NAIST-IS-DD1161003

Doctoral Dissertation

Post-Compensation of TWTA Nonlinearity for Satellite Communications

Takehiro Ishiguro

February 7, 2013

Department of Information Systems
Graduate School of Information Science
Nara Institute of Science and Technology

A Doctoral Dissertation
submitted to Graduate School of Information Science,
Nara Institute of Science and Technology
in partial fulfillment of the requirements for the degree of
Doctor of ENGINEERING

Takehiro Ishiguro

Thesis Committee:

Professor Minoru Okada	(Supervisor)
Professor Kenji Sugimoto	(Co-supervisor)
Associate Professor Takeshi Higashino	(Co-supervisor)

Post-Compensation of TWTA Nonlinearity for Satellite Communications[*]

Takehiro Ishiguro

Abstract

Recently, data size of high definition video and other digital data have been growing larger. Along with that, more and more channel capacity of satellite communication has been required. To enlarge channel capacity of satellite communication, there are two major ways. The first method is to apply multi-level modulation, which transmits more information per sample than conventional modulation scheme. The second method is to use frequency band efficiently by superposing two or more signals in one channel. Both methods can be applied without any hardware modification of satellite transponder and are able to be applied on current satellite systems.

In most conventional high power satellite transponder, TWTA (Travelling Wave Tube Amplifier) has been used as HPA (High Power Amplifier) and due to its nonlinear characteristics, TWTA is been operated with large input backoff to avoid nonlinear distortion of the output signal. However, high CNR (Carrier to Noise Ratio) condition is necessary for multi-level modulation to be used because the signals are tightly aligned on the constellation. Therefore, low backoff for satellite transponder is preferable when applying multi-level modulation.

Conventional satellite systems with superposed signal must also be operated with large backoff because of inter-carrier interference caused by the amplifier's nonlinearity. In both cases, power efficiency of satellite amplifier will decrease because of the large backoff. To utilize the power efficiency of satellite amplifier to the full, nonlinear characteristics of satellite amplifier must be dealt with.

---

[*] Doctoral Dissertation, Department of Information Systems, Graduate School of Information Science, Nara Institute of Science and Technology, NAIST-IS-DD1161003, February 7, 2013.

In this dissertation, a novel nonlinearity compensation scheme to suppress the nonlinear interference and to use satellite transponder's power effectively for more channel capacity is proposed. Here, a nonlinearity compensation scheme for the receiver side is considered because of the implementation cost and effect to the network system. The nonlinearity compensation proposed in this dissertation is processed by applying reverse nonlinear characteristics of satellite amplifier to received signal. Then in this dissertation, the nonlinearity compensator is implemented to the receiver of two typical satellite networks, multi-level modulated network and carrier superposed network, for performance evaluation. As a result, it is confirmed that the proposed scheme has reduced the degradation caused by the amplifier's nonlinearity in both networks.

However, this nonlinearity compensation scheme simply applies reverse nonlinear characteristics of the amplifier and has probability of emphasizing noise component at low backoff condition. To avoid noise emphasis, an enhanced nonlinearity compensation scheme for multi-level modulation, where the amount of compensation is decided from which amplitude range the received signal is included in, is proposed. Also the performance of enhanced compensation scheme is shown in this dissertation. From the simulation result, it is shown that this scheme for multi-level modulation could improve the transmission performance more under low input backoff condition, compared to the originally proposed scheme.

Keywords:

Satellite communications, carrier superposing, multi-level modulation, TWTA, nonlinearity compensation

Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

Satellite communication has been researched for more than fifty years, and this field has grown extremely to be an indispensable technology. Satellite communication is mainly purposed for telecommunications, data transmission, and television broadcasting. Nowadays there are alternative solutions like optical fiber, though still satellite communication is used in many important situation because it has absolute advantages over alternatives. Once the satellite is carried into orbit around the Earth, it is very easy and inexpensive to construct a communication channel even across the distance. Another benefit is that it is possible to easily construct a broadcasting network only by aligning the reception antenna towards broadcasting satellite.

However, current satellite communication is reaching several limitations over operation. First is the maximum number of satellites that could be placed into the orbit. If two satellites that share the same frequency band are placed too close to each other, the earth station's antenna must have narrow and precise directivity to avoid interference to each other. Second is the bandwidth limitation problem. The network which shares multiple satellites or satellite that are close in orbit have to share the frequency band. Therefore, the maximum number of channels that could be assigned to those satellites are limited. The allocation of satellites and frequency usage are arbitrated by an international organization called ITU (International Telecommunication Union) [13].

To effectively use the limited frequency band and to reuse those frequency band, many schemes have been proposed. For example, combination of multi-beam satellite and SS-TDMA (Satellite Switched Time Division Multiple Access) [12] is one of the major schemes to reuse the frequency band. In SS-TDMA system, connections between spot-beam antennas on the satellite are switched along with the TDMA base frame. Each earth station sends a signal to the transponder when spot-beam antenna on the satellite that receives signal is connected to the spot-beam antenna aiming receiver earth station. From this, transmitter and receiver can use the same frequency band because they are splitted spatially and at the same time, different pair of earth stations can communicate using different spot-beam antenna. This scheme also makes use of the guard time of TDMA slots by switching circuit at that time. Though SS-TDMA is effective scheme, it requires a large number of switches corresponding to the maximum number of channel combination and complicated synchronization function.

There are other schemes like carrier superposing (common band) [10] and multi-level modulation for effective use of frequency band that can be adopted to conventional satellite system without large modification. Carrier superposing technique assigns two or more carriers in the same frequency band and multi-level modulation transmits multiple data bits per symbol. These schemes enhance the frequency utilization efficiency, but more and more demand on greater data transmission rate has been arising because of the high definition video broadcasting and larger internet traffic. This research focuses on these two schemes to improve the data rate of conventional satellite communication.

To apply above two schemes to conventional satellite system and properly operating it without large modification of earth station, a higher satellite transmission power and high power efficiency are required. Though, to increase the satellite transmitter's power, the nonlinear distortion of satellite's high power amplifier (HPA) [28] must be conquered or else amplifier with larger gain must be installed to the satellite transponder to obtain more power with the same amount of nonlinear distortion, which is unrealistic option.

Nonlinear distortion is a problem for most of the HPAs. It is impossible to design and construct HPA without any nonlinearity. Signals suffer from more nonlinear distortion when amplifier's operation level is set closer to the saturation level. From this, the satellite's amplifier must be operated at a level with a certain amount of backoff from saturation level to avoid nonlinear distortion. Although when backoff increases, the potential of satellite amplifier is not being fully used and the power efficiency of satellite decreases. Otherwise, if the amplifier is driven near saturation level, any type of compensation is required to reduce the nonlinear distortion of received signal.

1.2 Objective

Objective of this dissertation is to propose an effective scheme that relieves nonlinear distortion of satellite amplifier, which can be apply to conventional satellite systems, and apply that scheme to practical satellite networks to evaluate the performance of the scheme.

In many cases, TWTA (Travelling Wave Tube Amplifier) [22] has been used as HPA for satellite transponder because it has high gain, wide band, and power efficiency. TWTA has two major nonlinear characteristics, AM/AM conversion and AM/PM conversion, which are output amplitude characteristic and output phase characteristic, respectively. For TWTA nonlinearity compensation, these two characteristics are to be concerned. These characteristics can be represented with simple equations by Saleh's model [24] and therefore, the inverse characteristics can also be formulated in a simple form.

This inverse function can be implemented before and after the satellite amplifier. However, if this compensator is installed at the transmitter earth station, the bandwidth of transmitter's output signal will be expanded due to the reverse nonlinear distortion. Also in carrier superposed satellite network, the amount of nonlinear distortion cannot be estimated at the transmitter side because two or more carriers are superposed at the transponder [27, 3]. Therefore in this research, post-compensation is chosen as the type of compensation.

In this dissertation, post-compensation scheme for satellite TWTA is proposed. First, this post-compensation scheme is implemented to multi-level modulated satellite network, a general type of network, for performance evaluation. Then this scheme is implemented to carrier superposed satellite network. The evaluation is done by computer-based simulation to prove the effectiveness of proposed scheme.

1.3 Outline

This dissertation is organized as follows. In Section 2, the fundamental of satellite communication is explained. Then in Section 3, nonlinearity of HPA used in satellite communication and its countermeasures are explained. In Section 4, the main theme of this dissertation, post-compensation scheme is detailed. For evaluation of proposal scheme, in Section 5 and 6, proposal scheme is applied to two typical satellite networks. In Section 5, multi-level modulation network, a more common satellite system is the target and in Section 6, carrier superposed network, another high efficient satellite communication system, is the target application. Section 7 details the algorithm of another post-compensation scheme optimized for low input backoff situation on multi-level modulated satellite network, and also evaluates the performance of the scheme. Finally in Section 8, the summary, conclusion, and future work of this dissertation is noted.

2. Satellite Communication

2.1 Introduction

Before going further about the nonlinearity, the basic overview of satellite communication is explained in this section.

In satellite communication, transmitter earth station sends signals to receiver earth station via space station (satellite transponder). Some communication network like satellite mobile phone switches multiple low earth orbit (LEO) satellites as the transponder because it has short propagation delay and smaller propagation loss. On the contrary, most satellites for communication are geostationary satellite (GEO) because of its large covering area and stable network. Geostationary satellites are launched to circular orbit of height 35800km to make the satellite orbit around the earth at the same speed of earth rotation. In this way, the relative position of geostationary satellite against earth surface is static, and the satellites can be seen in the same location on the sky.

Satellite communication has following features that are not found on terrestrial communications.

- Wide bandwidth and high speed communication.
- Wide coverage area with a single satellite.
- Earth station can be added for instant expansion of network inside service area.
- Multiple earth stations can receive the same signal. Capable of broadcasting.
- Accessible from multiple earth station.
- Highly reliable. Does not affected by disaster like wired network.
- Transmission quality is unrelated to the distance.
- Round trip transmission delay of 0.25 second.

From the above list, the most important feature of satellite communication is multiple accessibility. In conventional satellite communication, users in the coverage area share a transponder. This means, any earth station in the same coverage area can transmit a signal to that satellite and receive signal from that satellite. When two or more users tried to transmit a signal to the same satellite on the same frequency band at the same time, each signal will interfere with each other. There are two ways to avoid this conflict and share the transmission capacity among all earth stations. The first way is called "Multiplexing", and the second way is called "Multiple Accessing". Multiplex techniques like TDM (Time Division Multiplex) and FDM (Frequency Division Multiplex) are a common method not only for satellite communication but also for optical fiber and fixed terrestrial wireless communication to share frequency resource. Multiple access technique is used to connect single station to multiple station and is mainly for wireless communication. Further information is detailed in the next section.

Other than multiplexing and multiple accessing, we must clarify important factors like modulation scheme and other network configurations to discuss the nonlinearity of satellite channel. In this section, first, configurations of satellite network, which is related to satellite system's nonlinearity, is explored. Then the frequency usage and power efficiency problem of satellite communication, which are deeply connected to the problem of nonlinearity [19], is explained. Finally, in this section, the summery of current satellite network is expressed.

2.2 Configurations of Satellite Network

In this section, multiple access scheme, modulation scheme, and other network configurations for satellite communication are introduced. These configurations are very important as it gives great impact on satellite transmission performance.

2.2.1 Multiple Access

Multiple access technique is a scheme to avoid signal conflict over different stations when multiple stations simultaneously communicate with each other using common transponder. Without this scheme, collision will occur between connections and therefore, it is impossible to connect multiple earth stations to each

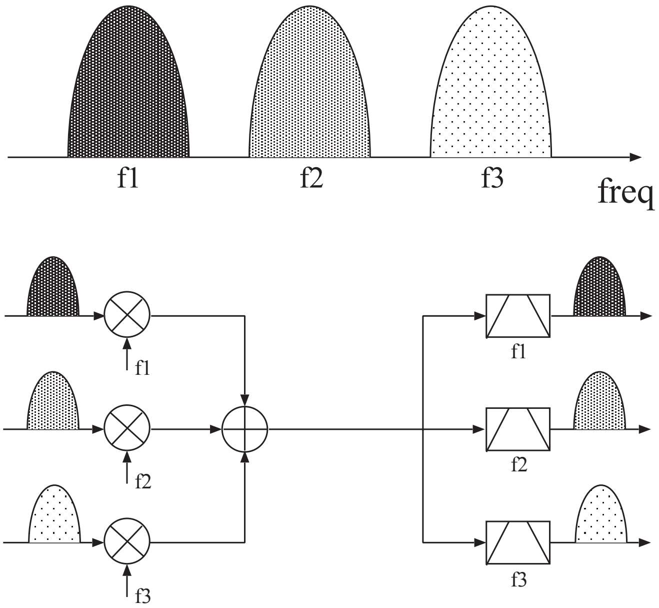


Figure 1. The idea of FDMA.

other and control the connections. All multiple access scheme requires a type of controller to govern the access of each earth station.

There are three major multiple access control schemes that are used in satellite communication. First is FDMA (Frequency Division Multiple Access) which assigns each earth station a different frequency band to avoid interference. Another is TDMA (Time Division Multiple Access) which assigns each earth station a different time slot to send and receive signals. The last is CDMA (Code Division Multiple Access) which assigns each station a different code for spread spectrum. Each scheme is explained below.

FDMA

The Idea of FDMA is shown in Figure 1. In FDMA transmission, first, entire frequency band that is available is divided to multiple sub-bands. Then each earth station sends a signal over sub-band that other stations are not occupying, sharing the frequency band of the transponder. Two styles, demand assignment and pre-assignment, can be chosen for frequency band assignment of each station. In demand assignment method, each earth station requests sub-band when it is

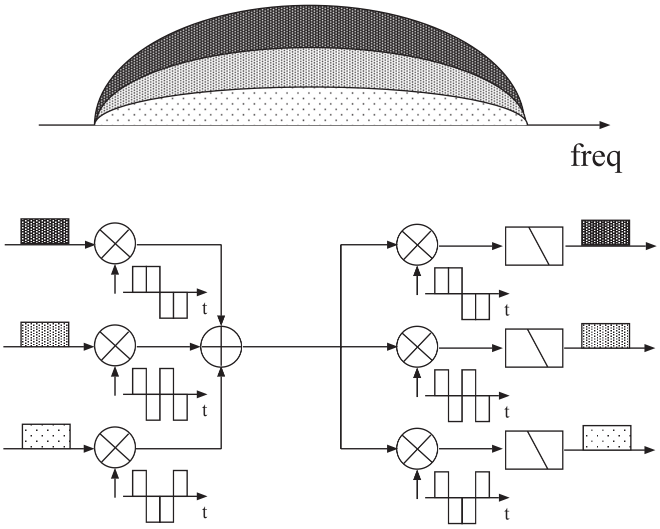


Figure 2. The idea of CDMA.

needed and the band is released when it is unused. This method can increase the frequency usage efficiency but requires a channel assignment controller that is usually implemented in the same transponder. The frequency bandwidth that is assigned to each station can be heterogeneous. Contrarily, pre-assignment method assigns all sub-bands to each earth station in advance and is fixed during operation. This method does not require a controller on satellite transponder, but frequency usage could drop due to unused channels.

When the number of access station increases, intermodulation interference will be emphasized, and to keep the transmission quality at high, satellite transponder must limit the input power (take more input backoff) to operate its amplifier under linear region. Otherwise, the intermodulation noise will lead to growth of input power and will cause nonlinear distortion of the output signal. This limitation of input power brings down the channel capacity.

Compared with other multiple access method, HPA and modem of FDMA stations is simpler but requires more linearity.

CDMA

The Idea of CDMA is shown in Figure 2. CDMA is a method to transmit signal after spreading spectrum using different codes that are assigned to each station. In the transmitter, the signals are primary modulated by schemes like PSK (Phase Shift Keying) shown in the next section, and then modulated to spread spectrum signal using unique spreading code like pseudo-random code to be sent. The spread spectrum signal has extremely wide frequency spectrum compared to primary modulated signal. The signal sent from other station that is spread with different code will act as noise against desired signal and the total power of noise will be larger than the desired signal. The receiver correlates the received signals by using despreading code which corresponding to the code applied in the transmitter to retrieve the original signal. In this process, the desired signal's power is condensed to bandwidth before it is spread but other channel's signal and noise will not be affected by this process and keep its power spectrum. Therefore, the desired signal's power spectrum surpasses the other component's power spectrum.

Compared with other multiple access method, CDMA has low channel capacity due to the limitation of transponder's bandwidth. However, this method can communicate without having initial acquisition procedure and has privacy and interference tolerance. The number of satellite network using CDMA is few compared to other multiple access schemes like FDMA and TDMA.

TDMA

The Idea of TDMA is shown in Figure 3. In TDMA method, multiple earth stations send the signal to satellite transponder in the same frequency band but in a different time slot so that they do not overlap with each other. Each earth station is assigned to a time slot within a TDMA frame which is a cyclic period for transmission and reception. As same as FDMA, there are two ways for the time slot assignment, demand assignment and pre-assignment.

Compared with other methods, in TDMA, only a single carrier occupies the transponder at each moment. So intermodulation interference will not be generated when number of accessing earth station increases. However, a slight descent of channel capacity occurs because of the pre-amble and transmission overheads needed for TDMA. Also, a change of distance between the satellite and the earth station makes it difficult to control the signal transmission timing even more dif-

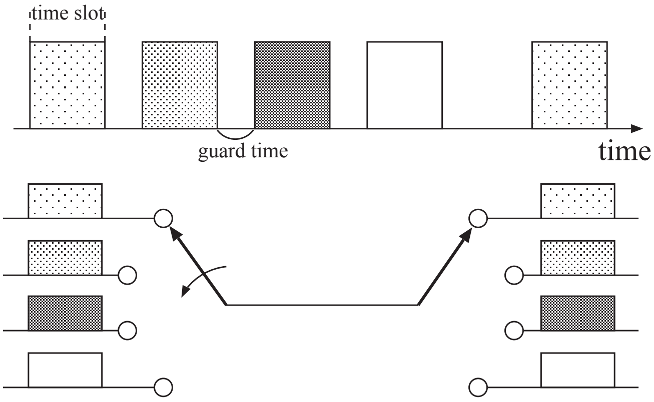


Figure 3. The idea of TDMA.

ficult when transmission rate becomes higher. Therefore in most cases, guard time is inserted between the time slots to avoid signal overlapping.

Currently, SS-TDMA (Satellite Switched TDMA), a type of TDMA used for multi-beam satellite, has been introduced for better use of guard time. In multi-beam satellite communication, narrow directivity beam (spot-beam) antennas are combined to compose a multi-beam antenna that covers the whole service area and each spot-beam antenna handles a part of the service area. In this way, each earth station can transmit signal independently without interfering. Guard time in SS-TDMA is used to switch the connection between the spot-beam antennas to have a different communication paths. The advantage of SS-TDMA is that multiple spot-beam antennas can transmit signal at the same time slot because they do not interfere with each other. The disadvantage of SS-TDMA is that when the number of earth station increases, it requires many switches to construct all pattern of paths.

Multiple Access and Nonlinearity

According to the above information, multiple access scheme except for the TDMA can cause an intermodulation interference because two or more uncorrelated signals occupy the channel. When the number of carriers increases, the more interference it will receive. Though in this research, this kind of situation is not concerned for the simplicity of simulation and therefore nonlinear distortion caused by multiple access is not concerned.

2.2.2 Modulation

For modulation, there are two categories. One is analog modulation and the other is digital modulation. In old time, FM (Frequency Modulation), which is a type of analog modulation, was the most common modulation scheme used in satellite communication. At that time, the satellite's transmission power was limited and the number of channel transmitted via satellite was small. FM transmission was chosen for a long time because it allowed high quality audio and TV signals to be recovered in the baseband channel with a low C/N ratio at the receiver. It was also chosen because it could utilize wide frequency band and could be realized with simple hardware. Nowadays the number of the channel has increased and more efficient modulation scheme has been desired. To answer to these demands, digital modulation schemes have been adopted to satellite communications.

There are many reasons and advantages for choosing digital modulation. It is easy to multiplex data signals into high speed data stream and vice versa. Without many analog devices, sophisticated signal processing can be performed with ICs (Integrated circuit). In addition, it is much simpler to apply digital modulation to TDMA than to apply analog modulation.

There are three types of the parameter that could be used to digitally modulate signals. Those are amplitude, frequency, and phase and the modulation schemes for each are called ASK (Amplitude Shift Keying), FSK (Frequency Shift Keying), and PSK (Phase Shift Keying) respectively. There are many variants of these three basic modulations. Within those modulation schemes, PSK is the most widely used in satellite communication. Here, PSK and APSK (Amplitude-Phase Shift Keying) is detailed because those are used in this research.

PSK

PSK modulation is commonly used in satellite communication because it has low symbol error rate at the same CNR (Carrier to Noise Ratio) compared to other modulation schemes. Therefore, it is suitable for networks that are difficult to achieve high CNR like satellite communication. PSK is a scheme where phase of the carrier signal is shifted according to the transmitting baseband symbols.

For the demodulation of PSK signals like this, synchronous detection or delay detection is usually adopted.

QPSK (Quadrature Phase Shift Keying) is one of the most widely used modulation scheme used in satellite communication. It is a type of PSK modulation that sends the signal by synthesizing two carrier waves that have phase of $\pi/2$ apart, with each waves binary modulated using sequence of serial parallel converted signals. When both channel's signal changes at a same time, the phase changes π at maximum and invokes envelope fluctuation on modulated signal under limited bandwidth.

APSK

APSK is a combination of ASK and PSK, where both amplitude and phase of the carrier wave is modulated. 16APSK or 32APSK is commonly seen in recent satellite communication. In those modulation schemes, 4 or 5 bits of transmitting binary signals are converted to 16 or 32 points of constellation respectively, and modulated with the same way as QPSK using two carrier waves. From this, more information could be packed in to a single transmitting symbol but should be operated under higher CNR because the distance between the constellation is closer than that of QPSK under the condition of the same power.

2.2.3 Other Network Configurations

Besides the transmitting signals, there are many other network configurations that are involved in satellite communication. One of the most important configurations that are not explored above is the network layout, or in other words, how earth stations communicate with each other. One perspective to categorize network layout is the direction of propagating signals. There are unidirectional and bidirectional satellite communications. The example of unidirectional satellite communication is satellite TV broadcasting, which TV station just transmit video contents and end users just receive the program. On the other hand, the example of bidirectional satellite communication is an internet connection of remote area through communicational satellite.

Another perspective is the number of node which is connected to single earth station. If one station is connected to another single station, that is called "Point-

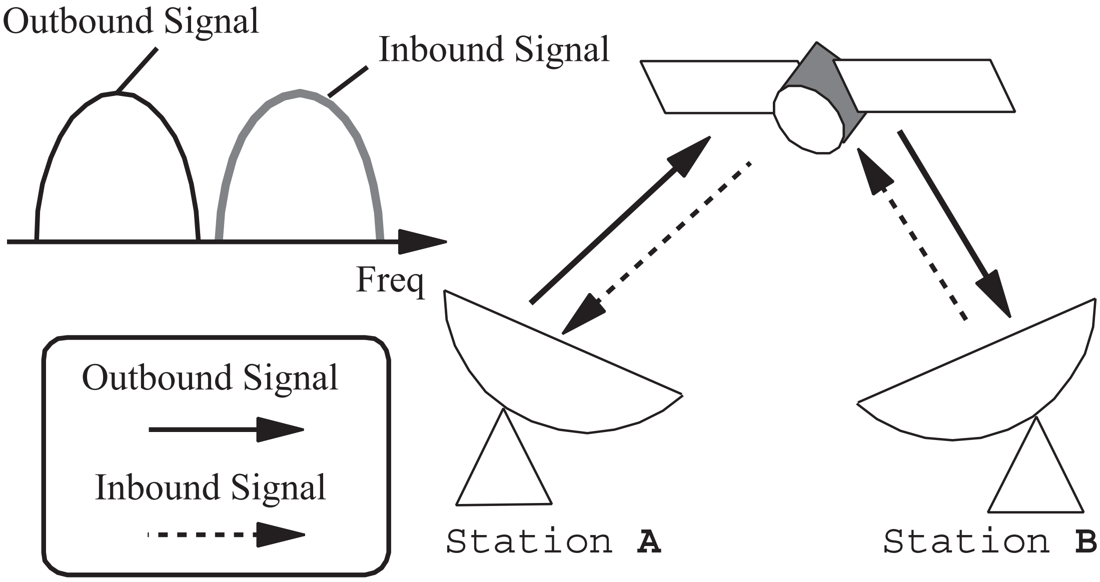


Figure 4. P to P satellite system

to-Point" (P-P) connection, and if one station is connected to multiple stations, that is called "Point-to-MultiPoint" (P-MP) connection. More information about P-P and P-MP connections are detailed below.

P - P

Figure 4 shows the layout of P-P satellite network. In P-P satellite system, one earth station only communicates with another earth station at a time. The signal can be unidirectional or bidirectional but in most cases, bidirectional network is adopted. Two earth stations are symmetric and either of the stations can be the transmitter or the receiver. They also have about the same signal transmission power. An example of P-P satellite network is intercontinental satellite communication.

P - MP

Figure 5 shows the layout of P-MP satellite network. In P-MP satellite system, one large earth station (hub) communicates with very small aperture terminals (VSAT). VSATs have small transmission power compared to hub station. This network can also be unidirectional or bidirectional. For example, unidirectional

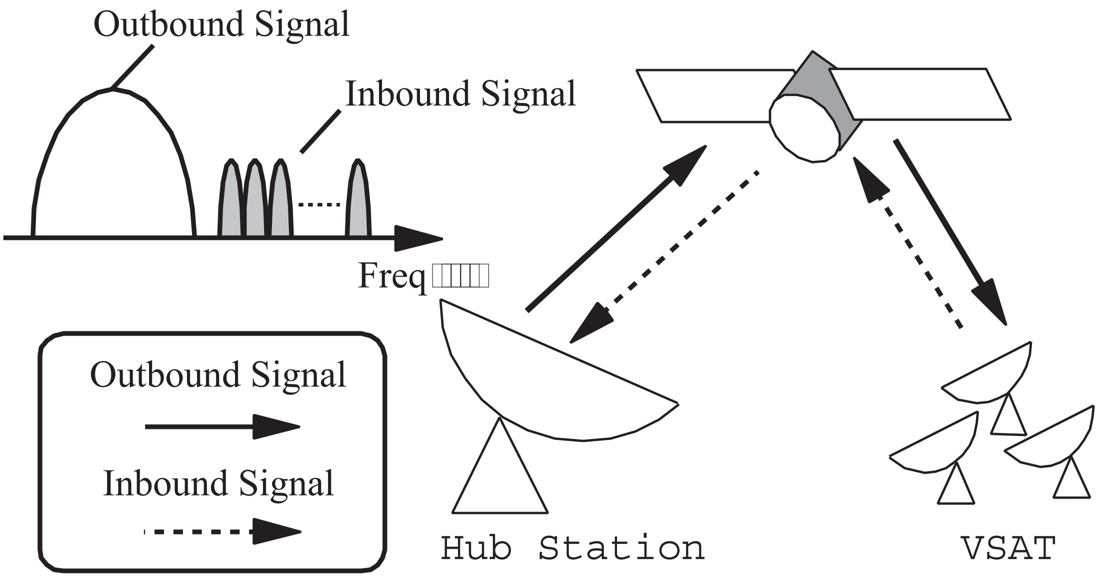


Figure 5. P to MP satellite system

P-MP network is used for broadcasting information to wide area quickly, and bidirectional P-MP network is used for on-demand video delivery service.

2.3 Problems of Current Satellite Communication

Currently, more and more highly intelligent devices have been developed and the size of data that are been exchanged over the network is increasing. This trend has increased the demand of more channel capacity to satellite systems. However, this is a challenge for satellite communication because the number of satellites that could orbit is limited. As mentioned before, if two satellites that use the same frequency band are placed too close to each other, it may cause interference to each other. To avoid the interference, the earth station's antenna must have narrow and precise directivity, which is unrealistic in terms of cost.

Based on above facts, there are two ways to expand satellite channel's capacity without adding or modifying the satellite. In this part, these two methods are shown.

2.3.1 Frequency usage

The first way to increase channel capacity is to use frequency more efficiently. If more information could be squeezed into same bandwidth, or reduce the bandwidth required to transmit same signal, then the channel capacity will increase. There are many researches for better frequency usage. For example, there is a method proposed for spectrum control, which split and compress transmitting frequency band to fit into available frequency band on satellite transponder.

Author has also researched a method called "carrier superposing", which superpose two frequency band into one band to achieve double frequency usage efficiency [10]. When using this technique, canceller must be installed to the receiver to cancel out undesired signal that is superposed to the desired signal. This means that by adding canceller to the receiver, it is possible to achieve twice of frequency efficiency. However, two uncorrelated signals are superposed, so the nonlinearity of satellite amplifier becomes more serious problem.

2.3.2 Transmission Power

Another way to increase channel capacity is to increase the received signal's CNR. At a glance, this seems to have no effect on channel capacity improvement, but if CNR increases, there is a choice of using multi-level modulation schemes. Multi-level modulation schemes like 16APSK and 32APSK are normally used in CNR condition higher than 20dB. Though, free-space propagation loss is very large because geostationary satellite is 35,786km above the earth which makes CNR lower. Earth station's receiver adopts LNA (Low Noise Amplifier) which is located near the antenna to amplify such weak signal with a small amount of noise.

There are two ways to improve the received signal's CNR. One is to adopt larger antenna for earth station to receive. In this way, higher CNR can be achieved easily but with high cost and some antennas are already in large size. Another way is to increase satellite transponder's output power. However, the satellite's power is limited because the energy is supplied from attached solar panel. Also, it is very expensive to replace satellite's amplifier to one that has higher output. As a result, the only possible way to increase satellite's output power is to operate the amplifier with smaller input backoff as far as using conventional amplifier, causing more nonlinear distortion to the signal.

2.4 Conclusion

In this section, brief overview of satellite communication system is shown. Satellite communication has many unique features. Of many features, multi accessibility and broadcasting ability are the most important features of satellite communication. To utilize its multi accessibility the most, many multiple access method has been adopted to satellite communication. Additionally, there are network layouts like P-MP systems that are specific for satellite communication. Some of these techniques shown above are adopted to terrestrial communication with many other techniques that are not shown here. This is because these technologies are brought from state-of-the-art researches, which are usually done under the initiative of government in the name of space development.

From the prevalence of high definition videos and other large size data, more and more channel capacity of satellite network is desired. However, changing the hardware configuration of satellite transponder is unrealistic from the point of cost. To achieve higher channel capacity with current satellite transponder, which has limited power supply, and minimum modification to earth station, operating satellite amplifier near saturation level and taking measures to nonlinear effect is necessary. Next section refers about more detail of satellite amplifier's nonlinearity and general idea of the countermeasures that have been considered until now.

3. Nonlinearity and Linearization Technique

3.1 Introduction

In the previous section, basics of satellite communication is explained. There are many types of satellite network, but they all use HPA which has nonlinear characteristics to amplify weak signal received at satellite transponder. Currently, most of the satellite transponders are configured to take large input backoff to avoid large nonlinear distortion of the signal and this prevents satellite from utilizing maximum output power. To use satellite's limited power more effectively, this dissertation proposes a nonlinearity compensation scheme. Though before the proposal, nonlinear characteristics of the satellite amplifier must be analyzed.

First in this section, a detail of nonlinear amplifier which is used in conventional satellite systems is explained. Then, typical nonlinear characteristic models that represent the nonlinear characteristics of HPAs are explained. After that, many linearization technique of amplifier's nonlinearity that have been researched recently are explained.

3.2 Nonlinear Amplifier

Almost all amplifiers with high output power are nonlinear amplifier. They are been used in many places like satellite transponder, earth station, and many other terrestrial wireless transceivers for microwave communication. There are two major types of nonlinear amplifier that are used in such places, TWTA (Travelling Wave Tube Amplifier) and SSPA (Solid State Power Amplifier). In this section, these two types of HPAs are detailed.

Nonlinear characteristics of HPA can be classified into two forms. One is AM/AM (Amplitude to Amplitude) conversion and the other is AM/PM (Amplitude to Phase) conversion. AM/AM conversion is a relationship between input and output amplitude of the amplifier. One way to evaluate the AM/AM characteristic is to find a point where the gain of amplifier drops in 1dB from linear gain, which is called 1dB compression point (P1dB). AM/PM conversion is a relationship between input amplitude and output phase of the amplifier. The phase of the output signal varies corresponding to the input signal's amplitude.

3.2.1 TWTA

TWTA is an amplifier consist of elongated vacuum tube with an electron gun at one end and a magnetic containment field around the tube to control the electron beam. RF input and electron beam are passed through the RF circuit, usually a wire helix or coupled cavity, and emphasized RF output is collected at the other end of RF circuit. The RF circuit acts as a delay line, in which RF signal travels at the same speed along the tube as an electron beam. RF signal interacts with electron beam and velocity modulation occurs, which induces more current into the RF circuit.

Helix TWTA has a simple structure, extremely wide operating frequency band (from 300MHz to 50 GHz), and high output power. This output power depends on heat capacity of helix. Helix is usually cooled by water but if more power is induced to the helix, the thickness of helix must be increased or better thermal conductivity material must be used to prevent helix from overheating. On the other hand, coupled cavity TWTA has a series of coupled cavities arranged axially along the tube, which acts as a helical waveguide. Coupled cavity TWTA has higher output power than helix TWTA but has narrow frequency band compared to helix TWTA.

Compared with SSPA, TWTA has wider output frequency band and higher output power. Also, the power usage efficiency is larger than SSPA. However, TWTA has greater nonlinearity compared to SSPA. In conventional satellite transponder, the output power was the most important, so TWTA was used in many satellites with large input backoff to prevent signals from being non-linearly distorted. Now more power is required for satellite transponder, so the nonlinearity of TWTA is becoming an issue. In this research, TWTA is chosen for the target of nonlinearity compensation because it is widely used in satellite communication.

3.2.2 SSPA

SSPA is an amplifier that uses field effect transistors (FET) to provide large scale amplification of signals at gigahertz frequencies. A name ”solid state” comes from where it does not use any vacuum tube, only consists of power semi-conductor circuits. Conventional SSPA uses GaAs FET, which has about 100W of power resistance at maximum. To achieve higher output power, SSPA combines multiple FETs. SSPA is used in many low power earth stations and some small satellite transponders.

Compared with TWTA, SSPA has higher stability, reliability, and longer life because it does not require extensive cooling equipment like TWTA. Moreover, it is compact and inexpensive, it can be operated from a low voltage supply, and also has more linear characteristics than TWTA. However, the defect of SSPA is that it has lower output power and narrower output frequency band than TWTA. In recent years, many types of SSPA have been researched, and some that uses new semi-conductor material like GaN FET are reported to have power close to TWTA. From great improvement of SSPA, SSPAs are beginning to taking places of TWTA that are used in satellite communications. Still, many satellite transponder uses TWTA and moreover, SSPA also has a certain amount of nonlinearity.

3.3 Nonlinearity Model

Many researchers have been proposing models that represent nonlinear characteristics of HPA. Models for the nonlinearity can be classified into three types; a nonlinearity model with memory, quasi-memoryless model, and memoryless model or instantaneous model. The main reason why memory effect appears is from thermal change and power supply's DC bias drifting. In this research, to make the story simple, nonlinear characteristics are presume to be memoryless.

The following section describes typical memoryless nonlinearity models. They all based on the fact that nonlinear characteristics that should be represented are only AM/AM conversion and AM/PM conversion characteristics. From those memoryless nonlinearity models, Saleh's model described below is applied as satellite amplifier's nonlinearity in this research.

3.3.1 Polynomial Model

Polynomial model is a nonlinearity model which represents output function of the amplifier with finite polynomial equation of the input sequence

$$\boldsymbol{x} = [x_1, x_2, \cdots, x_L]^T, \tag{1}$$

where L is the number of input sequences used to calculate the output. Then the output polynomial function can be represented as

$$\boldsymbol{y} = \sum_{k=0}^{N} \alpha_k \boldsymbol{x}^k, \tag{2}$$

where N is the order of the polynomial function and α are the coefficients.

The coefficients α can be determined using least-squares estimation by finding the values that give minimum error to actual output of the amplifier. Polynomial function will be representing the actual characteristics of amplifier precisely when the order N becomes large. Contrarily, the calculation cost becomes large when order N is larger. Usually, polynomial model is used only to represent AM/AM conversion of the amplifier, and a different model like linear phase change model is applied to AM/PM conversion.

3.3.2 Saleh Model

Saleh Model [24] was constructed to represent the nonlinear characteristics of TWTA. In Saleh model, two equations that represent AM/AM conversion and AM/PM conversion are defined. AM/AM conversion is represented by

$$g(A) = \frac{\alpha_g A}{1 + \beta_g A^2}, \tag{3}$$

where A is amplitude of the input signal at that moment, and α_g, β_g are coefficients to adjust output amplitude. Similarly, AM/PM conversion is represented by

$$\Phi(A) = \frac{\alpha_\Phi A^2}{1 + \beta_\Phi A^2}, \tag{4}$$

where A is the same as above equation and α_Φ, β_Φ are coefficients to adjust output phase rotation.

As shown in above equations, both AM/AM and AM/PM conversion is based only on the instantaneous amplitude of the input signal. Also parameters $\alpha_g, \beta_g, \alpha_\Phi, \beta_\Phi$ are used to adjust nonlinear characteristics to be closer to actual TWTA, where TWTAs have individual variance. To decide the parameters, TWTA's nonlinear characteristics can be extracted from actual amplifier by measuring the relationship of input and output signal.

In this research, this Saleh model is applied for nonlinear characteristics of TWTA because it is simple and is sufficient to express the nonlinearity of most TWTA used in satellite communication.

3.3.3 Ghorbani Model

Ghorbani model was developed to represent SSPA's nonlinearity because SSPA has different nonlinear characteristics than TWTA. It represents SSPA's nonlinear characteristics better than Saleh model. Same as Saleh model, Ghorbani model has two equations each representing AM/AM conversion and AM/PM conversion characteristic. AM/AM conversion is represented by

$$g(A) = \frac{x_1 A^{x_2}}{1 + x_3 A^{x_2}} + x_4 A \tag{5}$$

where A is amplitude of the input signal, same as Saleh's and x_1, x_2, x_3, x_4 are coefficients to adjust output amplitude. AM/PM conversion is represented by

$$\Phi(A) = \frac{y_1 A^{y_2}}{1 + y_3 A^{y_2}} + y_4 A \tag{6}$$

where A is the same as above equation and y_1, y_2, y_3, y_4 are coefficients to adjust output phase rotation.

As you can see from the equations, it is possible to give same AM/AM and AM/PM conversion characteristics as Saleh's model by setting parameters as so and parameters can also be configured to have more linear characteristics. These parameters can be configured to achieve the same characteristics as actual SSPA nonlinearity.

3.3.4 Rapp Model

Rapp model was developed for SSPA nonlinearity. Rapp model is represented in the form of one equation for AM/AM conversion only. AM/AM conversion is represented by

$$g(A) = v \frac{A}{\left(1 + \left[\frac{vA}{A_0}\right]^{2p}\right)^{\frac{1}{2p}}}, \ p > 0, \ A_0 \geq 0, \ v \geq 0 \tag{7}$$

where p is a smoothness coefficient, A_0 is saturation level, and v is small signal gain.

Rapp model has the following features. It has smooth transition near saturation point of AM/AM conversion, and the function that represents AM/PM conversion is not defined in Rapp's model because AM/PM conversion of SSPA is negligibly small compared to TWTA's AM/PM conversion characteristic. The larger the smoothness coefficient p becomes, the output function becomes more linear and the transition near saturation becomes sharper.

3.4 Linearization Technique

As shown above, there are many models proposed to represent the nonlinear characteristics of HPAs. What they all have in common is the conversion function of AM/AM and AM/PM characteristics. That is to say that those two conversions are the only nonlinearities that have to be concerned to prevent signal from receiving nonlinear distortion. In this section, a brief description of many linearization techniques that are proposed to relieve nonlinear distortion is noted.

3.4.1 Pre-distortion

The first linearization technique shown in this section is the pre-distortion scheme. Pre-distortion is a scheme which applies reverse nonlinear characteristics of satellite amplifier to the input of the amplifier to achieve linear output. Ordinary pre-distorter consists of attenuator for AM/AM pre-distortion and phase shifter for AM/PM pre-distortion.

Pre-distortion scheme can be adopted very easily and is an inexpensive method because it can be installed to transmitter which is on earth. This scheme also does not require any controller to adjust the compensation. Negative points of this scheme are that pre-distortion can only be applied when amplifier's nonlinear characteristics are known ahead and is sensitive to drifting bias. Moreover, this scheme expands signal's frequency spectrum caused by reverse distortion. Transmitter's output spectrum is restricted by filter so under-compensation will essentially occur.

3.4.2 Feedforward

Feedforward is a scheme which compares input and output signal of nonlinear amplifier and adds the differential signal, which is amplified by another amplifier, to the output of primary amplifier. In this scheme, amplifier with the same gain and characteristics as main amplifier must be adopted to have full compensation. Also, the delay lines are inserted to match the signal timing.

As described above, feedforward scheme is implemented in satellite transponder so the cost will be expensive to apply feedforward compensator to conventional satellite transponder. In addition, feedforward scheme requires two HPAs that have the same power, so it is very difficult to apply this scheme to satellite transponder which has very high power amplifier, because of limited power resource. Moreover, it has bandwidth limitation to passing signal from the reason of circuit delay of the control loop and secondary amplifier.

3.4.3 Feedback

Feedback scheme controls the input signal of nonlinear amplifier by referring to the output of the amplifier. It draws an output signal and gives attenuation to it to compare it with an original input signal. Then a variable attenuator and phase shifter, which are controlled by differential signal, are inserted before the input of nonlinear amplifier to adjust its output signal for nonlinearity compensation.

Same as feedforward scheme, feedback scheme is also expensive to install because it is applied to satellite transponder. It also has limitation over signal bandwidth due to the signal delay of the control loop. However, compared with feedforward scheme, this scheme has difficulty on stability of the control loop. Feedforward and feedback scheme are not used commonly because of these disadvantages.

3.4.4 LINC

The last scheme shown here is LINC (LInear amplification using Nonlinear Components). In LINC scheme, the input signal is divided into two constant envelope signals and those signals are fed to two individual amplifier. Then the amplified signals are combined to achieve amplified original signal. In this way, two nonlinear amplifiers can be used to achieve linear output because splitted signals have smaller power, which means those amplifiers are operated in larger backoff.

When there is a difference on output gain or phase between two amplifiers, distortion will be generated on synthesized signal. This distortion gives out-of-band spectrum that cause intersymbol interference. Therefore, output control of two amplifiers are very important. Moreover, the amplifiers must have the same characteristics and suitable modulation scheme is required.

3.5 Conclusion

In this section, first, two types of nonlinear amplifier is introduced. Of those two amplifiers, TWTA is targeted for nonlinearity compensation of this research. Next, four major models that represent the nonlinearity characteristics of the amplifier is explained. Here, Saleh model is adopted for this research because it well represents TWTA's nonlinear characteristics. Finally, four different types of linearization technique are explained in this section.

The four linearization techniques each have different advantages and disadvantages but of those techniques, pre-distortion scheme has been widely researched because it is easy to apply and is capable to be applied at many types of satellite systems. However, in some typical satellite network like carrier superposed network, pre-distortion scheme can not be applied. Therefore in this research, another nonlinearity compensation technique, post-compensation is proposed.

4. Post-Compensation Technique

4.1 Introduction

To decrease interference caused by nonlinear amplifier for typical satellite networks, post-compensation scheme is proposed to compensate nonlinear distortion of TWTA at the receiver side. In this section, the algorithm of proposal post-compensation is explained. The basic idea of proposal method is to give a reverse nonlinear distortion to the signal at the receiver to gain originally transmitted signal.

4.2 Proposed Nonlinearity Compensation Scheme

4.2.1 Nonlinearity Compensation Algorithm

The TWTA output signal $u(t)$ against the input signal $s(t)$ can be expressed by [5]

$$u(t) = s(t) \times G[s(t)], \tag{8}$$

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

$$G[s(t)] = \frac{1}{s(t)} g(|s(t)|) \exp(jf(|s(t)|)). \tag{9}$$

The function $g(r)$ and $f(r)$ represent AM/AM and AM/PM conversion characteristics of nonlinear devices, respectively. For TWTA, amplitude of the input vector is distorted according to AM/AM characteristics [25, 20]

$$g(r) = \frac{\alpha_x r}{1 + \beta_x r^2}, \tag{10}$$

and phase of the input vector is distorted according to AM/PM characteristics [25]

$$f(r) = \frac{\alpha_\phi r^2}{1 + \beta_\phi r^2}, \tag{11}$$

where r is the amplitude of the input vector and α, β are TWTA parameters.

If we can know the original signal before TWTA distortion, that is the signal compensated and linearized. In post-compensation, the original TWTA input signal can be estimated by calculating

$$g^{-1}(y) = -\sqrt{\frac{\alpha_x^2}{4\beta_x^2 y^2} - \frac{1}{\beta_x}} + \frac{\alpha_x}{2\beta_x y}, \tag{12}$$

where y is the amplitude of received signal vector. This equation can be derived from above equation(10). After received signal's amplitude is fixed with equation(12), the signal's phase is rotated inversely according to equation(11).

These processes of nonlinearity compensator are shown in Figure 6. z in the figure represents input signal of nonlinearity compensator. If we do not consider the effect of noise and wave deformation due to filters, $g^{-1}(|z|)$ at ⓐ in Fig.6 regenerates original signal level r where the AM/AM distortion caused by satellite's nonlinear amplifier is removed. Next, by reading the original amplitude of each sampling point, the angle of phase distortion $f(r)$ caused by satellite's TWTA can be estimated. Then this angle θ can be used to rotate the signal reversely at ⓑ in Fig.6 to remove AM/PM distortion. As a result, signal before TWTA distortion can be achieved at ⓒ. Linearization by these methods is actually performed by digital signal processing at receiver side.

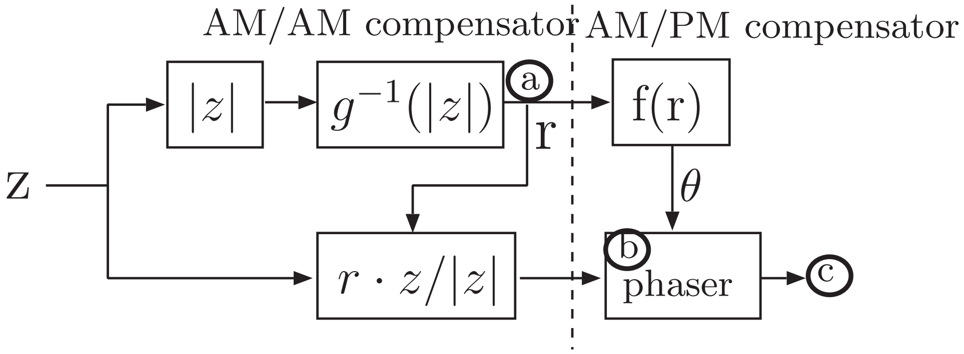


Figure 6. Process and algorithm of nonlinearity post-compensator.

Because the thermal noise is added to the receiver's input and the distortion due to the filters between TWTA and compensator, the waveform of the TWTA output changes at the input of the compensator. From this, the theory of linearization mentioned above will not be satisfied and thus the signals output from compensator do not exactly match to the satellite's input signal. Figure 7 shows a case when TWTA input signal does not return to its original vector due to noise and filter. This error finally becomes major reason of the dispersion of the constellation of inbound signal. The simulator explained next is used to explore the effect of thermal noise and filter on nonlinearity compensation. If carriers other than opposed two waves are commonly amplified in the same transponder, proposed compensation can be performed by receiving all these carriers. Therefore, by this method, it is possible to expand this algorithm to the case of multi-user and multi-frequency for one transponder that the inter-modulation is caused.

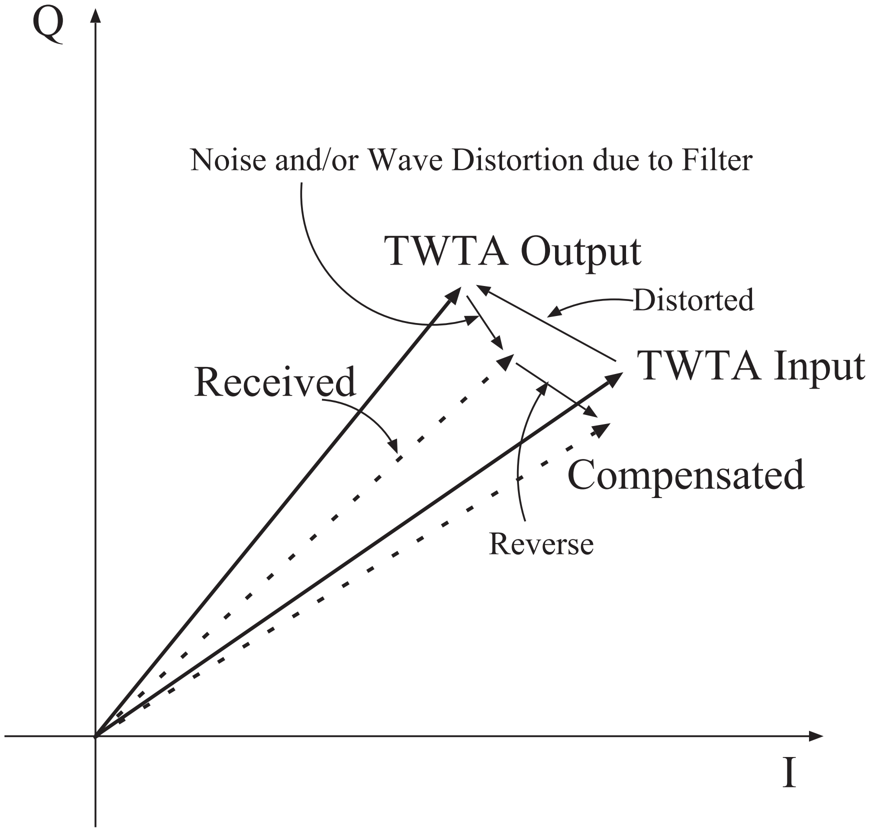


Figure 7. An example of compensation of distorted signal due to the noise and/or wave distortion by receiving filter.

4.3 Conclusion

In this section, a post-compensation method of satellite TWTA's nonlinearity is described. In this method, signal received at the earth station is passed through nonlinearity compensator, which fixes the signal's amplitude and phase based on reverse function of TWTA's nonlinear characteristics.

This post-compensation method is applicable to most of the satellite systems simply by adding compensator in the receiver. By using proposal method, it is possible to operate satellite transponder with smaller backoff and higher output power to achieve higher power usage efficiency. The next two sections are an example of the application of proposal scheme.

5. Nonlinearity Compensation for Multi-level Modulation Systems

5.1 Introduction

Recently in satellite communications, application of 16APSK and 32APSK are being considered [9, 8, 35] to improve transmission capacity for high quality video broadcasting and other digital contents. Compared to ordinary PSK, these modulation schemes have larger channel capacity but smaller intersymbol distance and is sensitive to nonlinearity of the network. Many researches to decrease the effect of system's nonlinearity and its compensation have been proceeding recently. These researches can be categorized into two groups; ones that decrease the PAR (Peak to Average power Ratio) of modulated signals and others that relieve the nonlinearity of the system.

Example of former researches are modulation with hexagonal constellation which has lesser PAR than QAM (Quadrature Amplitude Modulation) and PAR reduction method which smoothen transition over the constellation by using special coding and waveform shaping on bandwidth limited signals [29, 31, 30]. Reducing PAR is effective to relieve nonlinearity of the network, though when thinking the effect of nonlinearity to multi-level modulation, not only PAR but also difference of minimum and maximum amplitude becomes the problem, and the effect of nonlinearity against modulation like QAM and APSK that uses amplitude and phase for coding, cannot be removed by those PAR reduction methods. Moreover, power loss and bandwidth loss caused by PAR reduction must be concerned.

On the other hand, pre-distortion method explained in Section 3.4, which estimates the distortion vector generated at satellite transponder and adds reverse distortion vector to the output signal at the transmitter to cancel out the distortion [14, 15], is an example of the latter researches. This method can also improve transmission performance by relieving nonlinearity of the system but can cause spectrum spread of the transmission signal with nonlinear pre-distortion process. Additionally, higher linearity is required for the transmitter's amplifier because pre-distortion might emphasize the amplitude change of the modulated signal.

In this section, a post-compensation method is applied to multi-level modulated satellite network. Proposed method estimates the phase and amplitude distortion that signal suffer at satellite from the amplitude of received signal and compensate it by giving reverse distortion to the signal. Generally, multi-level modulation is used with very high CNR environment and such condition gives small error to the estimation of distortion vector. Therefore, this compensation method is suitable for multi-level modulation network. This method can be implemented easily by using recent digital signal processing technology.

5.2 Channel Model

In this section, satellite system model and its modulation scheme is detailed. Satellite system that is described in this section is a general satellite communication system like the one for video transmission.

5.2.1 Satellite System

System of satellite communication consists of three parts, transmitter, receiver, and satellite. Here, the detail of each part is explained.

In transmitter, signals to be sent to other stations are generated. First in the transmitter, those signals are modulated in many ways. The fundamental modulation schemes are shown in Section 2.2.2, and the modulation scheme used in this research is explained in the next section. The modulated signals are passed through a filter to eliminate out-of-band signals, and upconverted to higher frequency. Finally at the transmitter, the signals are amplified with HPA and transmitted to satellite using large antenna.

The important fact is that from band limitation, AM component of signal waveform is emphasized. AM component will be smaller if the output filter passes the signal of wider frequency band. However, output filter cannot be configured too wide band because there are other signals transmitted at neighbor band that could interfere with each other. In the receiver, signals are demodulated with reverse process of transmitter. Filters used at the transmitter and receiver are rolloff filter which has the same specification, and two filters are combined to fulfill Nyquist criterion.

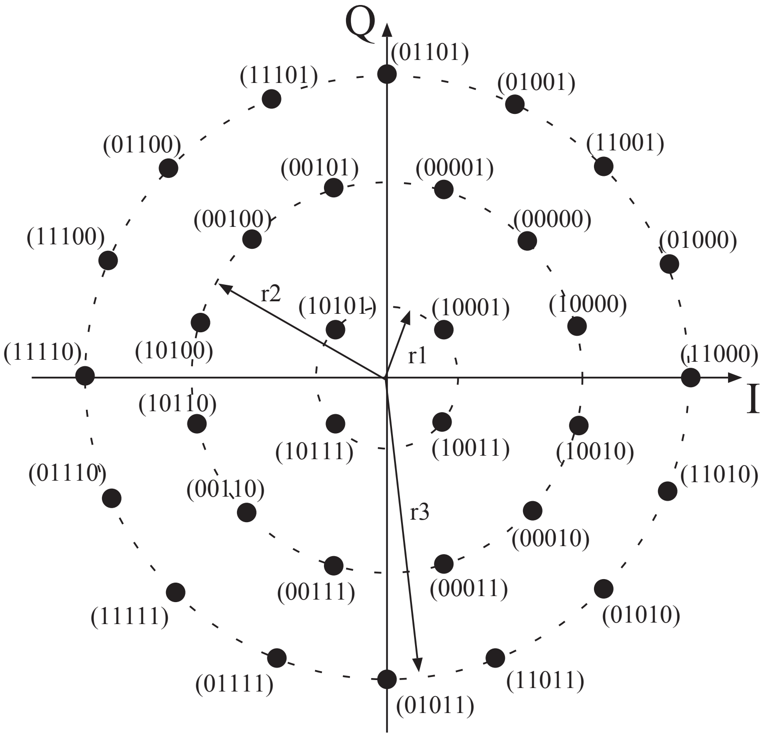


Figure 8. 32 APSK Signal Constellation

Satellite station receives signals sent from the transmitter and convert those signals to different frequency band. After the conversion, out-of-band signals are eliminated by passing through a filter, and signals are amplified by satellite's TWTA to be sent to receiver station. Filter used at satellite transponder is generally a precipitous filter with frequency band wider than earth station's filter so that it will not give an effect to the signals. Also backoff of satellite amplifier has been taken enough for linear amplification because TWTA has nonlinearity characteristics. Nonlinearity of TWTA is explained in Section 3.2.1.

5.2.2 Modulation Scheme

By referring to DVB-S (Digital Video Broadcasting - Satellite) [33], QPSK have been commonly used for digital satellite communication but recently the channel capacity has been growing larger and hence in DVB-S2, multi-level modulation schemes like 16APSK and 32APSK (Figure 8) have been adopted. Usually, such modulation schemes are supposed to be used in high CNR and linear channel condition, and it is difficult to transmit information without error in low CNR and/or nonlinear affected channel. In such condition, modulation schemes like QPSK that have tolerance to noise and nonlinear distortion have been adopted to transmit information securely.

APSK is a modulation scheme which codes information with both amplifier and phase of the signal. Therefore, its transmission error rate will be degraded greatly by the nonlinearity of the channel. Another important fact is that unlike PSK modulations, all symbol's amplitude are not the same in APSK. Nonlinear distortion that inner ring and outer ring of constellation receives differs (outer ring receives larger distortion compared to the inner ring). From this, transmission error rate will also differ by which signal constellation a modulation scheme uses. Here, distance between each ring of the constellation is defined as [26]

$$\gamma_1 = r2/r1, \tag{13}$$

$$\gamma_2 = r3/r1. \tag{14}$$

Each values γ_1, γ_2 are standardized in DVB-S2 and determined from system's coding rate.

5.3 Simulation Results and Discussion

In this section, proposed post-compensation scheme is adopted to practical satellite system which uses 32APSK signal for transmission performance evaluation.

This research is about the nonlinearity so the satellite amplifier's operation level is very important parameter. In general, TWTA's operating point can be represented in forms of input backoff(IBO) or output backoff(OBO). In this dissertation, IBO is used to determine the operation point. IBO and OBO are defined by the following equations

$$\mathrm{IBO} = -10\log_{10}\frac{E\{|A_{RX}|^2\}}{A_I^2}, \tag{15}$$

$$\mathrm{OBO} = -10\log_{10}\frac{E\{|A_{TX}|^2\}}{A_O^2}, \tag{16}$$

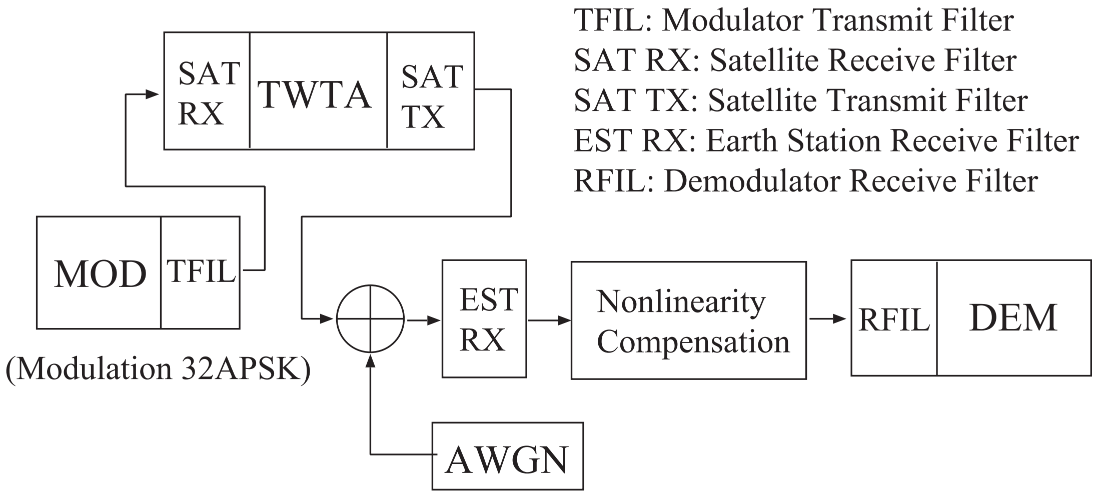


Figure 9. Channel Model of Nonlinear Satellite Channel for 32APSK Transmission with Nonlinearity Compensation

where A_{RX}, A_{TX} are amplitude of satellite transponder's input and output signal respectively, and A_I, A_O are the maximum amplitude of satellite transponder's input and output respectively. $E\{\}$ is an averaging operation.

5.3.1 Simulation Model

Figure 9 shows transmission channel model for the simulation of the network system. In this simulation, filters are not shown in Figure 9 (for example filters for RF transmitter and receiver, frequency converter) are not concerned because they have sufficiently wide frequency band. In this simulation, only the filters which have effect on waveform transmission and nonlinearity compensation are concerned. To decrease the thermal noise component, filter with the same frequency band as satellite transponder's filter (but different type) is inserted before the nonlinearity compensator of the receiver.

Transmission characteristics are determined by AM/AM and AM/PM characteristics of nonlinear component and filter's bandwidth and out-of-band attenuation characteristic. Therefore in this section, each value on Table 1 is simulated to find how the change in filter's bandwidth and rolloff rate effect the nonlinearly distorted signal and performance of compensator.

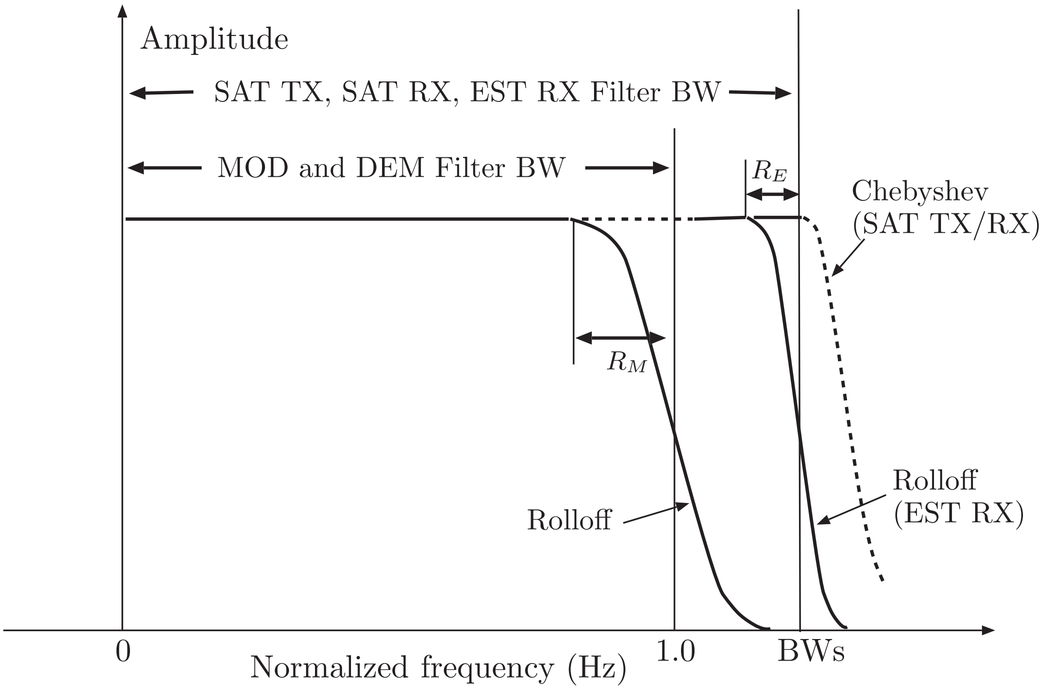


Figure 10. Filter bandwidth of modem, satellite TX/RX, and earth station RX filters

In Table 1, signal bandwidth is normalized to 1.0. If satellite and receiver's normalized bandwidth BW are increased, bandwidth of signal reception path (from satellite TWTA to nonlinearity compensator) will be wider compared to signal bandwidth. Then the deformation of the signal will be smaller and compensator's functionality will be better from the property of compensation algorithm shown in Section 4.2.

Figure 10 shows the relationship between filter bandwidth used in modulator/demodulator and transmission path. For satellite transponder's transmission/reception filter, a 7th-order Chebyshev filter with 4 types of bandwidth is concerned, and for modulator and demodulator's filter, root cosine rolloff filter with 4 types of rolloff rate is concerned (total of 16 combination of bandwidth

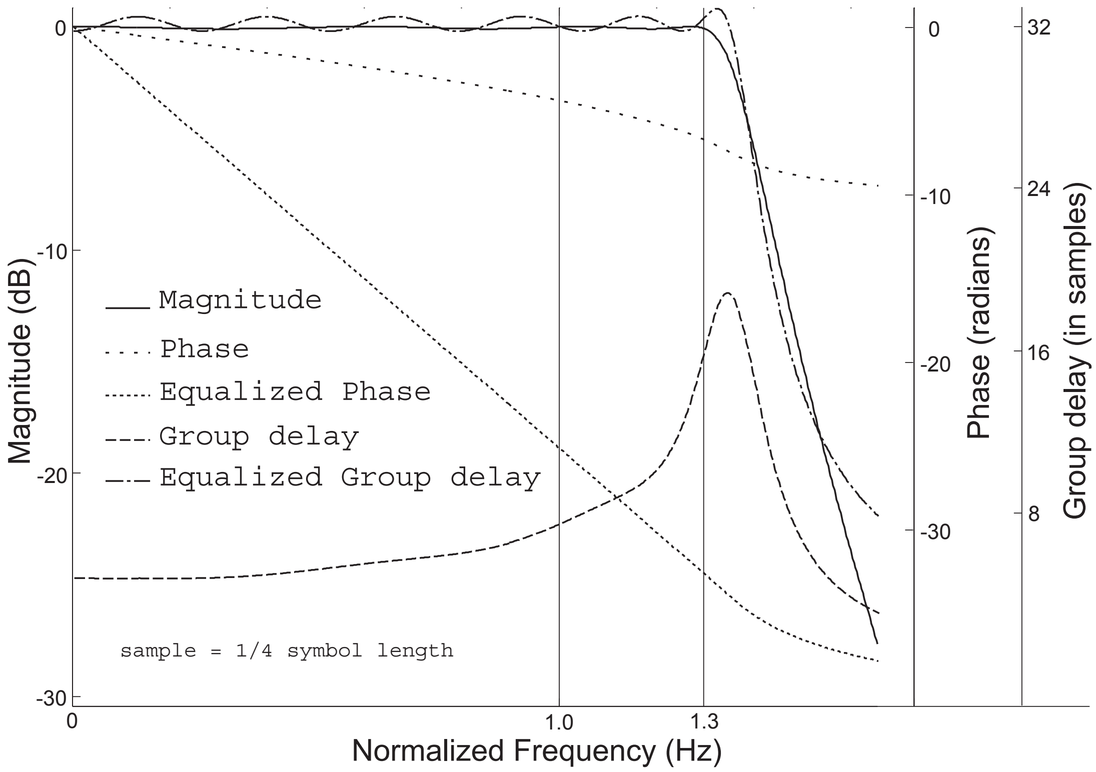


Figure 11. A design of Chebyshev filter used in the satellite TX/RX filter (in case of BW=1.3)

and rolloff rate). Chebyshev filter's group delay is equalized with 10th-order equalizer. When rolloff rate of mod/demod becomes larger, transmitted signal's amplitude variance will be smaller and effect of nonlinearity is expected to be lesser. Figure 11 shows amplitude, delay, and phase characteristics of satellite's transmission/reception filter.

Besides filter characteristics, parameters α, β for nonlinearity characteristics appear in Equation (10) and Equation (11) are chosen as shown in Table 1. Also, radius parameters for 32APSK constellation used in the simulation are shown in Table 1. These values are cited from parameter in related work [15] and specification of DVB-S2 [34].

Table 1. Simulation parameters for 32APSK transmission via nonlinear satellite channel

<table>
<tr><td rowspan="4">Filters</td><td>Name</td><td>Normalized Bandwidth (BW)</td><td>Rolloff Factor or Type</td></tr>
<tr><td>MOD TFIL
DEM RFIL</td><td>1.0</td><td>$R_M : 0.1, 0.2, 0.3, 0.4$</td></tr>
<tr><td>SAT TX FIL
SAT RX FIL</td><td>$1.1, 1.2$
$1.3, 1.4$</td><td>7th order Chebyshev with 10th order delay equalizer</td></tr>
<tr><td>EST RX FIL</td><td>$1.1, 1.2, 1.3, 1.4$</td><td>$R_E : 0.2$</td></tr>
<tr><td>Nonlinearity Parameters</td><td colspan="3">In Eq.(10)&(11)
$\alpha_x = 1.0, \beta_x = 0.25, \alpha_\phi = \pi/12, \beta_\phi = 0.25$</td></tr>
<tr><td colspan="2">TWTA Input Backoff</td><td colspan="2">$3 - 30$ dB (3dB step)</td></tr>
<tr><td colspan="2">Nonlinearity Compensation</td><td colspan="2">with and without</td></tr>
<tr><td colspan="2">32APSK Constellation</td><td colspan="2">$\gamma_1 = 2.72, \gamma_2 = 4.87$</td></tr>
<tr><td colspan="2">Oversampling factor</td><td colspan="2">4</td></tr>
<tr><td colspan="2">Number of Symbols</td><td colspan="2">2,000,000</td></tr>
</table>

5.3.2 Transmission Characteristics

In this section, the degradation of nonlinear transmission path and performance of proposed compensation scheme is evaluated by bit error rate and constellation of received signal. Then from those results, the effectiveness of proposal scheme is considered. From the limitation of space, not all figures of the result are listed here. Only the figures that are needed to discuss the performance of proposal scheme are listed.

Bit Error Rate Performance As shown in Table 1, 16 combinations of modulator/demodulator filter (MOD TFIL, DEM RFIL) and satellite transmission path filter (SAT TX/RX, EST RX) are tested with and without nonlinearity compensation by changing input backoff to measure signal's bit error rate (BER) performance. White Gaussian noise is applied to 2,000,000 symbols (10,000,000 bits) of signal, enough number of samples, for BER measurement.

Here, the combination of filters are noted as (mod/demod filter's rolloff rate : satellite transmission path's bandwidth). From the limitation of space, only three cases Case1 (0.1:1.1), Case2 (0.2:1.2), and Case3 (0.3:1.3) are shown in Figure 12 – 14 respectively. Among those three cases, Case1 has the worse BER performance and least improvement of the compensation. In Case1, even with enough backoff of IBO=18dB, BER floors around 10^{-4}. The reason for this is that in Case1, low rolloff rate causes large deformation of signal waveform which leads to greater nonlinear distortion. Moreover, satellite bandwidth to signal bandwidth rate is small which makes nonlinearity compensator's input waveform a lot different than TWTA output. It is easily inferable that both of these effects lessen the compensation performance.

From simulation results of above 16 combinations, required CNR of achieving BER $= 10^{-3}$ at rolloff rate 0.1 and 0.3 are read off. In Figure 15 and 16 are change of required CNR when varying satellite bandwidth over different TWTA input backoffs at rolloff rate 0.1 and 0.3 respectively. The discontinuance of lines on the figure means BER $= 10^{-3}$ could not achieved in such condition.

From both figures, the following facts can be said.

a) By choosing rolloff rate over 0.2 for modulator/demodulator filter, it is possible to achieve large compensation effect in IBO above 9dB.

b) Satellite bandwidth should be more than 1.2 to achieve stable compensation. (Thus, bandwidth usage efficiency should be below 1/1.2.)

As well in Figure 15 and 16, the BER floors even when system is linear at rolloff rate of 0.1 and satellite bandwidth of 1.1, from the effect of filters with precipitous attenuation band. Also, the BER characteristics of IBO=18dB with and without compensation are nearly the same with linear case because in that region, the system is very close to linear.

Improvement of Required CNR Next, from the BER data in Section 5.3.2, required CNR to achieve BER $= 10^{-3}$ when changing input backoff for two cases (0.3:1.4) and (0.2:1.2), are shown in Figure 17. From the figure, it is obvious that

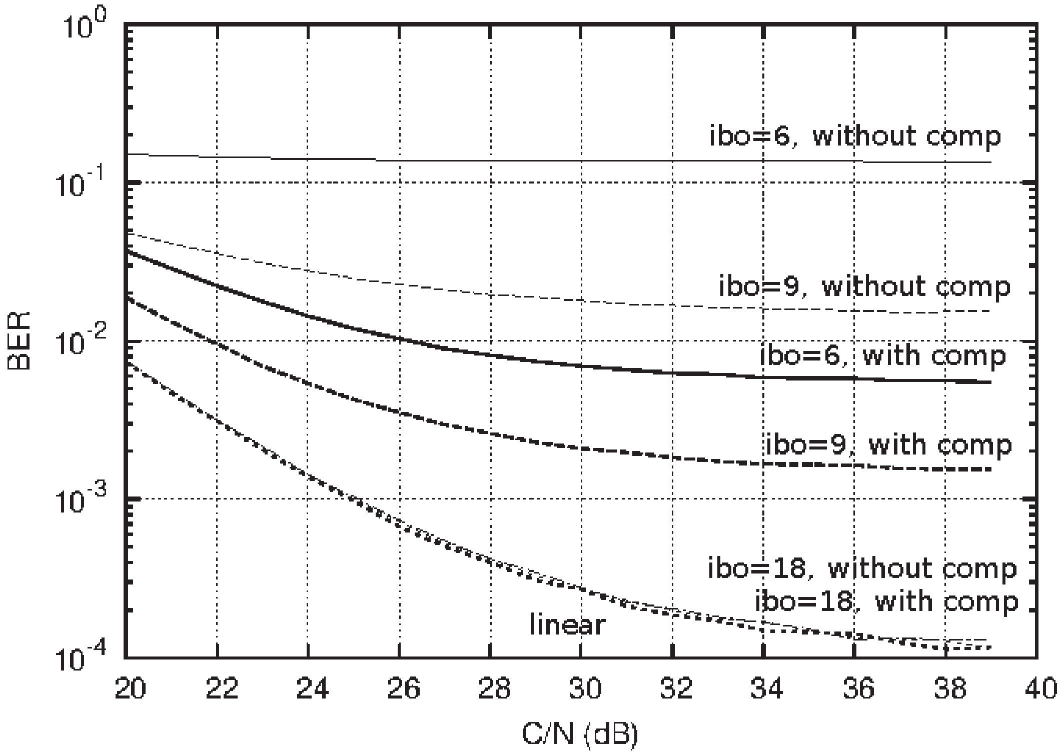


Figure 12. BER Performance of 32APSK Signal through Nonlinear Channel with and without Nonlinearity Compensation (Rolloff Rate 0.1, Bandwidth 1.1)

with IBO above 18dB, two lines of with compensation and without compensation overlaps. This is because in IBO above 18dB, system is almost in the linear region. Improvement can be seen in the region of IBO below 15dB and at IBO 10dB, approximately 2-3 dB of improvement can be seen from the figure. Also without nonlinearity compensation, BER gets worse quickly below IBO 10dB and breaks the system but with compensation, the system could be operated few dBs lower than without compensation. However, irregular bump on the curve can be seen with compensation below IBO 8dB region. This reason is concerned with the evaluation of the constellation in the next Section 5.3.2.

Evaluation with Constellation In this section, the performance of nonlinearity compensator is evaluated in another way, by the appearance of constellation. Figure 18 shows signal constellation of three cases of TWTA input backoff of

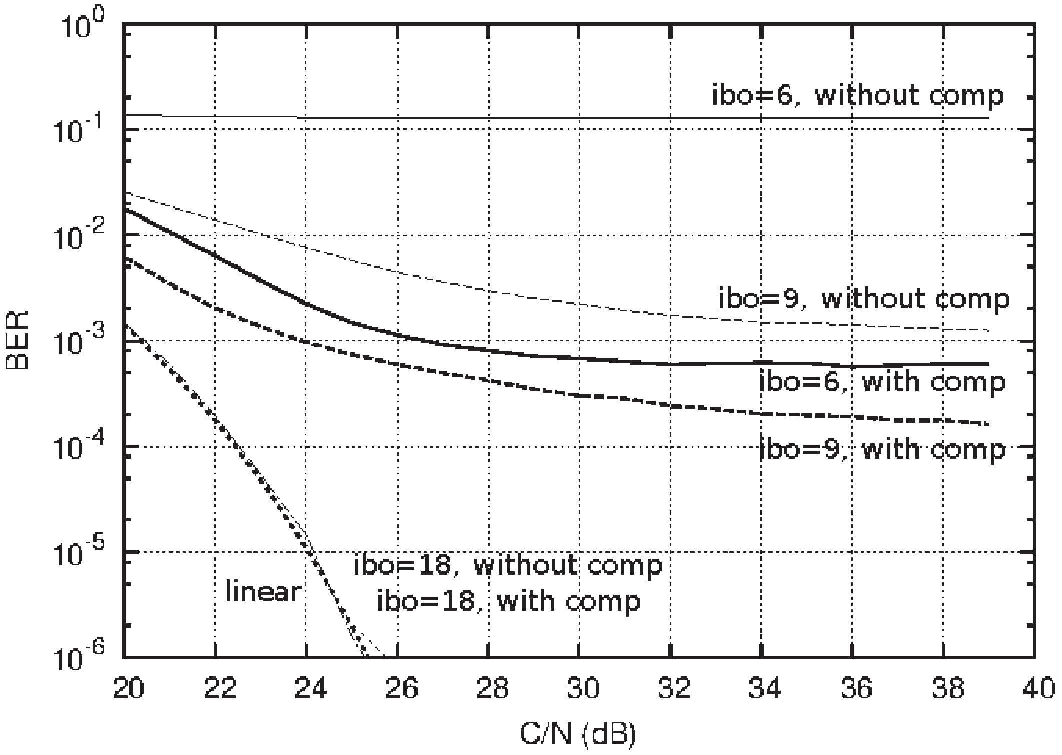


Figure 13. BER Performance of 32APSK Signal through Nonlinear Channel with and without Nonlinearity Compensation (Rolloff Rate 0.2, Bandwidth 1.2)

6dB, 9dB and 12dB, each with and without nonlinearity compensation. (0.3:1.4) is chosen as the combination of filters. Here, the thermal noise is not concerned.

From Figure 18, the effect of nonlinearity compensator could be confirmed in strong nonlinearity condition of IBO 6dB, especially in inner two rings of the constellation. Also, it is possible to know that the angle of the outer ring's constellation point is shifted by phase distortion of TWTA when there is no compensation, but with compensation, the shift is resolved. Moreover, there are certain improvement by the compensation even in linear system of IBO 12dB. As noted in Equation (16), IBO is defined by average power and even when IBO is 12dB, the most outer ring of 32APSK constellation suffers from nonlinearity of the TWTA. Moreover in IBO 6dB, the outer ring of the constellation is assumed to be near the saturation level.

Then Figure 19 shows the constellation of received signal at IBO 9dB with

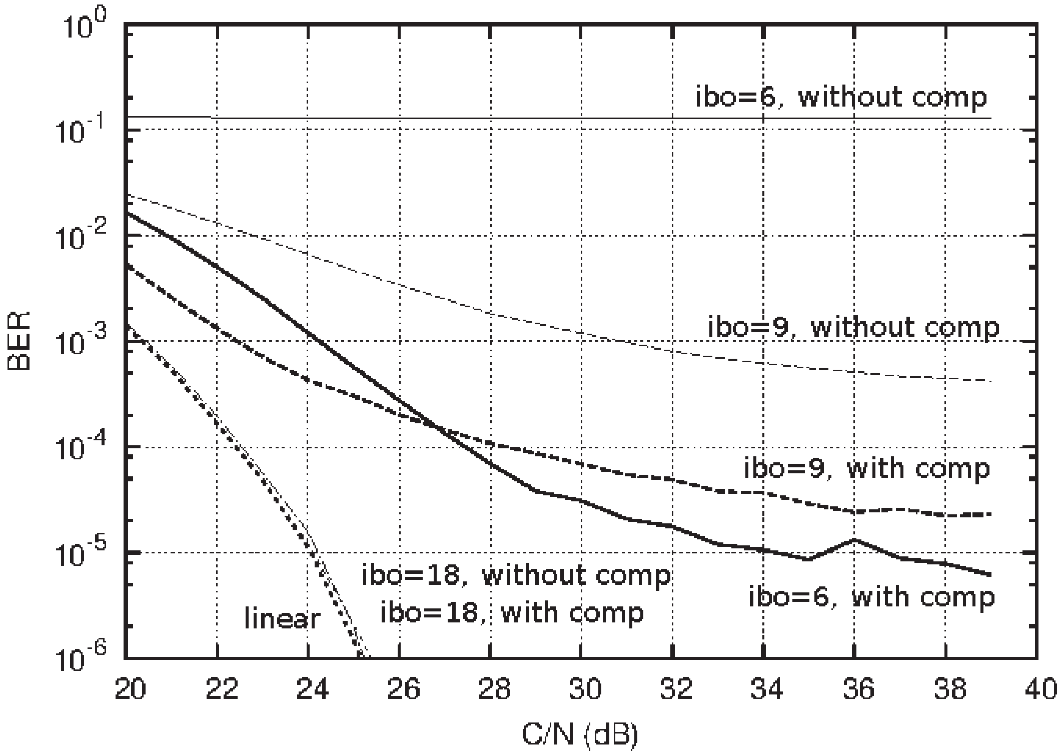


Figure 14. BER Performance of 32APSK Signal through Nonlinear Channel with and without Nonlinearity Compensation (Rolloff Rate 0.3, Bandwidth 1.3)

thermal noise added, for both cases of with and without nonlinearity compensation. In the figure, it is possible to confirm the remarkable improvement by nonlinearity compensator for inner two rings of constellation and same as above, the most outer ring's phase shift is been resolved. Though with compensation, rarely the signal constellation of the outer ring has larger spreading than without compensation. The reason for this is that the outer ring signal has smaller backoff than average and receives more nonlinear distortion. When noise which increases the amplitude is added to such signal, miss-compensation occurs and the compensator will recover the amplitude and phase of the signal to the wrong value.

From Figure 19, it is possible to say that compensation process which fixes distorted signal vector to the original vector fully works from IBO 18dB (near linear) to 10dB region. However in IBO below 10dB region, distortion of the

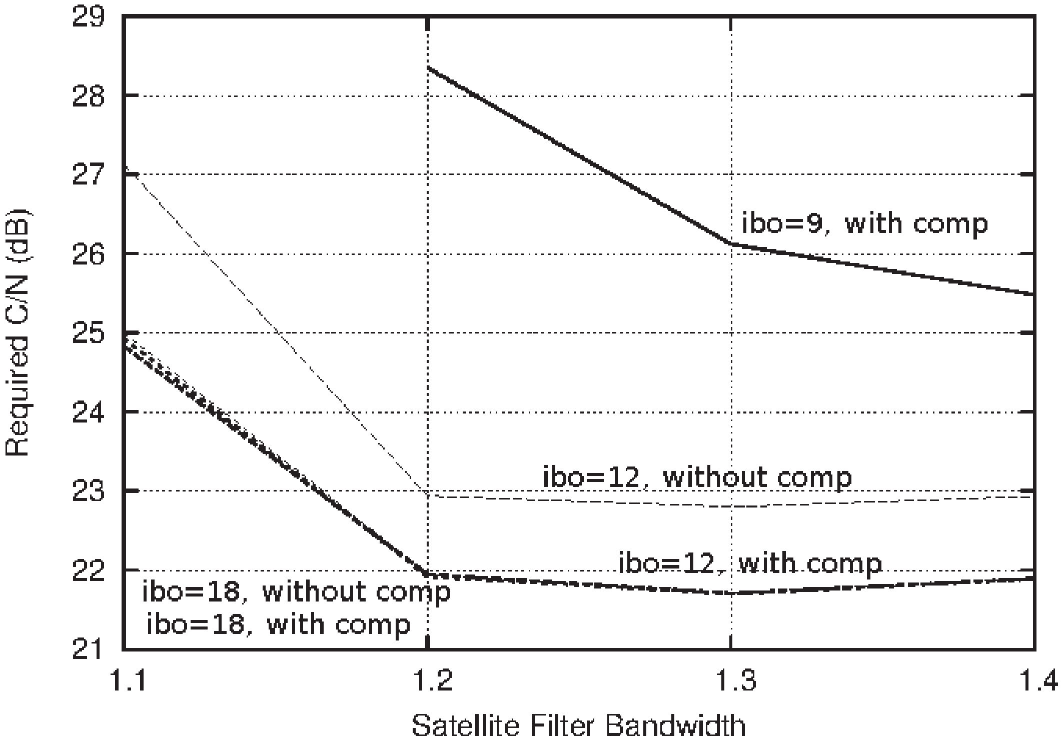


Figure 15. Required C/N to obtain BER = 10^{-3} as a function of Satellite as a parameter of Input Backoff(Rolloff Rate 0.1)

outer ring signal increases alongside the effect of nonlinearity reaches the inner ring signals and malfunction of nonlinearity compensator starts to appear. The degradation stops once around IBO 8 - 6 dB, but below 5dB the signal variance extremely increases and compensation function breaks down.

5.4 Conclusion

In this section, post-compensation scheme and its application to 32APSK satellite communication has been proposed. Furthermore, the effect of proposed scheme has been evaluated by software simulation and the bit error rate and required CNR, constellation of received signal has been concerned. From the results, it is possible to say that the post-compensation scheme has large improvement on multi-level modulation network which is operated under high CNR condition.

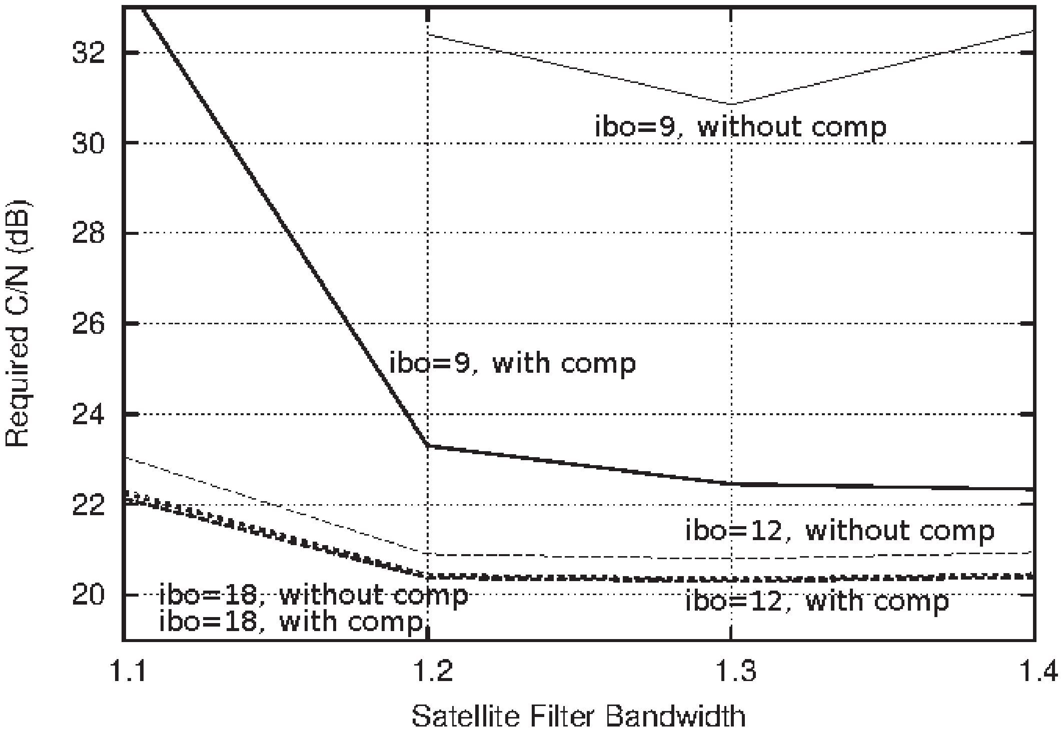


Figure 16. Required C/N to obtain BER = 10^{-3} as a function of Satellite as a parameter of Input Backoff(Rolloff Rate 0.3)

Moreover, the effect of proposed compensator greatly differs by how the system's filters are chosen.

The proposal scheme had difficulty of implementation by using analog circuits but now using digital signal processing technologies, it is comparatively easy to be implemented. Additionally, this scheme can be concluded in the receiver by configuring nonlinearity characteristics of satellite TWTA so modulation schemes that reduce PAR could be used together with proposal scheme to achieve higher improvement. Moreover, this scheme is applicable not only to 32APSK but also to various modulation schemes to improve receiver's performance and to downsize the antenna. In the next section, proposed nonlinearity compensation scheme is adopted to another type of satellite system, carrier superposed satellite communication.

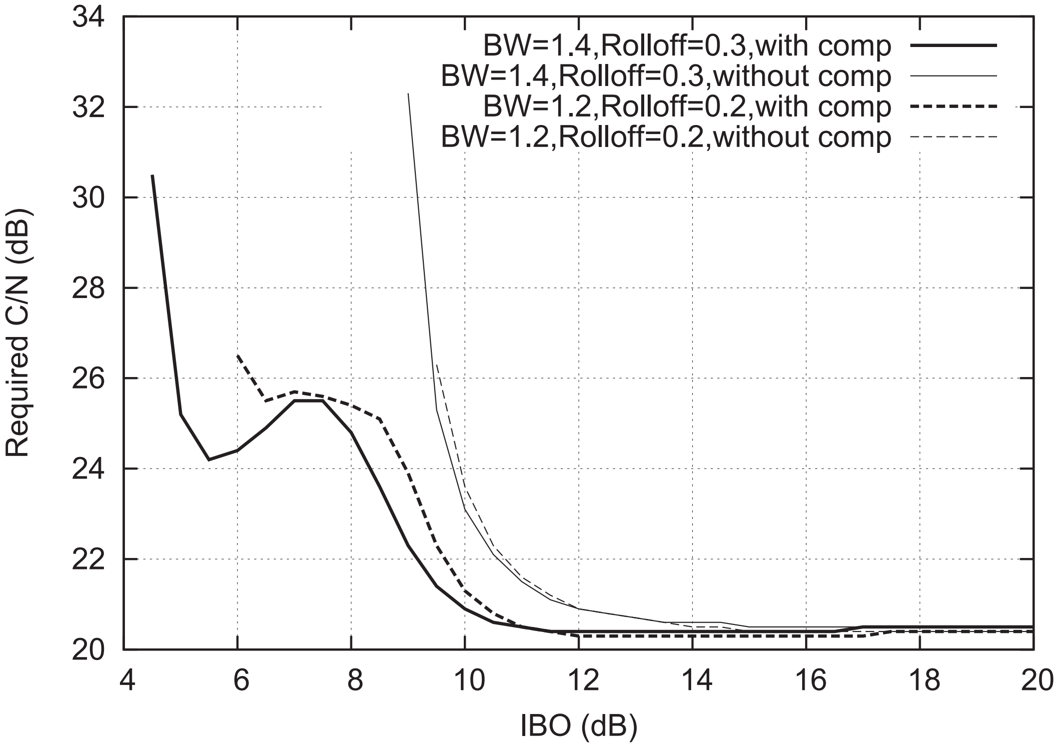
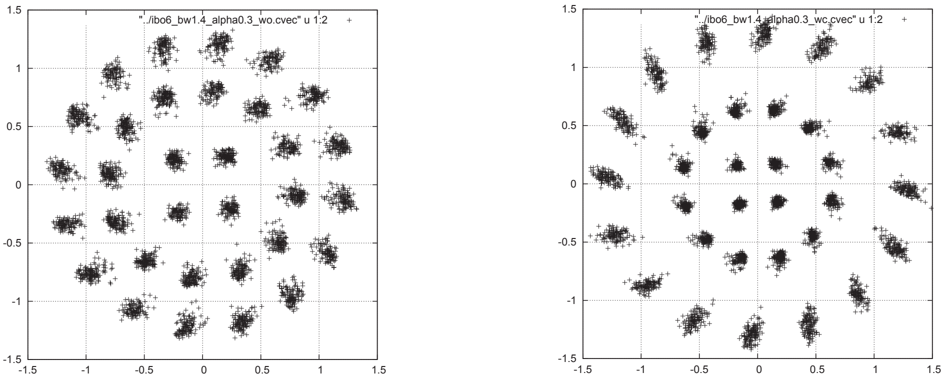
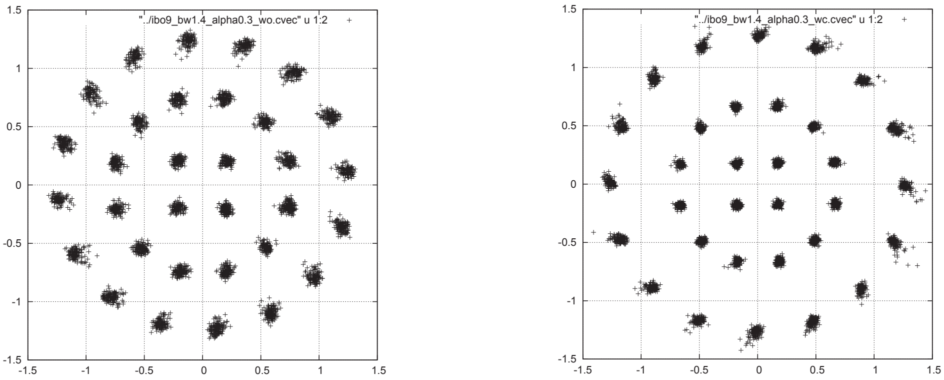


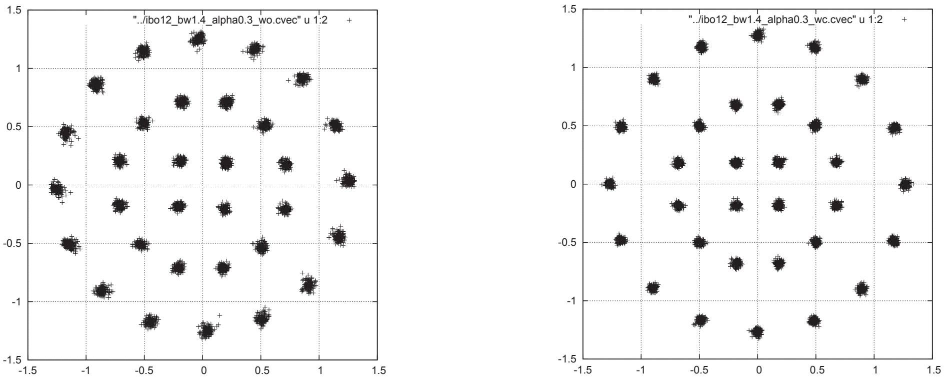
Figure 17. Required C/N to obtain BER = 10^{-3} as a function of Input Backoff (IBO) for two cases of Filters



IBO 6dB, without compensation (a) IBO 6dB, with compensation

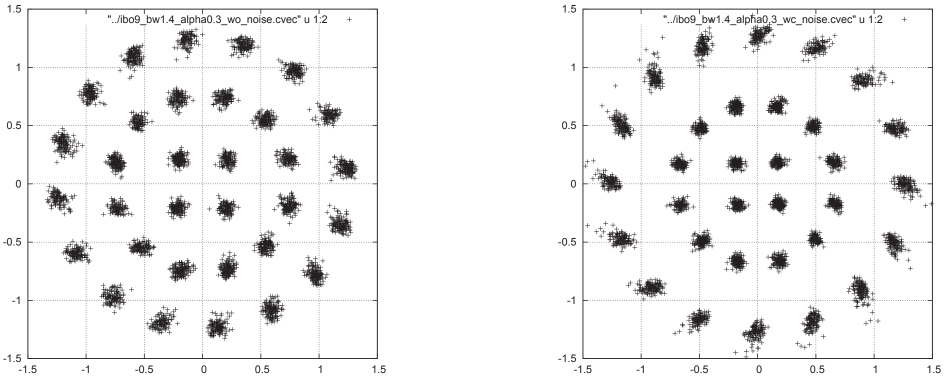


IBO 9dB, without compensation (b) IBO 9dB, with compensation



IBO 12dB, without compensation (c) IBO 12dB, with compensation

Figure 18. Signal Constellation of different Backoffs and its improvement with compensation (BW=1.4, Rolloff Rate 0.3, CNR=∞)



IBO 9dB, without compensation,
with noise

IBO 9dB, with compensation,
with noise

Figure 19. Effect of thermal noise to Signal Constellation (BW=1.4, Rolloff Rate 0.3, CNR=30dB)

6. Nonlinearity Compensation for Carrier Superposed Systems

6.1 Introduction

As demand for high speed, high quality image transmission increases, improvement of frequency utilization efficiency becomes more and more important for satellite communications. For such improvement, the carrier superposing technique has been proposed as an effective scheme [11, 36, 1].The modem which implements carrier superposing technique is also available now[32]. In a carrier superposing system, outbound signal (signal from the local station) and inbound signal (signal from the remote station) uses the same frequency band, and from this, the frequency efficiency can be doubled at maximum. Moreover, this technique can be applied to two major types of satellite communication systems [21], point-to-multipoint (P-MP, also called as VSAT) network and point-to-point (P-P) network [18]. Both outbound and inbound signals are transmitted on the same frequency band, so the signal sent from the local station and bounces back to the local station will be an undesired signal, interference on the desired signal sent from the remote station. Therefore, an interference canceller, which removes signals transmitted from itself must be adopted at the receiver. Canceller generates a replica signal that is very similar to undesired signal in all four perspectives, timing, phase, waveform and amplitude, and subtracts replica signal from received signal [4]. The key for this technique is how to generate highly similar replica signal. When the replica signal generated by the canceller is highly similar to undesired signal, the output of canceller is nearly the desired signal, though when the similarity falls down, the difference between undesired signal and replica signal will be remaining noise and will degrade bit error rate (BER) performance when demodulating desired signal [4].

The authors have proposed several interference cancellation and replica generation methods. For example, the authors proposed a method for measuring the round trip time between the earth and satellite stations by making use of matched filter [18]. They also proposed a method for generating replica signal by demodulating undesired signal [21]. From these advances, a designing and constructing method for canceller in practical condition has been established, and the undesired signal suppression performance on a linear system was verified. However, further research of authors has shown that when such canceller is used in a system that operates Traveling Wave Tube Amplifier (TWTA) at nonlinear region, to save the energy of satellite transponder, the performance degrades seriously [37, 17, 16, 5, 6].

Generally, for systems with nonlinear amplifier, it is well known that BER performance of a single carrier PSK/QAM system is degraded by amplitude distortion (AM-AM) and phase distortion (AM-PM) [7]. Many schemes have been proposed to diminish the effect of nonlinearity and to compensate nonlinearity. For example, transmitting signal with modulation method that has relatively small change of the envelope like Offset QPSK is one of the most fundamental way to lessen the effect of nonlinearity [23]. Additionally, there has been research on the optimization of signal constellation for APSK multi-level modulation [20].

Moreover, many schemes have been proposed to compensate satellite's nonlinearity [2, 38], etc.. One type of compensation is pre-compensation, which estimates the amount of satellite's nonlinear distortion and apply reverse distortion vector before transmitting the signal. Pre-compensation is a valid method for broadcasting video signals [15]. However, this pre-compensation method is only valid when satellite TWTA is operated with a single carrier. For carrier superposing system concerned in this dissertation, signals are distorted based on synthesized waveform of inbound and outbound signals. In this case, when focusing on one signal, distortion that signal receives from nonlinear TWTA largely varies by the interaction between the other signal's amplitude and phase. Therefore, compensation and nonlinear effect diminishing method for single carrier systems cannot be applied to carrier superposed system, where multi-carriers sent from each stations are synthesized. Especially, pre-compensation method at the transmitter side is meaningless.

Recently, Kojima et al. have proposed pre-compensation method which reduces the effect of satellite's nonlinear distortion by adding reverse distortion to the sending signal at transmitter [15]. For carrier superposing system concerned in this dissertation, interaction between each carrier emphasizes the amplitude component and will enlarge the effect of nonlinear distortion. Therefore, the signal's BER degradation will be larger than that of a single carrier transmission. Additionally, it is impossible to apply nonlinear effect diminish method or nonlinearity pre-compensation method to carrier superposed system because the composition of superposed signal is distorted by TWTA, not the individual signals sent from each station.

From these backgrounds, authors have recently researched post-compensation technique for improvement of transmission property on nonlinear system using superposed signal. One of the ideas proposed previously [16, 5] is a method that minimizes the difference between replica signal and undesired signal distorted on satellite by giving same distortion to replica signal generated at the receiver. However, this method is only valid when undesired wave's power ratio is dominant in received signal's power, which is P-MP VSAT network. This dissertation proposes a nonlinearity compensation method which is applicable to not only P-MP systems but also to the system with any power ratio of outbound and inbound, to compensate nonlinear distortion for a network like P-P.

The proposed scheme compensates distorted synthetic wave of desired and undesired waves at the receiver, by distorting the whole received signal to the reverse side of distortion that satellite's TWTA gives. This scheme has the capability of removing distortion of both desired and undesired wave, which composes received signal, at a same time. Previously, this type of process was very difficult to be implemented on analog circuits. It becomes much easy due to recent year's advancement of digital signal processing technology. In our method, when satellite TWTA and compensator are directly connected only with transmission path loss, path will be linear, and distortion will be perfectly compensated in principle. Contrarily, due to the filters between TWTA and receiver, and additive thermal noise to receiving signal, estimation of each signal's precise distortion amount will be difficult, and the compensator will be disturbed. The difference between actual distortion and estimated distortion becomes the degradation from ideal value. This point is an important issue of this study for post-compensation.

In this research, obvious improvement is shown by simulating this environment with software. In the simulation, signal is modulated with QPSK. On the other hand, there is another problem that degradation of compensation performance can be caused by the mismatch of satellite's distortion vector and its reverse, compensation vector, just like when receiving signal level changed due to rain fall attenuation. In the section, this level variance tolerance is also evaluated using the simulator by changing the level in the range of assumed AGC (Automatic Gain Control) level variance compression. These performance evaluations of compensator are done with BER performance and constellation of desired signal before and after it is compensated.

In addition, main focus of this section is verifying nonlinearity degradation of superposed signal and evaluating proposed compensation scheme. From this, it is possible to think the problem is in the transmission path, not in the interference canceller. Therefore in the simulation, synchronization function of canceller, which is already been verified in the previous paper [18], is assumed to operate ideally.

6.2 Carrier Superposed Network with Nonlinear Compensation

6.2.1 Carrier Superposed Network

Figure 4 in Section 2.2.3 shows P to P satellite communication system model used in this research where two opposite carriers have the same level. In this figure, the channel is setup between two earth stations A and B. Here we state the signal carrier from station A to station B an outbound signal and signal carrier from station B to station A an inbound signal.

In conventional satellite communication systems, outbound and inbound signals are transmitted on a different frequency band. In contrary, in carrier superposed system, those signals are superposed and transmitted on the same frequency band. From this, either the outbound or inbound signal's frequency band will be free, and both carrier frequency can be twice as wide as before, which means doubling the frequency band usage efficiency. To retrieve wanted signal from received signal, unwanted signal, in this case self transmitted signal, which is superposed on wanted signal must be cancelled out. This is done by subtracting the replica of self transmitted signal from received signal.

In addition, each frequency band width and power of superposing signals do not have to be the same. However, the total power of superposed signals must be configured under the consideration of maximum transponder power. For example, the total power will be double if two signals with the same power and same frequency band width are superposed, and under the condition of constant power, the power of each carrier must be set 3dB lower than the original power. As explained above, the nonlinearity compensation proposed in this paper also intends to transmit superposed signals without lowering the power level.

6.2.2 Interference Canceller

Interference is cancelled by generating replica of unwanted signal and subtracting it from received one [4, 18]. In Fig.20, two earth stations transmit signals, and the signals to the right and left are denoted by $S_1(t)$ and $S_2(t)$, respectively.

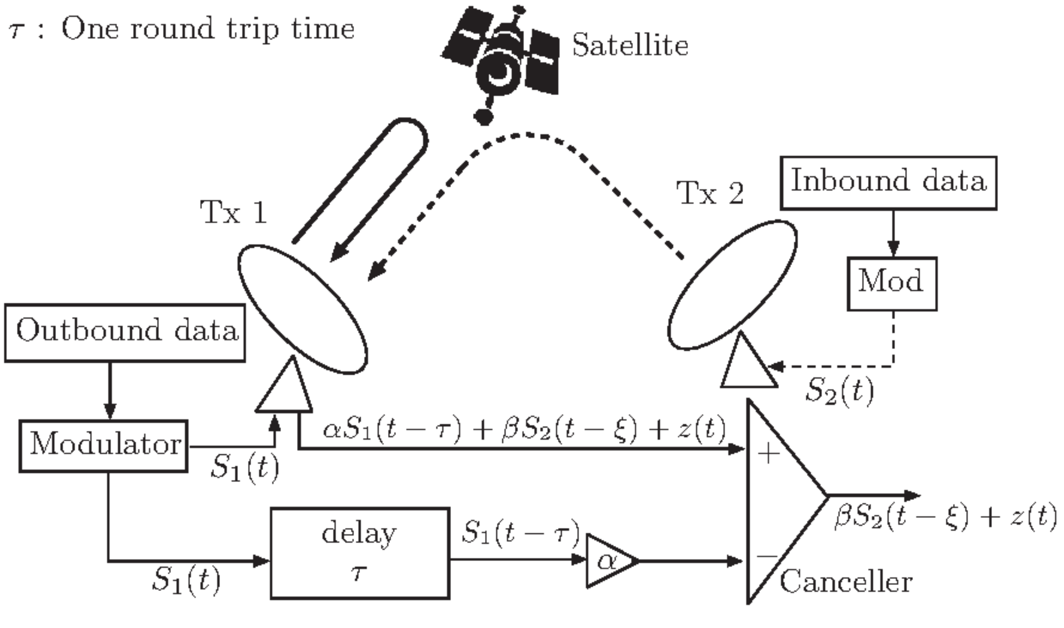


Figure 20. Concept of interference canceller for superposed transmission.

Let us assume that the cancellation is performed at the earth station to the left in the figure. Since both earth stations transmit the signal at the same frequency, the received signal is the sum of $S_1(t)$ and $S_2(t)$. The received signal at the station $r(t)$ is given by:

$$r(t) = \alpha S_1(t-\tau) + \beta S_2(t-\xi) + z(t), \tag{17}$$

where α and τ are the round-trip propagation path loss and round-trip delay between the station and the satellite, and β and ξ are the propagation path loss and trip time between two earth stations via satellite. Further, $z(t)$ is an additive white Gaussian noise (AWGN) component.

At the canceller, the transmitted signal, $S_1(t)$, is applied to the delay block whose delay time is set to be the same as the round-trip delay, τ. The output of the delay block $S_1(t-\tau)$ is then fed to the variable gain amplifier to adjust amplitude of the replica and the interference signal. If the adjustment is perfect, the gain of the variable gain amplifier is set to be α. The output of the variable gain amplifier is then subtracted from the received signal. The output of the interference canceller $u(t)$ is given by

$$u(t) = r(t) - \alpha S_1(t-\tau) = \beta S_2(t-\xi) + z(t). \tag{18}$$

From this equation, we can find that the interference signal, $S_1(t)$, is successfully cancelled. In order to cancel the interference from the received signal, it is necessary to estimate the round-trip delay of the received signal. Here, we have shown that the accuracy affects the suppression performance of the canceller [4, 18].

It is also required to adjust the phase and amplitude of both outbound signal and its replica signal. Our previous paper handles the solution to these requirements and has shown that they are performed by applying extended matched filter with phase locked loop [18].

6.2.3 Problem of Interference Canceller in Nonlinear Channel

In satellite communications, transponder TWTA is preferable to be operated near the saturated region in order to use its power efficiently fully. However, if used in the saturated region, the signals amplified there suffer from the effects of intermodulation and distortion due to AM/AM and AM/PM properties. Figure 21 shows typical nonlinear characteristics of the TWTA used in ordinary communication satellite. In Fig.21, so called 1dB compression of the TWTA is about 9dB in IBO. So, we will define in this paper that the region of input backoff less than 9dB is nonlinear and that more than 9dB is linear region. In the case of carrier superposed system, two or more carriers are amplified together. Figure 22 shows an example of vector diagram of input and output signals through TWTA.

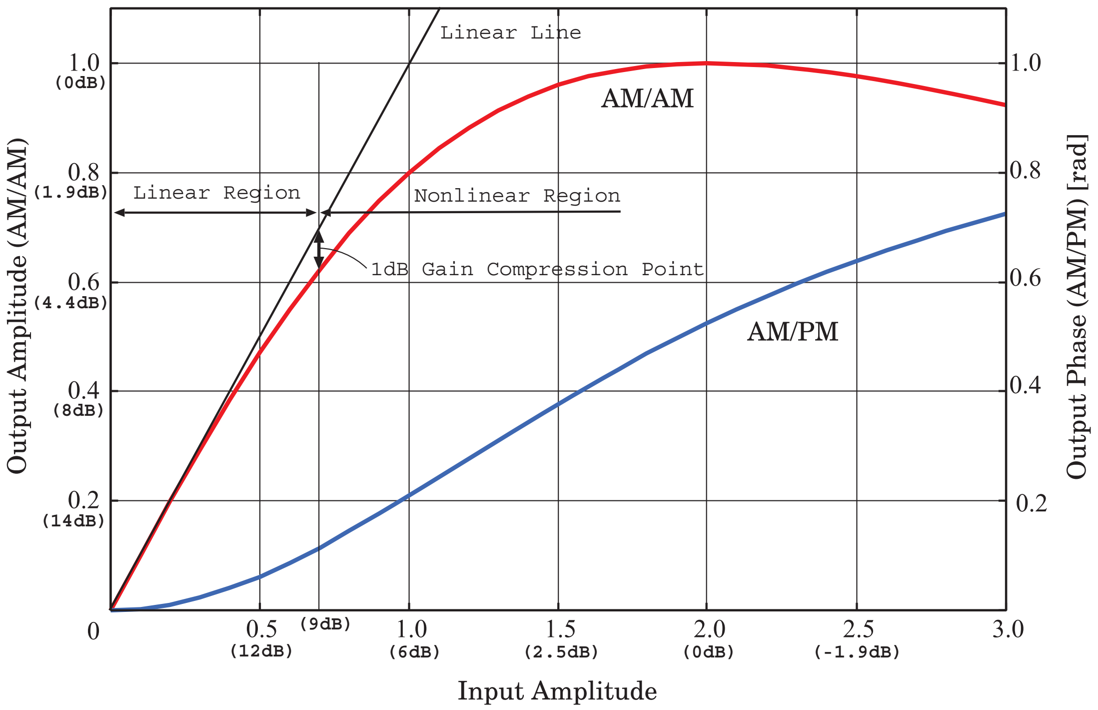


Figure 21. Typical nonlinear characteristics of TWTA
(() is the IBO and OBO (dB))

When transmitting outbound signal vector is represented as S_{out} and inbound signal vector is represented as S_{in}, superposed signal vector can be represented as S_c and it will be the input of TWTA. TWTA output signal vector S_{co} will be shifted from S_c based on amplitude and phase distortion.

If the power of outbound is large enough compared with inbound, the output of TWTA will be almost the same as the TWTA output when only outbound signal is input, so to cancel the interference, nonlinear distorted outbound must be fed to the canceller. On the other hand, if the power of inbound is not negligible compared with outbound as concerned in this study, TWTA output will be different from nonlinear distorted outbound signal and this difference causes interference if simply fed to the canceller.

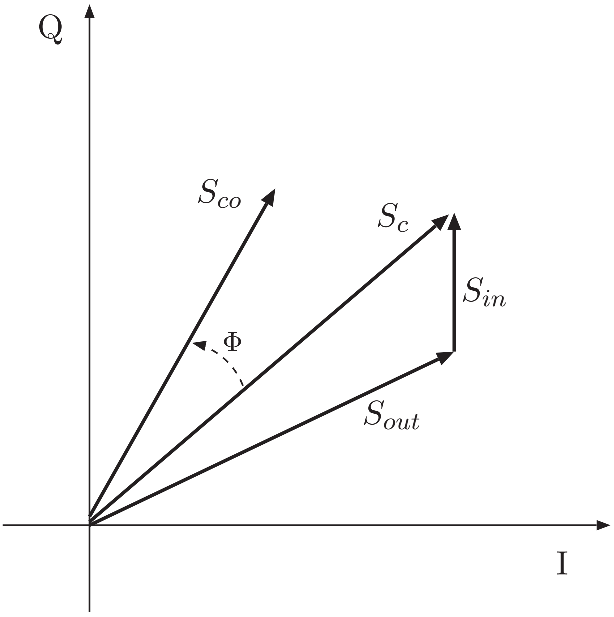


Figure 22. Signal vectors of TWTA input and output

6.3 Performance Evaluation

6.3.1 Simulation Model and Parameters

Figure 23 shows the block diagram of simulator. The purpose of this simulator is to verify the performance of nonlinearity compensator. Therefore, the delay tracking mechanism is not implemented in this simulation model. The upper path in the figure represents the satellite signal path, and lower path represents the replica signal path inside the earth station. To make the transfer function of two paths equal, filters used in the satellite path are also inserted in replica path. Nonlinearity compensator is inserted before the interference canceller to fix the distortion that signal receives in TWTA. The root cosine roll-off filter is inserted after transmitter's modulator, TWTA, and before nonlinearity compensator, receiver's demodulator. These filters suppress sideband signal and noises, and also adjust symbol timing between replica signal path and satellite signal' one.

Table 2 and 3 show the parameters for the simulation and the parameter for TWTA nonlinearity, respectively. The bandwidth (BW) in Table 2 is normalized

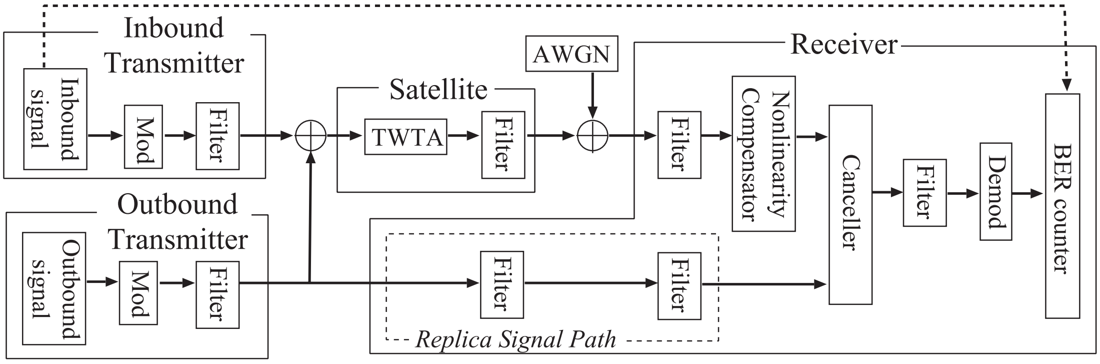


Figure 23. Block diagram of the simulator

by the symbol rate of the signal. The parameters in Table 3 are applied to the nonlinear characteristics as shown in Fig.21. Generally, there is a certain amount of variation in characteristics among each TWTA. Also, it depends on the number of carriers amplified by the same amplifier. To determine g^{-1} and f in Fig.6, it is possible to choose the parameters in Table 3 closest to the actual value by acquiring nonlinear characteristics of TWTA from the operator of satellite. Here, it is assumed that actual data of satellite TWTA has been acquired. Reverse nonlinear characteristics can be accurately calculated by the data.

Table 2. Simulation Parameters

System Parameter	Modulation Method	QPSK
	Modulator Transmit Filter	[1]BW = 1.0 k = 0.35
	Satellite Transmit Filter	BW = 1.2 k = 0.35
	Earth Station Receive Filter	BW = 1.2 k = 0.35
	Demodulator Receive Filter	BW = 1.0 k = 0.35
	Number of Symbol	200,000
	Over Sampling Factor	4
Transmission Channel	DUR (inbound/outbound ratio)	0dB
	Channel	AWGN

[1] BW: Normalized bandwidth, k: Rolloff factor

Table 3. Nonlinearity Parameters

Eq.(10)		Eq.(11)	
α_x	1.0	α_ϕ	$\pi/12$
β_x	0.25	β_ϕ	0.25

6.3.2 Results and Discussions

The operating point of TWTA is determined by the input back-off (IBO) and/or output back-off (OBO) as

$$\begin{aligned} \mathrm{IBO} &= -10\log_{10}\frac{E\{|A_{OB}+A_{IB}|^2\}}{A_I^2}, && (19)\\ \mathrm{OBO} &= -10\log_{10}\frac{E\{|A_{SAT}|^2\}}{A_O^2}, && (20) \end{aligned}$$

where $E\{\}$ is an expected value which has meaning of averaging and A_{IB}, A_{OB}, and A_{SAT} are amplitude of inbound, outbound, and transmitting signal from satellite respectively; A_I^2 is the input power of the sum of outbound and inbound signals which gives maximum power of TWTA, and A_O^2 is the maximum output power of the TWTA.

Figure 24 shows bit error rate (BER) curve when changing input backoff. Eight lines represent BER at input back-off (IBO) = 3,6,9,12dB each with compensation and without compensation. It is shown that when IBO is small, which means TWTA operation point is in nonlinear region, the difference of BER between compensated signal and non-compensated signal becomes larger.

Figure 25 shows degradation for each IBO with compensation and without compensation. From this figure, it is obvious to know that when IBO is more than 9dB, the channel characteristic becomes more linear and therefore the difference between using compensator and not using compensator becomes small. Contrarily, the effect of proposed compensator can be easily confirmed at IBO below 9dB which is nonlinear region. Therefore by adopting proposed scheme, it is possible to transmit superposed signals under the condition of nonlinear region. When transmitting superposed signals, transmission power will increase

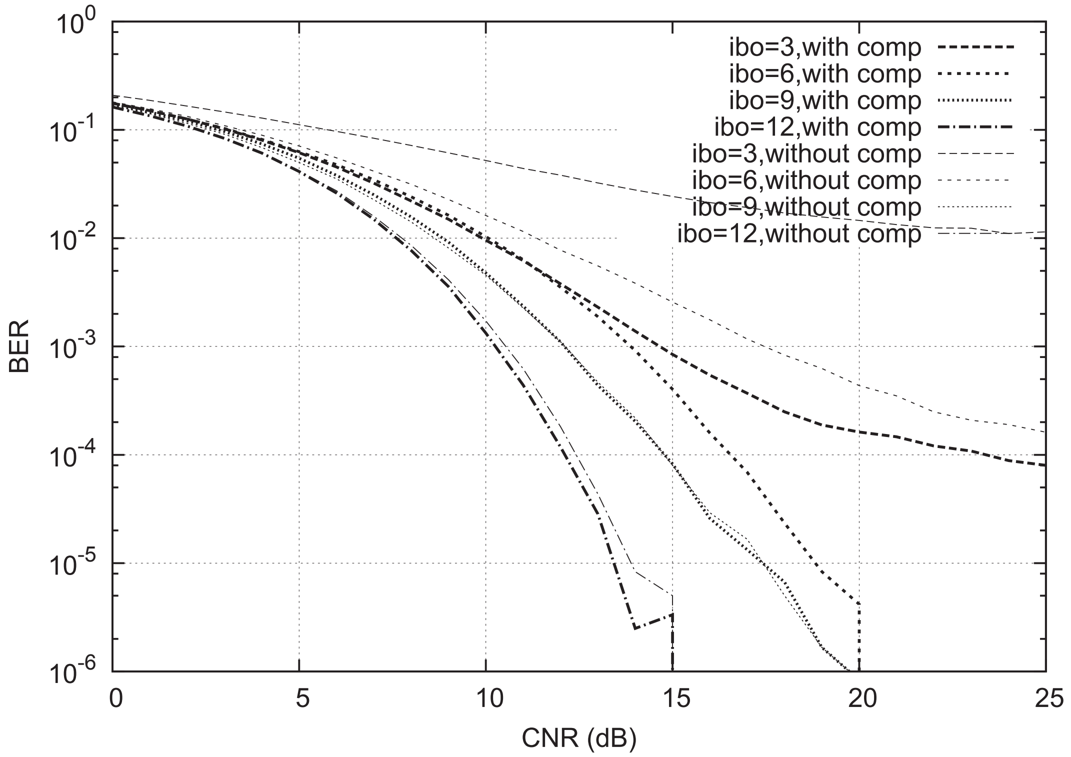


Figure 24. Effect of changing input back-off on bit error rate of inbound signal

in exchange of having double frequency band efficiency at most. Conventionally, satellite transponder is operated with constant input power and in this case, CNR is decreased because the power of each superposed carrier must be lowered by 3dB compared to a single carrier transmission. By adopting proposed scheme, it is possible to transmit the signals without lowering the power of each carrier by using nonlinear region of the TWTA, of which operating point is 3dB higher than single carrier transmission.

Next, the effect of rainfall attenuation is considered. The proposed compensation is performed under the condition that the signal is received within a range of acceptable power level by which the total path from TWTA to the compensator becomes linear. However, this condition cannot be satisfied if the received signal level is changed by rainfall or some other reasons. Figure 26 shows the change of BER when the TWTA output level (received signal level) is deviated by ±6dB from the determined normal value. Two lines in the figure represent the BER

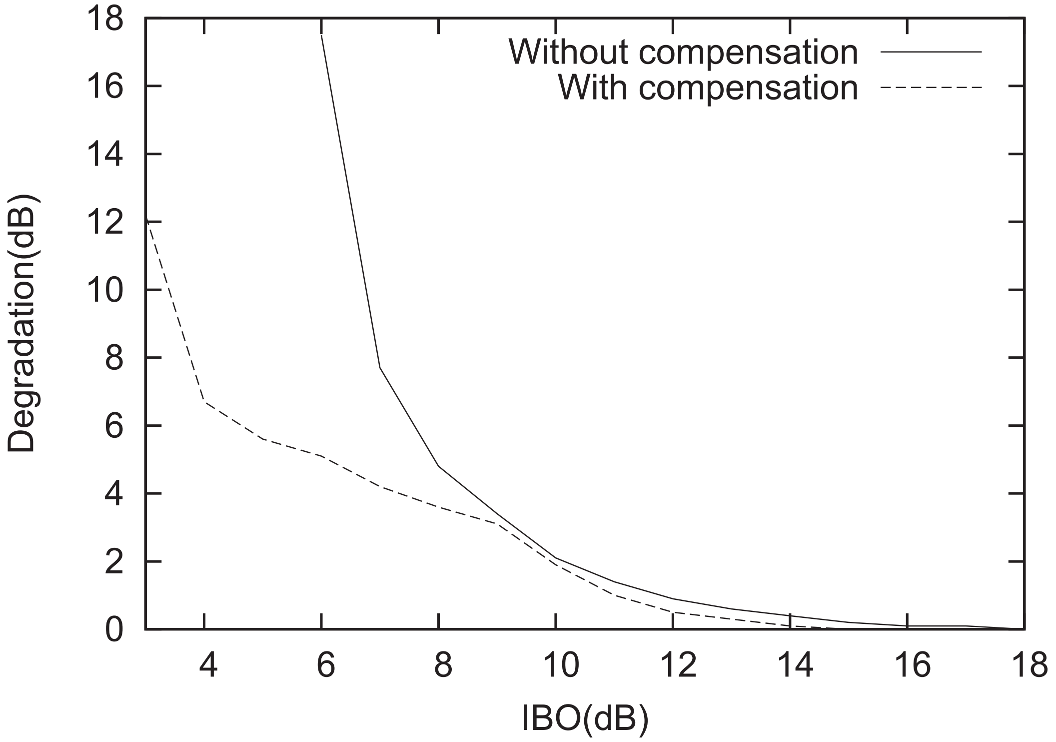


Figure 25. Degradation due to TWTA nonlinearity with and without compensation (Degradation of CNR from linear case to obtain BER 10^{-4}dB)

change when centers are IBO = 8dB, CNR = 14.0dB and IBO = 10dB, CNR = 13.0dB. For both conditions, each of satellite transponder's IBO value and channel's CNR value are fixed. This result shows that when environment changes and channel attenuation varies for ±1dB, BER varies by a factor of 10^{-1}. By using AGC at the receiver input, the change of compensator input level due to the rainfall can be compressed within 1 (±0.5dB)dB or so. This means the degradation due to the change of down link level can be acceptable.

Figure 27 and Figure 28 are QPSK constellation of received inbound signals when IBO are 6dB and 12dB, respectively. Each figure shows the constellation when both nonlinearity compensator is disabled and enabled. As explained above for Fig.25, these figures show that the effect of compensator increases when IBO is smaller, which means nonlinearity is larger.

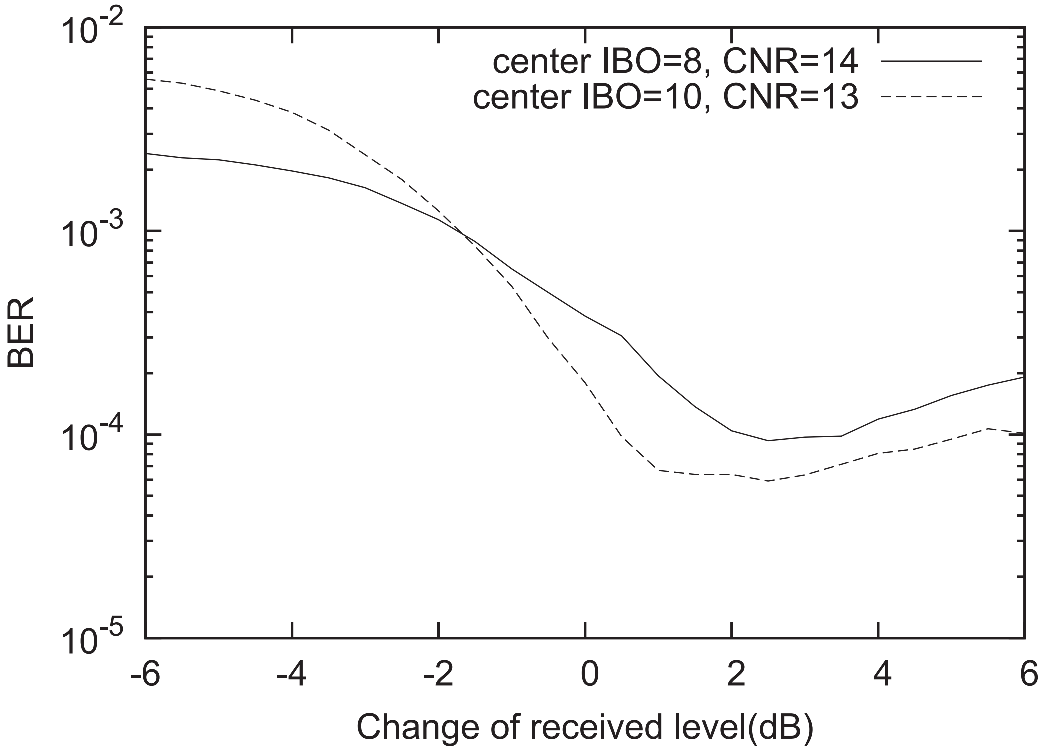
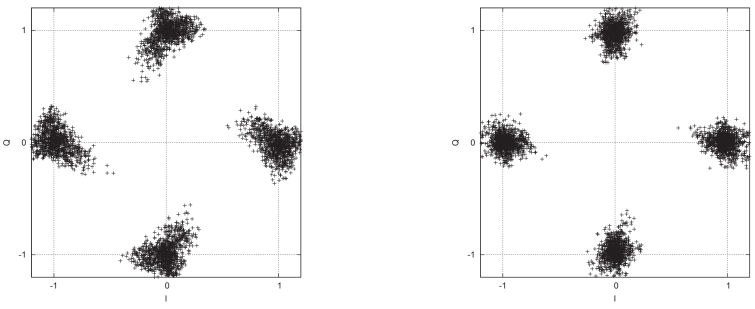


Figure 26. BER difference when rain attenuation level changes.

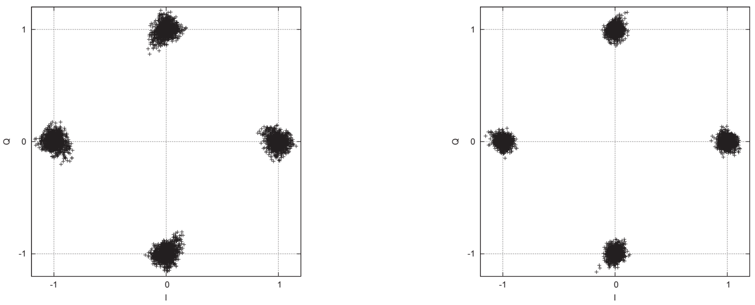
6.4 Conclusion

In this paper, a nonlinearity compensation scheme for carrier superposed point to point (P-P) satellite communication system using interference canceller was proposed. In order to show the effectiveness of the proposed scheme, a basic software simulation is performed. The result of simulation shows that it is possible to reduce the degradation caused by nonlinearity of satellite TWTA. The scheme is specifically effective to the system like carrier superposing in which the satellite receiving power increases due to the signal superposing. This scheme reduces the distortion of received signal vector, and it can be applied to not only to superposed signals but also to single carrier communication systems and conventional broadcasting signals. Previously, it was very challenging to operate reverse-nonlinear calculation for all of the received signal in real-time, but now the digital signal processing technologies have made it possible. The result also



Without compensation With compensation

Figure 27. Constellation of received signal at CNR=∞ IBO=6dB



Without compensation With compensation

Figure 28. Constellation of received signal at CNR=∞ IBO=12dB

shows that BER degradation due to operating point mismatch when environment condition changes like rainfall attenuation is about ±1dB, which is acceptable.

For future work, we are planning to verify the performance of proposed nonlinearity compensator with multi-level modulation such as 32APSK (Amplitude Phase Shift Keying) for more practical use in current satellite systems. In general, multi-level modulation is used in high CNR condition, which means it is more preferable to nonlinearity post-compensator.

7. Optimization for Multi-level Modulation with Low Input Backoff

7.1 Introduction

In Section 5, nonlinearity compensation scheme proposed in Section 4 is adopted to multi-level modulated satellite system. It could be said from Figure 17 that in the region of IBO below 10dB, the proposed compensator has a certain amount of improvement. However, the improvement is diminished and staggered around IBO 7dB due to miss-compensation caused by noise.

When multi-level modulated signal is compensated by the proposed scheme, the effect of noise added to the signal varies among different amplitude level. For low amplitude signals, the noise component will be compressed by proposed nonlinearity compensator. On the other hand, for high amplitude signals, the noise component will be emphasized by the compensator because of the reverse nonlinearity characteristic of TWTA. This can be confirmed from Figure 19. For the constellation of received signal without compensation, signals of all three level, inner ring, middle ring, and outer ring, have about the same circle scattered pattern. Contrarily, for constellation with compensation, signals with the smallest amplitude have dense circle pattern, but signals with the largest amplitude have obliquely stretched pattern which seems to be causing the degradation under low IBO condition.

In this section, a nonlinearity post-compensation scheme is optimized for multi-level modulation satellite system at low IBO. The purpose of this scheme is to compensate TWTA nonlinearity of satellite transponder and also suppress the noise emphasis of multi-level modulated signal under low IBO condition. This section first explains the algorithm of enhanced post-compensation scheme and then shows the result of simulation for performance evaluation.

7.2 Algorithm of Optimized Compensation

As mentioned in Section 4.2, the conversion equation of nonlinearity compensation is given by Equation (12). However, there are two points that this method is not necessarily optimum for multi-level modulation under low IBO condition.

Before applying this equation, received signal must be restored to the original signal level because its amplitude is used for the compensation. If signals are adjusted to the wrong level, this could cause miss-compensation for all signals. Another point is that signal with largest amplitude of such condition can be near saturation level. Therefore, the noise component of those signal can be largely emphasized.

In this section, the above two concerns are dealt with, and algorithm which is suitable for such condition is proposed. The first part explains a new method of how to adjust received signal's level closer to the transmitted signal. Second part explains an optimized conversion equation for nonlinearity compensation that suppresses the emphasis of the noise component in such condition.

7.2.1 Gain Adjustment for Multi-Level Modulation

Signal level changes by propagation loss, antenna gain, filter loss, additive noise, and other elements in the channel. Though the amplitude information of received signal is used to compensate nonlinearity of satellite TWTA and for accurate compensation, the signal level of nonlinearity compensator's input must be tuned to an appropriate level, which is the output level of satellite amplifier in this case.

In the originally proposed scheme, the level of received signal is recovered by adjusting the signal's power to OBO level, which is expressed as Equation (16). In this equation, A_{TX} is calculated by substituting A_{RX} to Equation (10). This process is sufficient for modulation schemes with constant envelope like QPSK. However, this does not match to the actual level of satellite transmitted signal if signal's amplitude has multiple level. This is because $|A_{RX}|^2$ is an average power of satellite amplifier's input and A_{TX} derived from this value differs from actual average power of satellite amplifier's output.

For example, if IBO is 3dB and average satellite input signal is normalized to 1.0, multi-level signal adopted at Section 5 will be as follows. The input and output of satellite transponder will be (0.37:1.00:1.80) and (0.36:0.80:0.99), where each value is the amplitude of (inner ring:middle ring:outer ring) of the constellation, respectively (Here the maximum amplitude of input and output are set to 2.0 and 1.0 respectively, same as simulation in Section 5.). Then the average amplitude of input and output calculated from each signal's amplitude and occurrence probability will be 1.41 and 0.86, respectively. Though, if the average amplitude of satellite transponder is derived from average input 1.41 and Equation (10), it will be 0.94. Generally, the difference between 0.94 and 0.86 has no effect on the performance of compensator if the output of satellite TWTA is directly fed to the compensator. Though for the calculation of AWGN (Additive White Gaussian Noise), the output of satellite TWTA is normalized after derived from Equation (10). Therefore, the difference between 0.94 and 0.86 becomes the reason which caused the error in the original scheme and this difference will be larger if IBO is set to a lower value. This problem is specific to the simulator used in this dissertation because usually, the gain adjustment for compensator will be done when the network is configured.

To avoid the error caused by above reason, another approach is proposed here. If the receiver knows the IBO and constellation pattern of the transmitter, then the following method can be adopted. First, the nonlinearity compensator calculates the amplitude of each signal that is input to satellite amplifier by reconstructing the signal from original APSK constellation and taking backoff to it. In the case of 32APSK used in Section 5, three different amplitude values are calculated from two radius rates $\gamma 1, \gamma 2$ for 32APSK constellation and IBO value to take backoff from saturation level. Then the output of satellite amplifier for each amplitude are calculated by Equation (10). Finally, the average power of the output is calculated from constellation pattern and output amplitude of each signal. This average power is used to recover the signal power of received signal to the level that satellite transponder transmitted.

The process of above algorithm is shown in Figure 29. The meaning of this process is to emulate the signal flow of transmitter and satellite transponder inside the receiver to achieve the average power of satellite transmission signal. In this way, more accurate average power for multi-level modulation could be estimated, and nonlinearity compensation scheme explained next will be more effective.

7.2.2 Nonlinearity Compensation with Step Function

Even if the signal level is adjusted to where it should be, proposed nonlinearity compensation scheme will emphasize the noise component when multi-level modulated signal is sent with low IBO. Therefore in this section, more suitable

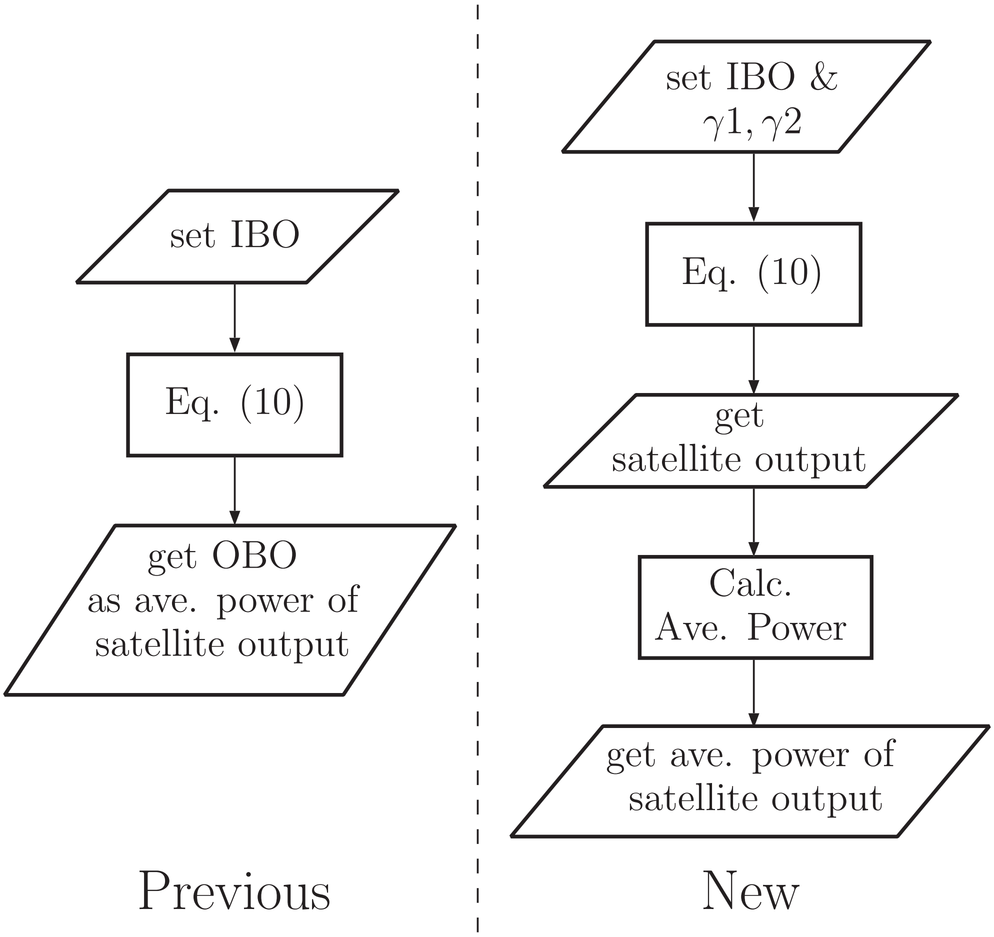


Figure 29. Flow chart of the original and a new level adjustment.

nonlinearity compensation algorithm is shown.

The example of the new compensation is shown in Figure 30. In the originally proposed scheme, the amount of compensation is determined from the original amplitude of the transmitted signal, which is derived from Equation (12). Instead of using Equation (12), first in the preparation phase, amplitude of nonlinearly distorted signal r*, amount of phase rotation p*, and the amplitude compression rate g* are calculated for each amplitude of ideal signal. Next in nonlinearity compensation phase, compensation is applied to the received signal according to its amplitude. Range of amplitude splitted by borders b*, which contains the

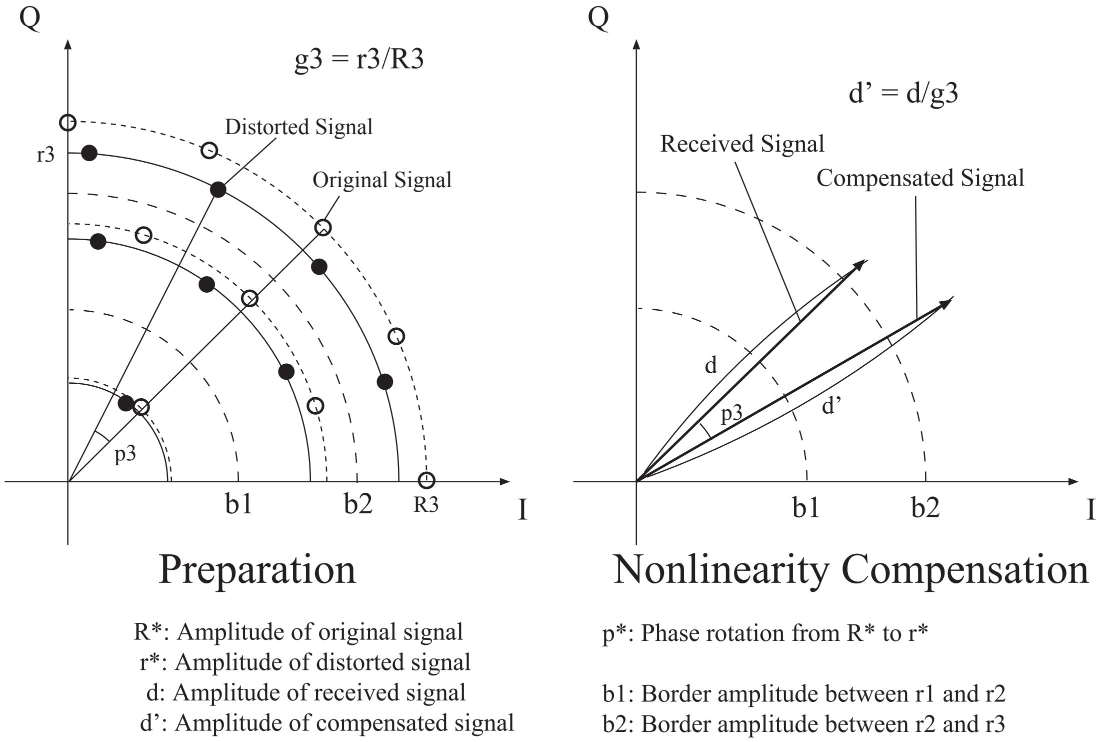


Figure 30. Example of new nonlinearity compensation with 32APSK.

amplitude of received signal is chosen, and nonlinearity compensation is processed using g* and p* corresponding to the chosen range.

By using above scheme, the amount of compensation for both amplitude and phase does not change when a certain amount of noise is added to the signal, unless the noise is large enough to make received signal cross over the border amplitude between another constellation level. This scheme can only be used under the condition where the largest amplitude of the transmission signal does not exceed the saturation level. If this exceeds, first and second largest amplitude of nonlinearly distorted signal is closely located or they might switch places.

7.3 Simulation Results

Simulation results of the new compensation scheme is shown in this section. For the simulation, model shown in Figure 9 and parameters shown in Table 1 is used as it is with only the replacement of nonlinearity compensator. Therefore, the channel configuration is same as the simulation done in Section 5.

Here, for the simplicity of analysis, two types of simulation results are shown. One is required CNR and the other is constellation. The BER performance is not shown here because the enhancement of the new compensation algorithm could be shown in terms of required CNR.

7.3.1 Improvement of Required CNR

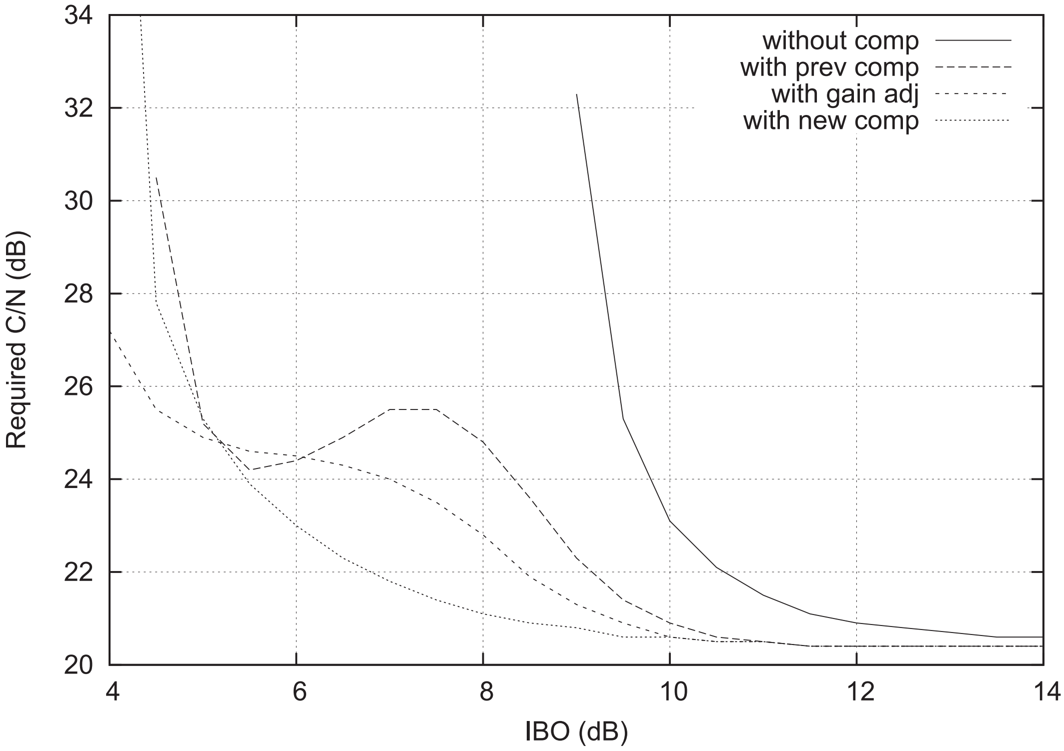


Figure 31. Required C/N to obtain BER = 10^{-3} as a function of Input Backoff (IBO) for BW=1.4, Rolloff=0.3.

In this section, the performance of new nonlinearity compensator is evaluated in the aspect of required CNR. Same as the original simulation, here required CNR is defined as CNR to achieve BER = 10^{-3} when changing input backoff. Required CNR is achieved for three kinds of algorithm, original compensation

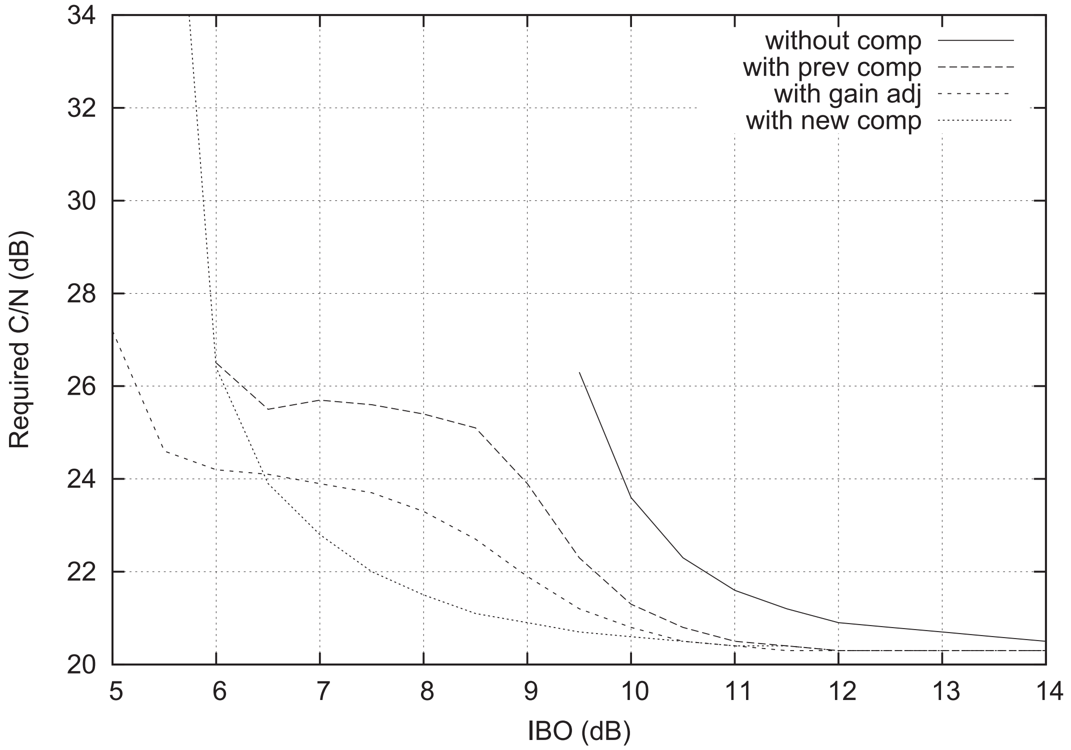


Figure 32. Required C/N to obtain BER = 10^{-3} as a function of Input Backoff (IBO) for BW=1.2, Rolloff=0.2.

algorithm, original compensation with new gain adjustment, and new compensation algorithm, each with two filter configurations, which is shown in Figure 31 and 32, respectively.

From the figures, it is possible to say that gain adjustment and step function improve the required CNR in all region of IBO. The bump that exists in original compensation around IBO 7dB is flattened by using gain adjustment, and is totally cleared by using new compensation algorithm. Moreover, when IBO is extremely low, original compensation with gain adjustment gives better result than new compensation. The reason for this is that when IBO is extremely low, all signals will be included in noise emphasis region and step function will give negative effect to it.

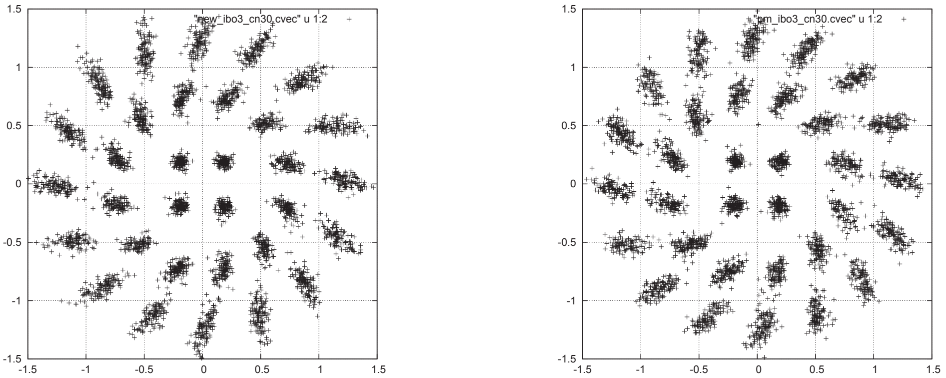
7.3.2 Evaluation with Constellation

In this section, the performance of new compensation algorithm is evaluated by the appearance of constellation. Figure 33 shows signal constellation of three cases of TWTA input backoff of 3dB, 5dB and 7dB, each with gain adjustment and new compensation algorithm. (Rolloff,BW)=(0.3 : 1.4) is chosen as the combination of filters.

From Figure 33, it is possible to say that the outer constellation are spread wider with only gain adjustment but by applying step function, the spreading of outer constellation is lessen in all IBO region. However, for inner and middle constellation, results with step function has round and larger spreading than only with gain adjustment. This is because the negative effect explained in the previous section. Also, there are slight phase rotation of outer constellation that is not compensated enough with only gain adjustment.

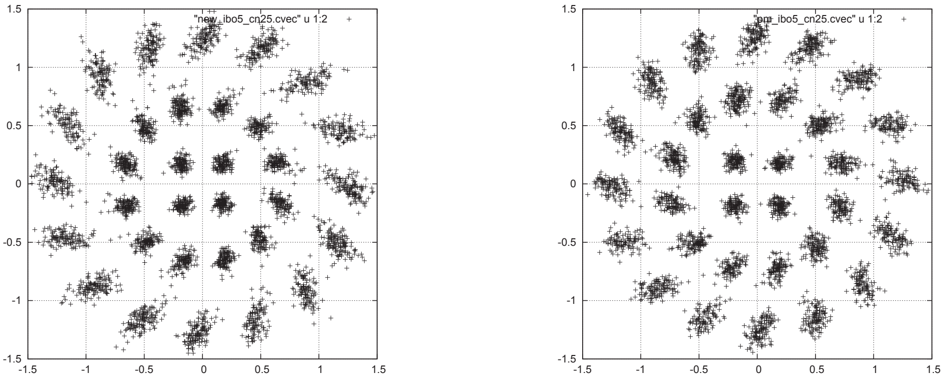
7.4 Conclusion

In this section, originally proposed nonlinearity compensation scheme has been optimized for multi-level modulation and two new algorithm, gain adjustment and step function have been proposed. Furthermore, the effect of proposed scheme has been evaluated by software simulation and the required CNR, constellation of received signal has been concerned. From the results, it is possible to say that new compensation scheme has large improvement on multi-level modulation network under low IBO region. Moreover, by applying these schemes, multi-level modulation system can be operated in lower IBO condition than with original nonlinearity compensator.



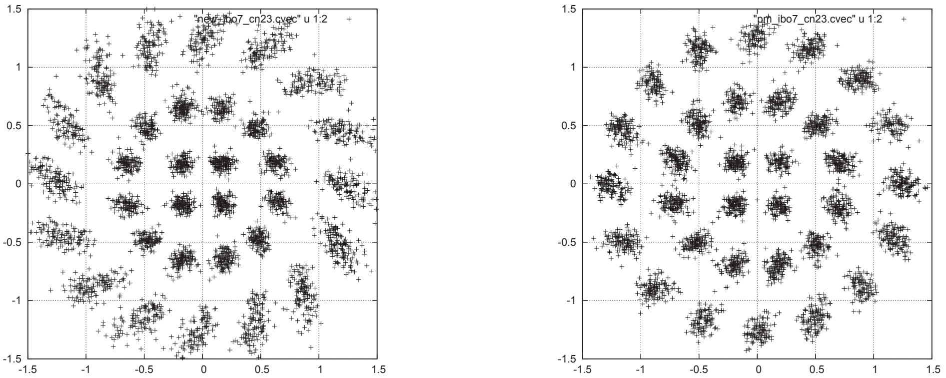
IBO 3dB, CNR 30dB,
with gain adjustment

IBO 3dB, CNR 30dB,
with gain adj and step function



IBO 5dB, CNR 25dB,
with gain adjustment

IBO 5dB, CNR 25dB,
with gain adj and step function



IBO 7dB, CNR 23dB,
with gain adjustment

IBO 7dB, CNR 23dB,
with gain adj and step function

Figure 33. Signal Constellation of different Backoffs when gain adjustment and step function is applied. (BW=1.4, Rolloff Rate=0.3)

8. Conclusion

8.1 Summary and Conclusion

In this dissertation, a nonlinearity compensation scheme which compensates satellite TWTA's nonlinearity characteristics at the receiver side is proposed. Then the compensation scheme is implemented to two typical satellite network systems for performance evaluation. The two typical systems are multi-level modulation network and carrier superposed network. The performance of proposed scheme is confirmed by software simulation and the result has shown that in both networks, proposed compensation scheme has decreased the degradation of transmission performance caused by satellite TWTA's nonlinearity characteristics. The followings briefly explain the content of each section of this dissertation.

In Section 2, the fundamental of satellite communication is introduced. First in Section 2, multiple configurations of satellite network system are introduced. For more detail, multiple access, modulation, and network layout (P-P and P-MP) are explained there. All of these network configurations are very important and gives great impact on nonlinearity of the system. Then the problems of current satellite communication are overviewed. Current satellite system has two major issues, insufficiency of frequency band and transmission power. To resolve these problems, nonlinearity of satellite transponder's high power amplifier must be dealt with.

In Section 3, nonlinear amplifiers, its mathematical models, and linearization techniques are introduced. First in Section 3, two types of nonlinear amplifier, TWTA and SSPA and their characteristics are explained. Then four models that represent the above two amplifier's nonlinearity characteristics are explained. In this research, TWTA which is the most common HPA used in satellite transponder, is selected to be used and therefore Saleh's model is adopted as a nonlinearity model. At last, four linearization techniques are detailed for comparison.

In Section 4, the algorithm of post-compensation scheme which is proposed in this dissertation, is detailed. The idea of this scheme is to analyze the nonlinearity characteristics of satellite TWTA and compensate distorted signal by adding reverse nonlinear distortion of TWTA to the received signal. In this section, the reverse characteristics of TWTA is derived from Saleh's model, which is explained in the previous section. By using this scheme, it is possible to compensate the nonlinearity of satellite channel in many types of satellite network with only adding compensation circuit to the receiver. This scheme can also be used with other nonlinearity compensation methods such as PAR reduction method.

In Section 5 and 6, the post-compensation scheme proposed in the previous section is applied to two typical satellite networks for performance evaluation. In Section 5, first, the proposed scheme is adopted to multi-level modulation network. Multi-level modulation is widely used in current satellite communication to improve the channel capacity of the network. However, this type of modulation is used in high CNR condition and is easy for transmission quality to be degraded by channel nonlinearity. In Section 6, post-compensation is adopted to carrier superposed network. When carrier superposition is used with nonlinear channel, an inter-modulation interference occurs and transmission quality degrades unless large backoff is taken. In both satellite networks, the proposed compensation scheme have improved the transmission performance even when amplifier is operated in small backoff.

In Section 7, a compensation scheme is enhanced and optimized for low IBO condition on multi-level modulated signals. Here, two new algorithm, gain adjustment and step function for multi-level modulation is proposed. Then these two functions are applied to original multi-level modulation simulator for performance evaluation. From the results, it is possible to confirm the improvement of these two schemes in low IBO region.

8.2 Future Work

The future work for this research is as follows. First of all, all of the work in this research is done with software simulation. Therefore, the results for the proposed schemes are not completely verified yet, and the hardware implementation and experiment must be done to completely show the effectiveness of these schemes. This may be a hardware implementation using FPGA and field experiment using actual satellite transponder with TWTA.

Secondly, for more improvement, not only the nonlinearity of satellite amplifier but also other components such as satellite's filter might be the target of compensation at the receiver. To accomplish this, effect of satellite's filter and other component must be analyzed and a new filter distortion compensation algorithm should be combined to current nonlinearity compensator.

Thirdly, author have been working on nonlinearity compensation on the receiver side, but another nonlinearity compensation scheme for transmitter side can be applied together. There are many nonlinearity compensation schemes on the transmitter side that is proposed for satellite communication. Methods like PAR reduction can be combined to systems in this research.

In this research, the characteristics of channel distortion is assumed to be well known. Though in some cases, these distortion characteristics might be unknown or might dynamically change. To deal with these kinds of situations, proposed compensation scheme must be upgraded to work without knowing these characteristics.

Acknowledgements

First of all, I would like to express my utmost gratitude to Professor Minoru Okada for his continuous support and greatly helpful advises on my work as my supervisor. He provided me with general knowledge in communication theory and practices, as well as fruitful discussion during my study and valuable comments and suggestions during writing this dissertation at Network Systems Laboratory (old Communications Lab.), Nara Institute of Science and Technology (NAIST).

I would like to express my gratitude to Dr. Takao Hara (Associate Professor at NAIST before his retirement) for his guidance and constructive advises during my study. He had greatly supported my study before and after his retirement.

I thankfully appreciate Professor Kenji Sugimoto and Associate Professor Takeshi Higashino for their suggestions, comments, and discussions to compose this dissertation.

I express my gratitude to Assistant Professor Ryusuke Miyamoto (currently at Osaka University), Associate Professor Masato Saito (currently at University of the Ryukyus), and Assistant Professor Ziji Ma, to their helpful advises on my study.

I would like to thank Mr. Tomonori Sato, Mr. Shinichi Watanabe, Ms. Hiromi Takahata (doctorial course student of Osaka University), members of Network Systems Lab., for their kind advises and help.

I would like to thank Dr. Hiroki Sugano (currently working with Accell Corp.), Dr. Masayuki Hiromoto (currently working with Matsushita Electric Corp.), and Mr. Jaehoon Yu (doctorial course student of Osaka University) for their constructive advises and technical tutorship.

I would like to thank all other members of Network Systems Lab. and previous Communications Lab. who worked with me as colleagues in my research.

I gratefully thank Ms. Miki Kioi and Ms. Mieko Hayashi, secretary of Network Systems Lab. and previous Communications Lab. for their support on my life in the laboratory.

References

[1] Mark D. Dankberg, Mark J. Miller, and Michael G. Mulligan. Self-interference cancellation for two-party relayed communication. U.S. Patent #5,596,439 issued 1997, Jan, 21, filed 1995, Aug, 1. ViaSat,Inc.

[2] Gang Feng, Le-Min Li, and Shi-Qi Wu. A modified adaptive compensation scheme for nonlinear bandlimited satellite channels. In *Global Telecommunications Conference, 1991. GLOBECOM '91. 'Countdown to the New Millennium. Featuring a Mini-Theme on: Personal Communications Services*, pages 1551 –1555 vol.3, dec 1991.

[3] J. C. Fuenzalida, O. Shimbo, and W. L. Cook. Time-domain Analysis of Intermodulation Effects Caused by Nonlinear Amplifiers. *COMSAT Technical Review*, 3(1):89–127, Spr. 1973.

[4] Takao Hara, Michihiro Ichikawa, Minoru Okada, and Heiichi Yamamoto. Canceller design for carrier super-positioning frequency re-use of vsat satellite communications. *The transactions of the Institute of Electronics, Information and Communication Engineers. B*, 88(7):1300–1309, 2005-07-01.

[5] Takao Hara, Kenta Kubo, and Minoru Okada. Adaptive back-off nonlinearity compensation for interference canceller in carrier super-positioning satellite communications. *IEICE Transactions on Communications*, 94(7):2022–2031, 2011.

[6] Takao Hara, Hiroki Matsuda, Kenta Kubo, and Minoru Okada. Performance improvement of interference canceller for carrier super-positioning by the nonlinearity compensation in satellite communications. In *The Sixth International Conference on Wireless and Mobile Communications (ICWMC2010)*, september 2010.

[7] Takao Hara, Yoshikazu Tsuji, and Heiichi Yamamoto. Design optimization of a tdma burst modem for small earth stations in a channel containing two nonlinear devices. In *Electronics and Communications in Japan (Part1: Communications)*, volume 87, pages 47–62, 2004.

[8] A. Hashimoto and Y. Suzuki. A new transmission system for the advanced satellite broadcast. *Consumer Electronics, IEEE Transactions on*, 54(2):353 –360, may 2008.

[9] Akinori HASHIMOTO, Youichi SUZUKI, Hisashi SUJIKAI, Shoji TANAKA, Takeshi KIMURA, and Kazuyoshi SHOGEN. A transmission system for the advanced bs digital broadcasting. *Technical report of IEICE. SAT*, 107(83):13–18, may 2007.

[10] Noriaki Ishida. Common-band satellite communication system. *Technical report of IEICE. SAT*, 97(556):107–114, feb 1998.

[11] Noriaki Ishida. Common-band satellite communication system. *Technical report of IEICE. SAT*, 97(556):107–114, 1998-02-20.

[12] Y. Ito, Y. Urano, T. Muratani, and M. Yamaguchi. Analysis of a switch matrix for an ss/tdma system. *Proceedings of the IEEE*, 65(3):411 – 419, march 1977.

[13] ITU Radiocommunication Sector. `http://www.itu.int/en/ITU-R/`.

[14] Masaaki KOJIMA, Akinori Hashimoto, Yoichi SUZUKI, Takeshi KIMURA, Shoji TANAKA, and Tomohiro SAITO. Experimental verification of prototype non-linear compensation technique based on signal point error estimation over satellite transponder. *Technical report of IEICE. SAT*, 110(136):91–96, jul 2010.

[15] Masaaki Kojima, Yoichi Suzuki, Akinori Hashimoto, Hisashi Sujikai, Shoji Tanaka, Takeshi Kimura, and Kazuyoshi Shogen. Non-linear compensation technique based on signal point error estimation on satellite transmission system. *Technical report of IEICE. SAT*, 108(440):37–42, February 2009.

[16] Kenta Kubo, Hiroki Matsuda, Kayoko Osawa, Taro Shimada, Shigeo Naoi, Yozo Takeda, Ryusuke Miyamoto, Takao Hara, and Minoru Okada. Experimental test of frequency reuse interference canceller in the path containing nonlinear twta. *Technical report of IEICE. SAT*, 109(254):23–28, 2009-10-22.

[17] Kenta Kubo, Ryusuke Miyamoto, Takao Hara, and Minoru Okada. Nonlinear compensations for interference canceller of super-positioning satellite system. *Technical report of IEICE. SAT*, 109(254):35–40, October 2009.

[18] Shoko Kuroda, Sho Tanaka, Shigeo Naoi, Yozo Takeda, Ryusuke Miyamoto, Takao Hara, and Minoru Okada. Development of an interference canceller in satellite communications using a multi-level modulation with superposed transmission. *IEICE Transactions*, E92-B(11):3354–3364, 2009-11.

[19] Cheng-Po Liang, Je-Hong Jong, W.E. Stark, and J.R. East. Nonlinear amplifier effects in communications systems. *Microwave Theory and Techniques, IEEE Transactions on*, 47(8):1461 –1466, aug 1999.

[20] Vincenzo Lottici, Marco Luise, and Ruggero Reggiannini. Adaptive nonlinear compensation of satellite transponder distortion for high-level data modulations. In *Seventh International Workshop on Digital Signal Processing Techniques for Space Communications*, Oct. 2001.

[21] Mayumi Osato, Hiroyuki Kobashi, Robert Y. Omaki, Takao Hara, and Minoru Okada. Development of signal canceller in the carrier super-positioning satellite networks. In *Proceedings of the Third International Conference on Wireless and Mobile Communications*, ICWMC '07, pages 35–, 2007.

[22] J.R. Pierce. Theory of the beam-type traveling-wave tube. *Proceedings of the IRE*, 35(2):111 – 123, feb. 1947.

[23] John Proakis. *Digital Communications*. McGraw-Hill, 5 edition, 2008. p195.

[24] A.A.M. Saleh. Frequency-independent and frequency-dependent nonlinear models of twt amplifiers. *Communications, IEEE Transactions on*, 29(11):1715 –1720, november 1981.

[25] Giovanni Santella and Franco Mazzenga. A model for performance evaluation in m-qam-ofdm schemes in prescence of nonlinear distortions. In *Vehicular Technology Conference, 1995 IEEE 45th*, volume 2, pages 830–834, jul 1995.

[26] Jiri Sebesta. Efficient method for APSK demodulation. In *Proceedings of the 3rd International Conference on Applied Mathematics, Simulation, Modelling, Circuits, Systems and Signals*, ASMCSS'09, pages 187–190. World Scientific and Engineering Academy and Society (WSEAS), 2009.

[27] O. Shimbo. Effects of intermodulation, am-pm conversion, and additive noise in multicarrier twt systems. *Proceedings of the IEEE*, 59(2):230 – 238, feb. 1971.

[28] Osamu Shimbo. *Transmission Analysis in Communication Systems.* Computer Science Press, 6 edition, 1988.

[29] M. Tanahashi and H. Ochiai. A multilevel coded modulation approach for hexagonal signal constellation. *Wireless Communications, IEEE Transactions on*, 8(10):4993 –4997, october 2009.

[30] M. Tanahashi and H. Ochiai. Trellis shaping for controlling envelope of single-carrier high-order QAM signals. *Selected Topics in Signal Processing, IEEE Journal of*, 3(3):430 –437, june 2009.

[31] M. Tanahashi and H. Ochiai. Turbo decoding of concatenated channel coding and trellis shaping for peak power controlled single-carrier systems. *Communications, IEEE Transactions on*, 58(1):9 –15, january 2010.

[32] Comtech EF Data CDM-625. `http://www.comtechefdata.com/products/modems/cdm-625`.

[33] Digital video broadcasting. `http://www.dvb.org/`.

[34] ETSI EN 302 307. `http://www.etsi.org/deliver/etsi_en/302300_302399/302307/01.02.01_60/en_302307v010201p.pdf`.

[35] **情通審答申諮問*2023*号「放送システムに関する技術的条件」のうち「衛星デジタル放送の高度化に関する技術的条件」**, 2008年7月29日.

[36] Hideki Toshinaga, Kiyoshi Kobayashi, Kohei Ohata, and Hiroshi Kazama. Interference cancellation for multimedia satellite communication systems employing superposed transmission. *Technical report of IEICE. SAT*, 100(484):5–10, 2000-12-01.

[37] T. Uratani, R. Miyamoto, T. Hara, and M. Okada. Performance of an interference canceller for p-mp satellite networks with nonlinear twta. In *International Symposium on Communications, Control and Signal Processing (ISCCSP'08)*, march 2008.

[38] Rafik Zayani and Ridha Bouallegue. Pre-distortion for the compensation of hpa nonlinearity with neural networks: Application to satellite communications. *International Journal of Computer Science and Network Security*, 7(3):97–103, March 2007.

Appendix

A. List of Publications

A.1 Journal

1. T. Ishiguro, T. Hara, and M. Okada, “Post-Compensation Technique for Carrier Superposed Satellite Channel Including Nonlinear TWTA”, *IEICE Transactions*, E95-B No.11, pp3420–3427, 2012-11.
2. 石黒 剛大, 原 孝雄, 岡田 実, “衛星通信多値変調信号の受信側での非線形補償”, *IEICE* **和文論文誌**, J96-B No.4, pp -, Apr. 2013

A.2 International Conference

1. T. Ishiguro, T. Hara, and M. Okada, “Nonlinearity Compensation Technique for Common Band Satellite Channel”, in *Proc. of SPACOMM 2012*, pp16–20, Apr, 2012
2. T. Ishiguro. T. Hara, and M. Okada, “Post-Compensation Technique for Carrier Superposed Satellite Systems using TWTA”, in *Proc. of ICESIT 2012*, pp69–72, Jan, 2012
3. H. Matsuda, T. Ishiguro, T. Hara, and M. Okada, “Nonlinearity Compensation for Super-Positioning Satellite System with Interference Canceller”, in *Proc. of AICT 2012*, pp20–25, Mar, 2011
4. T. Ishiguro, S. Kuroda, S. Tanaka, R. Miyamoto, T. Hara, and M. Okada, “A High Performance Interference Canceller with Narrow Input for Carrier Superposed Satellite Communication”, in *Proc. of Euromedia 2009*, pp117–121, Apr, 2009

A.3 Unrelated International Conference

1. T. Ishiguro and R. Miyamoto, “An Efficient Prediction Scheme for Pedestrian Tracking with Cascade Particle Filter and Its Implementation on Cell/B.E.”, in *Proc. of ISPACS 2009*, pp29–32, Dec, 2009

2. T. Ishiguro, R. Miyamoto, and M. Okada, “Feasibility Study of Pedestrian Tracking From a Moving Camera Using A System Model With Motion Information”, in *Proc. of World Automation Congress 2010*, Sep, 2010

3. T. Ishiguro, R. Miyamoto, and M. Okada, “GPU Implementation of Pedestrian Tracking Based on Particle Filter for On-Board Camera”, in *Proc. of International Workshop on Smart Info-Media Systems in Asia 2010*, Sep, 2010

4. T. Ishiguro, R. Miyamoto, and M. Okada, “Pedestrain Tracking Using Particle Filter with System Model Representing Camera Motion and HSV-based Observation”, in *Proc. of ICESIT 2011*, Feb, 2011