Compensations of Nonlinear Effects of TWTA for Signal Super-Positioning Satellite Communication Systems

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Abstract. The Carrier Super-Positioning Satellite System is a promising telecommunication system because the frequency efficiency is double that of existing satellite systems. In this technique, we can use the same frequency band for inbound and outbound signals which are currently used in separated bands. Interference canceller used in the carrier super-positioning system is degraded a lot by the nonlinear distortion of satellite TWTA. This paper proposes and verifies a method of compensation of nonlinearity for the interference canceller. It becomes clear that, by intentionally giving the same nonlinearity as that of the satellite to the generated replica, significant part of the interference caused by the nonlinearity can be removed.

Keywords: satellite communication, interference canceller, nonlinear distortion, frequency reuse technology, TWTA.

1 Introduction

As the traffic demand for high-speed images increases, along with severe compentition in the market environment, the effective utilization of frequency resources of satellite communications is more important than ever. Frequency reuses by carrier super-positioning is one of the efficiency method [1]. This is not only for effective use of the band but also for the demand on the expansion of applications by reducing the channel cost.

Many activities, including our own, for the studies of interference canceller used in this system have been reported for the last few years [2]-[12]. All these reports show that the interference canceller performs well in the linear systems. In this study including our previous one however, it has been verified that it is not true in the nonlinear system[10]. The interference is remainded un-cancelled

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if the signal is distorted and degrades the BER performance of wanted signals. The distortion is due to AM/AM and AM/PM conversion of the satellite TWTA.

In general, as for the compensation of nonlinear effects, many studies have been reported. Some of them propose a pre-compensation that reshapes the signals at the transmitted side[13]. However, they are all about regular signal transmission for non-superposed carriers or about amplifier devices; very few are about interference cancellers for carrier super-positioning.

In order to minimize the effects of such nonlinear distortion, this paper proposes a method to compensate the nonlinearity of the satellite in the canceller unit put in the receiver. As described in the many reference papers, it is common for the interference canceller for frequency superposing to generate replica of outbound signal and subtract it from received signal[6]-[9]. Both inbound signal and outbound signal are contained in the received signal. The outbound signal returned from the satellite is the unwanted signal which has to be cancelled in this case since the station does not want to receive outbound signal but want to receive inbound signal. Here it can be notified that the received signal sent back from the satellite transponder is distorted if the signal is fed to the nonlinear region of satellite TWTA while the replica generated in the canceller is free from the distortion. The canceller has been suffered from the performance degradation due to this difference between received signal and the replica.

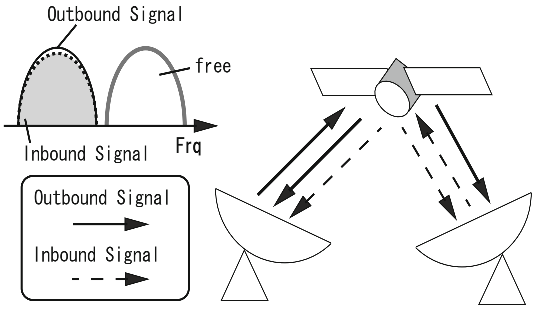
Our proposal is to compensate the nonlinearity for the canceller by simply giving distortion to the replica too. Then difference should be erased if the replica is distorted in the same way as the received signal is done by the TWTA.

This paper first explains the effects of TWTA onto the interference canceller, then shows the improvement of the performance of the canceller by our proposed method.

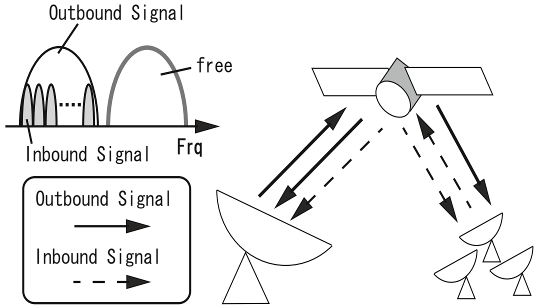
2 Interference Canceller

Fig.1 shows two typical network configurations for carrier super-positioning network. Fig.1(a) is for point-to-point paired carrier network. Both outbound (OB) and inbound (IB) carriers are superposed in the same frequency band. The level of both OB and IB carriers are the same in this case since size of antennas are the same for both stations. In this network, interference canceller is required to put at both stations.

On the other hand, Fig.1(b) shows the point-to-multipoint network called VSAT (Very Small Aperture Terminal) system. This network is composed of one large Hub station and many remote stations, and a wider band OB carrier is sent from Hub station to remote stations and plural narrower band IB carriers are from remotes to Hub. Since different diameter of antenna are used for Hub and remote stations in the VSAT system, the carrier level (power density) of OB is generally much higher than those of IB carriers. The difference is generally as well as 10dB and more. The interference canceller is then required only in the Hub station but not required in remotes since remote stations can demodulate high level OB carrier (wanted signal) as it is.



(a)P to P



(b)P to MP

Fig. 1. Carrier Super-Positioning System

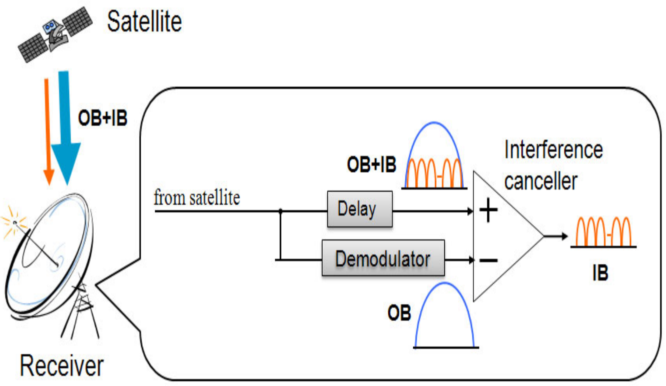


Fig. 2. Replica generation by demodulation

Interference canceller is realized by generating replica of unwanted signal and subtracting it from received signals. Two methods have been proposed by us. One is to demodulate unwanted signal from received signals and generating replica [5]. The other method is to shift transmitting signal with the amount of delay of one round trip time [11][12]. The former (method 1) is simple and useful for VSAT system but the accuracy of replica is affected by the bit error at the demodulation of unwanted signal. The latter (method 2) is not affected by such bit error but is required to measure the satellite one round trip delay accurately and continuously. The concept of interference canceller of method 1 is shown in Fig.2. In Fig.2, upper part is the path for received signal (OB+IB) and the lower part is for the path to demodulate unwanted signal and to generate replica (unwanted OB). Then, wanted signals (IB) are extracted at the output of the canceller.

3 Nonlinear Effects

3.1 Theoretical Description

In the satellite communications, the transponder TWTA is generally operated in the region of near saturation in order to use power effectively. Then, the signals amplified there suffer from the effects of inter-modulation and distorted due to the AM/AM and AM/PM conversion. Fig.3 shows the typical AM/AM and AM/PM conversion characteristics of the TWTA used in the conventional communications satellite. The amplitude and phase of the signal provided to the nonlinear amplifier are converted to new amplitude and phase respectively

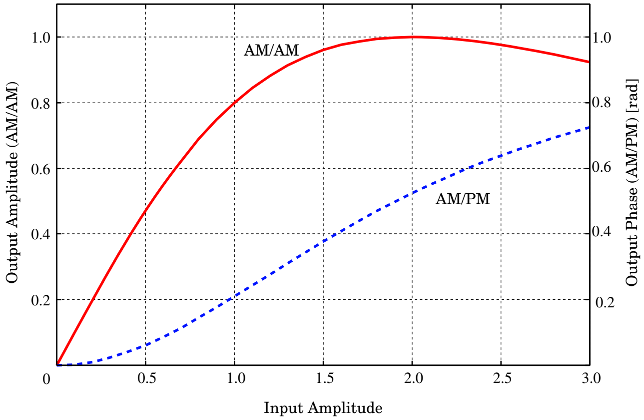


Fig. 3. Nonlinear characteristics of TWTA

Table 1. Parameters of TWTA characteristics

α_x	1.0
β_x	0.25
α_ϕ	$\pi/12$
β_ϕ	0.25

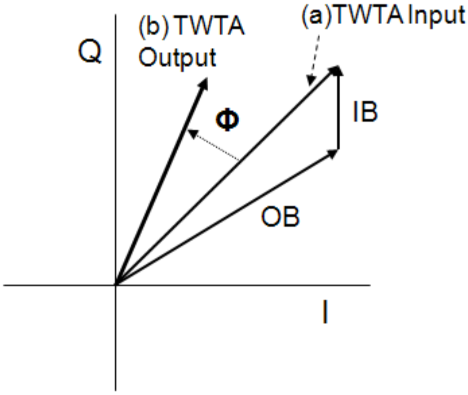


Fig. 4. Signal vectors of TWTA Input and Output

according to the conversion characteristics shown in Fig.3. Fig.4 shows vector diagram of input and output signal through the TWTA. Composite signal(a) of OB and IB is fed to TWTA and converted to the TWTA output signal(b). Here, if the power of OB is much larger than that of IB, the conversion which the composite signal is received by the nonlinearity is the same as that OB is received.

The TWTA output signal $u(t)$ against to the input signal $s(t)$ can be expressed by the equation(1) [14]

$$u(t) = s(t)G[s(t)] \tag{1}$$

where the amplifier gain $G[s(t)]$ is

$$G[s(t)] = \frac{1}{|s(t)|}g(|s(t)|)\exp(jf(|s(t)|)) \tag{2}$$

The function $g(r)$ and $f(r)$ represent AM/AM (amplitude modulation/amplitude modulation) and AM/PM (amplitude modulation/phase modulation) conversion characteristics of TWTA respectively. For the TWTA, the expressions for $g(r)$ and $f(r)$ are

$$g(r) = \frac{\alpha_x r}{1 + \beta_x r^2} \tag{3}$$

$$f(r) = \frac{\alpha_\phi r^2}{1 + \beta_\phi r^2} \tag{4}$$

where α_x is the small-signal gain, and $g_{max} = \frac{1}{\sqrt{\beta_x}}$ is the amplifier input saturation voltage. α_ϕ and β_ϕ is the parameters which decide AM/PM conversion characteristics. The AM/AM and AM/PM characteristics of TWTA and the parameters used in above equations are shown in Fig.3 and Table 1 respectively.

Here, let's consider that the power of IB is smaller enough, then the received signal fed to the input of the canceller is expressed by $u(t)$ shown in equation(1). On the other hand the replica which is provided to another input of the canceller is just expressed by $s(t)$. The difference between these two signals $R(t)$ is the remained signal which behaves as interference in this system.

$$R(t) = u(t) - s(t) \tag{5}$$

where $R(t)$ can be considered as the remained signal caused by the nonlinear effects. And we can define the suppression of the interference canceller δ in the nonlinear system by the ratio of the power of unwanted signal at the canceller input and the power of remained interference signal as

$$\delta = \frac{\overline{u(t)^2}}{\overline{R(t)^2}} \tag{6}$$

By the way, as easily expected in equation(5),$R(t)$ is zero since $u(t) = s(t)$ in the linear system if other factors such as quantizing error, carrier and timing synchronization errors etc.,in the canceller are ideally zero. As shown in equation (5) and (6), interference power is generated due to the nonlinear distortion of unwanted signal in the satellite transpoder. Our intention is, as mentioned above, to compensate the distortion by giving the same distortion to the replica. The principle of our proposal is simple. Namely, $R(t)$ becomes zero if we substitute $u(t)$ for $s(t)$ in equation (5).

Here the issue is how to estimate the nonlinear characteristics of satellite TWTA in the canceller unit. It is possible to know the TWTA nonlinearity itself by getting the data of transponder from the network operator. However even though it is possible, we still have to know the operation point of the satellite TWTA since the uplink power to the satellite frequently deviates due to the rain attenuation or to the other reasons. An approach to estimating nonlinearity is explained later.

3.2 Evaluation of Nonlinear Effects

A. **Perfomance Degradation.** The nonlinear verification test of interference canceller has been conducted by both computer simulation using reference model and laboratory test using FPGA based hardware prototype. The network simulated here is the VSAT system in which the level difference between OB and IB is 13 dB (refer to Fig.1(b)). One of the important performance parameters for the canceller is the purity of extracted inbound signal (wanted signal). The purity can be evaluated by the suppression of unwanted signal. The transmission path model used in the simulation is shown in Fig.5. The parameters used for the simulation is shown in Table 2. Simulated results of suppression performances are shown in Fig.6 and Fig.7.

Fig.6 shows both spectrum of received signals (which includes both 5MHz outbound and 1MHz inbound carriers) and extracted inbound signal in the linear

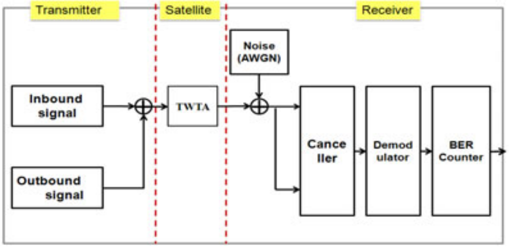


Fig. 5. Transmission Path Model of Computer Simulation

Table 2. Simulation parameters

Moduration Level	QPSK(OB)DQOSK(IB)
Symbol Rate	5Msymbol/s 1Msymbol/s
Power Density Difference (D/U)	13[dB]
The number of IB	4
Channel Model	AWGN
HPA Model	TWTA
Input Back-off	0-10[dB]

system. Fig.7 is those in the nonlinear system operated at 0dB IBO (Input Back Off). As shown in these figures, the inbound signal (wanted signal) is well extracted in case the system is linear but is not in the case the system is nonlinear. That is, signal to interference ratio (D/U ratio) in the nonlinear system is only 10 dB or lower.

Fig.8 shows hardware test results of both received signal spectrum and the extracted IB signal. Though similar test have been conducted but the results of hardware test is worse than those of computer simulation. The D/U ratio of extracted signal is only 6-7 dB in this case. The hardware test has been conducted by using method 2 [11].

B. **Compensation of Nonlinear Effects.** As mentioned before, our proposal is to give the replica the same nonlinear characteristics and compensate the satellite nonlinearity as shown in Fig.9. Fig.9 shows the basic block diagram in which the compensation is put at the output of outbound signal demodulator. The upper side of this block diagram is the path where the received signals (OB+IB) are provided to the canceller as they are. These signals are distorted if the satellite transponder is operated in the nonlinear region. And the lower path is to generate replica of OB (unwanted signal). The output of the demodulator is fed to the circuit where the same nonlinearity shown in Fig.3 is numerically given to the demodulated replica. Here, the nonlinearity can be simply realized by baseband processing of I and Q vector of PSK signal.

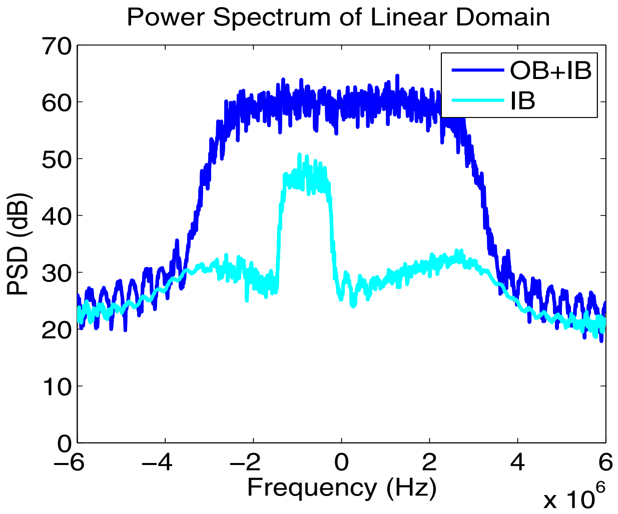


Fig. 6. Power spectrum of received signals(OB+IB) and extracted IB signal (Linear case)

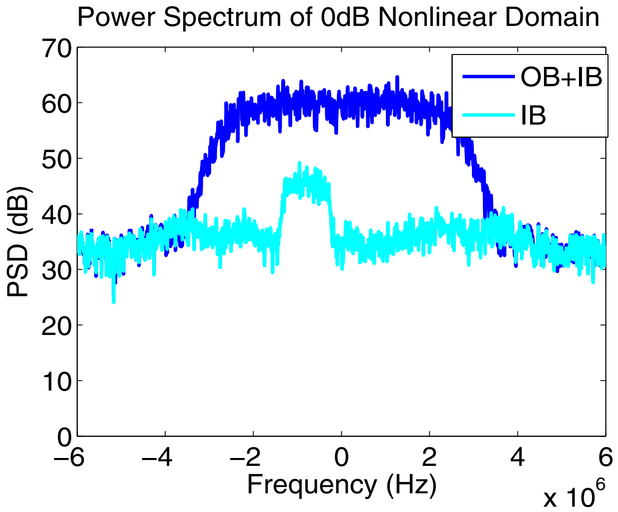


Fig. 7. Power spectrum of received signals(OB+IB) and extracted IB signal (Nonlinear IBO=0dB)

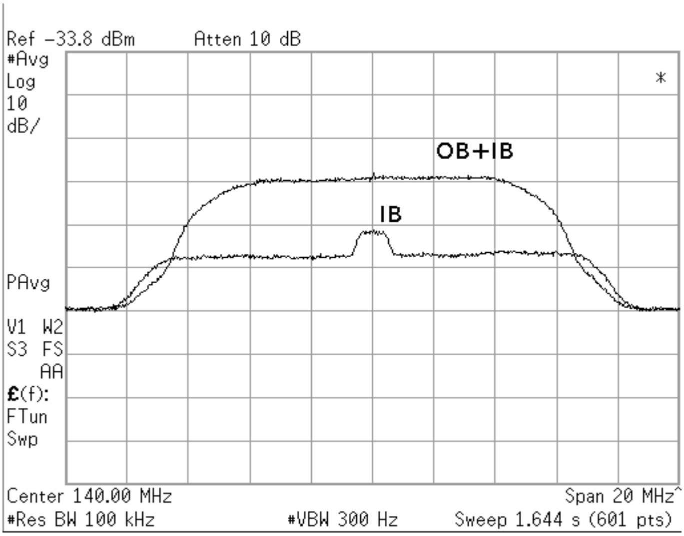


Fig. 8. Measured spectrum of output of FPGA based canceller

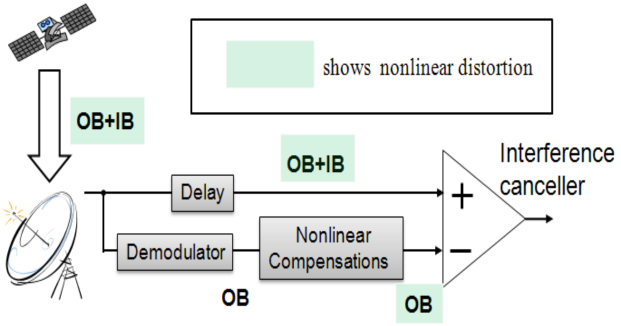


Fig. 9. Interference cancellar introduced nonlinear compensations

Firstly, the effects of the compensation on the purity of inbound signal after cancellation has been evaluated. Fig.10 shows the spectrum form of canceller input (IB+OB) and canceller output (IB). The operating point of the satellite TWTA is saturation (IBO=0dB). The ratio of the power density of OB to IB signal is 13 dB in this case. And the canceller output is for both cases of with and without compensator. As shown in this figure, it is clear that the purity of extracted IB is improved about 10 dB by adopting compensation.

Then lets show the BER performance of IB signal after cancellation. Fig.11 and Fig.12 show them for the case input back off (IBO) is 2 dB and 10 dB respectively. Fig.11 is the case which is the nonlinear system. In case IBO=2 dB, the improvement by the compensation is obvious though the improvement

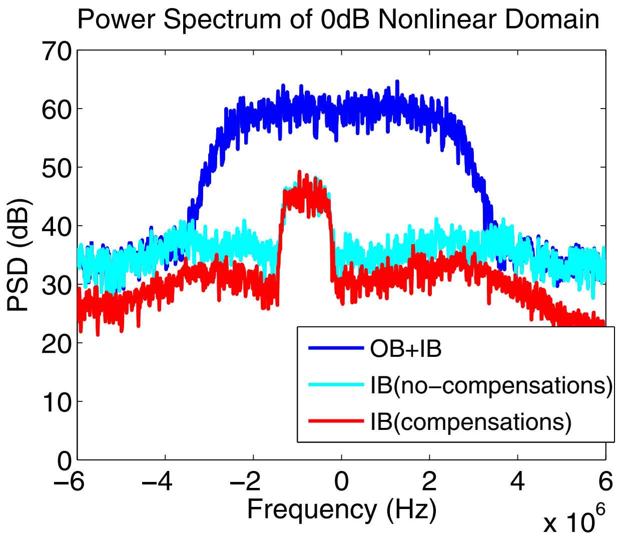


Fig. 10. Power spectrum of IBO=0[dB]

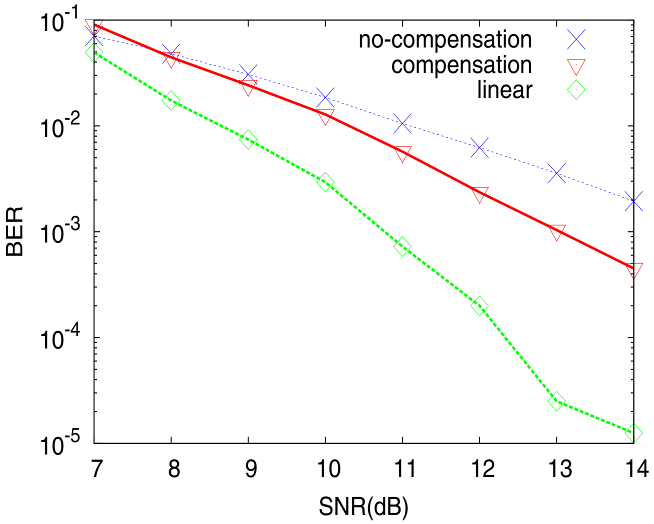


Fig. 11. BER performance of inbound signal(IBO=2[dB])

for the latter case is small. The system of the latter case (IBO=10dB) is close to linear and the degradation itself is very small whatever the compensation exists or not. Fig.13 shows the improvement of BER performance by the compensation for various input back off (IBO). In this simulation, it was assumed that the input back off for both satellite TWTA and the nonlinearity intentionally given

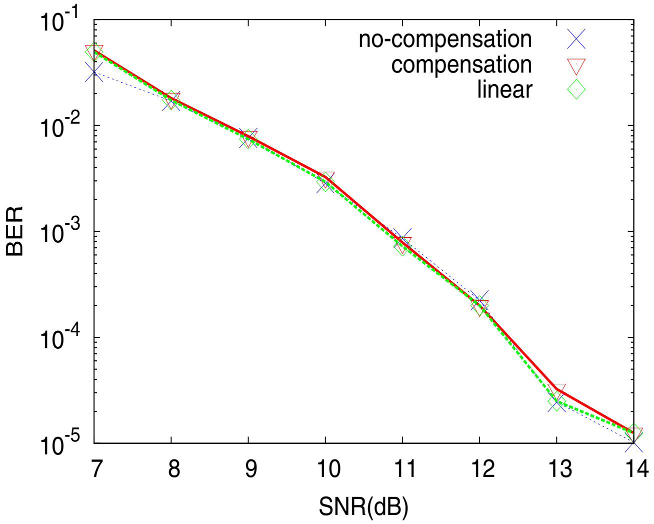


Fig. 12. BER performance of inbound signal(IBO=10[dB])

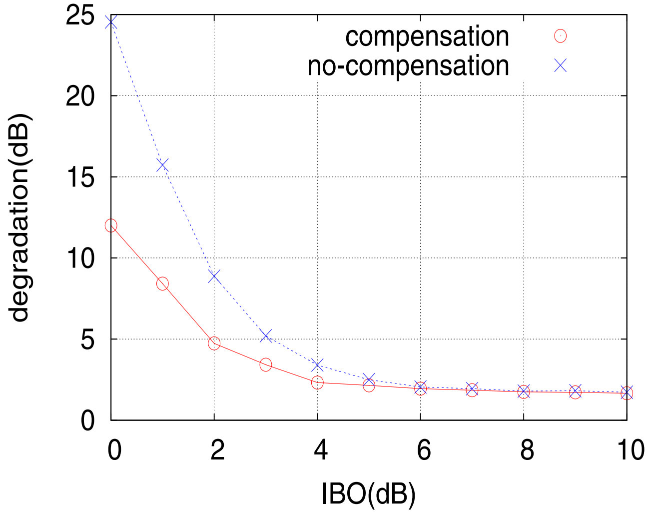


Fig. 13. BER degradation at 10^{-4}

to the canceller for compensation are the same. It can be said that the significant improvement is obtained by the proposed compensation.

C. **Automatic Tracking of TWTA Back Off.** In the previous section, it becomes clear that the nonlinear compensation works as far as the operating point (back off) of both satellite TWTA and the nonlinearity given to the replica

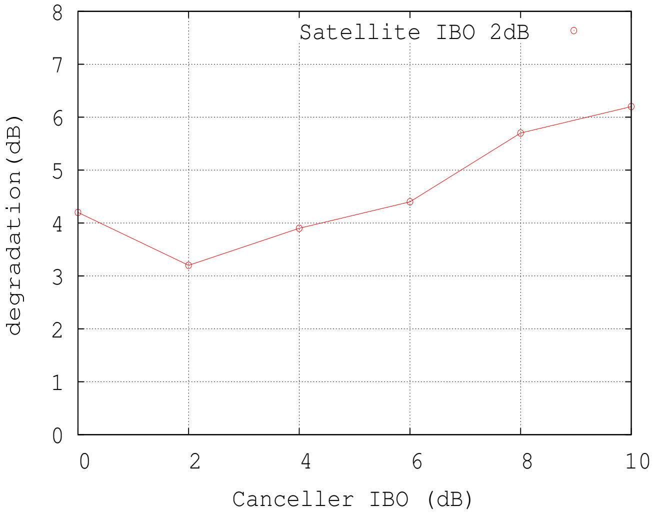


Fig. 14. BER degradation of IB signal at 10^{-3}

in the canceller is the same. For this, it is necessary for the canceller to know the operating point of the satellite.

Here we propose a method to track the back off of satellite TWTA automatically. Before introducing the proposed method, it is illustrative to review the performance of the compensator when the back off of the canceller has mismatch with that of the satellite TWTA.

Fig.14 shows the BER degradation of IB (wanted) signal as a function of the difference between back off of satellite TWTA and that of nonlinearity given to the replica. The degradation is minimum when the values of both back off are identical.

On the other hand, Fig. 15 shows the remained signal level of unwanted signal, that is interference power, at the output of the canceller for three different cases of back off of replica nonlinearity (0, 3, 6 dB) while keeping the satellite TWTA is the same (3 dB). This test was conducted by feeding OB signal only to the canceller. As shown in this figure, the power of remained unwanted signal proportionally increases as the difference between back off of the two nonlinearities is larger. This property can be expressed as shown in Fig.16. By utilizing this property, it is possible to estimate the satellite back off at the canceller unit in the earth station.

We prepare three paths in the canceller unit as shown in Fig.17. These three can be easily realized by signal processing without significant increase of hardware cost. One nonlinear element is provided to each path with three different back off such like y dB for upper path, x dB for middle path and $\frac{x+y}{2}$ dB for lower path. Here, the output level of nonlinear element of each path is normalized to be constant for any input back off. By this approach, we should get three

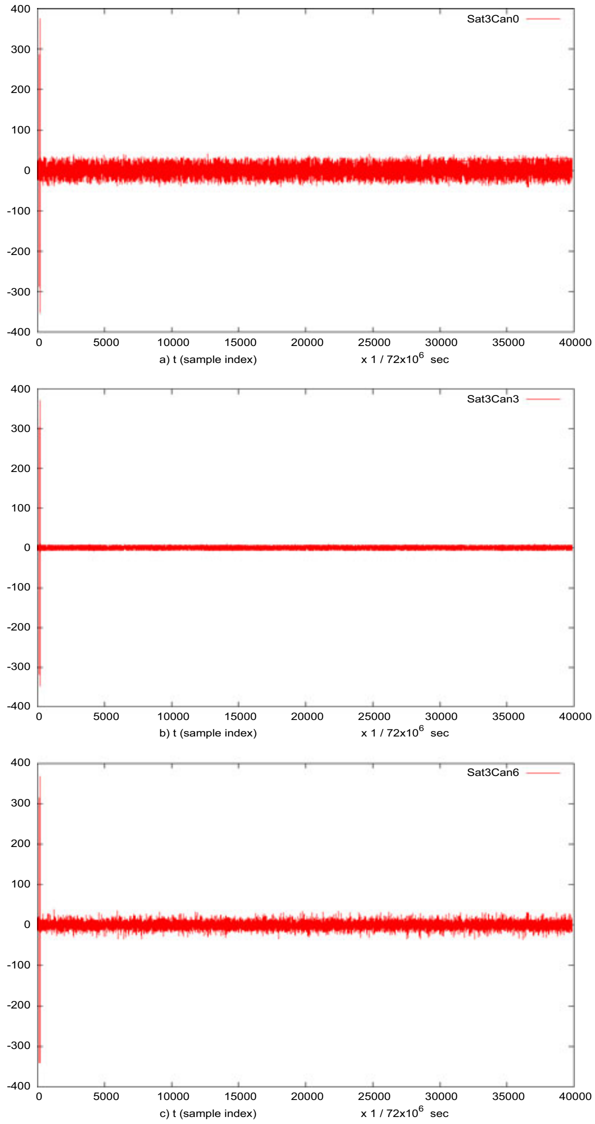


Fig. 15. Remained Unwanted Signal Level for Three Cases
a) Satellite IBO 3dB Canceller IBO 0dB
b) Satellite IBO 3dB Canceller IBO 3dB
c) Satellite IBO 3dB Canceller IBO 6dB

different levels of remained unwanted signals at the output of each path in Fig.17. Actually, wanted signal (IB) is extracted at the output of canceller. Therefore it is necessary to extract unwanted signal only from those wanted and unwanted power at the output. In order to do this, correlation technique by multiplying

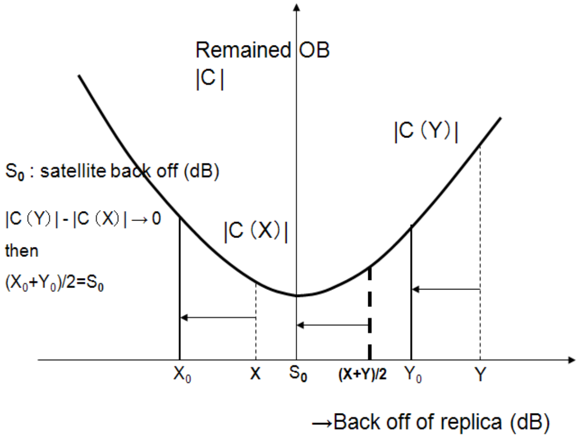


Fig. 16. Automatic Back Off Tracking

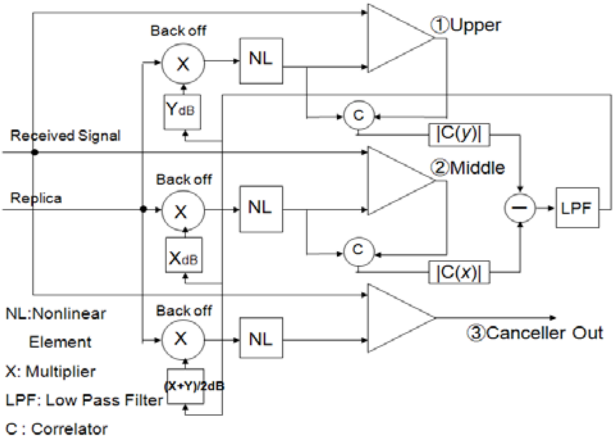


Fig. 17. Proposed Configuration of Satellite TWTA Back Off Tracking

replica signal to the canceller output is adopted here. By this operation, we can get the absolute value of correlation for three each path which has back off of y dB, x dB and $\frac{x+y}{2}$ dB.

Here let them be $|C(y)|$,$|C(x)|$ and $|C(\frac{y+x}{2})|$ respectively. Then, these are expressed as shown in Fig 16. By designing the automatic control which works so as to make the error $e = |C(y)| - |C(x)|$ becomes zero, then the back off $\frac{x+y}{2}$ dB at this moment should approach to the value of satellite TWTA back off s_0. The lower path in Fig. 17 is finally just the canceller output which nonlinearity is the same as the satellite. Thus the tracking loop of satellite TWTA back off can be realized by this method.

4 Conclusion

In order to minimize the performance degradation of frequency super-positioning interference canceller due to the nonlinearity of the satellite transponder, a method to compensate it by intentionally implementing same nonlinearity in the canceller is proposed. The study results show that it decreases the significant amount of degradation specifically in case the satellite is operated in the deep nonlinear region. Considering the case that the operationg point of satellite TWTA may change, we proposed a method of adaptive adjustment of both operating points of satellite nonlinearity and the nonlinearity given to the canceller for compensation.

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