PAPER 38 – A SURVEY OF POWER AMPLIFIER SIGNAL LINEARIZATION TECHNIQUES IN COMMUNICATION NETWORKS

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ABSTRACT
Radiofrequency power amplifiers are crucial components of communication networks. The inherent nonlinearity of these components causes in-band distortion, which worsens bit-error-rate performance, and spectrum regrowth, which causes interference in adjacent channels. Out-of-band emission requirements set by regulatory bodies are essentially violated by these distortions. At the output of the power amplifier (PA), crosstalk exists between the antenna branches due to mutual coupling and nonlinear distortion within the transmitted signal. Harmonic distortion is a result of the complexity of modern signal processing techniques and the nonlinear nature of PAs. For high spectral and power efficiency, PAs must operate linearly. Electronic isolators between PAs and antennas can prevent this crosstalk. However, they do not meet the design requirements of modern composite systems. They are rather avoided to achieve a suitable form factor. Very useful linearization strategies are therefore presented and discussed in this survey. The effectiveness of PAs, as well as the complexity and constraints of the system, are always taken into account while choosing the linearization approach. These are effective ways to linearize transmit signals from PA output. The techniques are found effectively suitable in all domains while maintaining the acceptable adjacent channel leakage ratio level.

KEYWORDS: Crosstalk, Distortion, Linearization, Massive MIMO, RF Power Amplifier, 3GPP.

1. INTRODUCTION

The escalating need for higher data rates, spectrum efficiency, and low cost have all been significant problems with cellular communication technology over the years. This demand is growing rapidly as wireless device deployments rise. Numerous radio technologies have also been created to manage the plethora of data-hungry applications that are constantly expanding. One of these essential technologies is massive MIMO (massive multiple input multiple outputs), also known as the advanced antenna system (AAS). Massive MIMO uses hundreds of small, tightly spaced antennas (Suryasarman & Springer, 2015). A representation of the layout is provided below in Figure 1.

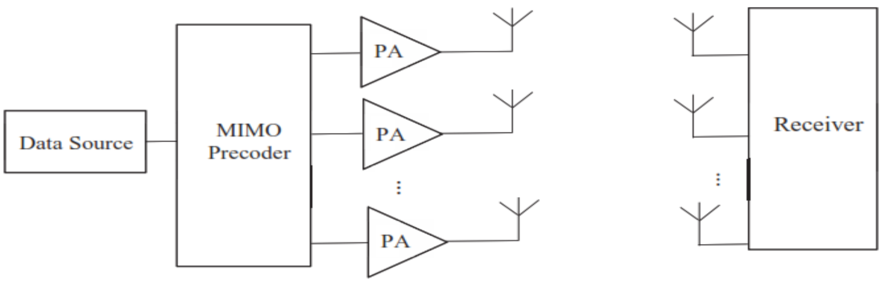

Figure 1. Multiple Input Multiple Output (MIMO) Structure

By using numerous transmitting and receiving antennas, multiple-input and multiple-output (MIMO) radio antenna technology makes use of multipath propagation. By establishing numerous signal paths to transmit the data and choosing specific paths for each antenna, a radio link's capacity can be greatly increased (Bland, 2016). In early developments, MIMO was initially defined as the use of numerous antennas at the transmitter and reception points. The concept is now acknowledged as a practical way to transmit and receive numerous data signals concurrently over a single radio channel using multipath propagation. High data rate broadcasting can be achieved by breaking a high-rate signal into several low-rate signals and sending them from transmitters that are spatially apart. Each receiver uses a variety of antennas to pick up the different cochannel signals that arrive from different angles. The radio frequency (RF) power amplifier (PA) of each transmitter branch, whose simple structure is shown in Figure 2, is crucial to the successful operation of numerous antenna systems. Its task is to increase the sent signal's power to a suitable degree for transmission. Due to its low strength, the produced signal needs to be amplified. This amplification is essential to account for channel route loss between the transmitter and the recipient.

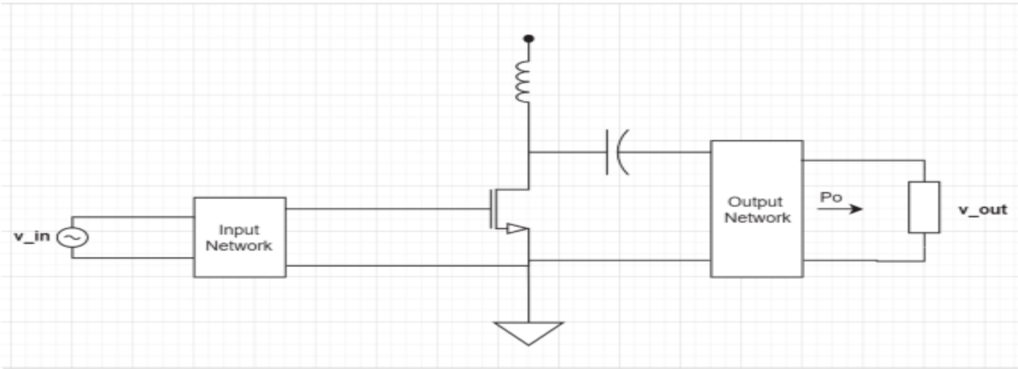

Figure 2. Radio Frequency Power Amplifier

Several technical issues arise at the power amplifier node in communication branches. These include nonlinear behaviour, perceptible signal distortions, and other kinds of interference that degrade the system's general functionality and the signal transmission's integrity (Brihuega et al., 2019). The distortions and irregular behaviour lead to crosstalk and mismatch (Hausmair et al., 2018).

2. THEORETICAL ANALYSIS

To handle both the high data rate and spectrum efficiency issues, newer modulation techniques like Wideband Code Division Multiple Access (WCDMA), Quadrature Amplitude Modulation (QAM), and Orthogonal Frequency Division Multiplexing (OFDM) have been developed. However, the result is a complex signal with a non-constant envelope, and a high peak-to-average power ratio (PAPR) (Jiang & Wu, 2018). At large PAPRs, power amplifiers exhibit nonlinear behaviour, as shown in Figure 3 as signal power fluctuation. The enhanced signal displays spectrum regrowth in such a case (Menon, 2016). This is considered a violation of the Third Generation Partnership Project (3GPP) specifications, which specify the highest allowed adjacent channel leakage ratio (ACLR) for mobile communication protocols (Al-qamaji & Abdalrahman, 2019).

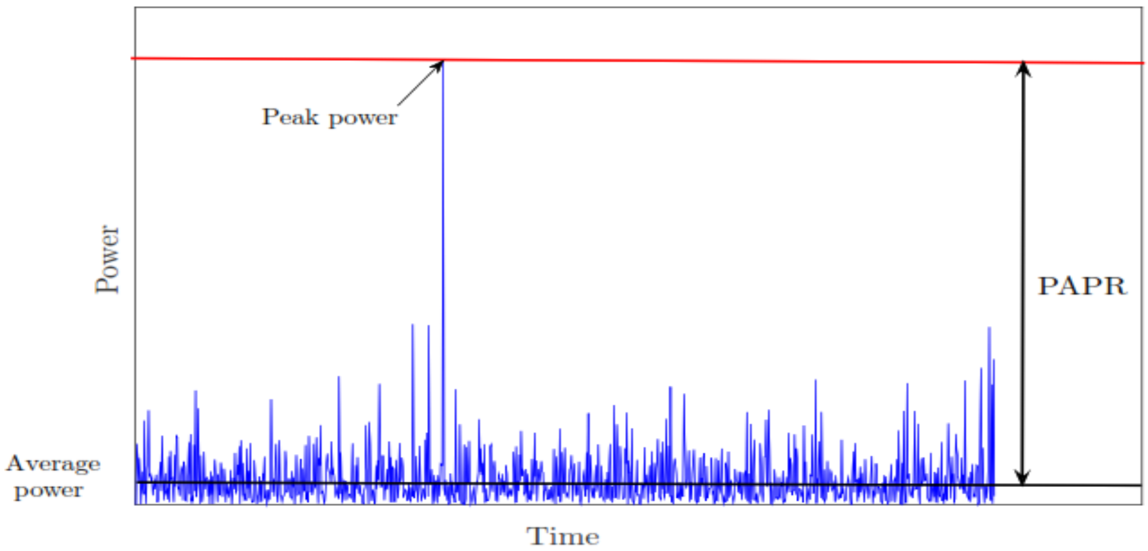

Figure 3. Power Fluctuation of Signal with High PAPR (Cheaito, 2017).

If the PAPR is strong, a high linear power amplifier is required at the transmitter. The linearity requirements can be met by lowering the PA far below its saturation limit. This leads to poor power efficiency which is especially unwanted in a mobile transmitter (Wan et al., 2015). Figure 4 below depicts the output response of PA.

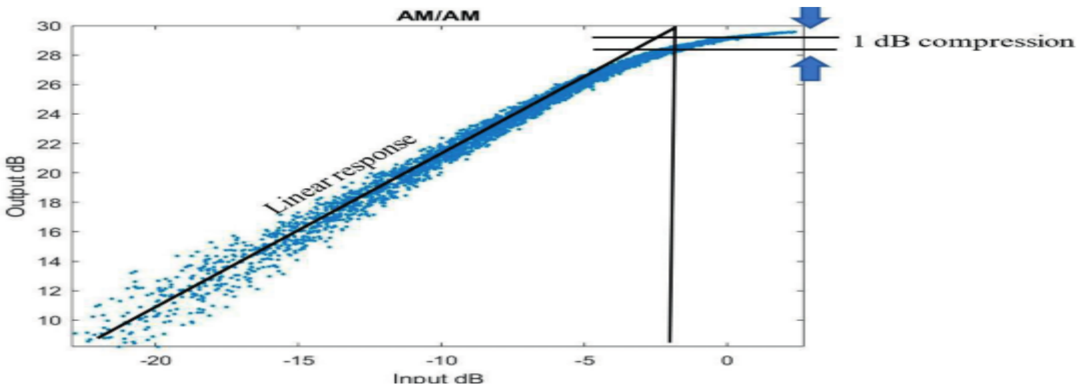

Figure 4. Power Amplifier Output Response.

When the PA is pushed above the linear zone, nonlinear distortion effects occur. Nonlinear distortion, which also creates harmonics and intermodulation signals outside of the intended frequency range, makes it more difficult to receive the signal. These unwanted distortion products, especially in adjacent frequency bands, conflict with other radio interface users (Jantunen, 2016). Both the 4G with MIMO and the 5G with massive MIMO have these naturally unfavourable effects, such as nonlinear before-PA, crosstalk on the transmitter side, and antenna crosstalk on both sides. Operation regions of the power amplifier are shown in the characteristics graph of figure 5. Power amplifiers must be run close to the compression region in order to achieve high power efficiency, which inevitably causes non-linear distortion of the output signal. Crosstalk is thus one of the challenges in the design of MIMO transceivers. It is present between different transmit and receive paths that are built in a single chipset (Bassam et al., 2019).

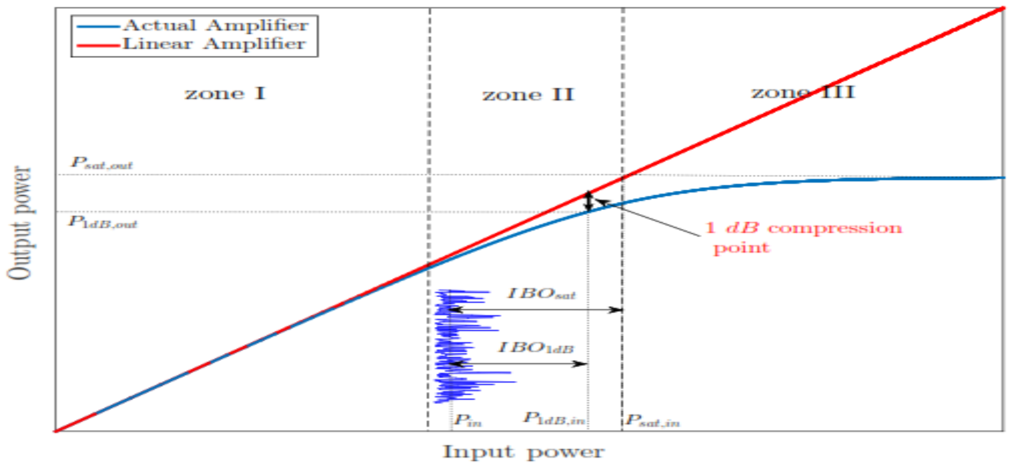

Figure 5. Power Amplifier Characteristics: Linear, Compression and Saturation Zones.

For situations where real antenna arrays driven by power amplifiers are not physically built, effective simulation environments are accessible. MATLAB, SIMULINK, and CADENCE are a few of them. These programming environments can be used to model, simulate, and evaluate dynamic systems and are all-purpose. Particularly for visualizing data and functions, working with matrices, and implementing algorithms, they offer a superior user interface. Mathematical tools as given below are some of the useful computational apparatus that can provide essential parameters where necessary:

i. Volterra Series: The finest methods for capturing and modelling the behaviours of nonlinear systems and functions are the Taylor and Volterra series. Taylor series can easily approximate the response of a nonlinear system to a specific input if the output of the system depends on the current value of the input. The Volterra Series is a functional extension of a dynamic, nonlinear, and time-invariant system. Because it can account for the memory effect, it is always simplified to a Memory Polynomial (MP) model equation.

ii. Normalized Mean Square Error, NMSE: This is a figure of merit that provides a measurement for the model accuracy and in-band distortion. It gives the difference between the actual measurement and the desired received signal. NMSE is determined using equation 1.

$$NMSE_{(Y_{desired} - Y_{actual})} = \frac{\sum_{n=0}^{N-1} |Y_d(n) - Y(n)|^2}{\sum_{n=0}^{N-1} |Y_d(n)|^2} \quad (1)$$

Y(n) denotes the measured signal at the output of the amplifier and Y_d (n) is the desired output signal.

iii. Adjacent Channel Leakage Ratio, ACLR: When a power amplifier is fed a wide band transmission signal, the output shows a noticeable frequency regrowth. This effect is also known as out-of-band distortion. This can be precisely captured and compared to known ACLR values from important performance indicators provided by standard organizations with the appropriate simulation tools. The ratio between the main signal and the power intermodulation signal is an indicator of quality. It can be defined as the ratio of the transmitted signal's power in the main or desired channel to that of the channel next to it as shown in equation 2.

$$ACLR = \frac{\int_{BW_{adj}} |Y(f)|^2 df}{\int_{BW_{main}} |Y(f)|^2 df} \quad (2)$$

Where Y(f) is the transmitted signal in the frequency domain, BW_{adj} is the signal bandwidth of the adjacent channel and BW_{main} is the signal bandwidth of the main channel. Both signals are assumed to have the same bandwidth.

iv. Least Square Method: This is generally a standard approach in regression analysis to approximate the solution of overdetermined systems by minimizing the sum of the square of the residuals made in the result of every single equation.

3. LINEARIZATION TECHNIQUES

Very nonlinear power amplifiers are used to drive the antenna components in communication systems and networks, resulting in significant nonlinear distortion (Brihuega et al., 2019). The radio frequency output signal exhibits spectrum regrowth due to the power amplifier's nonlinear behaviour in the frequency domain. Digitally modulated signals' spectrum widening creates neighbouring channel interference. In addition to spreading the transmitted spectrum, distortion also produces intersymbol interference, which increases the bit error rate (BER), thus contravening FCC regulations and 3GPP guidelines. This suggests that components such as power amplifiers and other parts must be linear. But for PA to display power efficiency, it must be operated in the nonlinear region. Using linearization techniques, this highly desired linear amplification is attained. The pre-distortion approach, the feedback method, and the feed-forward method are the three primary linearization techniques. These primary classes also have further variations as shown below. Figure 6 shows the linearization techniques.

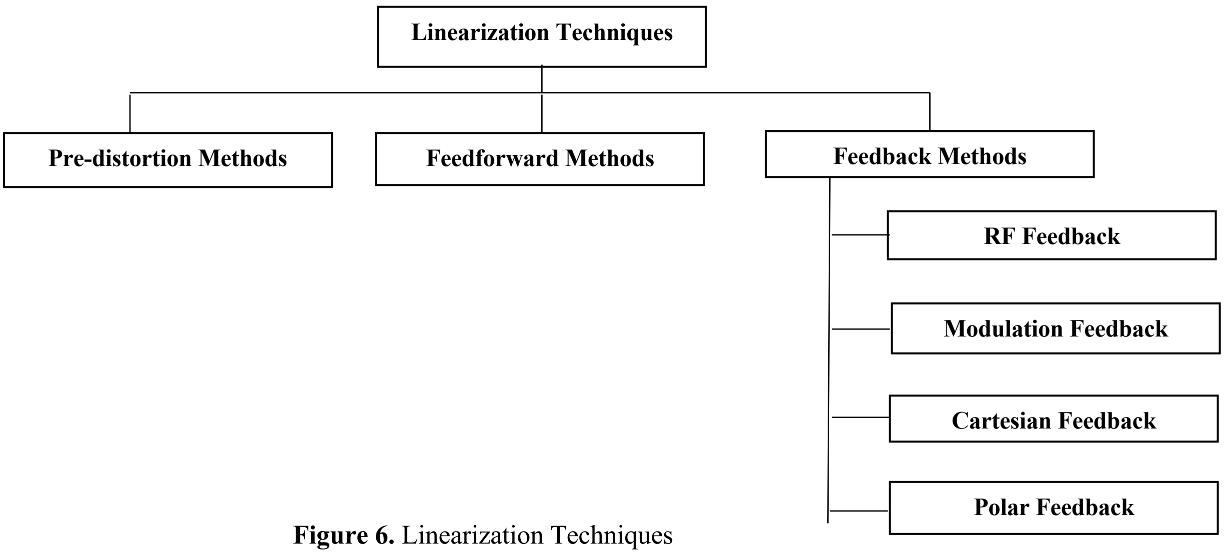

Figure 6. Linearization Techniques

3.1 FEEDFORWARD METHOD

This approach adds the radio frequency power amplifier output distortion to the PA output in the opposite phase after being extracted and amplified. Over time, this eliminates the distortion. Due to the error amplifier's high-power requirements and necessity for linearity, the approach has a low power efficiency (Goyal & Gupta, 2015). The couplers also cause a loss of power. The advantage, though, is in its capacity to lower distortion over a broad bandwidth. Also, the technique involves both phase and gain modifications, which makes implementation extremely challenging. The block diagram is displayed in figure 7.

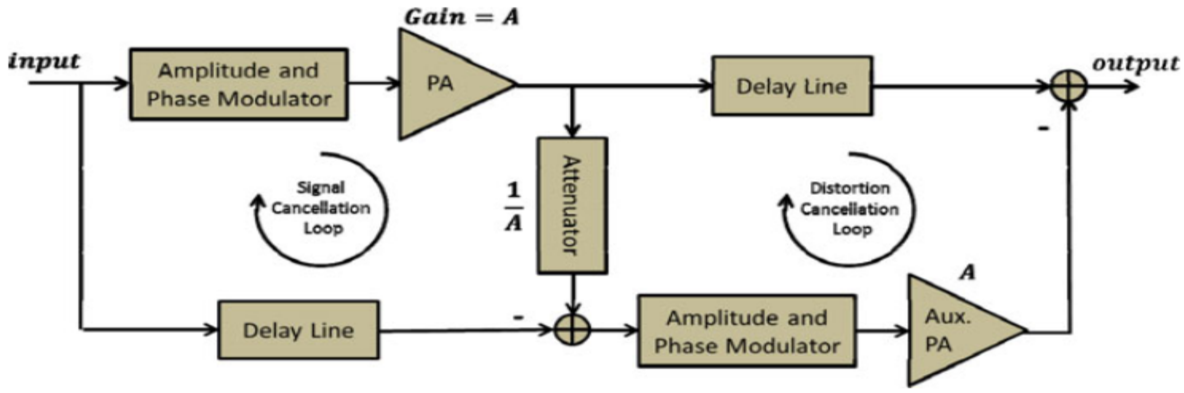

Figure 7. Block Diagram of Feedforward Linearization Technique (Cheaito, 2017).

3.2 FEEDBACK METHOD

One of the easiest methods for linearizing power amplifiers is the feedback technique. The goal is to make the output adhere to the PA's input. The controller, as depicted below, feeds back a portion of the output signal from the PA (Yadav, 2016). This is taken away from the power amplifier's input signal. As a result, the output is effectively optimized to be a linear and amplified representation of the input signal. Polar and Cartesian feedback are subtypes of the two fundamental types, RF feedback and modulation feedback as shown in Figure 8.

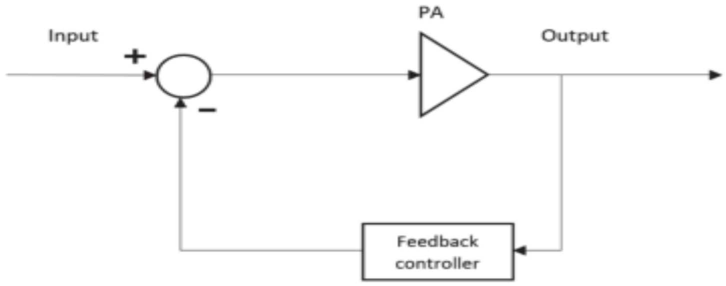

Figure 8. Feedback Linearization Method.

3.3 DIGITAL PRE-DISTORTION METHOD

The goal is to expand the input signal before the power amplifier so that the non-linearities caused by the PA can be balanced out (Kenney et al., 2015). To make the combined transfer characteristic of the RF power amplifier and the nonlinear device before it, linear, the notion entails the inclusion of the nonlinear element. Predistortion can be accomplished at either RF or baseband.

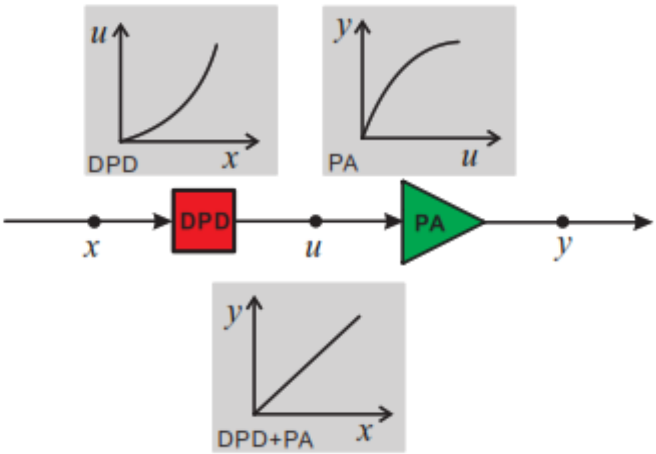

Figure 9. Principles of Pre-distortion Method (Guan & Zhu, 2017).

4. CONCLUSION

The crucial and inherently nonlinear behaviour of radio frequency power amplifiers was examined in this paper, as well as the long-term impact on performance estimation of modern antenna systems used in communication networks. Power amplifiers are essentially nonlinear devices, and the signal processing methods also clearly show that there is signal distortion. The bit-error rate is lowered by the in-band distortion and out-of-band distortion results in spectrum broadening, which causes interference in adjacent channels. By correctly activating the power amplifiers in every transmitting branch such that their output signals are linear and amplified versions of the input RF signal, energy and spectrum efficiency as well as overall system performance are significantly improved.

A figure of merit called the adjacent channel leakage ratio (ACLR) shows the proportion between the main signal and the power intermodulation signal. Comparisons can be made between the out-of-band distortion measured using the proper simulation tool and data from common regulatory organizations like the third-generation partnership project (3GPP). The details presented in this paper adequately provide very insightful and generic linearization concepts to the researchers in the field. The strategies that were just explained have their respective pros and disadvantages. System complexity and application area are the deciding factors for any technique selection.

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