Proposal of QAM-OFDM System with IDAR Method Designed for Satellite Channel

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ABSTRACT

The future satellite communication systems are required to support the higher transmission data rate for providing multimedia services by employing the efficient modulation method such as multi-level QAM. However, the employment of conventional single carrier transmission method with multi-level QAM which has larger PAPR (Peak to Averaged Power Ratio) would cause the fatal degradation of signal quality due to the non-linear amplifiers located at the earth station and satellite. To overcome this problem, this paper proposes broadband satellite communication systems by using the multi-level QAM-OFDM technique with IDAR (Improved Decision Aided Reconstruction) method, which is designed for satellite channel. In the IDAR method, the characteristics of non-linear amplifiers are required to be known at the receiver for mitigating the inter-modulation noise. This paper also proposes the estimation method for AM-AM and AM-PM conversion characteristics of non-linear amplifiers by using low PAPR preamble symbols. The various computer simulations are conducted in this paper to verify the effectiveness of proposed system in the non-linear satellite channel.

Keywords: OFDM, Satellite, Non-Linear Amplifier, IDAR, PAPR

1. INTRODUCTION

The future satellite communications including the fixed, mobile and broadcasting systems are required to support the higher transmission data rate for providing the multimedia services, which are already available in the terrestrial network [1]-[7]. To realize the higher data rate transmission in the satellite channel, it is requested to employ the efficient modulation method such as multi-level QAM. However, the employment of conventional single carrier transmission method with multi-level QAM which has larger PAPR would cause the fatal degradation of signal quality due to the inter-modulation noise incurred at the non-linear amplifiers located at the transmit earth station and satellite [9]-[14]. From this reason, the modulation method used in the current satellite communications is usually limited by low transmission data rate of using QPSK method, which has the robustness to the non-linear distortion fairly because of its better PAPR performance as compared with that for the multi-level QAM modulation method.

On the other hand, the Orthogonal Frequency Division Multiplexing (OFDM) technique has been received a lot of attentions especially in the field of terrestrial wireless communications because of its efficient usage of frequency bandwidth, robustness to the multi-path fading and enabling the employment of multi-level QAM with less complexity of receiver[15]-[19]. One of the disadvantages of using the OFDM signal is that its time domain signal has the larger PAPR, which causes the degradation of BER performance in the non-linear amplifier. From this reason, the OFDM has been considered as unsuitable transmission technique for the satellite channel although it has a potential capability to improve the transmission data rate by employing the multi-level QAM with less complexity structures of transmitter and receiver. To solve the problem of performance degradation due to the non-linear distortion for the OFDM signal, we have already proposed the OFDM technique with IDAR method designed for terrestrial wireless communication systems, which includes one non-linear amplifier at the transmitter such as wireless LAN system [20]. The proposed IDAR method can mitigate the non-linear distortion by using the decision data at the receiver and achieve the higher transmission data rate with keeping the better BER performance even in the non-linear channel. In the IDAR method, however the input and output relationships of non-linear amplifier characteristics are required at the receiver. The evaluation of proposed OFDM-IDAR method in [20] was assumed that the ideal input and output relationships of amplifier characteristics are known at the receiver.

In this paper, we propose the broadband satellite communication systems by using multi-level QAM-OFDM technique with IDAR method designed for the non-linear satellite channel, which includes two non-linear amplifiers located at the transmit earth

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station and satellite[20]-[21]. The proposed method could achieve the higher transmission data rate in the non-linear satellite channel with keeping the better BER performance than that for the conventional single carrier transmission technique of using multi-level QAM method. This paper also proposes the estimation method for non-linear amplifier characteristics, which is required for the IDAR method, by using the low PAPR preamble symbols inserted at the start of every frame. The proposed estimation method for non-linear amplifier characteristics could achieve the better accuracy even when the characteristics of non-linear amplifiers located at the earth station and satellite are changed frequently due to the aging or operation environments.

In this paper, Section 2 firstly presents the satellite system model. Section 3 proposes the OFDM-IDAR method designed for satellite channel, and Section 4 proposes the estimation method of non-linear amplifier characteristics, which are required in the IDAR method. Section 5 presents the various computer simulation results to verify the effectiveness of OFDM-IDAR technique with the proposed estimation method, and Section 6 draws some conclusions.

2. SATELLITE SYSTEM MODEL

Figure 1 shows the typical satellite system model assumed in the following evaluations. The non-linear amplifier located at the earth station is assumed by the Solid State Power Amplifier (SSPA), which is modeled by Rapp [22]. The AM-AM and AM-PM conversion characteristics of SSPA modeled by Rapp are given by the following equations, respectively.

$$F_E(\rho) = \frac{v\rho}{\left[1 + (\frac{v\rho}{A_0})^{2p}\right]^{1/2p}} \tag{1}$$

$$\Phi_E(\rho) = \alpha_\phi \left(\frac{v\rho}{A_0}\right) \tag{2}$$

where, $F_E(\rho)$ and $\Phi_E(\rho)$ show the AM-AM and AM-PM conversion characteristics of SSPA, respectively, and ρ is the amplitude of input signal, v is the gain factor, is the saturated output level, A_0 is the parameter to decide the non-linear level and p is phase displacement. In the following evaluations, the values for these parameters are assumed by $A_0 = 1, v = 1, p = 6$ and $\alpha_\phi = 0.01$ which can approximate the standard characteristics of SSPA.

The output signal of SSPA, which corresponds to the uplink signal in the radio frequency, can be given by the following equation.

$$S_{up}(t) = F_E\left[|s(t)|\right] e^{j\{\arg[s(t)] + \Phi_E[|s(t)|]\}} \tag{3}$$

where, $s(t)$ is the OFDM signal at the input of earth station amplifier SSPA. The signal given by (3) is transmitted to the satellite and then input to the satellite non-linear amplifier after converting from the uplink to down link radio frequency. The non-linear amplifier located at the satellite station is assumed by the Traveling Wave Tube Power Amplifier (TWTA), which is modeled by Saleh [23]. The AM-AM and AM-PM conversion characteristics of TWTA modeled by Saleh are given by the following equations, respectively.

$$F_s(\gamma) = \frac{\alpha_a \gamma}{(1 + \beta_a \gamma^2)} \tag{4}$$

$$\Phi_s(\gamma) = \frac{\alpha_\theta \gamma^2}{(1 + \beta_\theta \gamma^2)} \tag{5}$$

where, γ is the amplitude of input signal, α_a and β_a are the parameters to decide the non-linear level of power amplifier, and α_a and β_a are phase displacements. The values for these parameters are assumed by $\alpha_a = 2, \beta_a = 1, \alpha_\theta = 2$ and $\beta_\theta = 1$ which can approximate the standard TWTA.

Figure 2 shows the input and output relationships of AM-AM and AM-PM conversion characteristics for both SSPA and TWTA when the parameters are given by the above values. In this paper, we assume the higher non-linearity for the satellite amplifier (TWTA) than that for the earth station amplifier (SSPA) as shown in Fig.2. By using (3), the output signal of TWTA, which corresponds to the downlink signal in the radio frequency, is given by the following equation.

$$S_{dw}(t) = F_s\left[|s_{up}(t)|\right] e^{j\{\arg[s_{up}(t)] + \Phi_s[|s_{up}(t)|]\}} \tag{6}$$

The output signal of TWTA given in (6) includes the inter-modulation noises incurred at the SSPA and TWTA.

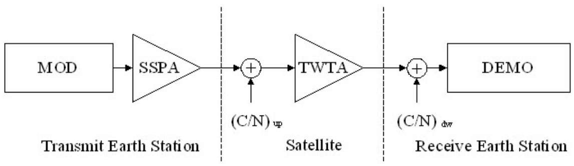


Fig.1: *Satellite system model.*

3. SATELLITE SYSTEM MODEL

This paper proposes OFDM-IDAR method designed for satellite channel, which included two high non-linear amplifiers located at the transmit earth station and satellite. To apply the OFDM technique to non-linear satellite channel, it is requested to mitigate the non-linear distortion occurred at the transmit earth station and satellite. The OFDM-IDAR method proposed in this section could compensate the non-linear distortion at the receiver by using the feature of OFDM signal in the time and frequency domains.

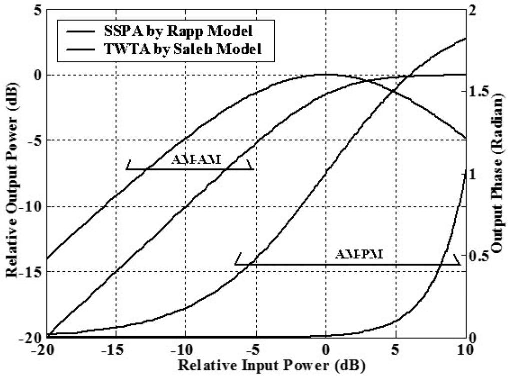


Fig.2: *Input and output relationships for SSPA and TWTA.*

Figure 3 shows the structure of receiver for the proposed OFDM-IDAR method designed for satellite channel. The received downlink radio frequency signal affected by the non-linear amplifiers at the transmit earth station and satellite amplifiers is given by the following equation.

$$r(t) = s_{dw}(t) + w(t) \tag{7}$$

where, $s_{dw}(t)$ is the downlink signal given in (6), and $w(t)$ is the additive white Gaussian noise (AWGN). The received RF signal $r(t)$ is first down converted (D/C) to the base band signal and digitized by A/D converter. The time domain sampled signal $r'(m,k)$ after compensating the phase rotation due to the AM-PM conversions of SSPA and TWTA and removing the OFDM guard interval (GI), can be expressed by the following equation.

$$\begin{aligned} r'(m,k) &= r(m,k)\cdot e^{-j\Phi^c_{ref}} \\ &= s(m,k) + i(m,k) + w(m,k) \end{aligned} \tag{8}$$

where, $s(m,k)$, $i(m,k)$ and $w(m,k)$ represent the original signal, composite inter-modulation noises incurred at the SSPA and TWTA, and AWGN on the k-th time domain sampled signal of m-th OFDM symbol, respectively. The phase rotation of Φ^c_{ref} due to the SSPA and TWTA at the operation points that is input back-off (IBO) can be estimated by using the low PAPR preamble symbols of which estimation method is proposed in Section 4.

The received time domain sampled signal given (8) is converted to the frequency domain signal by FFT, which is given by the following equation.

$$R'(m,n) = S(m,n) + I(m,n) + W(m,n) \tag{9}$$

In (9), the capital letter represents the frequency domain signal on n-th subcarrier of m-th OFDM symbol, which corresponds to its small letter given by (8) in the time domain. By using (9), the decision for the information data $\hat{S}(m,n)$ can be made for each sub-carrier in the frequency domain.

In the IDAR method, the time domain signal $\hat{S}(m,k)$, which is converted from the above decision data $\hat{S}(m,n)$ in the frequency domain, is used for the reconstruction of inter-modulation noise. This is based on the fact that the OFDM time domain signal converted from the decision data in the frequency domain, which includes even some decision errors, would be almost the same as the original time domain signal without error.

The decision data $\hat{S}(m,n)$ in the frequency domain can be expressed by the following equation.

$$\hat{S}(m,n) = S(m,n) + F(m,n) \tag{10}$$

where $F(m,n)$ is the decision error, which can be expressed by the following equation.

$$F(m,n) = \begin{cases} 0 & if\,\hat{S}(m,n) = S(m,n) \\ \hat{S}(m,n) - S(m,n) & if\,\hat{S}(m,n) \neq S(m,n) \end{cases} \tag{11}$$

The time domain signal, which is converted from the frequency domain signal of (10), is given by the following equation.

$$\begin{aligned} \hat{s}(m,k) &= \sum_{n=0}^{N-1} \hat{S}(m,n)\cdot e^{j\frac{2\pi nk}{N}} \\ &= \sum_{n=0}^{N-1} S(m,n)\cdot e^{j\frac{2\pi nk}{N}} + \sum_{n=0}^{N-1} F(m,n)\cdot e^{j\frac{2\pi nk}{N}} \\ &= sm,k + f(m,k) \end{aligned} \tag{12}$$

where, $s(m,k)$ shows the original time domain signal without decision error and $f(m,k)$ shows the time domain signal for the decision error occurred in the frequency domain. From (12), it can be seen that the decision error occurred in the frequency domain is spread over the N sample time domain signal and level of $f(m,k)$ would be relatively small as compared with $s(m,k)$. From this fact, it can be concluded that the time domain signal $\hat{s}(m,k)$ which is converted from the frequency domain signal $\hat{S}(m,k)$ including decision error, can be approximated by the original signal $s(m,k)$. Figure 4 (b) shows an example of relationships between $s(m,k)$ and $\hat{s}(m,k)$ when the number of decision errors occurred in the frequency domain is 5 as shown in Fig. 4 (a). From Fig.4 (b), it can be observed that the time domain signal for the decision error is much smaller then the original signal and the time domain signal $\hat{s}(m,k)$, which included 5 decision errors in the frequency domain is almost the same as the original signal without decision error. From this fact, the inter-modulation noise can be reconstructed in the time domain by using the decision data even including error in the frequency domain.

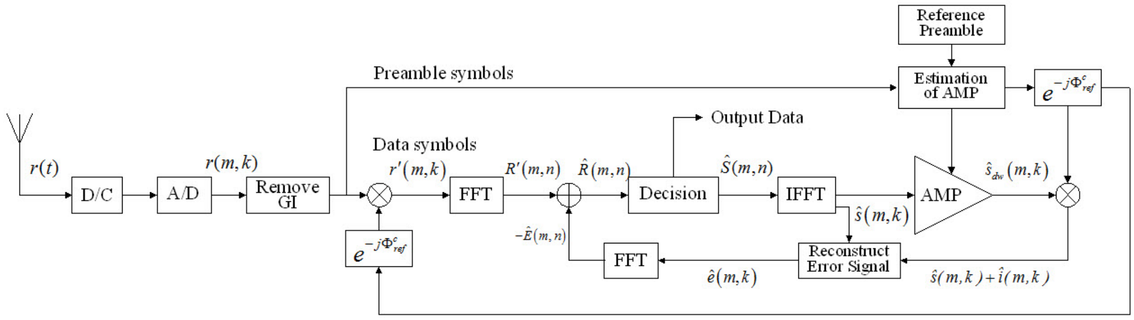


Fig.3: *Structure of proposed OFDM-IDAR receiver.*

In the reconstruction of inter-modulation noise, the operation of non-linear amplifier is performed to the time domain signal, which is converted from the decision data in the frequency domain. Here, it should be noted that the operations of non-linear amplifiers in the IDAR method are performed on the digital sampled data by assuming the same AM-AM and AM-PM conversion characteristics as that operated in the radio frequency at the earth station (SSPA) and satellite (TWTA). The estimation method for non-linear amplifiers characteristics of SSPA and TWTA is proposed in Section 4. The time domain signal at the output of AMP as shown in Fig.3 is given by the following equation.

$$\begin{aligned} r'(m,k) &= r(m,k) \cdot e^{j\Phi^c_{ref}} \\ &= s(m,k) + i(m,k) + w(m,k) \end{aligned} \quad (13)$$

where, $\hat{s}(m,k)$ is the time domain signal converted from the frequency domain decision data $\hat{s}(m,n)$, and F_p and Φ_P are the AM-AM and AM-PM conversion characteristics for AMP which is the composite characteristics of SSPA and TWTA. By using (13), the inter-modulation noises incurred at the SSPA and TWTA could be estimated by the following equation.

$$\begin{aligned} \hat{e}(m,k) &= \hat{s}_{dw}(m,k) \cdot e^{-j\Phi^c_{ref}} - \hat{s}(m,k) \\ &\approx \hat{s}(m,k) + \hat{i}(m,k) - \hat{s}(m,k) \\ &\approx \hat{i}(m,k) \end{aligned} \quad (14)$$

where, the phase rotation of Φ^c_{ref} due to SSPA and TWTA is given in Section 4. The inter-modulation noise given by (14) is then converted to the frequency domain signal by FFT. By subtracting the reconstructed inter-modulation noise $\hat{E}(m,n)$ in the frequency domain from (9) as shown in Fig. 3, the frequency domain signal coped with the inter-modulation noise can be obtained by the following equation.

$$\begin{aligned} \hat{R}(m,n) &= R'(m,n) - \hat{E}(m,n) \\ &= S(m,n) + \left\{ I(m,n) - \hat{I}(m,n) \right\} + W(m,n) \\ &\approx S(m,n) + W(m,n) \end{aligned} \quad (15)$$

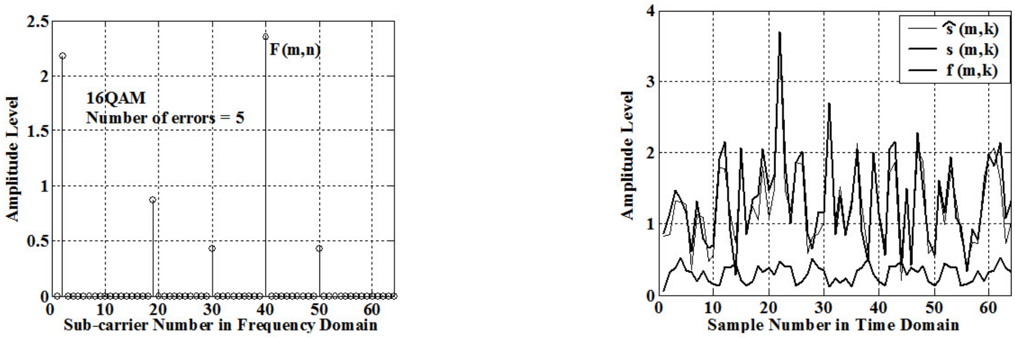
If the BER performance for the decision data on (15) is better than that for (9), the BER performance could be improved further by repeating the above procedures from (9) to (15).

4. ESTIMATION METHOD OF NON-LINEAR AMPLIFIER

In the OFDM-IDAR method proposed in Section 3, it is required for the input and output relationships of AMP, which includes the output power as a function of input power (AM-AM) and the output phase as a function of input power (AM-PM). These AM-AM and AM-PM conversion characteristics are also required to update at the receiver frequently because they may be changed due to the aging or the operation environments of earth station and satellite. The actual operation point (IBO: Input Back off) of satellite TWTA would be also changed because the signal power in the uplink would be fluctuated due to the rain attenuation.

The non-linear amplifier characteristics are usually measured by changing the power level of continuous waves (pure tone signal), of which signal envelope is the constant in the time domain. However, the pure tone signal has the line spectrum at the operating radio frequency with larger power level and this line spectrum would cause very large co-channel interference to other satellite systems employing the same frequency band.

Taking into account these conditions, we propose the estimation method for characteristics of non-linear amplifiers by using low PAPR preamble symbols. Fig. 5 shows the proposed frame structure for the estimation of non-linear amplifier, which consists of K low PAPR preamble symbols and L data symbols. As shown in Fig.5, K low PAPR preamble symbols with increasing their power levels are transmit-



(a) Frequency domain signal. (b) Time domain signal.

Fig.4: *Decision error signal in frequency and time domains.*

ted to the receive earth station before transmitting the data symbols.

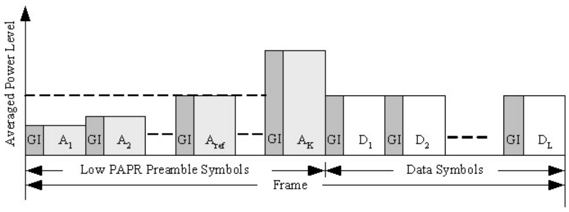
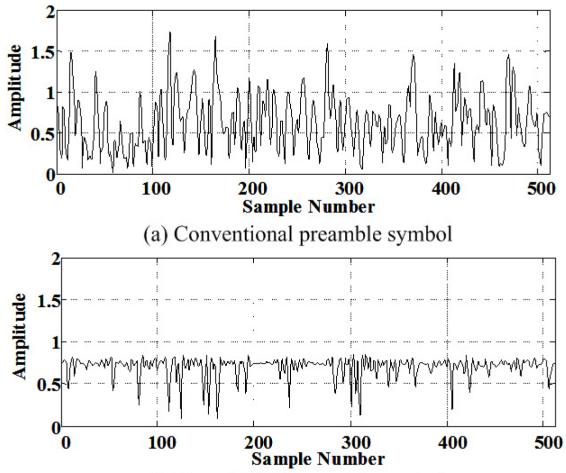


Fig.5: *Structure of proposed frame format.*

In the generation of low PAPR preamble symbol, we employed the time-frequency domain-swapping algorithm [18], which can optimize the phase value for each OFDM sub-carrier so as to minimize the PAPR. In the optimization of phase value for preamble symbol, the amplitude of all sub-carriers in the preamble symbol is kept by the constant value. From this fact, the frequency spectrum of low PAPR preamble symbol becomes flat over the whole allocated bandwidth. Fig. 6 shows an example of time domain signals both for low PAPR preamble symbol and conventional OFDM symbol. From the figure, it can be observed that the low PAPR preamble symbol has the similar feature of pure tone signal with the constant envelope in the time domain, while its frequency spectrum density is flat over the whole occupied bandwidth. From these features of low PAPR preamble symbol, it is possible to measure the input and output relationships of non-linear amplifier precisely and not to interfere to other systems using the same frequency band.

From the proposed frame structure as shown in Fig.5, it can be seen that the power levels of preamble symbols has the certain dynamic range at the center of reference preamble symbol of which power level is taken as the same as that for the data symbols. Therefore, the relative non-linear amplifier characteristics, which are normalized by the power level of reference preamble symbol can be estimated by measuring the received power level and phase difference



(b) Low PAPR preamble symbol

Fig.6: *Envelope of preamble symbol in the time domain.*

of received low PAPR preamble symbols.

4.1 Estimation of AM-AM Conversion Characteristics

The input power level for the composite non-linear amplifier can be expressed in the values relative to the transmission power level of reference preamble symbol as shown in Fig.5, because the relative transmission power levels between the preamble symbols are known at the receiver. If the input power level of reference preamble symbol is assumed by 0dB, the relative input power levels for all preamble symbols can be given by the following equation.

$$P_m^{input} = 10log_{10}\left(\frac{P_m^t}{P_{ref}^t}\right) \quad (m = 1 \sim K) \tag{16}$$

where, P_m^t and P_{ref}^t are the transmission power levels at the m-th preamble symbol and reference preamble symbol, respectively. The output power level as a function of input power level given by (16) can be estimated by measuring the received power level for the preamble symbols at the receive earth station. The received power level for the preamble symbol m can be measured in the time domain by using the following equation.

$$P^r_m = \frac{1}{N}\sum_{k=0}^{N-1}|r(m,k)|^2 \qquad (17)$$

where, N is the number of sample points in one OFDM symbol. By using the all measured power levels for preamble symbols, the preamble symbol with the maximum power level can be detected by the following equation.

$$P^r_{max} = \underset{m=1\sim K}{Max}\left[P^r_m\right] \qquad (18)$$

By using (18), the relative output power level of composite AMP at the corresponding relative input power level of (16) can be given by the following equation.

$$P^{output}_m = 10\log_{10}\left(\frac{P^r_m}{P^r_{max}}\right)\ (m = 1\sim K) \qquad (19)$$

By using (16) and (19), the relative combined AM-AM conversion characteristics for SSPA and TWTA can be estimated as a function of the input power levels for K preamble symbols. The AM-AM conversion characteristics between measurement results of two consecutive preamble symbols can be estimated by using the interpolation method.

4.2 Estimation of AM-PM Conversion Characteristics

The output phase as a function of input power level (AM-PM) for the composite characteristics of SSPA and TWTA can be estimated by measuring the phase differences in the frequency domain between the transmitted and received sub-carriers for the preamble symbols. The received preamble symbol in the frequency domain can be given by the following equation.

$$R(m,n) = S(m,n)\cdot e^{j\{\Phi_E(\sqrt{P^e_m})+\Phi_S(\sqrt{P^s_m})\}} \qquad (20)$$

where, $S(m,n)$ is the transmitted data on n-th subcarrier of m-th symbol, P^e_m and P^s_m are power levels of m-th preamble symbol at the input of SSPA and TWTA, respectively. Since the transmitted data $S(m,n)$ in the preamble symbols are known at the receiver, the averaged phase rotation due to both SSPA and TWTA can be estimated by the following equation.

$$\begin{aligned}\Phi^c_m &= \frac{1}{N}\sum_{n=0}^{N-1}\arg\left[\frac{R(m,n)}{S(m,n)}\right] \\ &= \Phi_E\left(\sqrt{P^e_m}\right) + \Phi_S\left(\sqrt{P^s_m}\right)\end{aligned} \qquad (21)$$

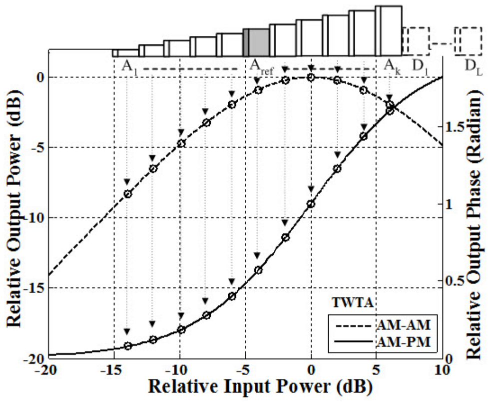
By using (16) and (21), the output phase as a function of input power level (AM-PM) can be estimated for the composite characteristics of SSPA and TWTA. The AM-PM conversion characteristics between two measurement results of two consecutive preamble symbols can be estimated by using the interpolation method.

The averaged phase rotation obtained at the reference preamble symbol will be used for the compensation of phase rotation for the data symbols as used in (8) and (14), because the averaged power level of reference preamble symbol is taken as the same as that for the data symbols as shown in Fig.5.

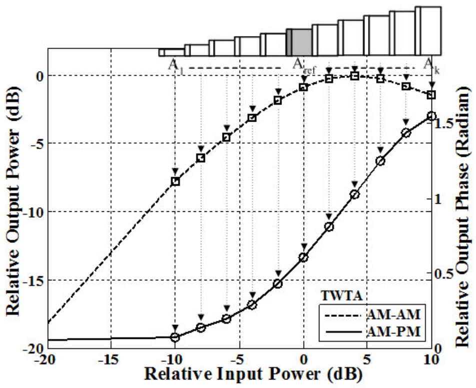
The required dynamic range of power level between the first and K-th preamble symbols can be decided on the basis of averaged power level of transmission data symbol and possible dynamic range of power level for OFDM data symbol in the time domain. The dynamic range of power level for OFDM signal is usually around 30dB from -20dB to 10dB at the center of averaged power level of 0dB. From these facts, the required dynamic range of power level over the preamble symbols can be set from -10dB to +10dB in which the power level of reference symbol is set by 0dB. Here, the input and output relationships of non-linear amplifier from -20dB to -10dB can be estimated precisely by using the extrapolation method, because these regions of non-linear amplifier can be assumed as the linear characteristics.

Figure 7 shows the actual and estimated input and output relationships of non-linear amplifier characteristics when the input power level of reference preamble symbol is -4dB. Here, the input level of reference preamble symbol is corresponding to the IBO of data symbols. To simplify the explanation, the non-linear amplifier is assumed only to use TWTA. From Fig.7 (a), it can be seen that the input level of non-linear amplifier for 11 low PAPR preamble symbols is changed from -14dB to 6dB by 2dB step at the center of reference preamble symbol of which level is -4dB. By using the proposed estimation method described above, the estimated input and output relationships of non-linear amplifier characteristics can be given as shown in Fig.7 (b). In Fig.7 (b), it should be noted that the estimated characteristics of non-linear amplifier is obtained only by the relative input and output relationships, which is normalized by the power level of reference preamble symbol. Since the inter-modulation noise is reconstructed by using the decision data, which has the same power level as the reference preamble symbol, the relative input and output relationships of non-linear amplifier can be used in the IDAR method as described in the previous section.

By using the proposed estimation method, the higher estimation accuracy can be achieved even when the characteristics of non-linear amplifiers located at the earth station and satellite are changed frequently due to the aging or operation environments including the uplink rain attenuation, because the characteristics of non-linear amplifier can be estimated every frame by using the low PAPR preamble symbols. The accuracy of proposed estimation method with the interpolation and extrapolation methods would depend on the number of employed preamble symbols and power allocation method of preamble symbols over K preamble symbols. The detailed evaluation on the estimation accuracy of proposed estimation method is presented in the next section.



(a) Actual input and output relationships of non-linear amplifier.



(b) Estimated input and output relationships of non-linear amplifier.

Fig.7: *Schematic figure of proposed estimation method.*

5. PERFORMANCE EVALUATIONS

This section presents the various computer simulation results to verify the performance of OFDM-IDAR method with the proposed estimation method. Table 1 shows the simulation parameters to be used in the following evaluations. The modulation method is assumed by 16QAM with coherent detection method and the channel model is AWGN channel, which corresponds to the fixed and broadcasting satellite systems. The achievable transmission data rate for the proposed OFDM-IDAR method is 90.1Mbit/s by using the frequency bandwidth 25MHz out of 27MHz which is taken into account the interference to to adjacent channel. In the table, the parameters for conventional single carrier (SC) transmission with 16QAM are also shown as the purpose of comparison with the proposed OFDM-IDAR method. The frame length for the proposed method is assumed by 22.73ms including 11 low PAPR preamble symbols and 1000 data symbols. Assuming this frame structure, the non-linear amplifier characteristics both for SSPA and TWTA can be estimated every 22.73ms, which would be enough small cycle to cope with the fluctuation of amplifier characteristics due to the aging or operation conditions including the rain attenuation in the uplink.

Table 1: *Complexity (per bit) of different iterative timing recovery schemes.*

Allocated occupied bandwidth	*26MHz*
Modulation method	*16QAM*
Earth station amplifier	*SSPA*
Satellite amplifier	*TWTA*
Conventional Single Carrier Transmission (SC) Method	
Number of sample points/data symbol	*4*
Number of data symbols / frame	*128*
Type of Tx and Rx filters	*Root Nyquist*
Roll-off factor	*0.4*
Transmission data rate	*104 Mbit/s*
Proposed OFDM-IDAR Method	
Number of FFT points	*512*
Number of sub-carriers	*128*
Symbol duration	*4.92 us*
Guard interval	*0.1 us*
Number of preamble symbols / frame	*11*
Number of data symbols / frame	*1000*
Frame duration	*5.08 ms*
Transmission data rate	*100.8 Mbit/s*

5.1 Accuracy of Proposed Estimation Method

The estimation accuracy for the characteristics of composite AMP would be much dependent on the design of low PAPR preamble symbols including the number of preamble symbols and power allocation method for them. Table 2 shows three cases of preamble symbol designs for the evaluation of proposed estimation method. All cases are taken by 20dB as the dynamic range from -10dB to 10dB. The number of preamble symbols for Cases 1, 2 and 3 are taken by 21, 11 and 5, respectively. In Table 2, the Ideal means that the characteristics of non-linear amplifiers both for SSPA and TWTA are given by equations (1), (2), (4) and (5). Table 2 shows the computer simulation results on the required C/N to achieve BER=10^{-4} for all cases. In the simulation, only the downlink noise (C/N)dw is considered as 20dB and IBO for the earth station SSPA and satellite TWTA are taken by -3dB and -4dB, respectively. From the table, it can be observed that Cases 1 and 2 show the same required C/N to achieve BER=10-4 with 1.2dB degradation from the Ideal case, although the number of preamble symbols for Case 1 is larger than that for Case 2 by almost 2 times. Case 3 with fewer number of preamble symbols shows 2.8dB degradation from the Ideal case. From these results, it can be concluded that Case 2 using 11 preamble symbols of which power levels are increasing by 2 dB step from -10dB to +10dB is the best design for preamble symbols. In the following evaluation, Case 2 is used for the estimation of composite characteristics of AMP.

Figures 8 (a) and (b) show the estimated composite characteristics of AMP when IBO of SSPA is taken by -3dB and -10dB, respectively. In the simulation, Case 2 is used as the preamble design, and the downlink (C/N)dw is 20dB. The ideal characteristics of composite AMP when using the equations are also shown in the figures. From the figure, it can be observed that proposed method can estimate almost the same AMP characteristics as the Ideal case. Here it should be noted that the composite characteristics of AMP shown in Fig.7 (b) is almost the same as that for the satellite amplifier of TWTA when the IBO of earth station amplifier of SSPA is -10dB. This fact is come from that the non-linear characteristics of SSPA can be considered as the linear because of taking enough IBO at the transmit earth station.

Figure 9 shows the BER performances of OFDM-IDAR with proposed estimation method when changing the number of iterations of IDAR method. In the figure, BER performance when assuming the ideal characteristics of SSPA and TWTA are also shown as comparing with the proposed estimation method using Case 2. The IBO for the SSPA and TWTA are taken by -3dB and -4dB, respectively. From the figure, it can be observed that the BER performance of OFDM-IDAR with the proposed estimation method is slightly degraded as compared with the ideal case. It can be also observed that the BER performances for the proposed methods at $(C/N)_{dw}$ =20dB are converged when the number of iterations is taken larger than 6. From these results, the following simulations for OFDM-IDAR method are assumed to use 6 as the iteration number for the IDAR method.

Table 2: *List of power allocation methods.*

	Power allocation of preamble symbols	No. of preamble symbols	Required C/N at BER=10^{-4}
Ideal	*NA*	*NA*	19 dB
Case 1	-10dB to +10dB by 1dB step	21	20.2 dB
Case 2	-10dB to +10dB by 2dB step	11	20.2 dB
Case 3	-10dB to +10dB by 5dB step	5	21.8 dB

Figure 10 shows the BER performances at the downlink $(C/N)_{dw}$=20dB both for the conventional SC transmission method and OFDM-IDAR method when changing IBO of satellite TWTA. The IBO of transmit earth station SSPA is fixed by -3dB. In the figure, BER performances when assuming the ideal characteristics of SSPA and TWTA for IDAR method are also shown.

Here, the downlink $(C/N)_{dw}$ is defined by using the desired signal power at the output of satellite TWTA of which IBO is 0dB. In this definition of $(C/N)_{dw}$, the actual received C/N at the receive earth station would be changed from the given $(C/N)_{dw}$ according to the IBO of TWTA. The power of inter-modulation noise could be improved as decreasing IBO of TWTA while the desired signal power at the output of TWTA would be reduced. In other words, there is the trade-off between the inter-modulation noise power and the desired signal power according to the value of TWTA IBO. Therefore, the best BER performance could be achieved at the optimum value of TWTA IBO, which is compromised of them. The definition of C/N assumed here is based on the actual satellite communications systems, which are taken into account the desired signal power at the output of non-linear amplifier, and can evaluate the usage of power efficiency of non-linear amplifier.

From the figure, it can be observed that the OFDM-IDAR with proposed estimation method has the optimum TWTA IBO at -4dB, which can achieve the best BER performance, while the optimum TWTA IBO for the conventional SC transmission method is around -8dB. It can be also seen that the proposed method at the optimum TWTA IBO shows much better BER performance than that for the conventional SC method. In other words, the proposed OFDM-IDAR method can operate at the higher TWTA IBO with keeping the better BER performance than that for the conventional SC modulation method. From these results, it can be concluded that the proposed OFDM-IDAR method can achieve the higher usage of non-linear amplifier with keeping the better BER performance.

Figure 11 shows the BER performances both for the conventional SC and OFDM-IDAR methods when changing the downlink $(C/N)_{dw}$. In the simulation, the optimum IBO for satellite TWTA are taken by -4dB and -8dB for the proposed and conventional SC methods, respectively based on the results of Fig.10. The IBO of earth station SSPA is fixed by -3dB. From the figure, it can be observed that the OFDM-IDAR with the proposed estimation method shows slightly higher BER performance than that for the ideal estimation method. However, the proposed method can achieve much better BER performance than that for the conventional SC transmission method. From these results, it can be concluded that the proposed OFDM-IDAR with the estimation method for non-linear amplifier characteristics can achieve the higher transmission data rate with keeping the better BER performance than that for the conventional SC transmission method in the non-linear satellite channel.

5.2 BER Performance of OFDM-IDAR Method

Figure 9 shows the BER performances of OFDM-IDAR with proposed estimation method when changing the number of iterations of IDAR method. In the

figure, BER performance when assuming the ideal characteristics of SSPA and TWTA are also shown as comparing with the proposed estimation method using Case 2. The IBO for the SSPA and TWTA are taken by -3dB and -4dB, respectively. From the figure, it can be observed that the BER performance of OFDM-IDAR with the proposed estimation method is slightly degraded as compared with the ideal case. It can be also observed that the BER performances for the proposed methods at $(C/N)_{dw}$ =20dB are converged when the number of iterations is taken larger than 6. From these results, the following simulations for OFDM-IDAR method are assumed to use 6 as the iteration number for the IDAR method.

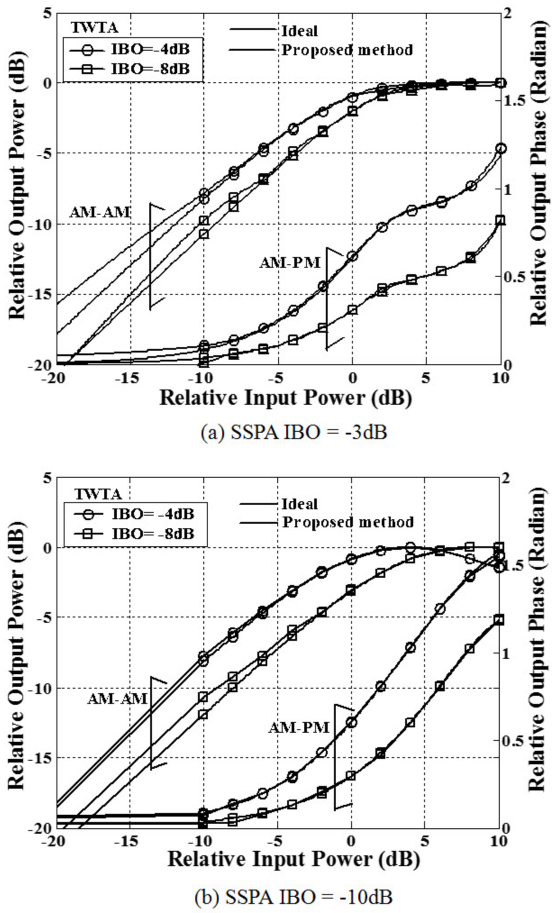


Fig.8: *Estimation accuracy of composite characteristics of SSPA and TWTA.*

Figure 10 shows the BER performances at the downlink $(C/N)_{dw}$ =20dB both for the conventional SC transmission method and OFDM-IDAR method when changing IBO of satellite TWTA. The IBO of transmit earth station SSPA is fixed by -3dB. In the figure, BER performances when assuming the ideal characteristics of SSPA and TWTA for IDAR method are also shown.

Here, the downlink $(C/N)_{dw}$ is defined by using the desired signal power at the output of satellite TWTA of which IBO is 0dB. In this definition of $(C/N)_{dw}$, the actual received C/N at the receive earth station would be changed from the given $(C/N)_{dw}$ according to the IBO of TWTA. The power of inter-modulation noise could be improved as decreasing IBO of TWTA while the desired signal power at the output of TWTA would be reduced. In other words, there is the trade-off between the inter-modulation noise power and the desired signal power according to the value of TWTA IBO. Therefore, the best BER performance could be achieved at the optimum value of TWTA IBO, which is compromised of them. The definition of C/N assumed here is based on the actual satellite communications systems, which are taken into account the desired signal power at the output of non-linear amplifier, and can evaluate the usage of power efficiency of non-linear amplifier.

From the figure, it can be observed that the OFDM-IDAR with proposed estimation method has the optimum TWTA IBO at -4dB, which can achieve the best BER performance, while the optimum TWTA IBO for the conventional SC transmission method is around -8dB. It can be also seen that the proposed method at the optimum TWTA IBO shows much better BER performance than that for the conventional SC method. In other words, the proposed OFDM-IDAR method can operate at the higher TWTA IBO with keeping the better BER performance than that for the conventional SC modulation method. From these results, it can be concluded that the proposed OFDM-IDAR method can achieve the higher usage of non-linear amplifier with keeping the better BER performance.

Figure 11 shows the BER performances both for the conventional SC and OFDM-IDAR methods when changing the downlink $(C/N)_{dw}$. In the simulation, the optimum IBO for satellite TWTA are taken by -4dB and -8dB for the proposed and conventional SC methods, respectively based on the results of Fig.10. The IBO of earth station SSPA is fixed by -3dB. From the figure, it can be observed that the OFDM-IDAR with the proposed estimation method shows slightly higher BER performance than that for the ideal estimation method. However, the proposed method can achieve much better BER performance than that for the conventional SC transmission method. From these results, it can be concluded that the proposed OFDM-IDAR with the estimation method for non-linear amplifier characteristics can achieve the higher transmission data rate with keeping the better BER performance than that for the conventional SC transmission method in the non-linear satellite channel.

6. CONCLUSIONS

This paper proposed the broadband satellite communication systems by using multi-level QAM-OFDM technique with IDAR method designed for satellite channel. This paper also proposed estima-

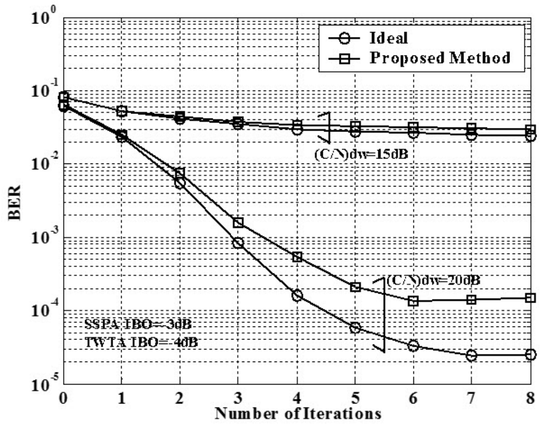


Fig.9: *BER performance versus number of iterations.*

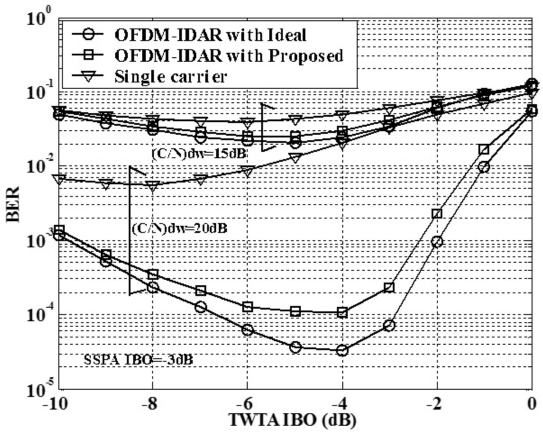


Fig.10: *BER performance versus IBO.*

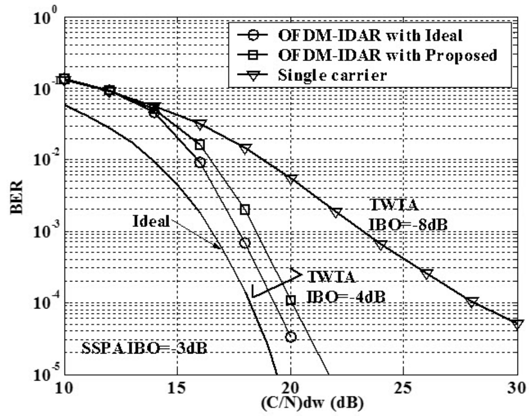


Fig.11: *BER performance versus downlink C/N when IBO is selected by optimum.*

tion method for non-linear satellite amplifiers by using the low PAPR preamble symbols, which is required for the IDAR method. From the computer simulation results, we confirmed that the proposed estimation method for non-linear amplifier characteristics can achieve the better accuracy and can be used in the IDAR method. We also confirmed that the OFDM-IDAR system with the proposed estimation method shows much better BER performance than that for the conventional single carrier transmission method in the non-linear satellite channel. From these results, it could be concluded that the proposed multi-level QAM-OFDM technique with IDAR method can be used in the fixed and broadcasting satellite systems to provide the multimedia broadband satellite services with keeping the better BER performance. This paper presented the evaluation results only in the AWGN channel assuming the fixed and broadcasting satellite systems. The proposed method could achieve the better BER performance even for the mobile satellite systems including multipath fading, because the proposed method is based on the OFDM technique.

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