SUMMARY One of the disadvantages of using OFDM is the larger peak to averaged power ratio (PAPR) of the time domain signal as compared with the conventional single carrier transmission method. The OFDM signal with larger PAPR will cause the undesirable spectrum re-growth and the larger degradation of bit error rate (BER) performance both due to the inter-modulation products occurring in the non-linear amplifier at the transmitter. The clipping method in conjunction with the Decision Aided Reconstruction (DAR) method is well known as one of the solutions to improve the BER performance with keeping the better PAPR performance. However, the DAR method is proposed to mitigate only the clipping noise and not for the inter-modulation noise. In this paper, we propose the improved DAR (IDAR) method, which can mitigate both the clipping noise and inter-modulation noise on the basis of DAR method. The proposed method enables the efficient usage of transmission power amplifier at the transmitter with keeping the better PAPR and BER performances. This paper presents various computer simulation results to verify the performance of proposed IDAR method in the non-linear channel.

key words: OFDM, non-linear channel, PAPR, clipping, DAR, IDAR

1. Introduction

The orthogonal frequency division multiplexing (OFDM) technique has been received a lot of attentions especially in the field of wireless communications because of its efficient usage of frequency bandwidth and robustness to the multi-path fading [1], [2]. From these advantages, the OFDM technique has already been adopted as the standard transmission technique in the wireless LAN systems and the terrestrial digital broadcasting systems [3]–[5]. The OFDM is also considering as one of the candidate transmission techniques for the next generation of mobile communications systems [6].

One of the disadvantages of using the OFDM signal is that its time domain signal has the larger peak to averaged power ratio (PAPR) as compared with the conventional single carrier modulation method [7]. The larger PAPR would cause the undesirable spectrum re-growth and the degradation of bit error rate (BER) performance both from the inter-modulation products occurring at the non-linear amplifier at the transmitter.

To overcome the above problem, a clipping method was proposed to improve the PAPR performance of OFDM signal [7]. Although this method can improve the PAPR performance relatively, the BER performance would be degraded at the receiver due to the clipping noise. The Decision-Aided Reconstruction (DAR) method was proposed to mitigate the clipping noise with keeping the better PAPR performance [8]. However, the DAR method was proposed on the assumption that the number of IFFT points is equal to the number of sub-carriers, that is the ideal Nyquist sampling frequency. The number of IFFT points is however required to be larger than the number of sub-carriers because of zero padding, which enables the usage of simple analogue filter to reject the aliasing occurring at the D/A converter. From this fact, the DAR method proposed in [8] is unable to employ in the actual OFDM system. To solve this problem, we proposed modified DAR method of using pre-filter, which can apply the actual OFDM system operating at the over sampling frequency [9]. The feature of proposed method is that the error signal due to the clipping noise is reconstructed by using the frequency domain signal instead of using the received time domain signal proposed in [8]. By using the frequency domain signal in the reconstruction of error signal, it is possible to compensate the distortion error due to the band limitation of pre-filter.

These DAR methods including the modified DAR method can only mitigate the clipping noise and not for the inter-modulation noise due to the non-linear amplifier. The BER performance would be degraded severely when the input back-off (IBO) of non-linear amplifier is taken at near to the saturation region, even though the PAPR performance is improved relatively by using the clipping method. The simple method to reduce the inter-modulation products is to set the IBO at the linear region. However, this method degrades the power efficiency of non-linear amplifier, and has serious problem on battery consumption especially for the cases of mobile terminal and portable wireless LAN terminal. In order to maximize the power efficiency of the transmitter, the non-linear amplifier is typically forced to work at near its saturation region, which will lead to the degradation of BER performance due to the inevitably high non-linearity.

In this paper, we propose the improved DAR (IDAR) method [10] in which the clipping noise as well as inter-modulation noise due to the non-linear amplifier could be mitigated on the basis of modified DAR method in [9]. The salient feature of proposed method is to enable the efficient...
usage of non-linear amplifier at the transmitter with keeping the better PAPR and BER performances. This paper also presents the method for generating the low PAPR preamble symbol, which can achieve the accurate estimation of multi-path fading channel response in the non-linear channel.

In the following of this paper, Section 2 presents the structure of OFDM transmitter with clipping method for the over sampling signal. Section 3 presents the proposed IDAR method including the method for generating the low PAPR preamble symbol. Section 4 presents the various computer simulation results to verify the performance of proposed IDAR method, and Section 5 concludes the paper.

2. Structure of OFDM Transmitter

Figure 1 shows the structure of OFDM transmitter with clipping method. In the figure, transmission data is first modulated in the frequency domain by using the certain modulation technique. The frequency domain signal \( X_n \) after adding the zero padding is converted to the time domain signal \( x_k \) by IFFT. Here, the zero padding is usually required to enable the usage of simple analogue filter to reject the aliasing occurring at the D/A converter. Then, the analogue signal is converted to the time domain signal with GI is clipped by the following equation so as to improve the PAPR performance.

\[
x_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j \frac{2\pi n k}{N}}
\]

(1)

where, \( N \) is the number of IFFT points which is larger than the number of sub-carriers \( M \), and the difference of \( N \) and \( M \) correspond to the number of zero padding. Then the guard interval (GI) is added to (1) to avoid the inter symbol interference (ISI) in the multi-path fading channel. The time domain signal with GI is clipped by the following equation so as to improve the PAPR performance.

\[
y_k = \begin{cases} 
  x_k & |x_k| \leq A \\
  A e^{j \arg(x_k)} & |x_k| > A 
\end{cases}
\]

(2)

where, \( y_k \) is the clipped signal with the maximum amplitude of \( A \). In this paper, the clipping level (CL) is defined by the following equation.

\[
CL (\text{dB}) = 10 \log(A^2 / E_s)
\]

(3)

where, \( E_s \) is the averaged power of transmitted signal.

Since the clipping operation given by (2) is the non-linear operation, the clipping noise would fall both in-band and out-band of OFDM desired signal bandwidth, which cause the degradation of BER performance and the undesirable spectrum re-growth, respectively. Although the undesirable spectrum re-growth can be reduced by using the pre-filter as shown in Fig. 1, the PAPR performance at the output of pre-filter might be degraded slightly due to the band limitation of pre-filter. The PAPR performance for the clipped signal with pre-filter is evaluated in Section 4. The employment of pre-filter is also problematic on the usage of conventional DAR method proposed in [8]. In the DAR method, the clipping noise is reconstructed by using the received time domain signal, which is distorted by the band limitation of pre-filter. To solve this problem, we proposed the modified DAR method [9] by using the in-band frequency domain signal, which is not affected by the pre-filter because the bandwidth of pre-filter is wider than the desired OFDM signal bandwidth.

The transmission data symbols at the output of pre-filter are formed by the burst frame as shown in Fig. 2. The burst frame consists of two preamble symbols and L data symbols. Two preamble symbols will be used for the synchronization both for the symbol timing and carrier frequency, and the estimation of channel frequency response at the receiver. This paper considers the wireless LAN systems operating in the indoor environments as one of the application fields for the proposed method. In the indoor environment, the multi-path fading can be usually modeled by the quasi-static condition that is, the time variance of channel frequency response is sufficiently slow over one burst frame duration because the moving speed of terminal can be considered as the static or very slow.

From this fact, the channel frequency response estimated by using the preamble symbols inserted at the start of every burst frame as shown in Fig. 2 can be used in the frequency domain equalization for the data symbols transmitted after the preamble symbols. The time domain signal formatted by the burst frame is converted to the analogue signal by D/A converter and reject the aliasing by using analogue filter as shown in Fig. 1. Then, the analogue signal is up converted (U/C) to the radio frequency (RF) and input to the non-linear amplifier. The RF signal at the output of non-linear amplifier can be given by the following equation.

\[
z(t) = A \sin(2\pi f t + \phi)
\]
\[ s(t) = F[|z(t)|] \cdot e^{i \arg(z(t))} \]  
\[ F[\rho] = \frac{\rho}{1 + (\rho/Bq)^{1/2q}} \]  
where, \( z(t) \) is the up converted RF signal, and \( F[\cdot] \) represents the AM/AM conversion characteristics of non-linear amplifier which is modeled by the following equation [7].

where, \( z(t) \) is the up converted RF signal, and \( F[\cdot] \) represents the AM/AM conversion characteristics of non-linear amplifier which is modeled by the following equation [7].

\[ F[\rho] = \frac{\rho}{1 + (\rho/Bq)^{1/2q}} \]  
where, \( \rho \) is the amplitude of input signal, \( B \) is the saturated output level, and \( q \) is the parameter to decide the non-linear level that is usually taken by 2 [11]. Figure 3 shows the input-output relative power characteristics when changing the parameter of \( q \). The non-linear amplifier shown in Fig. 3 is well known as the non-linear amplifier model of SSPA (Solid State Power Amplifier). The OFDM signal at the output of amplifier including the original signal \( x(t) \), clipping noise \( c(t) \), band limitation noise \( b(t) \) and the inter-modulation noise \( p(t) \) can be given by the following equation.

\[ s(t) = x(t) + c(t) + b(t) + p(t) \]  
where, all kind of noises which lead the degradation of BER performance at the receiver are assumed to be added to the original desired signal \( x(t) \) linearly. Here, it should be noted that these noises at the output of non-linear amplifier are unable to express separately as given in (6) because these noises are strongly related to the original signal \( x(t) \). However, the Improved DAR method proposed in the next section can estimate the summation of these noises together not separately by subtracting the decision data from the reconstructed signal at the receiver. Although it is inappropriate to express these noises separately, equation (6) is given here just as the assumption so as to explain the following proposed algorithm clearly.

### 3. Proposal of Improved DAR Method

In this section, we propose the improved DAR method, which can mitigate the clipping noise, band limitation noise and inter-modulation noise all of which are occurred at the transmitter as shown in Fig. 1.

#### 3.1 Structure of Proposed IDAR Receiver

Figure 4 shows the structure of proposed IDAR receiver. In the figure, 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 \( r_k \) after removing the GI can be expressed by the following equation.

\[ r_k = (x_k + c_k + b_k + p_k) \otimes h_k + w_k \]  
where, \( x_k \) and \( w_k \) represent the original signal and additive noise in the sampled time domain, respectively. \( c_k \), \( b_k \) and \( p_k \) represent the clipping noise, band limitation noise, and inter-modulation noise, respectively all of which are induced at the transmitter as shown in Fig. 1. \( h_k \) and \( \otimes \) denotes the time domain channel impulse response of multi-path fading and the operation of convolution, respectively. Then, the received sampled time domain signal is converted to the frequency domain signal by FFT, which is given by the following equation.

\[ R_n = (X_n + C_n + P_n) \cdot H_n + W_n \]  
In (8), the capital letter represents the frequency domain signal, which corresponds to its small letter given in (7). As comparing with the time domain signal given in (7), it can be seen the difference in (8) that the frequency domain signal includes no band limitation noise because the bandwidth of pre-filter located at the transmitter is usually taken wider than the desired signal bandwidth of OFDM signal and the amplitude and delay responses of pre-filter can be usually assumed as the flat over the desired signal frequency bandwidth of OFDM signal.

The frequency domain channel response affected by
multi-path fading can be estimated by using the preamble symbols inserted at the starting of every burst frame as shown in Fig. 2. Although the preamble symbols are inserted after the clipping circuit as shown in Fig. 1, the estimation accuracy of channel frequency response would be degraded due to the non-linear amplifier if the preamble symbols is generated by using the random pilot data pattern similar to the data symbol with larger PAPR. To solve this problem, it is requested to use the low PAPR preamble symbols for achieving the accurate estimation of channel response in the non-linear channel.

3.2 Generation of Low PAPR Preamble Symbol

In the generation of low PAPR preamble symbol, this paper employs the Time-Frequency domains swapping algorithm, which was proposed in [12], [13]. This algorithm is proposed to provide the multi-tone signal with low crest factor, which can be used for the measurement of frequency response for the non-linear circuit. By using this algorithm, the phase value for each frequency domain OFDM sub-carrier with keeping the constant amplitude can be optimized so as to minimize the PAPR performance in the time domain signal. Figure 5 shows the envelopes of preamble symbol in the time domain with and without the Time-Frequency domains swapping algorithm. The results of PAPR performances for Figs. 5(a) and (b) are 8 dB and 1.4 dB, respectively. From the figure and the results of PAPR performance, it can be concluded that the low PAPR preamble symbol can be used for the accurate estimation of multi-path fading channel response in the non-linear channel.

From the facts that the low PAPR preamble symbol is added at the output of pre-filter as shown in Fig. 1 and its envelope of time domain signal is almost constant as shown in Fig. 5(b), the received low PAPR preamble symbol in the frequency domain can be given by the following equation.

\[ R_n^p = X_n^p \cdot H_n + W_n^p \] (9)

As comparing with (8) for the data symbol, the clipping noise and inter-modulation noise can be ignored in (9). By using (9), the channel frequency response affected by the multi-path fading can be estimated by the following equation from the fact that \( X_n^p \) transmitted in the low PAPR preamble symbol is known at the receiver.

\[ \hat{H}_n = \frac{R_n^p}{X_n^p} = H_n + \frac{W_n^p}{X_n^p} \] (10)

By using (10), the data symbol can be equalized by the following equation in the frequency domain.

\[ \hat{R}_n = R_n / \hat{H}_n = X_n^p + C_n^p + P_n^p + W_n^p \] (11)

3.3 Mitigation of Clipping and Inter-Modulation Noise

In the conventional modified DAR method in [9], the clipping noise introduced at the transmitter is reconstructed in the frequency domain by using the decision data at the receiver, and subtract the reconstructed clipping noise from the received signal so as to improve the BER performance. However, the modified DAR method can compensate only the clipping noise, and not for the inter-modulation noise in the non-linear channel. This paper proposes the Improved DAR (IDAR) method, which can mitigate both the clipping noise and inter-modulation noise from the fact that the operation of non-linear amplifier given in (4) is very similar to the clipping operation given in (2). This means that the inter-modulation noise could be also mitigated by using the modified DAR method.

By using (11), the decision for the information data is made for each sub-carrier on the basis of the following equation.

\[ \hat{X}_n = \min_x |\hat{R}_n - X| \] (12)

By using (12), the signal distances between the received signal point and all candidates original signal points are calculated, and then find the signal point having the minimum signal distance, which corresponds to the most likely the transmitted data information. Here, it should be noted that (12) is given only for the purpose of theoretical analysis. The actual hardware usually employs the predetermined quantized decision boundary method instead of using (12), which can achieve the same performance as that for (12) with less complexity.

If there are decision errors in (12), the decision data \( \hat{X}_n \) can be expressed by the following equation.

\[ \hat{X}_n = X_n + F_n \]

\[ F_n = \begin{cases} 0 & \text{if } \hat{X}_n = X_n \\ \hat{X}_n - X_n & \text{if } \hat{X}_n \neq X_n \end{cases} \] (13)

where, \( X_n \) and \( F_n \) represent the original information data and error data at the \( n \) th sub-carrier. By using (13) in the frequency domain, the time domain signal after IFFT can be given by the following equation.
\[ \hat{x}_k = \sum_{n=0}^{N-1} X_n \cdot e^{j \frac{2\pi nk}{N}} + \sum_{n=0}^{N-1} F_n \cdot e^{j \frac{2\pi nk}{N}} = x_k + f_k \] (14)

From (14) in the time domain, it can be observed that if the number of error data in the frequency domain \( F_n \) is few, these few error data is spread over the OFDM symbol time duration after IFFT. Therefore, the amplitude level of \( f_k \) at \( k-th \) sampling becomes smaller as compared with \( x_k \) because the few error data in the frequency domain is spread over all the \( N \) sampling points within the OFDM symbol time duration. From this fact, it can be expected that if the number of error data is few after the decision of data information, (14) can be approximated by the original signal \( x_k \) given in (1). This means that the time domain signal which is converted by IFFT from the frequency domain decision data can be used for the reconstruction of error signal including the clipping, band limitation and inter-modulation noises by using the same manner as processed in the transmitter. Here, all the characteristics of clipping operation, pre-filter operation and AM/AM conversion operation of non-linear amplifier used in the following process are assumed to be the same as those for the transmitter as shown in Fig. 1. The clipped signal can be given by the following equation.

\[ \hat{y}_k = \begin{cases} \hat{x}_k & |\hat{x}_k| \leq A \\ Ae^{j \arg(\hat{x}_k)} & |\hat{x}_k| > A \end{cases} \] (15)

The clipped signal is also processed for the same operation of pre-filter and non-linear amplifier at the transmitter. The output signal after the non-linear amplifier operation is given by the following equation.

\[ \hat{s}_k = F[|\hat{x}_k|] \cdot e^{j \arg(\hat{x}_k)} \] (16)

where, \( \hat{s}_k \) is the time domain signal at the output of pre-filter as shown in Fig. 4. Here, it should be noted that the operation of non-linear amplifier in (16) is performed for the digital sampled data by assuming the same AM/AM conversion characteristics as that operated in the radio frequency at the transmitter. Since the time domain signal given by (16) includes the clipping noise, band limitation noise and inter-modulation noise, (16) can be approximated by the following equation.

\[ \hat{s}_k = \hat{s}_k + \hat{c}_k + \hat{b}_k + \hat{p}_k \] (17)

By using (17), the error signal including all types of noises can be given by the following equation.

\[ \hat{e}_k = \hat{s}_k - \hat{s}_k \]
\[ = \hat{c}_k + \hat{b}_k + \hat{p}_k \] (18)

The error signal is then converted to the frequency domain signal by FFT, which is given by the following equation.

\[ \hat{E}_n = \hat{C}_n + \hat{P}_n \] (19)

In (19), the band limitation noise in the frequency domain is not existed in the desired frequency bandwidth of OFDM signal because the bandwidth of pre-filter is taken wider than the desired OFDM signal bandwidth. By subtracting (19) from (11), the frequency domain signal coped with both the clipping noise and inter-modulation noise can be obtained by the following equation.

\[ \hat{R}'_n = \hat{R}_n - \hat{E}_n \]
\[ = X'_n + (C'_n - \hat{C}_n) + (P'_n - \hat{P}_n) + W'_n \]
\[ \approx X'_n + W'_n \] (20)

If the BER performance of (20) is better than that for (11), the BER performance could be improved further by repeating the above procedures from (12) to (20) as shown in Fig. 4. From the fact as mentioned above that the time domain signal given in (14) can be approximated by the original time domain signal given in (1) even when the BER performance of (20) is worse than that for (11), the divergence of BER performance would not occur during the iteration of above procedures. This fact will be also confirmed by the computer simulation results in the next section. The proposed IDAR method on the basis of above procedures could provide the better BER performance even when the non-linear amplifier is operated at the saturation region.

### 4. Performance Evaluation

This section presents the various computer simulation results to verify the performance of proposed IDAR method in the non-linear channel. Table 1 shows the list of simulation parameters used in the performance evaluations. In the following evaluation, the carrier to noise power ratio (C/N) is defined by using the desired signal power at the output of non-linear amplifier at IBO=0 dB. In this definition of C/N, the actual C/N for the received signal would be changed from the given C/N according to the value of IBO. 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. In other words, there is the trade-off between the inter-modulation noise power and the desired signal power according to the value of 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 radio

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<td>Modulation</td>
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communications systems with non-linear amplifier, which is taken into account the desired signal power at the output of non-linear amplifier, and can evaluate the usage of power efficiency for the non-linear amplifier. The modulation method is 16QAM and its demodulation method is the coherent detection with the frequency domain equalization method by using the low PAPR preamble symbols. The multi-path fading is modeled by two delay paths of which power ratio is 10 dB and delay spacing is 0.2 µs. The synchronization of symbol timing and carrier frequency is assumed to be ideal.

Figure 6 shows the PAPR performance at the output of pre-filter as shown in Fig. 1 when changing the clipping level (CL) as defined by (3). Here, the PAPR performance is evaluated by using the Cumulative Distribution Function (CDF). In the simulation, the oversampling ratio is 4 which is defined by the number of IFFT points to the sub-carriers. The pre-filter is assumed by 12th order Butterworth filter with 3 dB-bandwidth of 6 MHz. From the figure, it can be seen that the PAPR performance for the clipped OFDM signal with pre-filter can be improved relatively as decreasing the clipping level (CL) and those performance are much better than that for the conventional OFDM signal without clipping. From the figure, it can be concluded that the PAPR performance can be improved relatively even for the oversampling clipped signal with pre-filter.

Figure 7 shows the amplitude of estimated channel frequency response of multi-path fading when using the conventional and low PAPR preamble symbols in the non-linear channel with IBO of 0 dB. In the figure, the ideal channel response is estimated under the linear channel. The pilot data pattern used in the conventional preamble is the random pattern modulated by BPSK, which is similar to the data symbol with the larger PAPR. From the figure, it can be observed that the estimated channel frequency response using the low PAPR preamble symbol is very close to that for the ideal channel response and its accuracy of estimated channel response for the multi-path fading is much better than that for the conventional preamble symbol.

Figure 8 shows the BER performance for the conventional OFDM method when using the conventional and the low PAPR preamble symbol in the multi-path fading channel with non-linear amplifier. From the figure, it can be observed that the BER performance with the low PAPR preamble symbol is better than that for the conventional one especially when the IBO is set at the saturation region such as 0 dB and −2 dB. The difference of BER performance between them becomes smaller when the IBO is −6 dB because of increasing the linearity of the amplifier. From Figs. 7 and 8, it can be concluded that the low PAPR preamble symbols can achieve the accurate estimation of the channel frequency response and provide the better BER performance even when the non-linear amplifier is operated at the saturation region.

Figure 9 shows the simulation results of BER performances both for the conventional DAR and proposed IDAR methods when changing the clipping level (CL). In Fig. 9, the number of iterations for DAR and IDAR methods is 3 and the channel model is the Additive White Gaussian Noise (AWGN) channel at C/N=20 dB. From the figure, it can be seen that the BER performance of proposed IDAR method is much better than that for the conventional DAR method when IBO is 0 dB and CL is 8 dB. When IBO is 0 dB and CL is 8 dB, the clipping noise is very small and the degradation of BER performance may be dominated by only the intermodulation noise. From this fact, it is clear that the IDAR
method can mitigate the inter-modulation noise relatively even when the non-linear amplifier is operated at the saturation region. While the BER performance of DAR method is degraded severely due to the inter-modulation noise. On the other hand, the IDAR method shows the better BER performance as increasing IBO from $-4\text{ dB}$ to $0\text{ dB}$. This is from that the desired signal power becomes larger at the output of amplifier without the degradation of inter-modulation noise, which is mitigated by IDAR method. From the figure, it can be also observed that the BER performance of IDAR method is degraded drastically when the CL is less than $3\text{ dB}$. This is from that the decision data given by (12) at the first iteration is very erroneous due to the severe clipping, and accordingly it is very hard to reconstruct the error signal precisely. From Fig. 6, it can be seen that the CDF of PAPR performance when CL is $4\text{ dB}$ can be improved by $4\text{ dB}$ at $\text{CDF}=10^{-3}$ as compared with the conventional OFDM without clipping. From these results, the following simulations are assuming to use clipping level of $4\text{ dB}$ both for the DAR and IDAR methods.

Figure 10 shows the BER performance both for the DAR and IDAR methods when changing the number of iterations under the AWGN channel at $C/N=20\text{ dB}$. In the figure, the clipping level is $4\text{ dB}$ taken into account the above results. From the figure, the BER performance of DAR and IDAR methods are converged when the number of iterations is taken larger than 2 and 3, respectively. From the figure, it can be also observed that there is no divergence of BER performance when increasing the number of iterations up to 6. From these results, the following simulations both for DAR and IDAR methods are assuming to use 3 as the iteration number.

Figure 11 shows the BER performances both for the DAR and IDAR methods when changing the IBO. The channel model is AWGN at the various $C/N$. From the figure, it can be seen that the DAR method has the optimum value of IBO at around $-4\text{ dB}$ to $-2\text{ dB}$, which can achieve the best BER performance at the given $C/N$. The optimum IBO can be obtained as the result of compromise between the desired signal power and inter-modulation noise power at the output of non-linear amplifier as described above. As increasing and decreasing IBO from the optimum IBO, the BER performances for both cases become worse due to the increase of inter-modulation noise power and due to the decrease of desired signal power at the output of non-linear amplifier, respectively. As for the IDAR method, the BER performance is almost the same as the DAR method when the IBO is less than $-8\text{ dB}$ where the inter-modulation noise is very small because of linear operation of amplifier. However, the BER performance of IDAR method becomes better as increasing IBO, and the best BER performance is obtained when IBO is around $0\text{ dB}$. When comparing the best performances obtained by the DAR and IDAR methods, the IDAR method shows much better BER performances than those of the DAR method for all cases of $C/N$.

Figure 12 shows the BER performances both for the DAR and IDAR methods when changing the IBO under the multi-path fading conditions. In the simulations, the low PAPR preamble symbol is used for the estimation of channel response for both methods. From the figure, it can be observed that the IDAR method can achieve the better BER performance than that for the DAR method at all cases of $C/N$. From Figs. 11 and 12, it can be observed that the proposed IDAR method can mitigate the inter-modulation noise relatively even when the non-linear amplifier is operated at the saturation region, and concluded that the proposed IDAR
method can achieve the efficient usage of non-linear power amplifier.

Figures 13 and 14 show the BER performances for the conventional OFDM, DAR and IDAR methods when changing C/N under the AWGN and multi-path fading channels, respectively. In the AWGN channel shown in Fig. 13, it can be observed that the BER performance of DAR method is a little better than that for the conventional OFDM because the DAR method can achieve the less inter-modulation noise power by clipping method.

In the multi-path fading channel shown in Fig. 14, the DAR and conventional OFDM methods show almost the same BER performance because the degradation of BER performance due to the multi-path fading becomes the dominant. As for the IDAR method, the BER performance is much better than the conventional OFDM and DAR methods both in the AWGN and multi-path fading channels. From these figures, it can be concluded that the proposed IDAR method can achieve the highly efficient usage of non-linear amplifier with the better BER performance.

5. Conclusions

In order to maximize the power efficiency of non-linear amplifier for the transmission of OFDM signal, the power amplifier is usually forced to work at near its saturation region, which would lead to inevitably degradation of BER performance. In this paper, we proposed the Improved DAR method, which can mitigate both the clipping noise and inter-modulation noise on the basis of DAR method. The feature of proposed method is based on the fact that the non-linear operation of clipping is very similar to the operation of non-linear amplifier. The various computer simulation results showed that the proposed IDAR method can achieve the better BER performance as compared with the conventional DAR method even when the non-linear amplifier is operated at the saturation region. From these results, it can be concluded that the proposed IDAR method enables the efficient usage of non-linear power amplifier with the better BER performance.

As the future study, we must evaluate the performance of power spectrum density for the proposed IDAR method from the viewpoints of efficient usage of frequency bandwidth and efficient usage of non-linear power amplifier when the non-linear amplifier is operated at around the saturation region.

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References

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