

# Predistorter for Nonlinear Distortion Mitigation in GFDM Systems

Ari E. Jayati\* and Agus Margiantono

Department of Electrical Engineering, Universitas Semarang, Semarang, 50196, Indonesia;

Email: agusmargiantono@usm.ac.id (A.M.)

\*Correspondence: ariendang@usm.ac.id (A.E.J.)

**Abstract**—Next-generation wireless systems use the non-orthogonal modulation technique known as generalized frequency division multiplexing (GFDM). The nonlinearity of the high-power amplifier (HPA) greatly affects the performance of the wireless system. Without phase distortion and only amplitude distortion in the GFDM system using HPA Model Rapp. The effects of nonlinear distortion that occur involve distortion of the amplitude, signal constellation distribution, and spectral distribution. There are two contributions to this paper. First, the impact of HPA Model Rapp's nonlinear distortion on the GFDM system in the AWGN (additive white Gaussian noise) and Rayleigh channels was investigated. The simplicity of this model is the reason it was picked and has an AM/AM (amplitude modulation/amplitude modulation) curve. Second, the linearization of HPA with the use of a predistorter method in GFDM systems has been proposed. The nonlinear distortion impact of HPA can be mitigated by this predistorter. This technique is implemented in the transmitter section. The system performance investigated is determined by a bit error rate (BER) analysis, a constellation diagram, and a spectrum analysis. HPA generates a 55 dB rise in out-of-band (OOB) in the signal spectrum. The HPA effect was successfully compensated for by a 55 dB decrease in the OOB value of the predistorter system.

**Keywords**—GFDM, predistorter, HPA, rapp model, amplitude distortion

## I. INTRODUCTION

Next-generation wireless networks are characterized by flexibility, low latency, and high data rates. GFDM is a modulation system with non-orthogonal waveforms. The GFDM can outperform the weaknesses of orthogonal modulation systems such as OFDM, or orthogonal frequency division multiplexing, has a higher peak-to-average power ratio (PAPR). OFDM signal have a rectangular window filter, whereas GFDM signals have a raised cosine (RC) filter. Using a normalized filter, adding windowing will decrease the average strength of the GFDM signal while keeping the OFDM constant. As a result, PAPR in an OFDM signal is the sum of its exponential terms, whereas in GFDM, it is statistically

rising [1]. There has been investigation into PAPR in OFDM [2–5]. Due to the use of pulse shaping with an increased cosine to create a more effective bandwidth, GFDM also has a low OOB.

Base stations on future cellular systems will require faster processors, basebands, and radio frequency (RF) devices. HPA is a crucial component in a wireless communication system for communicating signals over a specified distance [6]. HPA is used to convert low-power RF signals into high-power signals so that they can be transmitted far away [7]. This is because cellular systems with long-distance coverage and transmission really need HPA [8]. HPA has three operating regions, namely cutoff, linear, and saturation. In general, to improve power efficiency, the linear zone close to the saturation region is where the HPA will work. The cellular transmitter's power efficiency rises and its battery life is increased as the HPA input power gets closer to saturation. However, if used in this environment, HPA will result in nonlinear distortion [9]. There are numerous impacts of nonlinear distortion brought on by HPA., including amplitude distortion, phase distortion, and signal constellation spread [10].

Moreover, outside of the frequency region, the nonlinear distortion effect generates harmonic and intermodulation signals which will interfere with adjacent channels [9]. As a result, the out-of-band signal will increase due to interference between adjacent subcarriers [11]. GFDM, like other multicarrier systems, employs HPA on the transmitter side. The HPA-based GFDM system is located in the downlink base station [12–14]. However, The combination of HPA nonlinear distortion in GFDM with strong M-ary modulation further complicates problems.

To assist base station transmitters in broadband communication systems, investigation on HPA structure for broadband and multiband has been proposed [6]. Research has been done on RF design and implementation for 5G networks and small cell system applications [14]. The analysis of BER, OOB radiation, and PAPR of the GFDM system under nonlinear distortion has also been the subject of numerous studies [15–17]. Four different methods can generally be utilized to combat nonlinear distortion in multicarrier systems. These techniques include input back-off (IBO) reduction [18], HPA

Manuscript received September 29, 2022; revised November 9, 2022; accepted December 25, 2022.

linearization [19], PAPR reduction [11], and signal reconstruction to eliminate nonlinear distortion [20].

The technique of reducing IBO has been studied by Falconer in 2007 by evaluating several PAPR reduction techniques combined with HPA adaptive predistorters that are applicable to generalized multi-carrier signals. However, this study uses the Rapp model for the solid state power amplifier (SSPA) nonlinear model and does not discuss the performance of the BER parameter. In 1995, Zenobio investigated the HPA adaptive memoryless linear predistorter system in OFDM by using the traveling-wave tube amplifier (TWTA) nonlinear distortion model, namely the Saleh model. But this study only analyzes Least Square Error (LSE) and Total Degradation (TD). Sendrei in 2014 proposed an iterative receiver on GFDM that had been given the PAPR reduction technique, namely clipping, but only analyzed the performance of BER, other parameters had not been analyzed. Reconstruction of the received signal is the last method, which was studied by Sendrei in 2015, which proposed Noise estimation and correction at the receiver in GFDM to overcome nonlinearity effects, but the types of nonlinear models have not been described in detail and the analysis discussed only the BER and Error Vector Magnitude (EVM). All these methods are applied to the OFDM system. However, research on the impacts of nonlinear distortion and There are only few methods for GFDM distortion correction.

Nonlinear distortion can be reduced using methods on either the transmitter side. The predistorter is used on the transmitter side to represent the inversion of the nonlinear HPA effect [19]. Predistorter research for the Saleh Model HPA mitigation has been carried out [21], but only tested on the AWGN channel.

Until now, there have been few studies that examine techniques to overcome nonlinear distortion in the GFDM system. The following are the paper's contributions:

The nonlinear impact of the HPA Model Rapp on the GFDM system passed through the AWGN and Rayleigh channels is investigated in this study. An amplitude distortion curve is used to characterize HPA. The Rapp model was used to simulate the AM/AM curve [22]. The literature uses this empirical model because it is simple.

This study applies a predistorter algorithm that is intended to linearize the GFDM system with the HPA Rapp model.

The main contribution is an investigation on predistorters capable of linearizing nonlinear distortion in GFDM receivers. Matlab simulations support these findings of GFDM systems on AWGN and Rayleigh channels. This strategy necessitates adjustments on the transmitter side (that is, at the cellular network's base station) rather than the receiver.

This paper is divided into the following sections: The system model, HPA features, and proposed technique are described in Section 2; the findings and discussion are presented in Section 3; and the conclusions are discussed in Section 4.

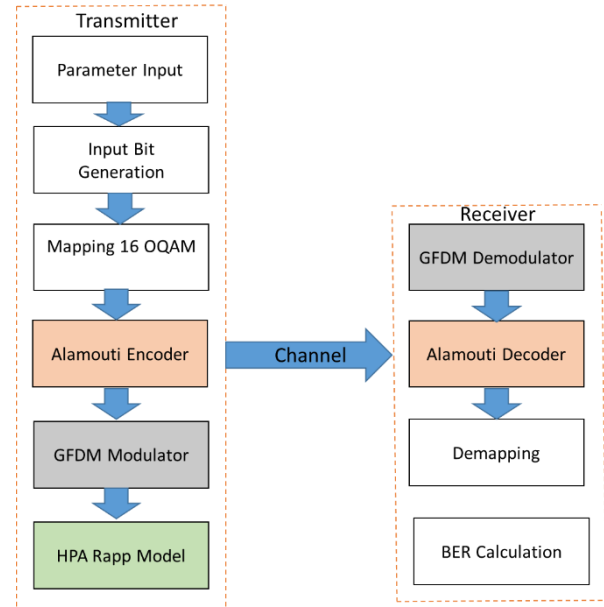


Figure 1. GFDM system with HPA.

## II. METHODS

### A. System Model

The GFDM system uses an HPA-added Offset Quadrature Amplitude Modulation (OQAM) mapping, as shown in Fig. 1. In the GFDM system's transmitter, the information signal in the form of binary bits is generated randomly. Following the OQAM mapper, the data is encoded with Alamouti. Next, the output of the encoder will be entered into the GFDM block. Before being transmitted through the antenna, The GFDM output is combined with the HPA. Furthermore, on the receiving end, the signal received by the antenna will be demodulated by the GFDM demodulator. Then, the demodulator output will be decoded. After that, a demapping process will be carried out to get the information signal back.

In this section, the processes that occur in the GFDM block will be explained. In the GFDM modulator, the flow of symbols resulting from the mapper in the form of Serial data is parallelized, which will be split into several blocks with a size of  $K \times M$ . The number  $K$  denotes the number of subcarriers, and  $M$  is a sub-symbol  $M$ . Every subsymbol produced by the decomposition process is upsampled in order to be transformed into an array of impulse signals.

The following equation describes how the GFDM signal will be sent as pulses and shifted in a circle [23]:

$$g_{k,m}(n) = g \left[ \left( n - \frac{mK}{2} \right) \bmod KM \right] e^{\frac{j2\pi k}{L_p} \left( n - \frac{L_p-1}{2} \right)}, \quad (1)$$

where  $n = 0, 1, \dots, KM-1$ , and  $L_p$  denotes the prototype filter's length, a prototype filter called  $g_{k,m}(n)$  has versions that have been shifted in the time and frequency domains, The subcarrier index is  $k$ , and the subsymbol index is  $m$ . The prototype filter above is made up of two

parts:  $\left[ \left( n - \frac{mK}{2} \right) \bmod KM \right]$  and complex exponential numbers. The first element is a circular filter that acts as a

temporal slider to separate one symbol to other. The second component serves as a frequency domain signal transfer.

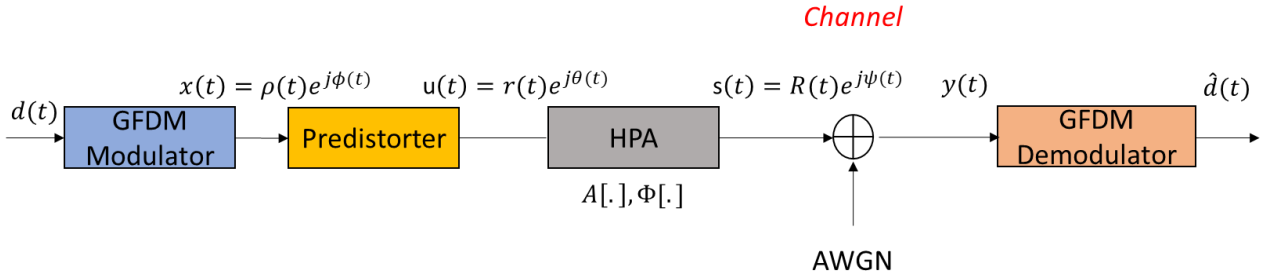


Figure 2. GFDM system with predistorter.

It was written as GFDM output signal  $\mathbf{x}[n]$  [24]:

$$\mathbf{x}[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} u_{k,m} \mathbf{g}_{k,m}[n] \quad (2)$$

or in the form of a matrix [35]:

$$\mathbf{x} = \mathbf{A}\mathbf{d}, \quad (3)$$

where:  $\mathbf{x} = (x[n])^T$ , consists of samples  $x[n]$ ,  $\mathbf{d} = \text{vec}(\mathbf{D}^T)$ , where  $\mathbf{D}$  is a matrix containing a matrix of complex data symbols with size  $K \times M$ . In the equation below,  $\mathbf{g}_{k,m} = (\mathbf{g}_{k,m}[n])^T$  is a matrix contained in  $\mathbf{A}$ .

$$\mathbf{A} = [\mathbf{g}_{0,0} \dots \mathbf{g}_{K-1,0} \dots \mathbf{g}_{0,1} \dots \mathbf{g}_{K-1,M-1}].$$

Parallel-to-serial blocks first modulate the data before converting it into serial form. To keep the transmission signal's circular structure, a cyclic prefix is appended to GFDM. Moreover, after multi-path effects are implemented in the channel, it enables the frequency domain to be delivered equally to the receiver [25]. The spectral efficiency will be increased by replacing every symbol with a cyclic prefix in each GFDM block [24].  $K \times M$  is the total number of symbols used in this investigation, which is 120, so the amount of Cyclich Prefix (CP) used is  $0.25 \times K = 0.25 \times 8 = 2$ .

Next, we will explain the HPA, which is added before the signal is passed through the antenna. The Rapp model is the HPA model that is employed. The Rapp model was chosen since it only exhibits amplitude distortion and not phase distortion. As a result, the Rapp model lacks AM/PM features  $F_p(\rho(t))$ . The phase angle feature of the signal is determined using the AM/PM converter. SSPA modeling typically employs this paradigm, which is only useful for AM/AM functions  $F_a(\rho(t))$ . For signal amplitude, AM/AM conversion is utilized. It is possible to write this as follows [23]:

$$F_a(\rho(t)) = \frac{\rho(t)}{\left(1 + \left(\frac{\rho(t)}{A_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}}, \quad (5)$$

$$F_p(\rho(t)) = 0,$$

where  $p$  is the smoothness factor regulating the change from the linear region to the saturation region, ( $p > 0$  and  $A_{sat}$  is the saturation level of the HPA input.

### B. GFDM Predistorter

The downlink system predistorter for the transmitter side HPA linearization in BS is the main topic of this paper. Predistorter was selected since it is the most straightforward HPA linearization technique, restricting the regrowth spectrum and nullifying amplitude distortion. The inversion of the nonlinear HPA responses is what the predistorter is intended to model. As seen in Fig. 2, this block is installed in front of the HPA to guarantee that the system output signal is linear.

The following equation can be used to express the GFDM modulator's output [26] with the addition of a predistorter before HPA:

$$x(n) = \rho(n)e^{j\Phi(n)} \quad (6)$$

where  $\rho(n)$  is the GFDM output signal's amplitude. The predistorter's output is constructed as follows [27]:

$$u(n) = r(n)e^{j\theta(n)} \quad (7)$$

where  $r(n)$  is the HPA input's amplitude and  $\theta(n)$  is the HPA input's phase.

It must fulfill the equation  $x(n) = s(n)$  in order to account for nonlinearity, such that:

$$r(n) = A^{-1}[\rho(n)] \quad (8)$$

$$\theta(n) = \phi(n) - \Phi[r(n)] \quad (9)$$

where the HPA's AM/AM and AM/PM characteristic functions, respectively, are  $A[.]$  and  $\Phi[.]$ . HPA output is as follows:

$$s(t) = R(t)e^{j\psi(t)}, \quad (10)$$

where the output amplitude  $R(n) = A[r(n)]$  and the phase output HPA  $\psi(n) = \theta(n) + \Phi[r(n)]$  are both present.

The algorithm summarizes the predistorter's steps for the GFDM system as follows:

Algorithm Predistorter modeling for GFDM systems		
1:	$\mathbf{d} \leftarrow \mathbf{b}$	▷ 16 OQAM mapping
2:	$\mathbf{A} \leftarrow \mathbf{g}$	▷ RRC pulse shaping
3:	$\mathbf{x} \leftarrow \mathbf{A}\mathbf{d}$	▷ GFDM output
4:	$x_i(n) \leftarrow \rho(n)e^{j\phi(n)}$	▷ predistorter input
5:	$r_k(n) \leftarrow A^{-1}[\rho(n)]$	▷ amplitude of predistorter
6:	$\theta_k(n) \leftarrow \phi(n) - \Phi[r_k(n)]$	▷ phase predistorter
7:	$u_k(n) \leftarrow r_k(n)e^{j\theta_k(n)}$	▷ predistorter output
8:	$R_k(n) \leftarrow A[r_k(n)]$	▷ amplitude of HPA
9:	$\psi(n) \leftarrow \theta_k(n) + \phi[r_k(n)]$	▷ phase of HPA
10:	$s_k(n) \leftarrow R_k(n)e^{j\psi(n)}$	▷ HPA output

### III. RESULT AND DISCUSSION

The use of the predistorter approach to reduce nonlinear distortion brought on by HPA model Rapp on the GFDM system was looked into. Before and after nonlinear distortion is applied, there are three performance parameters: constellation diagram, BER, and signal spectrum. The parameters for the GFDM simulation are as follows:  $K = 8$  subcarriers,  $M = 15$  subsymbols, mapping with 16 OQAM modulation, and pulse shaping using root raised cosine with a roll-of-factor of 0.3. The simulation parameters are displayed in Table 1.

TABLE I. PARAMETERS FOR SIMULATION

Parameter	Notation	GFDM
sampling Frequency	$f_s$	16
Subcarrier	K	8
Symbols per block	M	15
Samples per symbol	N	10
Pulse Shaping	g	RRC
Roll-of-factor	$\alpha$	0.3
Mapping		16 OQAM
Smoothing Factor	$p$	2

The AM/AM curve becomes linear after adding a predistorter, as shown in Fig. 3. This occurs as a result of the predistorter's ability to counteract the impact of nonlinear distortion. The simplest method for HPA linearization is the predistorter.

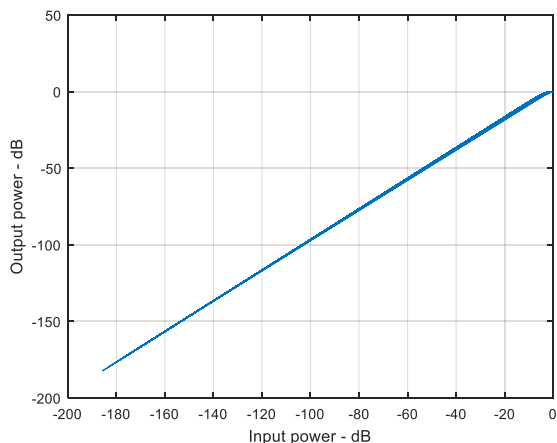


Figure 3. A predistorter's AM/AM characteristic curve.

The first parameter is the GFDM spectrum analyzer shown in Fig. 4. This curve will compare the spectrum of the HPA signal without and with a predistorter. The normalized Power Spectral Density (PSD) is plotted on the y-axis with the sampling frequency  $F_s$  on the x-axis. The GFDM spectrum after being given a predistorter resulted in a lower OOB compared to that with HPA alone. The predistorter modifies the signal before it is passed via the transmitter, reducing the nonlinear distortion visible at the HPA output [28]. Predistorters can be used to implement the polar opposite of HPA characteristics.

As depicted in Fig. 5, the predistorter's IBO was adjusted while analyzing the signal spectrum in GFDM. It was clear that the inband ripple, nonlinear distortion, OOB, and IBO were all changing in a negative direction.

The spectrum mask must be carefully considered when choosing the HPA operating points, and these points should be tuned for optimal power efficiency. The most important considerations in an HPA design are these two constraints: power efficiency and adjacent channel interference (ACI).

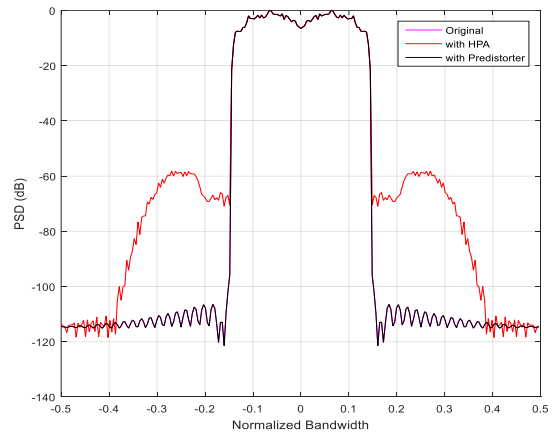


Figure 4. PSD of GFDM + HPA with and without predistorter.

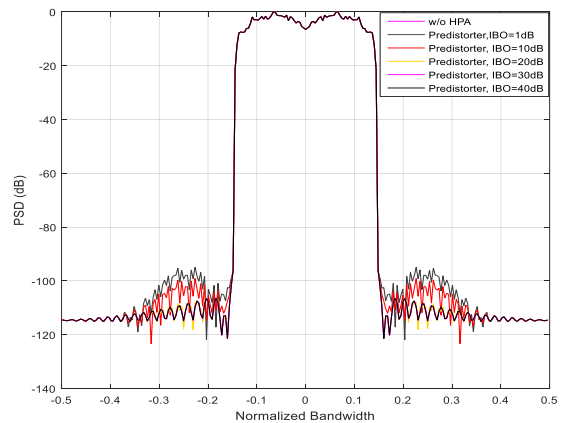


Figure 5. Comparison of input back-off (IBO) variations for PSD GFDM+predistorter.

The constellation diagram is the next parameter examined after the GFDM is given the nonlinear distortion of the Rapp model, as seen in Fig. 6.

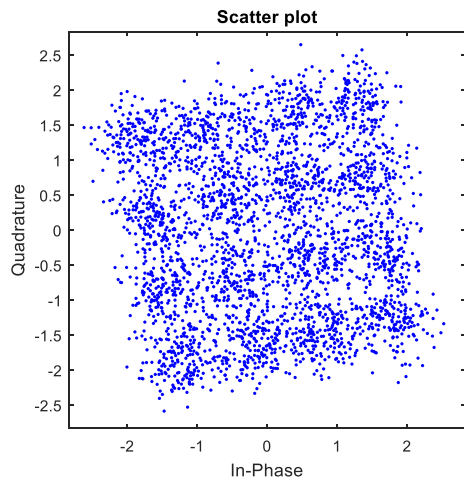


Figure 6. GFDM constellation without predistorter.

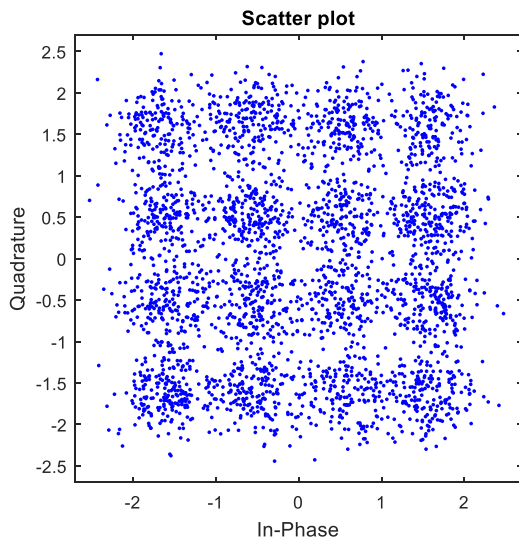


Figure 7. GFDM constellation with predistorter.

According to the findings of the study shown in Fig. 7, when GFDM is given a predistorter, the constellation reverts to its original location to avoid interfering with the receiving side's detection procedure. The signal is no longer distorted. From the constellation diagram, it can be seen that there is a division of decision areas so that these changes are followed by the detecting procedure. This can be regarded as an error vector that improves when a predistorter is applied. Without a predistorter, the EVM for GFDM is -4.97 dB, and with the GFDM system, the predistorter falls to -9.0 dB.

The last parameter investigated is BER. According to Fig. 8, GFDM's BER performance will suffer from nonlinear distortion. Fig. 8 compares four things, namely the theoretical curve of 16 QAM, GFDM with and without HPA, and GFDM with predistorters on AWGN and Rayleigh channels. The graph compares GFDM with and without predistorters. on AWGN and Rayleigh channels. The GFDM system with HPA experienced a decrease in BER performance on AWGN and Rayleigh channels. After being given a predistorter, the system in the AWGN

and Rayleigh channels has improved and is now close to the theoretical curve. The impact of nonlinear distortion in OFDM and GFDM has been investigated by [29].

Nonlinear distortion on OFDM will result in an increase in PAPR, an increase in OOB, and a drop in the Symbol Error Rate (SER). The OOB signal is greatly increased and the SER is significantly reduced by the impact of nonlinear distortion on the GFDM system [30]. The spread of the input signal diagram is then brought on by the GFDM system's nonlinear distortion, which also has an impact on the receiving side's decision point area [31].

Thus, it is more challenging to accurately detect the received signal. as a result of the received information being inaccurate, the system's performance declines. According to the simulation results, GFDM with a predistorter performs better than GFDM without one. In the next work, we will investigate the predators in the MIMO-GFDM system if given the HPA Model Rapp.

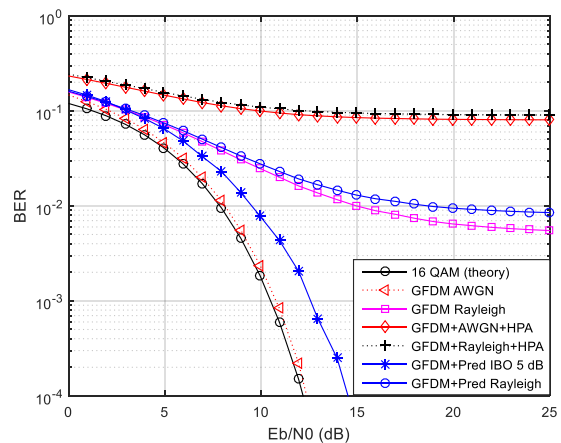


Figure 8. Comparison of GFDM with and without predistorters.

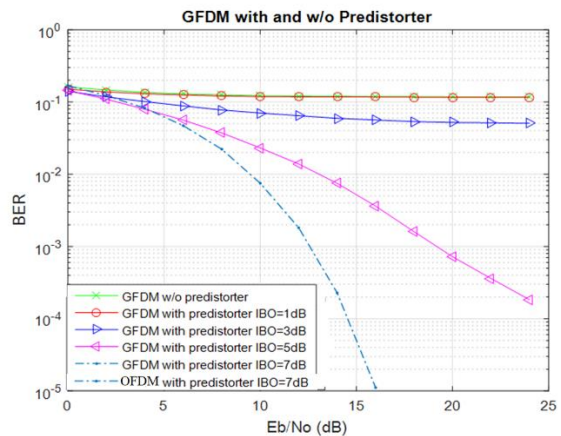


Figure 9. GFDM+predistorter bit error rate (BER) with IBO variation.

The GFDM BER with HPA and predistorter will be compared with the theoretical BER for the validity of the simulation results. Seen GFDM with a predistorter close to BER theory. The simulation can be said to be valid. The findings of the inquiry into IBO's impact on the GFDM system in the case of a nonlinear distortion are presented in Fig. 9. The graph shows that the BER value in the GFDM system lowers as the IBO rises. This is due to the

nonlinear distortion being reduced at larger IBOs. To test the validity of the predistorter, the BER between GFDM and OFDM was also compared. As can be observed, GFDM and predistorters perform as well to OFDM.

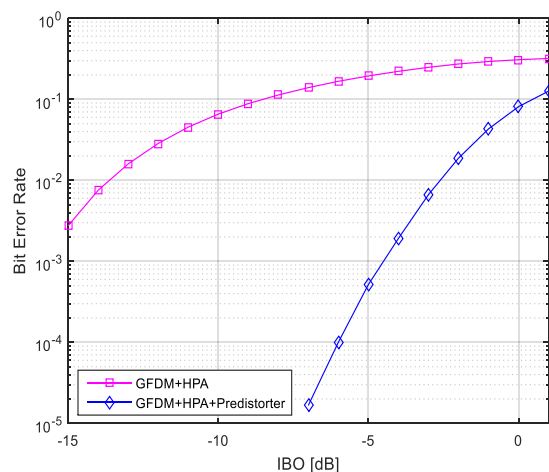


Figure 10. Comparison of BER and IBO GFDM using and without predistorters.

Fig. 10 compares the BER and IBO for the GFDM system with HPA both with and without predistorters. The study of the simulation results is made easier by using IBO's negative sign. According to the 6 dB IBO, the BER of GFDM with an HPA system is the highest at 0.1668, while the BER of GFDM with a predistorter is the lowest at 0.0001. Hence, it can be said that for higher IBO levels, the predistorter was successful in linearizing the nonlinear distortion caused by HPA. In order to have a smaller BER value, future research should concentrate on a modest IBO value.

#### IV. CONCLUSIONS

This paper investigates and analyzes the impact of HPA Model Rapp nonlinear distortion on the GFDM system on AWGN and Rayleigh channels. Furthermore, the predistorter technique is applied to the GFDM transmitter. This is to reduce the effects of HPA nonlinear distortion.

Simulation results that compare the performance of GFDM with HPA without a predistorter serve as an example of the usefulness of the suggested predistorter. The findings demonstrated that the impact of HPA nonlinear distortion can be diminished by adding a predistorter to GFDM. It has been demonstrated that systems with predistorters have superior spectrum parameters and lower BER values. Using HPA, the signal spectrum increased OOB to -60 dB. The OOB value dropped to -115 dB in the predistorter-equipped system in the meantime. When IBO was 5 dB, the BER value dropped from 0.1632 to 0.0007.

The limitation of this proposed method is that it only overcomes the nonlinear distortion of the SISO-GFDM transmitter system. Crosstalk, which results from interference between various signal pathways, as well as nonlinear distortion are both causes of interference in

MIMO systems. Future research should therefore take into account compensatory methods for the combined impacts of nonlinear distortion and crosstalk in the MIMO-GFDM system. The use of a predistorter in the MIMO-GFDM system with HPA Model Rapp will be examined in the upcoming work.

#### CONFLICT OF INTEREST

The authors declare no conflicts of interest.

#### AUTHOR CONTRIBUTIONS

Conceptualization, A.E.J., A.M.; methodology, A.E.J., A.M.; software; validation; formal analysis; inquiry; resources; data curation; writing—original draft preparation; writing—review and editing, A.A.E.J., A.M.; visualization; supervision; project management; and financing acquisition are all skills that A.E.J., A.M. possesses.

#### REFERENCES

- [1] Z. Sharifian, M. J. Omidi, A. Farhang, and H. Saedi-Sourck, "Polynomial-based compressing and iterative expanding for PAPR reduction in GFDM," in *Proc. the ICEE 2015 23rd Iranian Conference on Electrical Engineering*, Tehran, Iran, 10–14 May 2015, pp. 518–523.
- [2] G. Fettweis and M. S. Krondorf, "BitTner, GFDM — Generalized frequency division multiplexing," in *Proc. IEEE Vehicular Technology Conference, Barcelona*, 2009, pp. 1–4.
- [3] S. K. Chronopoulos, V. Christofilakis, G. Tatsis, and P. Kostarakis, "Preliminary BER study of a TC-OFDM system operating under noisy conditions," *J. Eng. Sci. Technol. Rev.*, vol. 9, pp. 13–16, 2016.
- [4] S. K. Chronopoulos, G. Tatsis, V. Raptis, and P. Kostarakis, "Enhanced PAPR in OFDM without deteriorating BER performance," *Int. Commun. Netw. Syst. Sci.*, vol. 4, pp. 164–169, 2011.
- [5] S. K. Chronopoulos, C. Votis, G. Tatsis, and P. Kostarakis, "In depth analysis of noise effects in orthogonal frequency division multiplexing systems, utilising a large number of subcarriers," in *Proc. 7th International Conference of the Balkan Physical Union*, La Herradura, Spain, 2010, pp. 967–962.
- [6] K. Gumber and M. Rawat, "A modified hybrid RF predistorter 5G linearizer for ultra-wideband systems," *IEEE J. Emerg. Sel. Top. Circuits Syst.*, vol. 7, pp. 547–557, 2017.
- [7] G. U. Maheswari, A. Govindasamy, and S. J. Thiruvengadam, "Performance analysis of filter bank multicarrier system with nonlinear high-power amplifiers for wireless 5G networks," *IET Signal Process.*, vol. 11, pp. 66–72, 2017.
- [8] P. Varahram, S. Mohammady, B. M. Ali, and N. B. Solomon, "Power efficiency in broadband wireless communications," CRC Press: Boca Raton, FL, USA, 2015.
- [9] P. Jantunen, "Modeling of nonlinear power amplifiers for wireless communications," Master's Thesis, Master of Science, Helsinki University of Technology, Espoo, Finland, 2004.
- [10] F. H. Gregorio, "Analysis and compensation of nonlinear effects of power amplifier," Dissertation, Helsinki University of Technology, Espoo, Finland, 2007.
- [11] A. Ortega and L. Fabbri, "Performance evaluation of GFDM over nonlinear channels," in *Proc. 2016 International Conference on Information and Communication Technology Convergence, ICTC 2016*, Jeju, Korea, 2016, pp. 12–17.
- [12] A. E. Jayati, W. T. Suryani, and Endroyono, "Characteristic of HPA nonlinear distortion effects in MIMO GFDM systems," in *Proc. 2018 ICTC*, Jeju, Korea, 2018, pp. 379–384.
- [13] L. Cho, C. H. Ting, C. Y. Chen, C. H. Yau, and C. Y. Hsu, "When UUDN meets 5G waveforms: New challenge of signal linearity?" in *Proc. 2017 IEEE International Conference on Applied System*

- Innovation: Applied System Innovation for Modern Technology*, Sapporo, Japan, 2017, pp. 770–773.
- [14] M. Abdelaziz, L. Anttila, S. Dikmese, M. Renfors, A. M. Wyglinski, and M. Valkama, “Flexible digital predistortion for future spectrally-agile waveforms and 5G radio systems,” in *Proc. 2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, Boston, MA, USA, 2015.
- [15] P. Miao and P. Chen, “Low-complexity PAPR reduction scheme combining multi-band hadamard precoding and clipping in OFDM-based optical communications,” *Electronics*, vol. 7, no. 11, pp. 1–16, 2018.
- [16] M. Matthe, D. Zhang, and G. Fettweis, “Iterative detection using MMSE-PIC-GFDM demapping for MIMO systems,” in *Proc. IEEE European Wireless (EW '16)*, 2016, pp. 473–479.
- [17] K. M. Gharaibeh, “Nonlinear distortion in wireless communication using matlab,” SI; John Wiley and Sons Ltd.: Hoboken, NJ, USA 2012.
- [18] D. Falconer; F. D. Lemoine, C. T. Lam, and M. Sabbaghian, “Power backoff reduction for generalized multicarrier waveforms,” in *Proc. Eur Signal Process Conf.*, Poznan, Poland, 2007, pp. 693–697.
- [19] S. S. K. C. Bulusu, H. Shaiek, D. Roviras, and C. Laetitia, “PA Linearization of FBMC-OQAM Signals with Overlapped Recursive Error Correcting Predistortion”, Proceedings of the International Symposium on Wireless Communication Systems (ISWCS), Poznan, Poland, 20–23 September 2016; pp. 533–537.
- [20] L. Sendrei and S. Marchevsky, “Nonlinear noise estimation and compensation in GFDM based communication systems for cognitive radio networks,” in *Proc. 2015 25th International Conference, Pardubice Radioelektronika (RADIOELEKTRONIKA)*, Czech Republic, 2015, pp. 313–316.
- [21] A. E. Jayati, Wirawan, T. Suryani, and Endroyono, “Nonlinear distortion cancellation using predistorter in MIMO-GFDM systems,” *Electronics*, vol. 8, no. 6, 2019.
- [22] C. Rapp, “Effects of HPA nonlinearity on a 4-DPSK/OFDM signal for a digital sound broadcasting system,” *Eur. Conf. Satellite Commun.*, pp. 179–184, 1999.
- [23] S. K. Bandari, “GFDM/OQAM implementation under rician fading channel,” in *Proc. Intl. Conference on Advances in Computing, Communications and Informatics (ICACCI)*, Cebu, Philippines, 2016, pp. 256–260.
- [24] M. Matthe, N. Michailow, I. Gaspar, and G. Fettweis, “Influence of pulse shaping on the bit error rate performance and out-of-band radiation of generalized frequency division multiplexing,” in *Proc. 2014 IEEE International Conference on Communications Workshops (ICC)*, Sydney, NSW, Australia, 2014, pp. 43–48.
- [25] N. Michailow, S. Krone, M. Lentmaier, and G. Fettweis, “Bit error rate performance of generalized frequency division multiplexing,” in *Proc. 2012 IEEE Vehicular Technology Conference (VTC Fall)*, Quebec City, QC, Canada, 2012, pp. 1–5.
- [26] A. Bo, Y. Z. Xing, P. C. Yong, Z. T. Tao, and G. J. Hua, “Effects of PAPR reduction on predistortion HPA,” *IEEE Trans. Electron. Consum.*, vol. 51, pp. 1143–1147, 2005.
- [27] D. D. Zenobio, “Adaptive linearization of power amplifiers in multicarrier orthogonal schemes,” in *Proc. IEEE Wireless Communication System Symposium*, Long Island, NY, USA, 1995.
- [28] I. Yoffe and D. Wulich, “Predistorter for MIMO system with nonlinear power amplifiers,” *IEEE Trans. Commun.*, vol. 65, pp. 3288–3301, 2017.
- [29] A. E. Jayati, Wirawan, and T. Suryani, “Analysis of non-linear distortion effect model based on saleh in GFDM system,” in *Proc. IEEE International Conference on Commnetsat*, Semarang, 2017, pp. 13–18.
- [30] A. E. Jayati, Wirawan, T. Suryani, and Endroyono, “Characteristic of HPA nonlinear distortion effects in MIMO-GFDM systems,” in *Proc. 9th International Conference on Information and Communication Technology Convergence*, ICTC 2018, IEEE, pp. 379–384, Oct 2018.
- [31] A. E. Jayati and B. Destyningtias, “The Analysis of the high-power amplifier distortion on the MIMO-GFDM system,” in *Proc. 10th IEEE International Conference on Communication*, 2021, pp. 253–258.

Copyright © 2023 by the authors. This is an open access article distributed under the Creative Commons Attribution License ([CC BY-NC-ND 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/)), which permits use, distribution and reproduction in any medium, provided that the article is properly cited, the use is non-commercial and no modifications or adaptations are made.