

PERFORMANCE ANALYSIS OF THE USE OF LINEAR APPROXIMATION METHOD TO IMPROVE MULTICARRIER COMMUNICATION IN NOISY ENVIRONMENTS

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ABSTRACT

Multicarrier communication systems, especially Orthogonal Frequency Division Multiplexing (OFDM), face challenges when it comes to performance, particularly due to high Peak-to-Average Power Ratio (PAPR). This issue can push power amplifiers into nonlinear territory, which, when combined with the additive noise found in wireless channels, leads to higher bit error rates and spectral regrowth. In this study, we introduce and assess a linear approximation method that's applied at the transmitter to tackle the dual challenges of power amplifier nonlinearity and channel noise in multicarrier communication systems. Our approach uses a first-order Taylor series expansion to linearize the Saleh model of a nonlinear power amplifier. We ran MATLAB simulations with 16-Quadrature Amplitude Modulation (16-QAM) OFDM signals, comparing the performance of our linearized system against the traditional nonlinear Saleh model under three different Additive White Gaussian Noise (AWGN) conditions: high (15 dB), medium (5 dB), and severe (-5 dB) Signal-to-Noise Ratios (SNR). We looked at various performance metrics, including Symbol Error Rate (SER), Error Vector Magnitude (EVM), Modulation Error Ratio (MER), and constellation diagram analysis. The results showed that our linear approximation method significantly boosts system performance across all SNR levels. At SNR = 15 dB, we saw improvements of 31.10% in SER, 31.04% in EVM, and 74.27% in MER. For SNR = 5 dB, the improvements were 19.74% in SER, 24.77% in EVM, and 37.55% in MER. Even in challenging conditions (SNR = -5 dB), our method still managed a 3.37% improvement in SER and 20.28% in EVM. The constellation diagrams illustrated a tighter clustering of received symbols and less distortion when linearization was applied. Overall, our findings indicate that using a straightforward first-order approximation for transmitter-side linearization effectively reduces in-band distortion and enhances resilience against channel noise, providing a computationally efficient alternative to more complex receiver-based compensation techniques.

Keywords: Linear approximation; multicarrier communication; OFDM; Saleh model; power amplifier nonlinearity; symbol error rate

1.0 INTRODUCTION

Multicarrier communication techniques, especially Orthogonal Frequency Division Multiplexing (OFDM), form the foundation of modern high-data-rate wireless systems. They are resilient to multipath fading and offer high spectral efficiency (Molisch, 2005). However, a major issue in OFDM systems is their high Peak-to-Average Power Ratio (PAPR). This drives power amplifiers (PAs) into their nonlinear operation range. Nonlinearity leads to in-band distortion, which degrades the Bit Error Rate (BER), and out-of-band spectral regrowth, which causes interference with adjacent channels (Rapp, 1999).

This issue worsens in noisy environments. Noise, like Additive White Gaussian Noise (AWGN), further distorts the received signal constellation. This results in a reduced Signal-to-Noise Ratio (SNR) and a higher symbol/bit error rate (Islam *et al.*, 2015). The combination of amplifier nonlinearity and channel noise is a significant barrier to achieving reliable, high-quality communication.

Traditional methods to reduce PA nonlinearity often rely on complex algorithms at the receiver for distortion compensation and signal detection (Dardari *et al.*, 2000; Ghannouchi and Hammi, 2009). For example,

techniques like iterative decoding and equalization have been used to address nonlinear distortions (Dardari *et al.*, 2000). While these methods work, they also raise the computational demands on the receiver. An alternative is to tackle the distortion at its source (the transmitter). By linearizing the PA's characteristics at the transmitter, the signal remains clear before it encounters the channel. This approach simplifies the receiver's role and may offer better overall system performance.

(Kim *et al.*, 2025) designed a high-gain multi-input Low Noise Amplifier. The design utilized cascode architecture and was implemented in a 65nm Silicon-on-Insulator (SOI) process. The design eliminated the need for switching which often introduces additional noise in the system. With their design, they were able to achieve a Noise Figure (NF) of 1.03dB which when compared with other works gave a better performance.

(Maruf *et al.*, 2025) proposed a cascode low noise amplifier circuit. The proposed circuit utilized a two-stage cascode topology which combined a common-source stage and a common-drain stage. With this design, they were able to optimize the power gain and noise figure. Using the Advanced Design System (ADS) software for simulation, their simulation result showed a noise figure of 0.541dB.

(Choi *et al.*, 2024) proposed a multi-gain low noise amplifier with fast switching mode. Their work consisted of architecture with a three-core input structure that supports multi-gain mode, achieved high gain and ultra-low noise performance. Their design eliminated the use of switches at the input stage to eliminate switch-related noise degradation typically found in traditional design. This proved advantageous as it improved the noise figure. Performance result showed a noise figure of 0.73dB.

This study aims to analyze the effectiveness of a linear approximation method used at the transmitter to enhance multicarrier communication in noisy conditions. Unlike most studies that focus on improvements at the receiver (Dardari *et al.*, 2000; Ghannouchi and Hammi, 2009), this work applies a mathematical linearization technique to boost the amplifier's performance directly at the transmitter. The goal is to show that this proactive linearization can significantly lessen the harmful effects of PA nonlinearity and channel noise.

2.0 MATERIALS AND METHODOLOGY

The research method aimed to clearly model, implement, and evaluate the proposed linear approximation technique against a standard nonlinear amplifier model in controlled noisy conditions.

2.1 System Model and Simulation Framework

The entire simulation was done in MATLAB. The communication chain, shown conceptually in Figure 1, included the following stages:

- i. Data Generation: Random integer data streams were created.
- ii. Modulation: The data was mapped to complex symbols using 16-Quadrature Amplitude Modulation (16-QAM). This choice was based on its spectral efficiency and sensitivity to nonlinear distortions.
- iii. OFDM Modulation: The 16-QAM symbols went through an OFDM modulator with an FFT size (N) of 100 and a cyclic prefix length of 16 to reduce inter-symbol interference.
- iv. Power Amplifier Model: The OFDM signal passed through a nonlinear power amplifier, which was modeled using the well-known Saleh model (Saleh, 1981).
- v. Linearization Block (Proposed Method): For the proposed system, the signal was pre-distorted using the linear approximation method before entering the Saleh model PA.
- vi. Channel Model: The amplified signal was sent through an AWGN channel. The SNR was set at 15 dB, 5 dB, and -5 dB to represent high, medium, and severe noise conditions, respectively.
- vii. Receiver Processing: At the receiver, standard OFDM demodulation and 16-QAM demapping were carried out.



Figure 1: Block diagram of the simulated system with the proposed linearization block.

2.2 Mathematical Foundation

2.2.1 Saleh Model

The Saleh model accurately characterizes the amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) conversions of a traveling-wave tube amplifier (TWTA) (Saleh, 1981). This is a mathematical model used to represent the non-linear behavior of amplifiers. It captures amplitude and phase distortions and uses four parameters to fit the model to measurement data (Yadav *et al.*, 2010). Mathematically, it is expressed as;

AM-AM Conversion:

$$g[y(t)] = \frac{\alpha_a x(t)}{(1 + \beta_a x(t)^2)} \quad (1)$$

AM-PM Conversion:

$$\phi[y(t)] = \frac{\alpha_\phi x(t)^2}{(1 + \beta_\phi x(t)^2)} \quad (2)$$

Where;

$g[y(t)]$ = AM-AM output magnitude distortion

$\phi[y(t)]$ = AM-PM output phase distortion

α_a and β_a = Saleh parameters for AM-AM distortion

α_ϕ and β_ϕ = Saleh parameters for AM-PM distortion

$x(t)$ = complex input signal

Expressing the Saleh equations in polar form gives;

$$output = g[y(t)]. e^{j\phi[y(t)]} \quad (3)$$

The parameters of the Saleh model used were the default parameters in MATLAB ($\alpha_a = 2.1587, \beta_a = 1.1517, \alpha_\phi = 4.0033, \beta_\phi = 9.1040$). These were used to introduce significant nonlinear distortion.

2.2.2 Linear Approximation Method

The proposed solution linearizes the Saleh model's nonlinear transfer function using a first-order Taylor series expansion around a carefully selected operating point, a . This linearization Approximation method is a mathematical method that is used to linearize non-linear equations. Its equation is shown in equation 4;

$$l(x) = f(a) + f'(a)(x - a) \quad (4)$$

$l(x)$ = approximation of the function $f(x)$ at a value x

x = input value

a = point where the tangent line is drawn (approximation point)

$f(a)$ = function's value at a

$f'(a)$ = derivative of the function evaluated at a

A linearization algorithm implemented using MATLAB was obtained for the Linear approximation method using the following steps;

- i. Model Implementation: The mathematical equations of the Saleh model [equations (1), (2) and (3)] were first implemented in MATLAB.
- ii. Linearization Point Selection: An appropriate point of approximation (a) in equation (4) was then selected through simulations to serve as the basis for the linearization.

- iii. Derivative Calculation: The derivative of the Saleh model's key equation (3) was computed to determine the slope for the linear approximation.
- iv. Slope Evaluation: This derivative in step 3 was then evaluated at the selected approximation point (a) to find the specific slope, $f'(a)$ at that location.
- v. Linear Equation Construction: Finally, the linear approximation was constructed using the point-slope form, incorporating the calculated values of $f(a)$ and $f'(a)$ at the point (a).

This pre-distortion reduces the PA's nonlinearity. As a result, the overall input-output characteristic is more linear than the original Saleh model.

2.3 Performance Metrics

We compared the performance of the standard Saleh model and the proposed linearized system using the following metrics:

- i. Symbol Error Rate (SER): This is the percentage of incorrectly detected symbols.
- ii. Error Vector Magnitude (EVM): This measures how far the received constellation points are from their ideal positions.
- iii. Modulation Error Ratio (MER): This is a signal-to-distortion ratio calculated from the EVM, $MER \approx -20 \log_{10}(EVM_{rms})$.
- iv. Constellation Diagrams: These are visual representations of the received symbols in the complex I-Q plane. They provide a clear view of the distortion's nature.

3.0 RESULT AND DISCUSSION

A total of fifteen (15) simulations were run with five (5) simulations run for each of the varied values of SNR levels. The mean in each case was calculated and a performance comparison was done between when the proposed solution was not applied i.e. the Saleh model result and when it was applied. For Case 1, the proposed solution improved SER by 31.10%, EVM by 31.04% and MER by 74.27%. For Case 2, it improved SER by 19.74%, EVM by 24.77% and MER by 37.55%. For Case 3, the SER was improved by 3.37%, EVM by 20.28% and MER by 14.79%. The tabulated simulation results are shown in Table 1.

Table 1: Simulation Results

Case 1: SNR = 15dB						
	Saleh Model			Linear Approximation Method		
S/N	SER	EVM	MER	SER	EVM	MER
1	0.7	186.1349	-5.3966	0.58	112.0245	-0.9863
2	0.74	183.3505	-5.2656	0.45	112.5407	-1.0262
3	0.63	164.6585	-4.3317	0.36	112.8296	-1.0485
4	0.66	132.5083	-2.4449	0.45	113.1194	-1.0707
5	0.68	156.2016	-3.8737	0.51	116.8506	-1.3526
Mean value	0.682	164.5708	-4.2625	0.47	113.4730	-1.0969
Case 2: SNR = 5dB						
	Saleh Model			Linear Approximation Method		
S/N	SER	EVM	MER	SER	EVM	MER
6	0.75	215.4551	-6.6671	0.58	164.5125	-4.324
7	0.75	242.5671	-7.6966	0.67	161.1347	-4.1438
8	0.76	213.3303	-6.5810	0.63	158.3292	-3.9912
9	0.78	180.2529	-5.1176	0.63	156.4196	-3.8858
10	0.77	207.9863	-6.3607	0.56	156.7268	-3.9029
Mean value	0.76	211.9183	-6.4846	0.61	159.4246	-4.0495

Case 3: SNR = -5dB						
	Saleh Model			Linear Approximation Method		
S/N	SER	EVM	MER	SER	EVM	MER
11	0.87	396.4076	-11.9628	0.86	379.1472	-11.5762
12	0.85	435.5426	-12.7806	0.91	415.0432	-12.3619
13	0.93	450.2488	-13.0691	0.84	349.6573	-10.8729
14	0.88	529.1858	-14.4722	0.82	352.6317	-10.9464
15	0.91	485.2507	-13.7193	0.87	334.4612	-10.4869
Mean value	0.89	459.3271	-13.2008	0.86	366.1881	-11.2489

3.1 Constellation Diagram Analysis

Case 1: SNR = 15dB

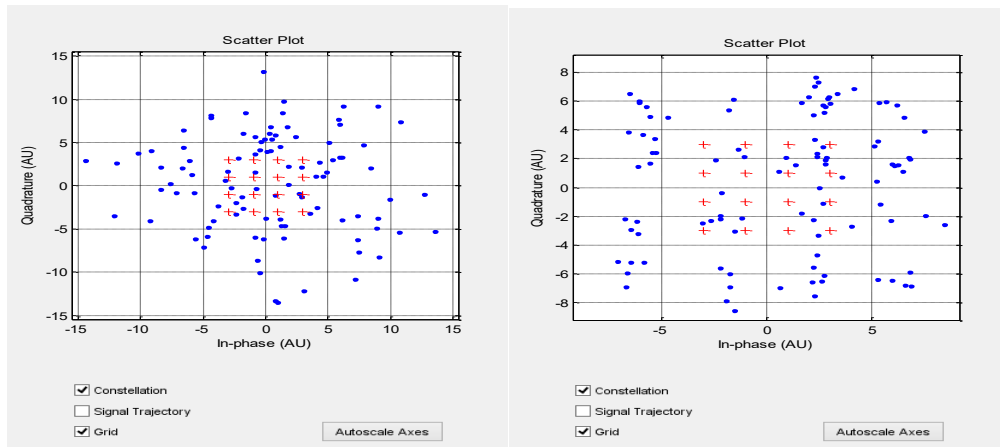


Figure 1: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

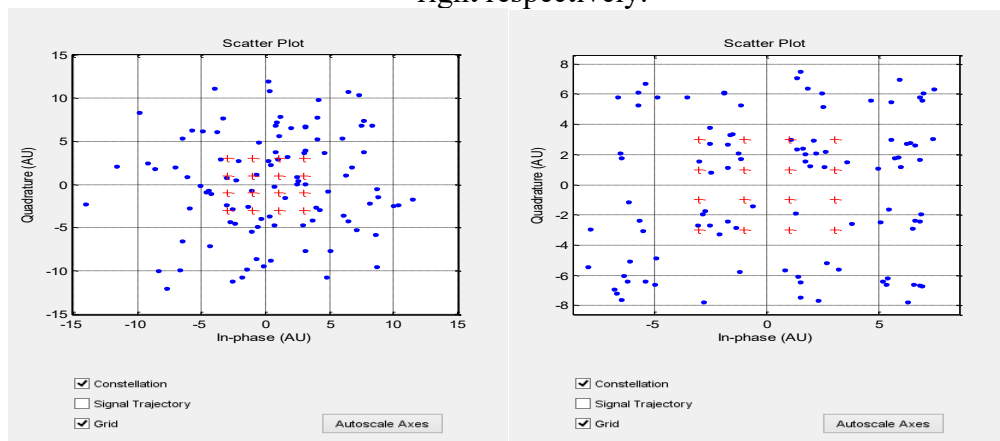


Figure 2: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

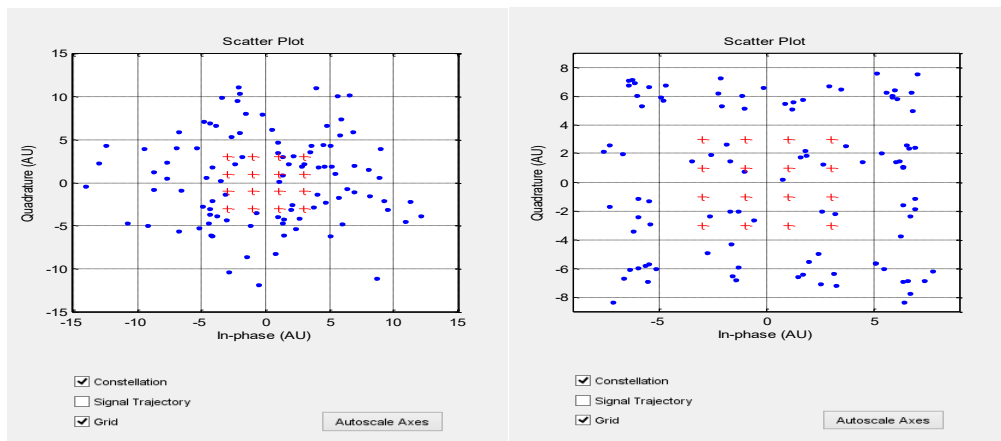


Figure 3: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

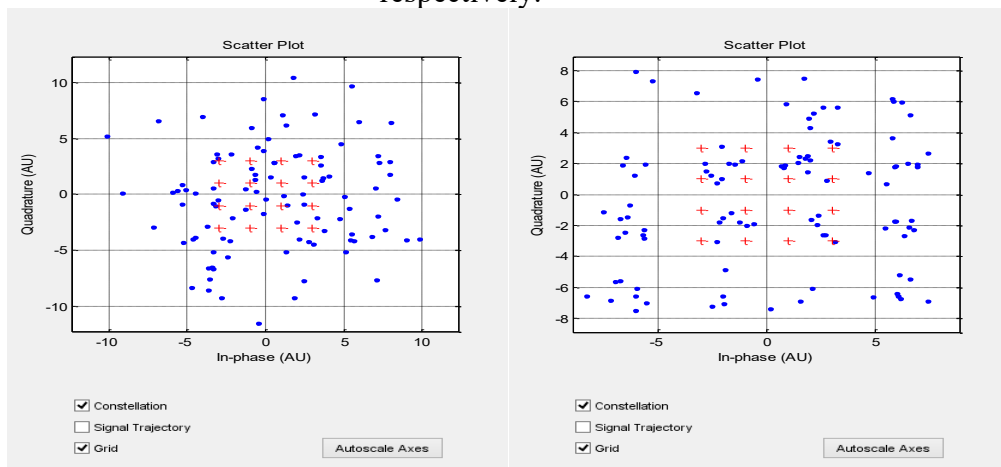


Figure 4: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

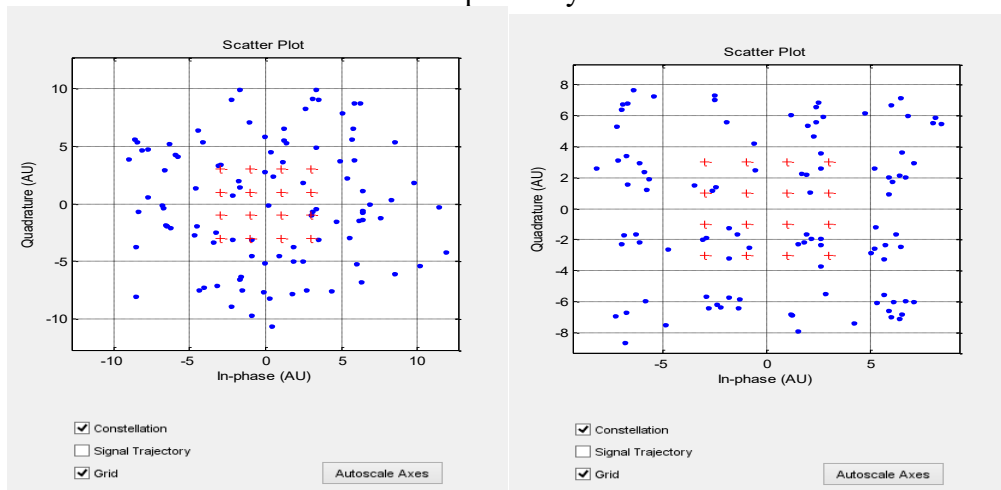


Figure 5: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

Case 1: SNR = 15 dB (Figures 1-5)

In the high SNR range (Figure 1-5), the harmful impact of PA nonlinearity is the main source of distortion. The Saleh model constellations (left) show a lot of clustering and spreading of the 16-QAM points, which is a typical sign of AM-AM and AM-PM distortion (Rapp, 1999). The outer points, which face more amplification compression, get pulled toward the center. In comparison, the constellations for the proposed linear approximation method (right) are much tighter and clearer. The linearization effectively counters the

compression and restores the square shape of the 16-QAM constellation. This visual improvement closely matches the 31.10% reduction in SER and 31.04% reduction in EVM.

Case 2: SNR = 5dB

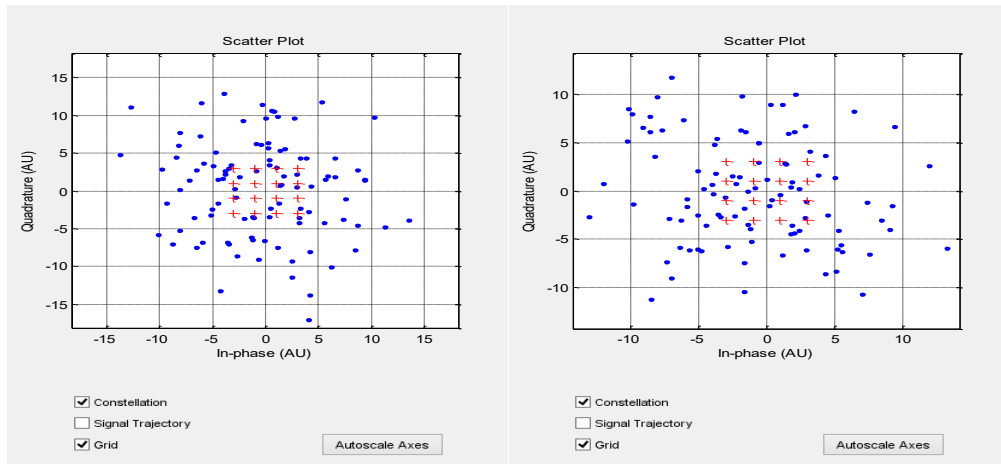


Figure 6: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

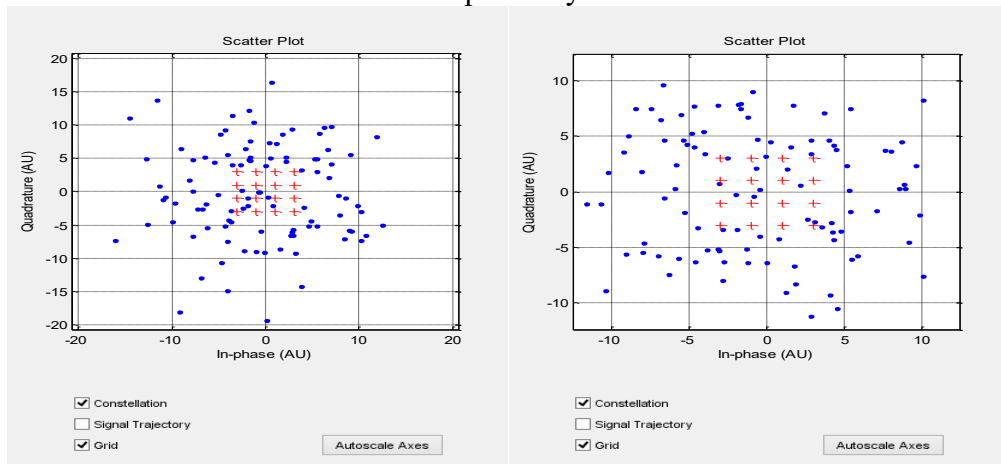


Figure 7: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

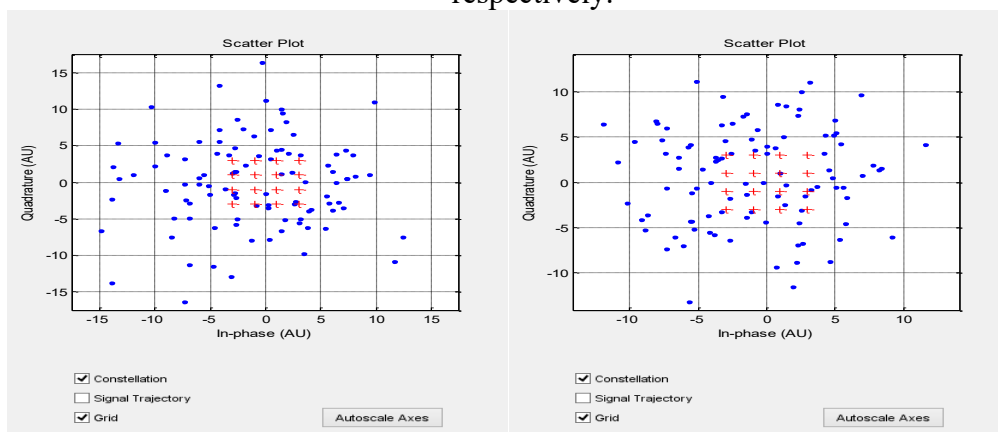


Figure 8: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

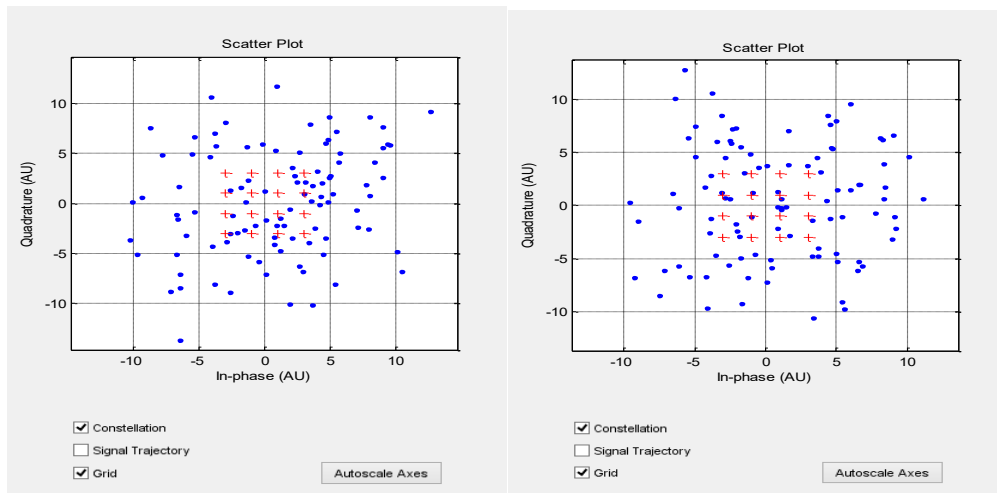


Figure 9: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

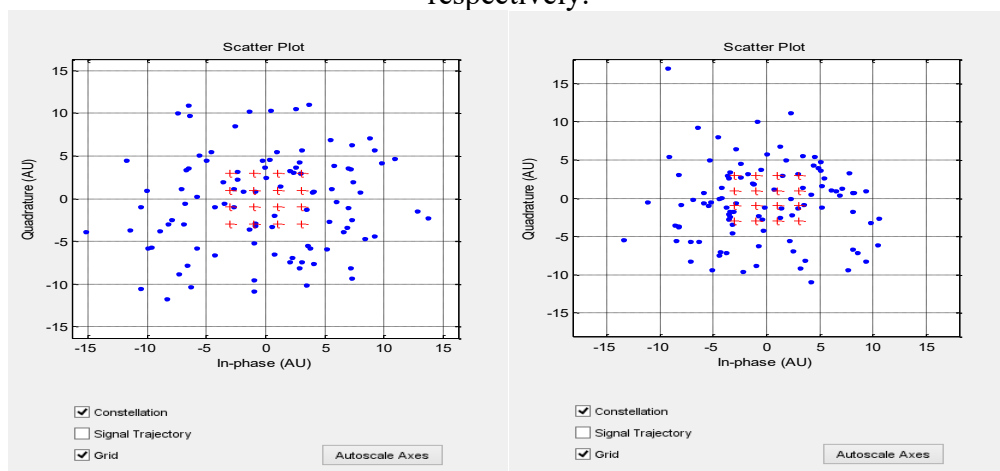


Figure 10: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

Case 2: SNR = 5 dB (Figures 6-10)

At a medium SNR of 5 dB (Fig. 6-10), the constellation diagrams for the Saleh model show clustering from nonlinearity and spreading from AWGN. The proposed method's constellations are also influenced by noise, but they keep a clearer structure. Reducing the intrinsic nonlinear distortion helps the receiver distinguish symbols better in noisy conditions. This results in observed improvements of 19.74% in SER and 24.77% in EVM.

Case 3: SNR = -5dB

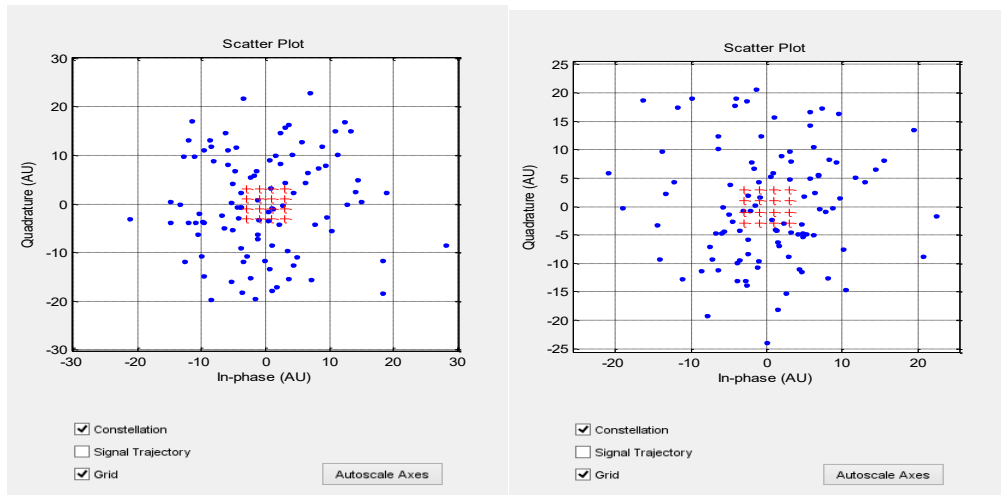


Figure 11: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

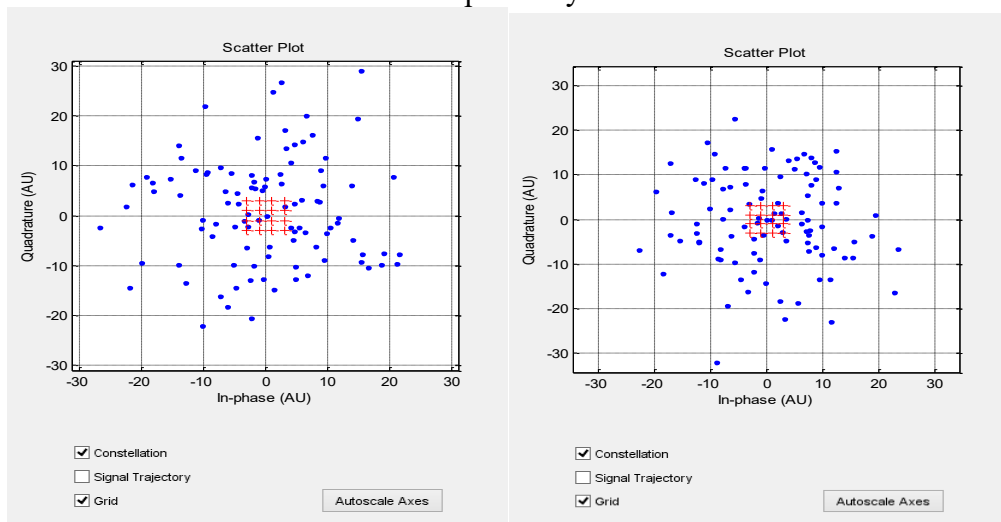


Figure 12: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

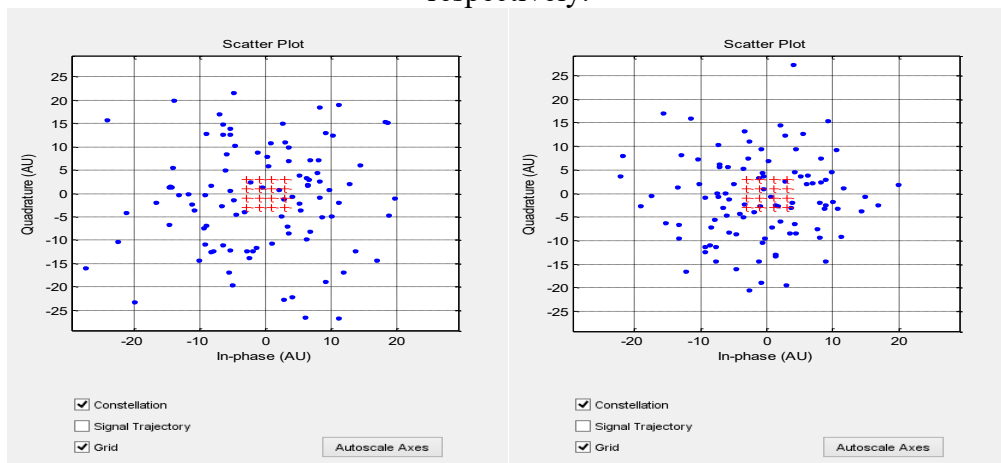


Figure 13: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

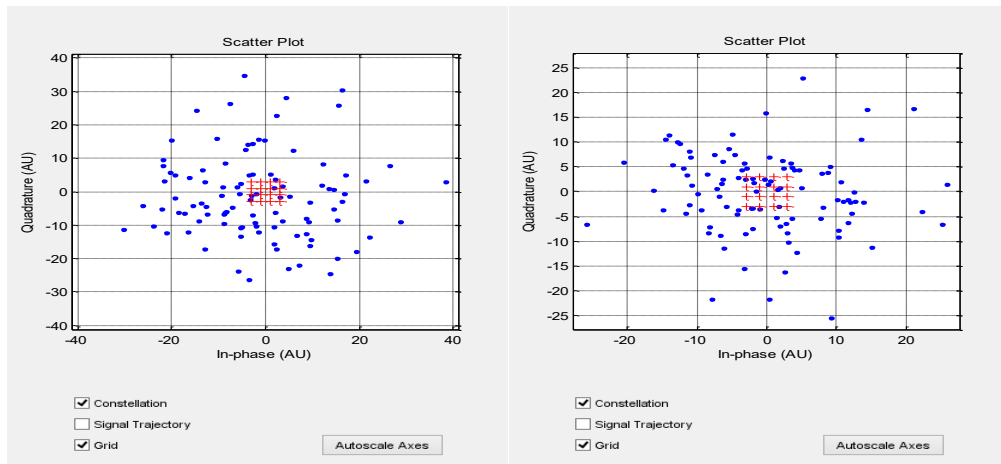


Figure 14: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

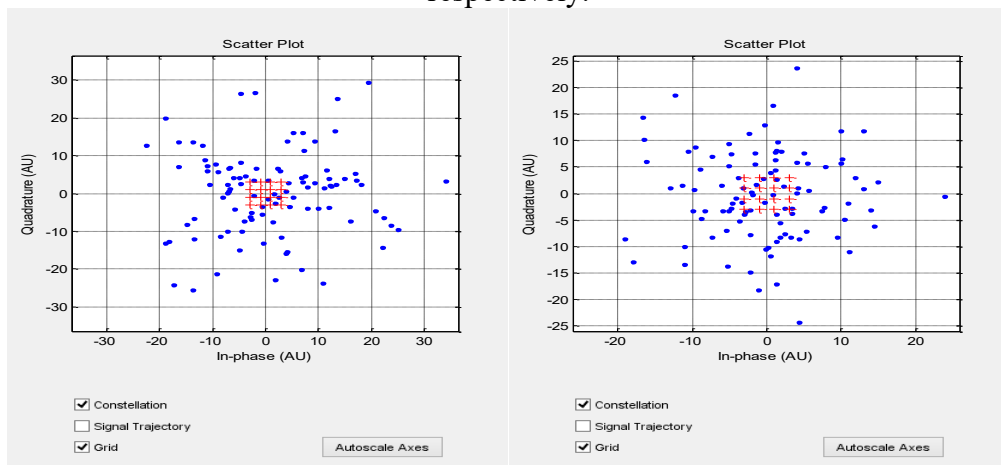


Figure 15: Constellation diagram showing Saleh model and linear approximation on the left and right respectively.

Case 3: SNR = -5 dB (Figures 11-15)

Under severe noise conditions (SNR = -5 dB, Fig. 11-15), the AWGN is the main source of degradation for both models. This is clear from the heavy scattering of points in all diagrams. However, even in this tough situation, the advantages of linearization are noticeable. The constellations for the proposed method show slightly less scattering and a more defined cluster pattern compared to the Saleh model. This small but steady visual improvement matches the 3.37% and 20.28% increases in SER and EVM. This shows that transmitter-side linearization offers a margin of robustness even when noise is the major issue.

4.0 CONCLUSION AND RECOMMENDATIONS

This study has shown how effective a linear approximation method can be in improving the performance of multicarrier communication systems in noisy environments. By linearizing the nonlinear Saleh model power amplifier at the transmitter, the proposed technique greatly reduces in-band distortion. The simulation results, confirmed through SER, EVM, MER, and constellation analysis, show significant performance improvements across a broad range of SNR conditions. The biggest gains were seen at higher SNRs, where nonlinear distortion limits performance. However, measurable improvements were also made under heavy noise, highlighting the method's flexibility.

The main takeaway is that linearization on the transmitter side is a powerful and often overlooked approach. It can help ease the demands on complex receiver-side compensation methods. The performance boost comes from correcting the signal before it gets distorted by the PA nonlinearity and channel noise.

Based on the findings of this work, the following recommendations are made for future research:

- i. Optimization of Approximation Point: The choice of the operating point $a=0.04+j0.04$ was based on observation. Future research should create an effective algorithm to dynamically choose the best linearization point based on the input signal's statistics and the PA's features.
- ii. Investigation of Higher-Order Modulations: Future work should assess the method's performance using higher-order QAM schemes (e.g., 64-QAM, 256-QAM). These schemes are more sensitive to nonlinearities and are common in modern standards like 5G and Wi-Fi 6.
- iii. Robustness in Fading Channels: Analysis should be expanded to include multipath fading channels (e.g., Rayleigh, Rician) to provide a clearer understanding of the technique's performance in real wireless situations.
- iv. Comparison with Other Techniques: A study comparing this linearization method with other techniques, like Digital Predistortion (DPD) or the Doherty architecture (Yadav *et al.*, 2010), would help put its performance and complexity trade-offs in context.

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