system model, two-way satellite communication channels are considered, where one gateway (an earth station) and one terminal simultaneously exchange their data through a satellite with a nonlinear TWTA, as shown in Fig. 1. The gateway sends a wideband signal, such as a digital video broadcasting–satellite second generation (DVB-S2) signal [12], [13], to a terminal with a high transmit power and high gain antenna. The terminal transmits a narrowband signal, such as a digital video broadcasting-return channel via satellite second generation (DVB-RCS2) signal [14], to the gateway with a low power and low gain antenna owing to

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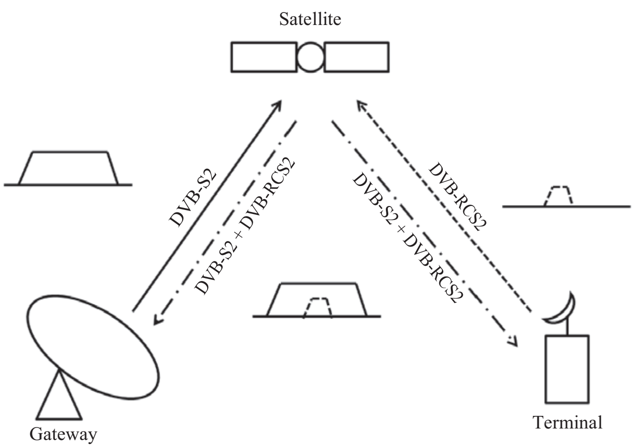

Fig. 1. System model.

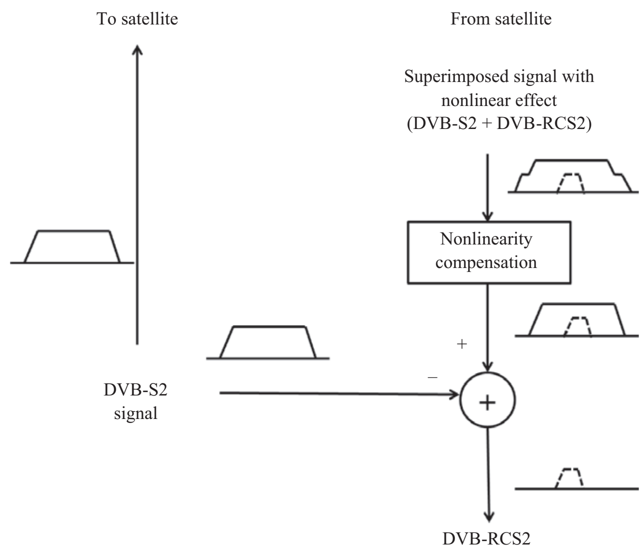

Fig. 2. Nonlinearity compensation and self-interference cancellation in a gateway.

terminal power and space limitations. In conventional satellite communication systems, the wideband signal in a forward link and the narrowband signal in a return link are transmitted by a satellite in a different frequency band. In the proposed system employing a shared band transmission, however, these two signals in the forward and return links are added and retransmitted to the earth station in the same frequency band. As a result, the frequency band for the return link can be saved. In particular, multiple terminals transmit multiple narrowband signals in a frequency division multiple access manner, and the spectral efficiency can be significantly increased.

At the terminal, the desired wideband signal has a much higher power than narrowband self-interference, which is transmitted by the terminal itself. This interference can be negligible and regarded as additional background noise. In contrast, in terms of the gateway, the power of the desired signal is much lower than that of the wideband self-interference, and the desired narrowband signal cannot be detected or decoded without cancellation of the self-interference. In this paper, we therefore focus on the self-interference cancellation at the gateway frontend. Moreover, owing to additive white Gaussian noise (AWGN) in the satellite and gateway frontend, a carrier frequency offset (CFO), timing and gain mismatches, and nonlinear effects distort the originally transmitted wideband signal. To properly cancel the self-interference, therefore, the gateway should conduct an accurate CFO estimation, gain and time matching, and compensation of the nonlinearity. The overall signal flow for self-interference cancellation in the gateway is shown in Fig. 2.

In a general wireless communication system, including the nonlinearity of the power amplifiers, a predistortion method is employed to compensate for the nonlinearity effects at a transmitter. However, a predistortion approach is not suitable for the system configuration considered in this paper. A nonlinearity compensation block and a nonlinear amplifier are commonly located in the same transmitter module. Thus, an adaptive algorithm can be directly applied with error signals between the desired pre-distortion output and the current output. Nearly zero delay occurs in calculating the error signal because the actual output signal with the updated coefficients of pre-distortion can be obtained with negligible delay. In the system model described herein, on the other hand, the pre-distortion function used to compensate the nonlinearity of a satellite's TWTA can be implemented not in the satellite, but in the gateway. This is because the satellite has already been launched and placed in orbit. Therefore, the delay in obtaining the output signal of a TWTA with the current pre-distortion coefficients is longer than the round-trip delay between the gateway and satellite, such as 250 ms. It thus requires a very long time to converge the pre-distortion coefficient; hence, a pre-distortion approach cannot be employed. To address this issue, a post-distortion approach to compensate the nonlinearity of a TWTA is proposed in this paper.

A system operation scenario is described as follows. First, the gateway broadcasts a wideband DVB-S2 signal through a satellite. After receiving the gateway signal of a forward link, the terminal can send back its narrowband signal, such as DVB-RCS2, to the gateway via the satellite. Based on this operation scenario, the gateway can calculate the coefficients to compensate the nonlinearity with an RLS algorithm based on a memory polynomial. These computed coefficients are inversely multiplied before the self-interference cancellation for the remaining

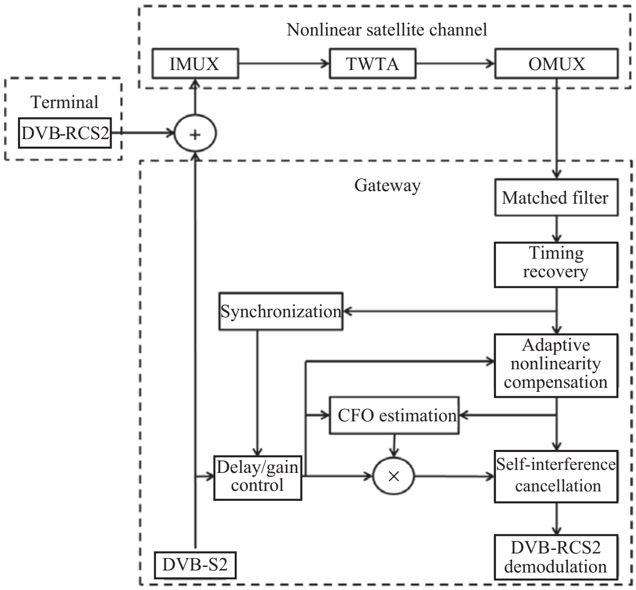

Fig. 3. Detailed structure of the proposed system.

operation of a shared band transmission. The detailed structure of the proposed system is shown in Fig. 3. The overall system operation is as follows:

Begin **Initialization Phase**: The returning DVB-S2 signal is received.
Step 1.1. Perform the matched filtering and timing recovery.
Step 1.2. Find the starting time of an appropriate packet.
Step 1.3. Train the coefficients of the adaptive nonlinearity compensation using an RLS algorithm.
End **Initialization Phase**.

Begin **Normal Phase**: A superimposed signal of DVB-S2 and DVB-RCS2 is received.
Step 2.1. Perform the matched filtering and timing recovery.
Step 2.2. Find the starting time of an appropriate packet (reuse the timing of Step 1.2).
Step 2.3. Compensate the nonlinearity by using coefficients obtained in Step 1.3.
Step 2.4. Perform the coarse, fine, and residual CFO estimation and distortion of the reference DVB-S2 signal.
Step 2.5. Eliminate the self-interference by using the reference DVB-S2 signal with CFO distortion.
Step 2.6. Extract and demodulate the DVB-RCS2 signal.
End **Normal Phase**.

III. Nonlinearity Compensation

In this section, the power amplifier models with the nonlinear properties are introduced. The signal distortion caused by nonlinearity can lead to severe performance degradation, especially in the shared band transmission system. Therefore, to solve this nonlinearity problem, we suggest the compensation model using an RLS algorithm.

1. Power Amplifier Model

To model the nonlinearity of a TWTA, the Saleh model has been widely used [4]. The amplitude-to-amplitude modulation (AM/AM) and amplitude-to-phase modulation (AM/PM) characteristics are described with the following equations:

$$g(r) = \frac{\alpha_x r}{1 + \beta_x r^2} \tag{1}$$

and

$$f(r) = \frac{\alpha_\phi r^2}{1 + \beta_\phi r^2}, \tag{2}$$

where r is the amplitude of the input, and α_x, β_x, α_ϕ, and β_ϕ are nonlinearity parameters. When the input signal is given by $x(t)$, the output signal is expressed by

$$y(n) = g(|x(n)|)\exp\big(jf(|x(n)|)\big). \tag{3}$$

Additionally, the recommended characteristics of AM/AM and AM/PM for a TWTA are provided in the DVB-Sx specifications. The reference MATLAB code is also provided. In this paper, these two different models are used to emulate the TWTA, as shown in Fig. 4. For the Saleh model, nonlinear parameters with $\alpha_x = 2.0$, $\beta_x = 1.0$, $\alpha_\phi = 3.0$ and $\beta_\phi = 2.0$ are used. The provided models do not include the memory effects. However, the input multiplexer (IMUX), output multiplexer (OMUX), and filters in a transmitter and receiver can cause memory effects.

To avoid the significant nonlinearity of a TWTA, a backoff of the TWTA operation point, that is, a reduction of the input signal power, is needed. A higher backoff guarantees greater linear output; nonetheless, it means a lower transmit signal power, even with the same TWTA. The input backoff (IBO) of a TWTA is characterized by

$$\mathrm{IBO} = -10\log_{10}\left(\frac{\mathrm{E}\{r^2\}}{A_\mathrm{I}^2}\right), \tag{4}$$

where r denotes the amplitude of an input signal to the TWTA at the operating point and A_I is the amplitude of the input signal at the saturation point, which achieves the maximum output power of a TWTA.

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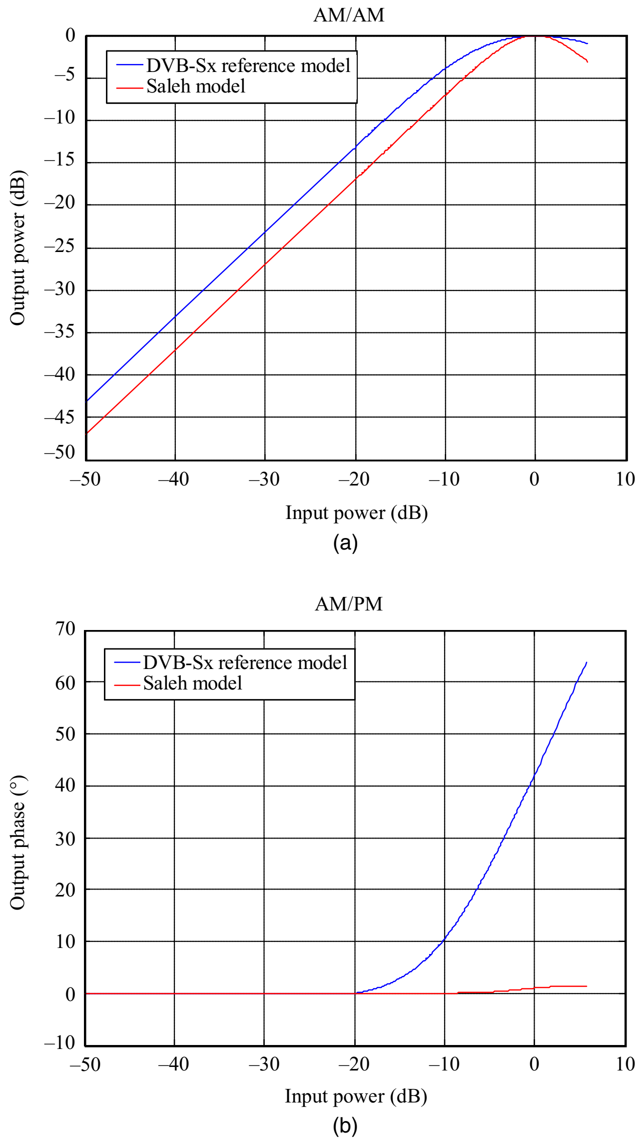

Fig. 4. Nonlinear characteristics of a TWTA in DVB-Sx reference model and Saleh model: (a) AM/AM and (b) AM/PM.

2. Nonlinear Compensation Model

To create a model for nonlinear compensation, the following memory polynomial approximation is employed as in [15] and [16].

$$y(n) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} h_{kl}^{*} x(n-l)|x(n-l)|^{2k}, \tag{5}$$

where $x(n)$ and $y(n)$ denote the baseband input and output of the compensator, respectively, and h_{kl} are coefficients characterizing the nonlinearity compensation. In addition, K and L denote the order of the polynomial and memory depth of the memory polynomial. To develop an adaptive algorithm for a nonlinear compensation, (5) can be rewritten as

$$y(n) = \mathbf{h}^{\mathrm{H}}\mathbf{x}(n), \tag{6}$$

where

$$\mathbf{h} = \begin{bmatrix} \mathbf{h}_0^{\mathrm{T}} & \mathbf{h}_1^{\mathrm{T}} & \cdots & \mathbf{h}_{L-1}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}, \tag{7}$$

$$\mathbf{h}_l = \begin{bmatrix} h_{0l} & h_{1l} & \cdots & h_{(K-1)l} \end{bmatrix}^{\mathrm{T}}, \tag{8}$$

$$\mathbf{x}(n) = \begin{bmatrix} \mathbf{x}_0^{\mathrm{T}}(n) & \mathbf{x}_1^{\mathrm{T}}(n) & \cdots & \mathbf{x}_{L-1}^{\mathrm{T}}(n) \end{bmatrix}^{\mathrm{T}}, \text{and} \tag{9}$$

$$\mathbf{x}_l(n) = x(n-l)\begin{bmatrix} 1 & |x(n-l)|^2 & \cdots & |x(n-l)|^{2(K-1)} \end{bmatrix}^{\mathrm{T}}. \tag{10}$$

Based on this model, we can estimate the nonlinear coefficients in (6). To obtain coefficient $\mathbf{h}$, the received signals are accumulated as

$$\mathbf{y}(n) = \mathbf{h}^{\mathrm{H}}\mathbf{X}(n), \tag{11}$$

where

$$\mathbf{y}(n) = [\, y(n) \quad y(n-1) \quad \cdots \quad y(n-M+1)\,], \tag{12}$$

$$\mathbf{X}(n) = [\, \mathbf{x}(n) \quad \mathbf{x}(n-1) \quad \cdots \quad \mathbf{x}(n-M+1)\,]. \tag{13}$$

When M is sufficiently large, we can obtain $\mathbf{h}$ using an inverse operation, that is,

$$\mathbf{h} = \mathbf{y}(n)\mathbf{X}(n)^{\mathrm{H}}\left(\mathbf{X}(n)\mathbf{X}(n)^{\mathrm{H}}\right)^{-1}. \tag{14}$$

However, the complexity of an inverse operation increases with K, L, and M.

To mitigate the time-varying nonlinearity, an adaptive nonlinearity compensation using an RLS algorithm is adopted. According to the operation scenario proposed in this paper, it is desired to obtain the convergent solution as soon as possible in the initialization phase before superimposing DVB-S2 and DVB-RCS2 signals. Therefore, we use the RLS approach, which has the fast convergence property. To this end, the least squares (LS) error function, that is, a cost function, is considered:

$$E(n) = \sum_{i=1}^{n} \lambda^{n-i}|e(i)|^2, \tag{15}$$

where

$$e(i) = s(i) - \mathbf{w}(n)^{\mathrm{H}}\mathbf{x}(i). \tag{16}$$

Here, $s(i)$ denotes a baseband transmit signal at the gateway, that is, a baseband input of a TWTA at the satellite without noise, and λ $(0 < \lambda \le 1)$ is a forgetting factor. Error $e(i)$ then indicates the difference between a TWTA input and an output of the nonlinear compensator with coefficients $\mathbf{w}(n)$. The RLS algorithm for calculating the optimal $\mathbf{w}(n)$, which minimizes the LS error function, is described [11] as

$$\mathbf{k}(n)=\frac{\lambda^{-1}\boldsymbol{\Gamma}(n-1)\mathbf{x}(n)}{1+\lambda^{-1}\mathbf{x}^{\mathrm{H}}(n)\boldsymbol{\Gamma}(n-1)\mathbf{x}(n)}, \quad (17)$$

$$\varepsilon(n)=s(n)-\mathbf{w}^{\mathrm{H}}(n-1)\mathbf{x}(n), \quad (18)$$

$$\mathbf{w}^{\mathrm{H}}(n)=\mathbf{w}^{\mathrm{H}}(n-1)+\mathbf{k}(n)\varepsilon^{*}(n), \text{and} \quad (19)$$

$$\boldsymbol{\Gamma}(n)=\lambda^{-1}\boldsymbol{\Gamma}(n-1)-\lambda^{-1}\mathbf{k}(n)\mathbf{x}^{H}(n)\boldsymbol{\Gamma}(n-1), \quad (20)$$

where $\mathbf{k}(n)$ and $\boldsymbol{\Gamma}(n)$ are the gain vector and inverse correlation matrix, respectively.

IV. Synchronization and Interference Cancellation

Before cancelling the self-interference, synchronization, such as symbol timing recovery, frame synchronization, CFO estimation, and compensation, should be established. The synchronization schemes are based on some algorithms used in the DVB-S2 modem [17]. For symbol timing recovery, the well-known Gardner algorithm [18] can be used; however, other synchronization schemes are not directly applied to the receiver for interference cancellation because the interference cancellation requires much higher performance, that is, more accurate synchronization. For frame synchronization, the conventional method should be modified to find the starting point of the desired packet. Specifically, it should distinguish the desired packet from the other packets by comparing the data part of the packet as well as the preamble part.

To simultaneously find the desired packet and its starting point, a new frame synchronization scheme is required. A conventional method, which is used in a receiver to decode a pure DVB-S2 packet, only needs to find the starting point of any packet. For self-interference cancellation, however, we must distinguish the appropriate packet to be cancelled with the other packets. The cross-correlation between a received signal and the known preamble—for example, the start of the frame (SOF) field in the DVB-S2 frame—is calculated, and the point with the maximum magnitude of the cross-correlation is selected to find the starting point of the packet. Additionally, to verify the appropriate packet, a cross-correlation with the initial data part of the packet is compared with the threshold. Therefore, the frame synchronization is established at the point where the magnitude of the cross-correlation with the preamble part is maximized, and the magnitude of the cross-correlation with the initial data part is greater than the threshold.

The CFO estimation accuracy should be improved to minimize the residual interference after cancelling the self-interference compared with that of a conventional DVB-S2 receiver. First, the preamble part—that is, the physical layer header (PLHEADER), which is composed of the SOF and physical layer signaling (PLS) code—is used for the initial CFO estimation [19]. The phase rotation of the received signal is calculated by multiplying the beginning of the received packet with the conjugate version of the preamble. Using a discrete Fourier transform (DFT) operation, the CFO estimation can be obtained. To enhance the accuracy of the initial CFO estimation, we can use a large-sized DFT after padding with zeros. More accurate CFO estimation can be achieved using the data part after correcting for the initial estimated CFO effects. To this end, the conjugate of the transmitted signal is multiplied with the received signal after compensating the initial CFO effects. The results of the multiplication have a linear phase depending on the residual CFO. The phase difference between samples can be used to obtain the residual CFO estimation.

After the synchronization processes, we can extract the desired narrowband signal by cancelling the self-interference. A replica of the received self-interference can be generated with the transmit signal by adjusting the gain, timing, and frequency offset. Because the interference has much higher power than the desired narrowband signal, a small mismatch between the self-interference and its replica can cause a significant performance loss when demodulating the narrowband signal. Therefore, this mismatch should be mitigated through an enhanced CFO estimation.

V. Numerical Results

To evaluate the system performance with self-interference cancellation, computer simulations were performed in various conditions. In the simulations, one gateway, one satellite, and multiple terminals were considered. The gateway transmitted a DVB-S2 frame with a normal type [12] to terminals through the satellite. This signal occupied the 100 MHz bandwidth and had a roll-off factor of 0.35.

The satellite received the signal, and it amplified and retransmitted it in a different frequency band. After receiving this DVB-S2 signal, terminals began sending a narrowband DVB-RCS2 signal, of which the bandwidth was 10% of the bandwidth of a wideband DVB-S2 signal. At the satellite, the received signal power of DVB-S2 was 30 dB higher than that of DVB-RCS2 because the gateway transmitted the forward link signal with a high transmit power and high antenna gain. The spectrums of these transmit signals at the satellite are shown in Fig. 5. The DVB-S2 signal shows a 20 dB higher power spectral density than the DVB-RCS2 signal because the DVB-S2 signal occupies a ten-fold wider bandwidth than the DVB-RCS2 signal. The spectrum of the DVB-RCS2 signal in the composite signal is not shown because its power is much lower than that of the DVB-S2 signal.

After synchronization and self-interference cancellation, a narrowband DVB-RCS2 signal became visible in the power spectrum, as shown in Fig. 6. To show this spectrum, a 15 dB IBO was assumed, and the signal-to-noise ratio (SNR) with respect to the DVB-RCS2 signal—the ratio of the DVB-RCS2 signal power to AWGN—was set to 12 dB. In the spectrum of the output signal of the interference cancellation, a narrowband signal showed an approximately 12 dB higher power spectral density than the background noise. Therefore, it can be considered that the residual interference after a self-interference cancellation had much lower power than the background noise, and the cancelling performance of the self-interference cancellation was acceptable under the given condition.

Figure 7 shows the constellations of a narrowband signal modulated with QPSK at 18 dB SNR with respect to a narrowband signal. As shown in Fig. 7(a), the

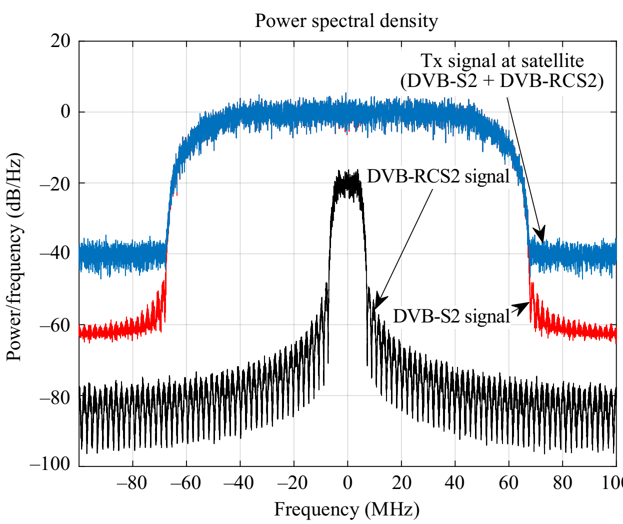

Fig. 5. Power spectrum of transmit signals (IBO = 15 dB).

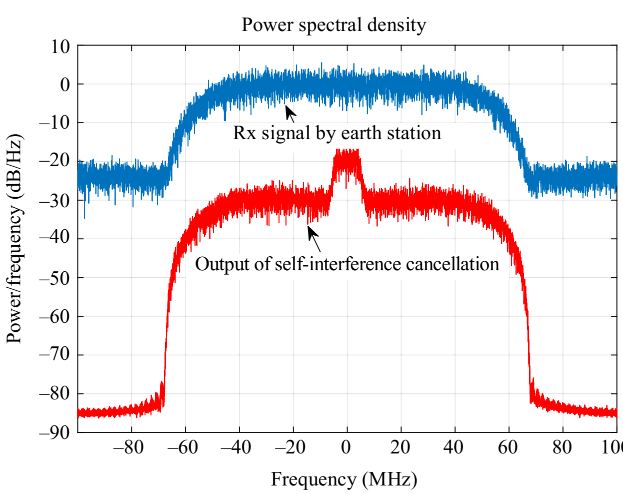

Fig. 6. Power spectrum of the desired narrowband signal after self-interference cancellation (IBO = 15 dB, SNR = 12 dB).

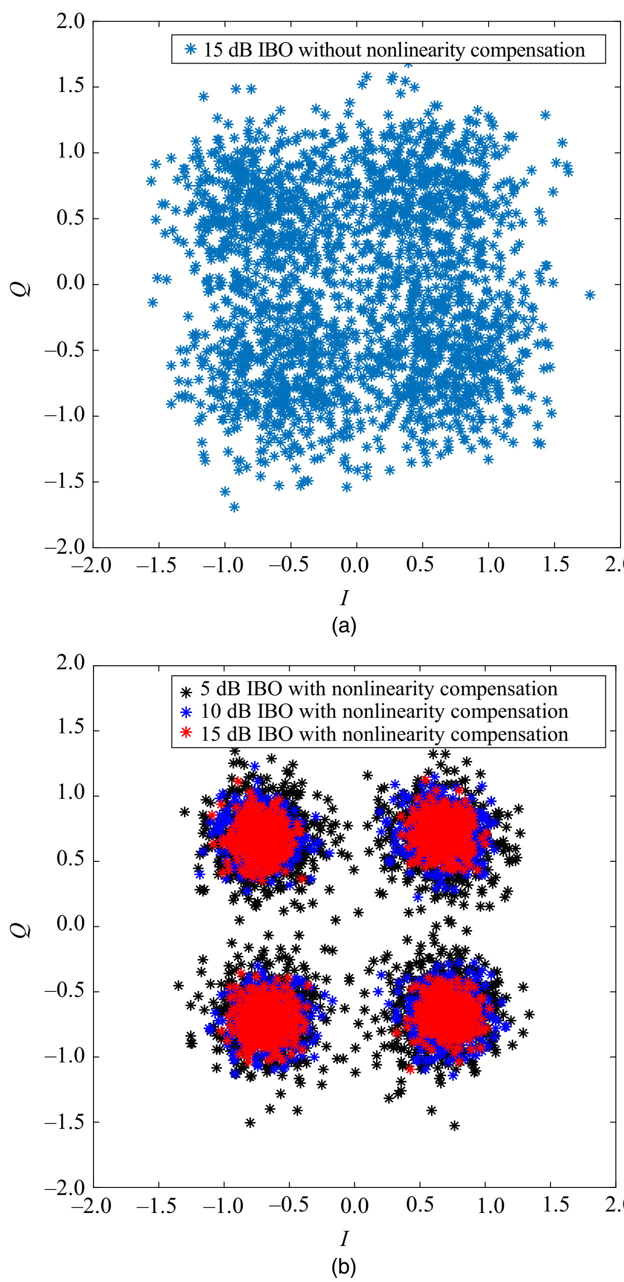

Fig. 7. QPSK constellations of a narrowband signal when SNR = 18 dB (a) without a nonlinearity compensation at 15 dB IBO and (b) with nonlinearity compensation at 5 dB, 10 dB, and 15 dB IBO.

constellation of the narrowband signal is spread out when the nonlinearity of the received signal with 15 dB IBO is not compensated. Figure 7(b) shows the constellations of the desired signal with different IBO values when the nonlinearity of a TWTA is compensated using the proposed RLS algorithm. In this paper, we assume that the order of the polynomial and memory depth in (6) are given by $K = 3$ and $L = 3$. As IBO increases, we can obtain a better performance because a nonlinear effect of a TWTA is reduced and is more effectively compensated.

To show the overall system performance in terms of the un-coded bit error rate (BER) of the narrowband signal, two different nonlinear models were adopted. One was the Saleh model with nonlinear parameters $\alpha_x = 2.0$, $\beta_x = 1.0$, $\alpha_\phi = 3.0$, and $\beta_\phi = 2.0$. The other was provided through the reference channel model for the DVB-Sx standards. Its AM/AM and AM/PM characteristics are shown in Fig. 4. BER curves with different IBOs under the two TWTA models are shown in Figs. 8 and 9. As shown in the figures, a nonlinear model does not have a large influence on the system performance. In Fig. 8, two different approaches to nonlinearity compensation are considered for performance comparison. One is the proposed RLS approach and the other is to use the inverse function of the Saleh model as in [4]. The approach proposed in [4] has limitations in practical environments because the perfect prior knowledge on TWTA nonlinearity is required and the nonlinearity should be modeled by the Saleh model. The proposed method shows worse performance than the conventional approach in [4] because the estimation error of the TWTA nonlinearity in the proposed method cannot be avoided. This performance loss caused by an estimation error is inevitable in realistic environments. Figure 9 shows the BER curves using the LMS and RLS algorithms to estimate nonlinear coefficients. For the LMS algorithm, we use the following update equation:

$$\mathbf{w}(n) = \mathbf{w}(n-1) + \mu \mathbf{x}(n) \varepsilon^*(n), \tag{21}$$

where μ is the step size. The coefficients are updated with step size $\mu = 0.001$. As shown in Fig. 9, the two approaches show the same performance when IBO is not less than 15 dB. With a low IBO, the proposed RLS approach shows better performance than the LMS approach. Figure 10 shows the convergence behaviors of the LMS and RLS algorithms with 15 dB IBO and 12 dB

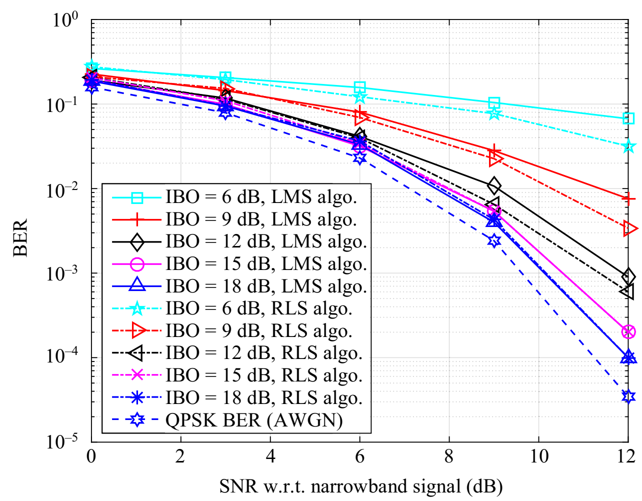

Fig. 9. BER performance of a narrowband signal after self-interference cancellation using the LMS and RLS approaches under the DVB-Sx reference model.

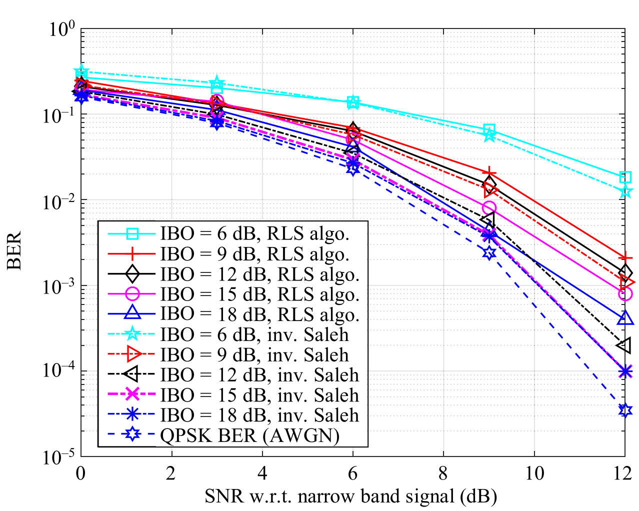

Fig. 8. BER performance of a narrowband signal after self-interference cancellation using the inverse Saleh and proposed RLS approaches under the Saleh model.

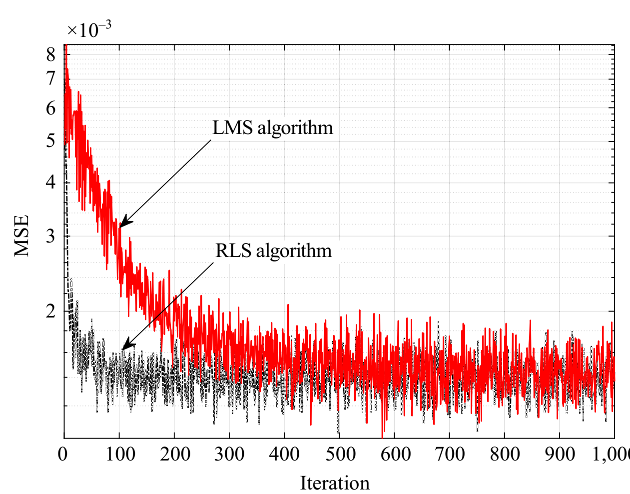

Fig. 10. Convergence behaviors of LMS and RLS approaches to estimate the coefficients for nonlinearity compensation (IBO = 15 dB, SNR = 12 dB).

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SNR. The RLS approach has a faster convergence characteristic than the LMS method; however, it has greater computational complexity. In this paper, the RLS algorithm is adopted to obtain the convergent solution as quickly as possible in the initialization phase of the proposed operation scenario.

Finally, we examined the system performance when multiple narrowband DVB-RCS2 signals were received by a gateway. For example, three narrowband signals occupying different frequency bands had 30 dB lower powers than the wideband DVB-S2 signal, as shown in Fig. 11. Figure 12 shows the BER performance of a narrowband signal at the center frequency when three terminals transmit their narrowband DVB-RCS2 signal in three consecutive frequency channels with a sufficient guard band. It is evident that the performance of the interference cancellation is independent of the number of narrowband signals if the received signal power of the narrowband signal is maintained.

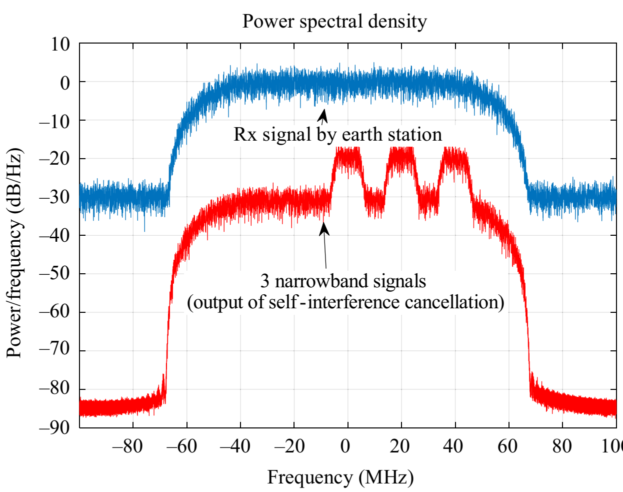

Fig. 11. Power spectrum of three narrowband signals after self-interference cancellation (IBO = 15 dB, SNR = 12 dB).

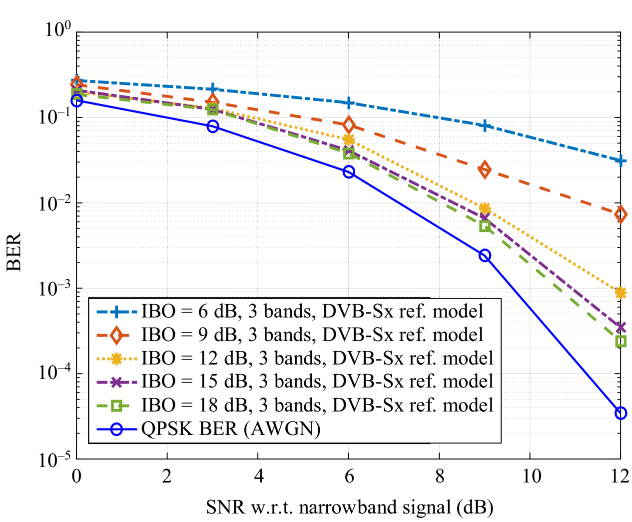

Fig. 12. BER performance of a narrowband signal after self-interference cancellation with the DVB-Sx reference model when three different narrowband signals are received.

VI. Conclusions

To improve the spectral and power efficiency of nonlinear two-way satellite communication channels, an adaptive nonlinearity compensation algorithm and an overall system operation scenario were proposed. The overall operation is divided into two phases: initial and normal. In the initial phase, coefficients of the nonlinearity compensator are adaptively calculated using an RLS algorithm. Nonlinearity in the superimposed signal of DVB-S2 and DVB-RCS2 are compensated using the predetermined coefficients. The desired DVB-RCS2 signal is extracted and demodulated after cancelling out the DVB-S2 self-interference in the normal phase. Additionally, modifications of a conventional synchronization mechanism, which is used in DVB-S2 receivers, are considered to obtain the acceptable performance of interference cancellation in the proposed system. The proposed approach achieved an optimal performance, specifically a theoretical bit error performance, in AWGN channels with less than 1 dB of loss at a 1% bit error probability.

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References

[1] S. Katti, S. Gollakota, and D. Katabi, “Embracing Wireless Interference: Analog Network Coding,” in *Proc. ACM SIGCOMM*, Kyoto, Japan, Aug. 2007, pp. 397–408.

[2] F. Rossetto, “A Comparison of Different Physical Layer Network Coding Techniques for the Satellite Environment,” in *Proc. Adv. Satellite Multimedia Syst. Conf. Signal Process. Space Commun. Workshop*, Cagliari, Italy, Sept. 2010, pp. 25–30.

[3] G. Cocco et al., “Practical Issues in Multi-user Physical Layer Network Coding,” in *Proc. Adv. Satellite Multimedia Syst. Conf. Signal Process. Space Commun. Workshop*, Vigo, Spain, Sept. 2012, pp. 205–211.

[4] T. Ishiguro, T. Hara, and M. Okada, "Post-Compensation Technique for Carrier Superposed Satellite Channel Including Nonlinear TWTA," *IEICE Trans. Commun.*, vol. E95-B, Nov. 2012, pp. 3420–3427.

[5] G.D. Collins, D.L. Anair, and M.J. Ready, *Adaptive Canceller for Frequency Reuse Systems*, US Patent 6,859,641, Feb. 2005.

[6] F.-W. Sun et al., *Method and System for Providing Two-Way Communication Using an Overlay of Signals Over a Non-linear Communications Channel*, US Patent 2003/0224723, Dec. 2003.

[7] H. Ju et al., "Novel Digital Cancelation Method in Presence of Harmonic Self-Interference," *ETRI J.*, vol. 39, no. 2, Apr. 2017, pp. 245–254.

[8] D. Korpi et al., "Adaptive Nonlinear Digital Self-Interference Cancellation for Mobile Inband Full-Duplex Radio: Algorithms and RF Measurements," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, San Diego, CA, USA, Dec. 2015, pp. 1–7.

[9] J. Malone and M.A. Wickert, "Practical Volterra Equalizers for Wideband Satellite Communications with TWTA Nonlinearities," in *Proc. Digital Signal Process. Signal Process. Educ. Meeting (DSP/SPE)*, Sedona, AZ, USA, Jan. 2011, pp. 48–53.

[10] M. Bauduin, S. Massar, and F. Horlin, "Receiver Design for Non-linear Satellite Channels: Equalizer Training and Symbol Detection on the Compressed Constellation," in *Proc. Int. Conf. on Military Commun. Inform. Syst. (ICMCIS)*, Brussels, Belgium, May 2016, pp. 1–6.

[11] S. Haykin, *Adaptive Filter Theory*, Upper Saddle River, NJ, USA: Prentice Hall, 2002.

[12] ETSI EN 302 307, "Digital Video Broadcasting (DVB); Second Generation Framing Structure, Channel Coding And Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications (DVB-S2)," V1.2.1, Aug. 2009.

[13] H. Wu et al., "Estimation of Physical Layer Scrambling Code Sequence of DVB-S2," *ETRI J.*, vol. 36, no. 2, Apr. 2014, pp. 329–332.

[14] ETSI TS 101 545-1, "Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 1: Overview and System Level Specification," V1.2.1, Apr. 2014.

[15] S. Choi, E. Jeong, and Y.H. Lee, "Adaptive Predistrortion with Direct Learning Based on Piecewise Linear Approximation of Amplifier Nonlinearity," *IEEE J. Select. Topics Signal Process*, vol. 3, June 2009, pp. 397–404.

[16] J. Kim and K. Konstantinou, "Digital Predistortion of Wideband Signals Based on Power Amplifier Model with Memory," *Electron. Lett.*, vol. 37, Nov. 2001, pp. 1417–1418.

[17] E. Casini, R. De Gaudenzi, and A. Ginesi, "DVB-S2 Modem Algorithms Design and Performance over Typical Satellite Channels," *Int. J. Satellite Commun. Netw.*, vol. 22, no. 3, May/June 2004, pp. 291–318.

[18] F.M. Gardner, "A BPSK/QPSK Timing-Error Detector for Sampled Receivers," *IEEE Trans. Commun.*, vol. 34, May 1986, pp. 399–406.

[19] S. Jung and D. Oh, "Frequency Estimation for Non-pilot Mode of DVB-S2 System," in *Proc. World Congress Eng. Comput. Sci.*, San Francisco, CA, USA, Oct. 2012, pp. 595–598.

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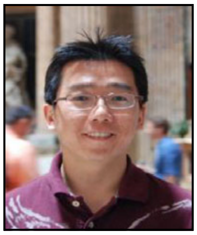

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