

# Mitigation of Non-linear Distortion Using PTS and IDAR Method for Multi-Level QAM-OFDM System

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## ABSTRACT

The future satellite communication systems are required to support the higher transmission data rate for providing the multimedia services by employing the efficient modulation method such as multi-level QAM. The employment of single carrier transmission with multi-level QAM 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, we have proposed the multi-level QAM-OFDM technique with IDAR (Improved Decision Aided Reconstruction) method designed for non-linear satellite channel. However, the proposed method could not mitigate the non-linear distortion sufficiently when modulation level becomes higher such as 64QAM. This paper proposes the combined scheme of partial transmission sequence (PTS) and OFDM-IDAR methods so as to enable the usage of higher multi-level QAM method, which can achieve the higher transmission data rate with keeping the better bit error rate performance in the non-linear satellite channel. The various computer simulations are conducted in this paper to verify the effectiveness of proposed method in the non-linear satellite channel.

**Keywords:** PAPR, Satellite channel, PTS, IDAR, QAM.

## 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. To realize the higher data rate transmission in the satellite channel, it is required to employ the efficient modulation method such as multi-level QAM [1]. However, the employment of conventional single carrier trans-

mission with multi-level QAM would cause the fatal degradation of signal quality due to the intermodulation noise incurred at the non-linear amplifiers located at the earth station and satellite. From this reason, the current satellite communications are usually limited by low transmission data rate with employing QPSK method, which has the robustness to the non-linear distortion because of its better PAPR (Peak to averaged power ratio) performance as compared with the multi-level QAM.

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 transmitter and receiver. One of the disadvantages of using the OFDM is that its time domain signal has the larger PAPR, which causes the degradation of BER performance in the non-linear amplifier [2]. From this reason, the OFDM has been also 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 of transmitter and receiver. To solve PAPR problem in the OFDM scheme, we proposed the OFDM-IDAR (Improved Decision Aided Reconstruction) method, which can mitigate the non-linear distortion and achieve the higher transmission data rate with keeping the better BER performance even in the satellite channel [3][4]. The feature of proposed OFDM-IDAR method is to reconstruct the non-linear distortion by using the decision data at the receiver. However, the proposed OFDM-IDAR method has some limitation on the usage of higher level of modulation method such as 64QAM because its higher level of modulation method causes a lot of decision error due to the non-linear amplifier and IDAR method could no more mitigate the non-linear distortion sufficiently. To reduce the non-linear distortion, it is required to improve the PAPR performance as much as possible for the OFDM signal at the transmission side. If the PAPR performance of the transmitting OFDM signal can be improved somehow at the transmission side, the non-

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linear distortion can be reduced and IDAR method could achieve the better BER performance even when the higher level of modulation method is employed in the satellite channel. In this paper we propose the OFDM-IDAR method in conjunction with the PAPR reduction method, which allows the employment of higher level of modulation method in the non-linear satellite channel.

In this paper, Section 2 firstly presents the satellite system model including the non-linear amplifiers at the earth station and satellite. Section 3 presents the partial transmission sequence (PTS) method as the PAPR reduction method at the transmit earth station and presents the IDAR method as the mitigation method of non-linear distortion at the receive earth station. Section 4 presents the various computer simulation results to verify the effectiveness of proposed OFDM-IDAR with PTS method in the non-linear satellite channel, and Section 5 draws some conclusions.

## 2. SATELLITE SYSTEM MODEL

Figure 1 shows the typical satellite system model assumed in the following evaluations. In this paper, the non-linear amplifier for the earth station is assumed to use the Solid State Power Amplifier (SSPA), which is modelled by Rapp [5]. The AM-AM and AM-PM conversions characteristics of SSPA modelled by Rapp are given by the following equations, respectively.

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

$$\Phi_E(\rho) = \alpha_\phi \left(\frac{\nu\rho}{A_0}\right)^4 \quad (2)$$

where,  $F_E(\rho)$  and  $\Phi_E(\rho)$  show the AM-AM and AM-PM conversion characteristics of SSPA, respectively, and  $\rho$  is the amplitude of input signal,  $\nu$  is the gain factor,  $A_0$  is the saturated output level,  $p$  is the parameter to decide the non-linear level and  $\alpha_\phi$  is phase displacement. In the following evaluations, the values for these parameters are assumed by  $A_0 = 1$ ,  $\nu = 1$ ,  $p = 6$  and  $\alpha_\phi = 0.025$ , which can approximate the standard characteristics of SSPA employed at the transmit earth station [3]. The non-linear amplifier assumed for the satellite station is assumed to use the TWTA, which is modelled by Saleh [6]. The AM-AM and AM-PM characteristics of TWTA modelled by Saleh are given by the following equations, respectively.

$$F_S(\gamma) = \frac{\alpha_a\gamma}{(1 + \beta_a\gamma^2)} \quad (3)$$

$$\Phi_S(\gamma) = \frac{\alpha_\theta\gamma}{(1 + \beta_\theta\gamma^2)} \quad (4)$$

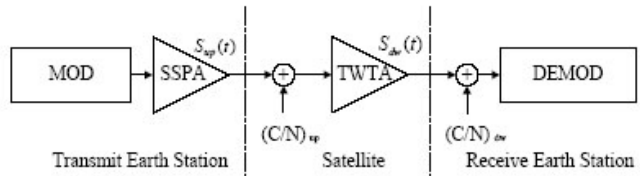


Fig.1: Satellite system model

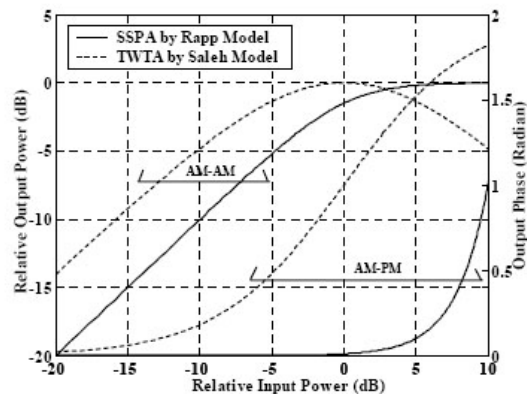


Fig.2: Input and output relationships for SSPA and TWTA.

where,  $\gamma$  is the amplitude of input signal,  $\alpha_a$  and  $\beta_a$  are the parameters to decide the non-linear level, and  $\alpha_\theta$  and  $\beta_\theta$  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 employed at the satellite station [3].

Figure 2 shows the input and output relationships of AM-AM and AM-PM conversions characteristics both for 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.

## 3. PROPOSAL OF OFDM-IDAR WITH PTS METHOD FOR SATELLITE CHANNEL

### 3.1 PAPR Reduction Method at Transmit Earth Station

Up to today, various kinds of PAPR reduction methods for OFDM signal were proposed such as the selected mapping method (SLM) [7] and the partial transmit sequence method (PTS) [7] [8]. Both methods can achieve the better PAPR performance by controlling the phase values of data sub-carriers at the transmitter, although these two methods are required to inform the phase information used for controlling the data sub-carriers to the receiver as the side information. In this paper, we employ the PTS method as the PAPR reduction method at the transmit earth station because the PTS method can achieve the bet-

ter PAPR performance with less complexity of required processing as compared with the SLM method [7]. The following presents the PTS method briefly.

Figure 3 shows the structure of OFDM transmitter with PTS method. In the PTS method, the data information in the frequency domain  $X_n$  is partitioned into  $V$  clusters as  $X_n^{(\nu)}$  ( $1 \leq \nu \leq V$ ). All sub-carriers including each cluster are multiplied by the same phase of  $c_n^{(\nu)} = e^{j\varphi_n^{(\nu)}}$  so as to reduce the PAPR performance. Here, the phase value considered in each cluster is given by the following equation.

$$\varphi_n^{(\nu)} = [0, 2\pi) \quad (1 \leq \nu \leq V) \quad (5)$$

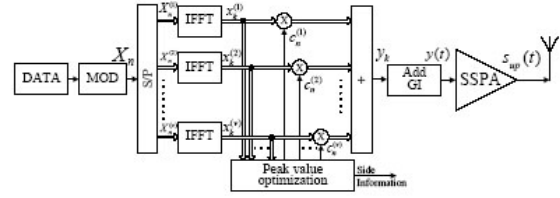
After multiplying the phase value for each cluster, the sub-carrier vector is given by the following equation.

$$Y_n = \sum_{\nu=1}^V c_n^{(\nu)} \cdot X_n^{(\nu)} \quad (6)$$

where, the controlling phases  $c_n^{(\nu)}$  used for all clusters are required to inform the receiver as the side information. The set of phase values for all clusters are optimized in the time domain so as to achieve the better PAPR performance, by using the following equation.

$$\begin{aligned} y_k &= \sum_{\nu=1}^V c_n^{(\nu)} \cdot IFFT \left\{ X_n^{(\nu)} \right\} \\ &= \sum_{\nu=1}^V c_n^{(\nu)} \cdot x_k^{(\nu)} \end{aligned} \quad (7)$$

From (6) and (7), it can be seen that the controlling phase values can be multiplied either in the frequency or time domains and the results on optimized PAPR performance are the same. Figure 3 shows the case of (7) where the optimization of phase value is performed in the time domain. In the PTS method, the better PAPR performance could be achieved, if phase value of  $c_n^{(\nu)}$  is chosen with continuous phase as given in (5), although the size of side information to be transmitted to the receiver would be increased. Since the side information is required to inform the receiver by using the data channel with the high signal quality, the larger size of side information would cause the degradation of system efficiency relatively. To solve this problem, the fixed number of discrete phase value is employed in this paper to reduce the size of side information, although the PAPR performance would be degraded slightly [7] as compared with that for using the continuous phase values. In this paper, we assume four discrete phase values as given by the following equation.



**Fig.3:** Structure of OFDM transmitter with PTS method.

$$\varphi_n^{(\nu)} \in \{0, \pi/2, \pi, 3\pi/2\} \quad (1 \leq \nu \leq V) \quad (8)$$

After optimization of phase value for each cluster, the time domain signal after adding the guard interval (GI) is converted to the uplink radio frequency and input to non-linear amplifier of SSPA. The output signal of SSPA, which corresponds to the uplink signal in the radio frequency, can be given by the following equation.

$$s_{up}(t) = F_E [|y(t)|] \cdot e^{j[\arg\{y(t)\} + \Phi_E\{|y(t)|\}]} \quad (9)$$

where,  $y(t)$  is the OFDM signal at the input of SSPA,  $F_E[\cdot]$  and  $\Phi_E[\cdot]$  represent the AM-AM and AM-PM conversions characteristics of non-linear amplifier given by (1) and (2), respectively. The output signal of SSPA given by (9) is transmitted to the satellite and then input to the satellite TWTA after converting from the uplink to downlink radio frequency. The output signal of TWTA, which corresponds to the downlink signal in the radio frequency, is given by the following equation.

$$s_{dw}(t) = F_S [|s_{up}(t)|] \cdot e^{j[\arg\{s_{up}(t)\} + \Phi_S\{|s_{up}(t)|\}]} \quad (10)$$

The receive earth station demodulates the data information from (10) by using the IDAR method, which is presented in the next section.

### 3.2 OFDM-IDAR Method for Satellite Channel

Figure 4 shows the structure of proposed OFDM-IDAR receiver with PTS method. In Fig.4, the received RF signal  $r_t$  is first down converted to the base band signal and digitized by A/D converter. The received time domain sampled signal after removing the guard interval (GI) is given by the following equation.

$$\begin{aligned} r_k &= s_{dw,k} + w_k \\ &= y_k + i_k + w_k \end{aligned} \quad (11)$$

where,  $s_{dw,k}$ ,  $w_k$  and  $i_k$  represent the output signal of TWTA, additive noise in the downlink, and inter-modulation noise on the k-th time domain sampled

signal, respectively. In (11),  $y_k$  is the desired signal in the time domain of which phase is optimized by PTS method at the transmit earth station. Here, the inter-modulation noise is assumed to add the desired signal  $y_k$  linearly. It should be noted that inter-modulation noise at the output of non-linear amplifier is unable to express separately as given in (11), because it is strongly related to the desired signal  $y_k$ . However, the inter-modulation noise is reconstructed separately in the IDAR method by using the decision data at the receiver. Although it is inappropriate to express the inter-modulation noise separately, (11) is given here just as the assumption so as to explain the following IDAR algorithm clearly. The received time domain sampled signal given (11) is converted to the frequency domain signal by FFT, which is given by the following equation.

$$R_n = Y_n + I_n + W_n \quad (12)$$

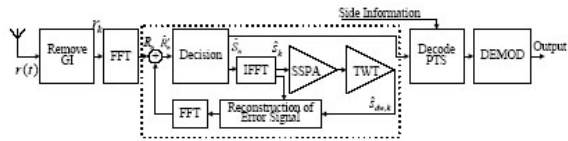
where, the capital letter represents the frequency domain signal, which corresponds to its small letter given by (11) in the time domain. The decision for (12) can be made by using the following equation.

$$\hat{Y}_n = \min_n |R_n - X_n| \quad (13)$$

where  $\hat{Y}_n$  is the decision data at the  $n$ -th sub-carrier. Here, it should be noted that the decision data  $\hat{Y}_n$  is not the transmitted information data  $X_n$ , because it includes the controlled phase value optimized by the PTS method as in (6). Since all the discrete phase values used in the PTS method are the factor of  $\pi/2$ , the decision can be made on the basis of (13), although the decision data is not directly correspondent to  $X_n$ .

The decision data in the frequency domain is converted to the time domain signal  $\hat{y}_k$  by IFFT, which corresponds to the reconstructed transmitted time domain signal. In the IDAR method, the time domain signal  $\hat{y}_k$  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 [4]. From this reason, the inter-modulation noise can be reconstructed by using the decision data in the time domain.

By using the time domain signal  $\hat{y}_k$ , the output time domain signal of SSPA and TWTA can be reconstructed by using the same manner as processed at the earth station and satellite. In the IDAR method, the operations of non-linear amplifiers both for the SSPA and TWTA are conducted on the digital sampled data by assuming the same AM-AM and AM-PM conversion characteristics as that operated in the



**Fig.4:** Structure of receiver with proposed OFDM-IDAR with PTS method.

radio frequency. The time domain signal at the output of SSPA and TWTA as shown in Fig.4 is given by the following equation.

$$\hat{s}_{dw,k} = F_P [|\hat{y}_k|] \cdot e^{j\{arg(\hat{y}_k) + \Phi_P(|\hat{y}_k|)\}} \quad (14)$$

where,  $\hat{y}_k$  is the time domain signal converted from the frequency domain decision data given in (13),  $F_P$  and  $\Phi_P$  are the AM-AM and AM-PM conversions characteristics which is the composite characteristics of SSPA and TWTA. This paper assumes that the composite characteristics of SSPA and TWTA are known at the receiver. By using (14), the inter-modulation noises incurred at the SSPA and TWTA can be estimated by the following equation.

$$\begin{aligned} \hat{e}_k &= \hat{s}_{dw,k} - \hat{y}_k \\ &\approx \hat{y}_k + \hat{i}_k - \hat{y}_k \\ &\approx \hat{i}_k \end{aligned} \quad (15)$$

The inter-modulation noise given by (15) is then converted to the frequency domain signal  $\hat{E}_n$  by FFT. By subtracting the reconstructed inter-modulation noise  $\hat{E}_n$  from (12), the frequency domain signal coped with the inter-modulation noise can be obtained by the following equation.

$$\begin{aligned} \hat{R}'_n &= R_n - \hat{E}_n \\ &= Y_n + \{I_n - \hat{I}_n\} + W_n \\ &\approx Y_n + W_n \end{aligned} \quad (16)$$

The above procedures are repeated until the better performance can be achieved in the IDAR method. Finally, the data information for each sub-carrier can be obtained by decoding the PTS, which is given by the following equation.

$$X_n = \sum_{\nu=1}^V \{c_n^{(\nu)}\}^* \cdot \hat{Y}_n^{(\nu)} \quad (17)$$

where,  $*$  is the complex conjugate and  $c_n^{(\nu)}$  is the controlled phase by PTS at the transmitter. These phase values are known at the receiver, because they are informed to the receiver as the side information.

**Table 1:** *Simulation parameters*

Allocated bandwidth	26MHz
Modulation method	64QAM
Detection method	Coherent
Number of FFT points	512
Number of sub-carriers	128
Symbol duration	4.92us
Guard interval	0.5us
Transmission data rate	141.6 Mbit/s
Non-linear amplifier	
Earth station	SSPA
Satellite station	TWTA

#### 4. PERFORMANCE EVALUATIONS

This section presents the various computer simulation results to demonstrate the performance of OFDM-IDAR with PTS method in non-linear satellite channel. Table 1 shows the list of simulation parameters used in the following computer simulations. In the following simulations, the side information for PTS is assumed to be informed to the receiver ideally. The modulation method is 64QAM and its demodulation method is the coherent detection.

In the following evaluation, the up-link C/N is assumed to be the noise free condition and only the downlink noise is added to the received signal. The IBO for the earth station amplifier of SSPA is fixed by -3dB. The downlink C/N is defined by using the desired signal power at the output of satellite non-linear amplifier of TWTA at IBO=0dB. In this definition of C/N, the actual C/N for the signal at the receive earth station would be changed from the given C/N according to the IBO of TWTA. In other words, the power of inter-modulation noise could be reduced as decreasing IBO while the desired signal power at the output of amplifier would be reduced.

Figure 5 shows the PAPR performance when changing the number of clusters for the PTS method at the transmit earth station. The number of discrete phase values is assumed by four kinds of phases 0, and  $3/2$ , which requires 2 bits for each cluster as the side information. In the figure, the PAPR performance is evaluated by using the Cumulative Distribution Function (CDF). From the figure, it can be seen that the PAPR performance for the PTS method can be improved relatively as compared with the conventional OFDM signal, especially when increasing the number of clusters.

Figure 6 shows the BER performances when changing the number of iteration in the IDAR method. The IBOs for satellite TWTA are taken by -4, -6 and -8dB respectively. The number of clusters for the PTS method is 4 and the downlink C/N is 25dB. From the figure, it can be observed that the proposed OFDM-IDAR with PTS method can

achieve the better BER performance than that for the conventional IDAR method when comparing at the same iteration number.

Figure 7 shows the BER performances when changing the number of iteration for the IDAR method. In the simulation, the IBOs for earth station SSPA and satellite TWTA are taken by -3dB and -6dB, respectively and the downlink C/N is 28dB. From the figure, it can be observed that the proposed OFDM-IDAR with PTS method can achieve much better BER performance than that for the OFDM-IDAR method. It can be also observed that the BER performance of proposed method is converged when the number of iterations is taken larger than 8. From these results, the following evaluations for proposed OFDM-IDAR with PTS method are assumed to use 8 as the IDAR iteration number.

Figure 8 shows the BER performances when changing the IBO for satellite TWTA. In the simulations, the IBO for the earth station SSPA is fixed by -3dB. The downlink C/N is defined by using the desired signal power at the output of satellite non-linear amplifier of TWTA at IBO=0dB. In this definition of C/N, the power of inter-modulation noise could be reduced 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 IBO, which is compromised of them. The definition of C/N assumed here is based on the actual satellite communications systems, which is 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 Fig. 8, it can be observed that the OFDM-IDAR with PTS method has the optimum IBO at -6dB, which can achieve the best BER performance, while the optimum IBO for the conventional OFDM-IDAR method is around -8dB. It can be also seen that the proposed method at the optimum IBO shows much better BER performance than that for the conventional method. In other words, the proposed OFDM-IDAR with PTS method can operate at the higher IBO with keeping the better BER performance than the conventional method. From these results, it can be concluded that the proposed OFDM-IDAR with PTS method can achieve the higher efficient usage of non-linear amplifier with keeping the better BER performance.

Figure 9 shows the BER performances for the conventional OFDM-PTS, OFDM-IDAR and the proposed OFDM-IDAR with PTS methods when changing the IBO of TWTA and the downlink C/N. From the figure, it can be observed that the proposed method can achieve much better BER performance than that for the conventional PTS and IDAR meth-

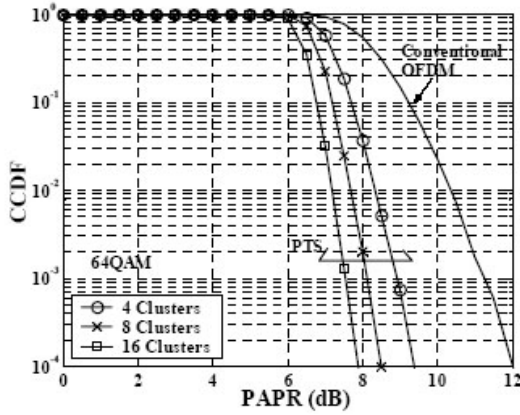


Fig. 5: PAPR performance.

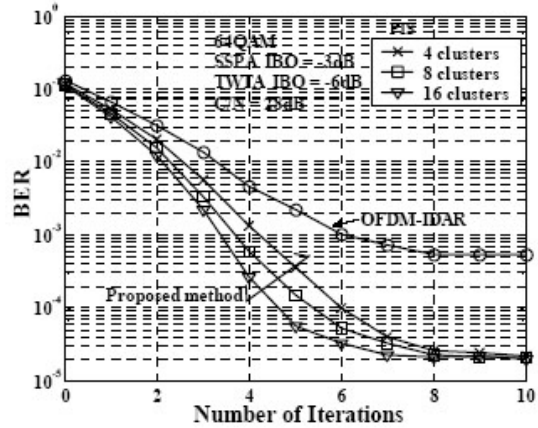


Fig. 7: BER vs. number of iterations for IDAR.

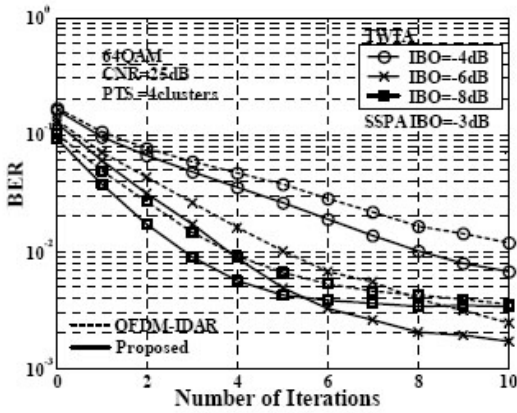


Fig. 6: BER performance vs. number of iterations for IDAR.

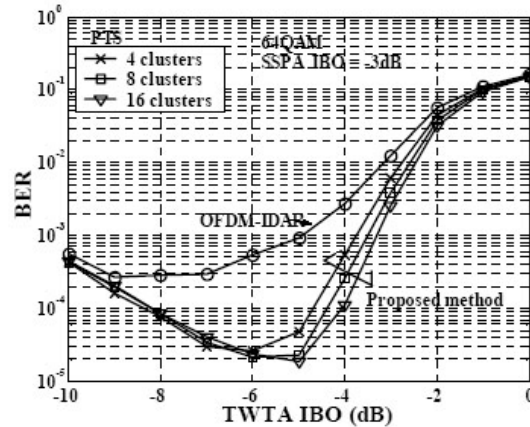


Fig. 8: BER performance vs. IBO of TWTA.

ods of which BER performances have error floor at the higher C/N. From the figure, it can be also observed that the OFDM-IDAR with PTS method shows much better BER performance than that for others conventional methods. From these results, it can be concluded that the proposed OFDM-IDAR with PTS method could achieve the higher transmission data rate with keeping the better BER performance in the non-linear satellite channel.

This paper proposed the OFDM-IDAR with PTS method, which can reduce the PAPR performance at the transmitter by PTS and can mitigate the non-linear distortion at the receiver by IDAR, respectively. This paper presented various computer simulation results to verify the effectiveness of proposed method. From the computer simulation results, we confirmed that the proposed method could achieve the higher transmission data rate with keeping the better BER performance in the non-linear satellite channel.

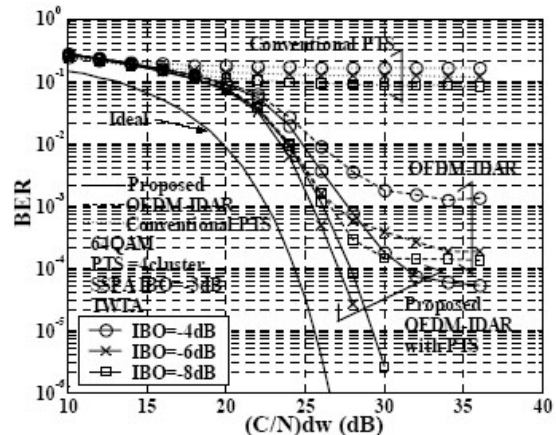


Fig. 9: BER performance vs. C/N.

## 5. CONCLUSIONS

This paper proposed the OFDM-IDAR with PTS method, which can reduce the PAPR performance at the transmitter by PTS and can mitigate the non-linear distortion at the receiver by IDAR, respectively. This paper presented various computer simulation results to verify the effectiveness of proposed method. From the computer simulation results, we confirmed that the proposed method could achieve the higher transmission data rate with keeping the better BER performance in the non-linear satellite channel.

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### References

- [1] C.E. Dimakis, S.S. Kouris and S.A. Kosmopoulos, "Performance evaluation of 16-QAM signaling through nonlinear channel in an AWGN and interference environment: a simulation approach," *IEE Proc.*, Vol. 137, No. 5, pp. 315-322, Oct. 1990.
- [2] D Dardari, V. Tralli and A Vaccari, "A theoretical characterization of nonlinear distortion effects in OFDM systems," *IEEE Trans. on Comm.*, Vol. 48, No. 10, pp. 1775-1764, Oct. 2000.
- [3] P. Boonsrimuang, K. Mori, T. Paungma and H. Kobayashi, "Employment of QAM-OFDM technique in satellite Channel," *Technical Report of IEICE*, Vol. SAT2004-98, pp. 21-23, July 2004.
- [4] P. Boonsrimuang, K. Mori, H. Kobayashi and T. Paungma, "Proposal of clipping and intermodulation noise mitigation method for OFDM signal in non-linear channel," *IEICE Trans. Commun.*, Vol. E88-B, No. 2, pp. 427-435, Feb. 2005.
- [5] C. Rapp, "Effects of HPA-nonlinearity on a 4-DPSK/OFDM-signal for a digital sound broadcasting system," *Proceedings of the Second European Conference on Satellite Communications*, Liege, Belgium, pp. 179-184, Oct. 22-24, 1991.
- [6] A. A. M. Saleh, "Frequency independent and frequency dependent nonlinear model of TWT amplifiers," *IEEE Trans. Commun.*, Vol. COM-29, pp. 1715-1720, Nov. 1981.
- [7] S. H. Muller and J. B. Huber, "OFDM with reduce peak-to-average power ratio by optimum combination of partial transmit sequences," *Electron. Lett.*, Vol. 33, No. 5, pp. 368-369, Feb. 1997.
- [8] S. H. Muller and J. B. Huber, "A comparison of peak power reduction methods for OFDM," *GLOBECOM '97*, Nov 1997, Arizona, USA.



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