

# Research and Experimental Verification of RF Distortion Calibration and Self-Interference Suppression Techniques in Multi-Antenna Full-Duplex Systems

Keng-Hwa Liu \*, Juinn-Horng Deng\*, Min-Siou Yang \*

\*Department of Electrical Engineering, Yuan Ze University, 135 Yuan-Tung Road, Chung-Li, Taoyuan, Taiwan  
s1088601@mail.yzu.edu.tw , jh.deng@saturn.yzu.edu.tw, s1114804@mail.yzu.edu.tw

**Abstract**—Complex distortion cancellation methods are often used at the radio frequency (RF) front end of multiantenna full-duplex transceivers to mitigate signal distortion; however, these methods have high computational complexity and limited practicality. To address these problems, the present study explored the complexities associated with such transceivers to develop a practical multistep approach for suppressing distortions arising from in-phase and quadrature (I/Q) imbalance, nonlinear power amplifier (PA) responses, and multipath self-interference caused by simultaneous transmissions on the same frequency. In this approach, the I/Q imbalance is estimated and then compensated for, following which nonlinear PA distortion is estimated and pre-compensated for. Subsequently, an auxiliary RF transmitter is combined with linearly regenerating self-interference signals to achieve full-duplex self-interference cancellation. The proposed method was implemented on a software-defined radio platform, with the distortion factor calibration specifically optimized for multiantenna full-duplex transceivers. Experimental results demonstrate that the method has high potential for enhancing the performance of multiantenna RF full-duplex systems.

**Keywords**—multi-antenna full-duplex systems, I/Q imbalance, self-interference, power amplifier nonlinear distortion, digital predistortion.

## I. INTRODUCTION

Wireless communication systems primarily operate in half-duplex mode because of the substantial self-interference that arises from simultaneous transmission and reception on the same frequency band. Despite the potential for higher spectrum efficiency in wire-less full-duplex transmission, effectively mitigating self-interference for full-duplex wireless receivers remains a critical challenge [1]. To address this problem, the present study developed an innovative approach for suppressing distortions that arise from in-phase and quadrature (IQ) imbalance, nonlinear power amplifier (PA) responses, and self-interference caused by simultaneous transmissions on the same frequency in radio frequency (RF) communication systems. Existing methods for mitigating RF signal distortion, such as antenna separation and self-interference cancellation, are limited by their demands on computational capacity and by the physical size of the hardware used to run them [2]. To overcome these limitations, active RF cancellation architecture and compensation rules are used in the proposed method [3], with direct RF cancellation

of self-interference signals conducted at the receiver. This method differs from the receiver-side interference suppression technique proposed in [4] and ensures that subsequent components, such as the low-noise amplifier, do not exacerbate the nonlinear distortion induced by self-interference. In the proposed method, an auxiliary transmission path is employed to actively cancel self-interference by combining channel response parameters with an active RF cancellation filter. In contrast to complex distortion cancellation methods, the proposed method involves using the least mean square (LMS) approach [5,6] to estimate channel response parameters, thus facilitating the estimation of generalized linear filter parameters for the auxiliary path [7]. The progressive compensation for individual distortion factors, including IQ imbalance (IQI) [8] and nonlinear PA response [9] in the proposed method, enables sequential suppression of all types of distortion, ultimately facilitating successful full-duplex communication. Traditional digital predistortion (DPD) techniques require the acquisition of all non-linear growths in signal bandwidth for algorithm processing. More information is required to characterize the bandwidth growth of a larger-bandwidth signal.

## II. PROPOSED METHOD

RF distortions at the transmitter are caused by the following factors: IQ imbalance; nonlinearity in PA responses; self-interference in multiple-input, multiple-output (MIMO) operation; and RF cancellation. The block diagram of the proposed multiantenna full-duplex transceiver system is displayed in Figure 1. This system contains a predistortion compensation system for the transmitter, which is essential for realizing robust, multiantenna full-duplex communication.

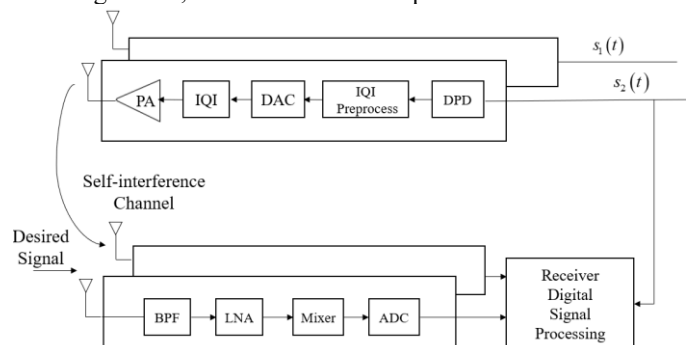


**Figure 1.** Block diagram of the proposed multiantenna full-duplex communication system with distortion compensation.

The transceiver of the proposed system comprises distinct transmission and reception units, each of which uses similar signal-processing methodologies. At the transmitter end, the following RF distortion factors are sequentially processed.

This study developed a method to address the limitations of existing methods for distortion estimation, pre-compensation, and self-interference cancellation. The steps involved in the proposed method are displayed in Figure 2.

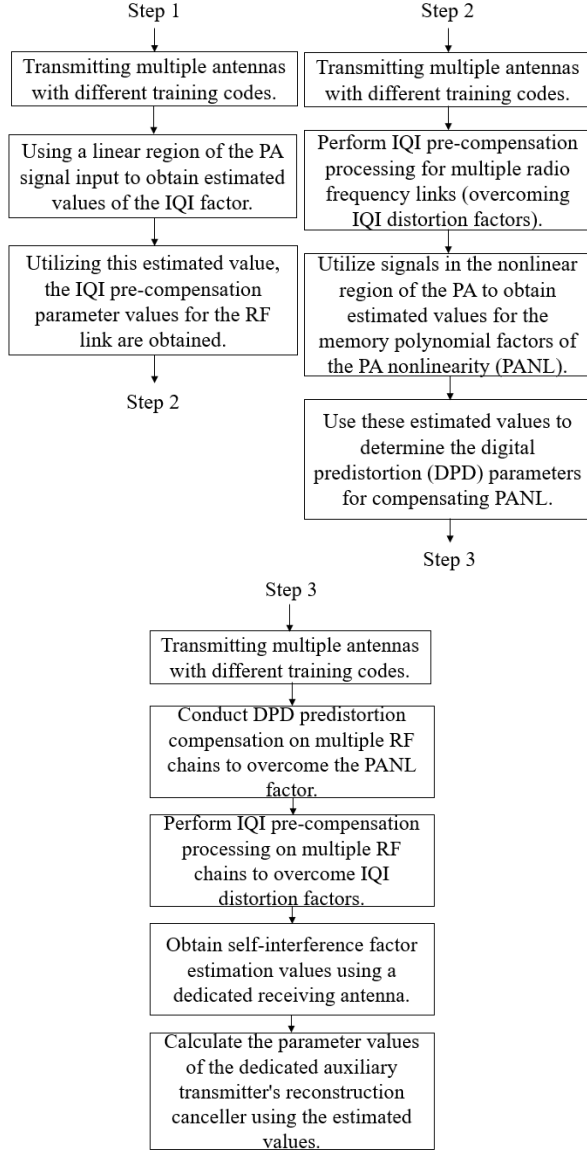


**Figure 2.** Steps involved in the proposed method.

Step 1 of the proposed method involves estimation of the IQ imbalance, Step 2 involves the estimation of the nonlinear PA distortion, and Step 3 involves using an RF canceller to mitigate self-interference. Initially, algorithms were employed from theoretical study and simulation analysis. Subsequently, the developed method was experimentally validated by implementing it on a software-defined radio platform. The ultimate objective was to create a platform that seamlessly integrates RF modules with field-programmable gate arrays

(FPGAs) and suppresses all types of RF distortion.

#### A. Compensation for IQ Imbalance

The estimated channel response, which includes the IQ imbalance, is used to calculate pre-compensation parameters for the auxiliary path. This process enables the design of an active RF generalized linear filter for distortion cancellation. Figure 3 shows the architecture developed for the active cancellation of RF self-interference signals in the main signal transmission path.

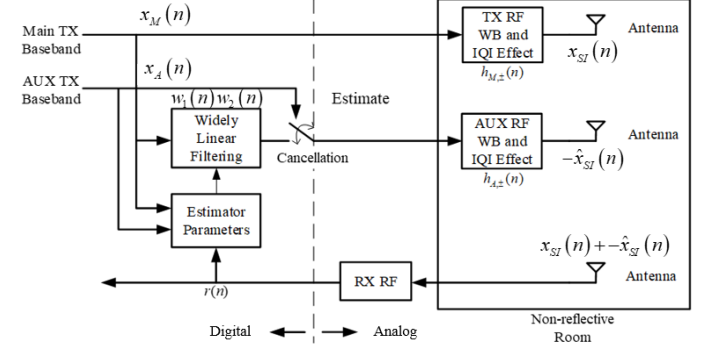


**Figure 3.** Architecture for the active cancellation of RF self-interference signals in the main transmission path.

The block diagram of the channel responses is shown in Figure 4.

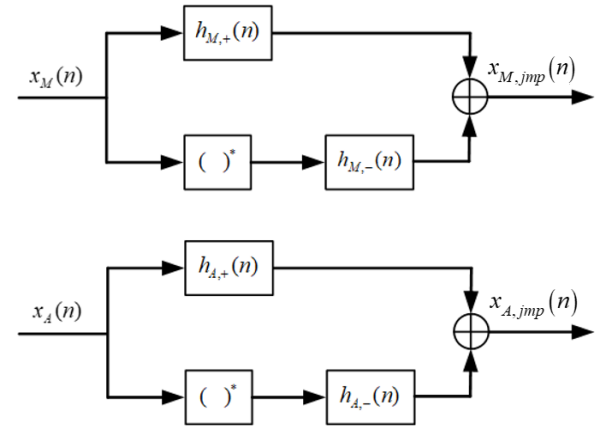


**Figure 4.** Block diagram of the channel responses and IQ imbalance in the main and auxiliary paths.

Figure 3 and 4 indicate that the transmission signals in the main path and auxiliary path are affected by IQ imbalance. This imbalance must be estimated with the channel response. A general linear filter is used on the received signal  $r(n)$  to estimate the pre-compensation values  $w_1(n)$  and  $w_2(n)$ , which are used to cancel the real and image signals, respectively. The parameters  $w_1(n)$  and  $w_2(n)$  are substituted into the aforementioned filter to obtain the reconstructed reverse  $x_{SI}(n)$  signal, where  $-\hat{x}_{SI}(n) = -x_{SI}(n)$ . Moreover,  $x_{SI}(n) + (-\hat{x}_{SI}(n))$  is set to approach 0 to improve the system performance. The IQ imbalance and channel estimation parameters (Figure 3) are determined using the signal  $r(n)$ .

This signal comprises two known training code I/Q signals, namely,  $x_M(n)$  and  $x_A(n)$ , which are transmitted on the main and auxiliary paths, respectively, and are affected by IQ imbalance. After these signals are transmitted into the air through the antenna, the demodulated received signals with IQ imbalance for the main and auxiliary paths are generated ( $h_{M,\pm}(n)$  and  $h_{A,\pm}(n)$ , respectively). Therefore,  $r(n)$  can be expressed as follows:

$$r(n) = \{h_{M,+}(n) \otimes x_M(n) + h_{M,-}(n) \otimes x_M^*(n)\} \\ + \{h_{A,+}(n) \otimes x_A(n) + h_{A,-}(n) \otimes x_A^*(n)\} \quad (1)$$

where  $x_M(n)$  represents the known quadrature phase-shift keying (QPSK)-modulated signal emitted by the main path with IQ imbalance,  $x_A(n)$  denotes the known QPSK-modulated signal emitted by the auxiliary path with IQ imbalance, and  $h_{M,\pm}(n)$  refers to the RF filter channel response for the main path with IQ imbalance. This response is expressed as follows:

$$h_{M,\pm}(n) = \frac{1}{2} [h_M^I(n) \pm \alpha_M e^{j\theta_M} h_M^Q(n)] \quad (2)$$

where  $h_M^I(n)$  and  $h_M^Q(n)$  represent the combined impulse response of the I/Q filters in the main path,  $\alpha_M$  and  $\theta_M$  represent the amplitude and phase imbalances, respectively, of the I/Q components in the main path. Moreover,  $h_{A,\pm}(n)$  represents the RF filter channel response of the auxiliary path affected by the IQ imbalance. This response is expressed as follows:

$$h_{A,\pm}(n) = \frac{1}{2} [h_A^I(n) \pm \alpha_A e^{j\theta_A} h_A^Q(n)] \quad (3)$$

where  $h_A^I(n)$  and  $h_A^Q(n)$  represent the combined impulse response of the I/Q filters in the auxiliary path,  $\alpha_A$  and  $\theta_A$  denote the amplitude and phase imbalances, respectively, of the I/Q components in the auxiliary path. The unknown channel response values  $h_{M,\pm}(n)$  and  $h_{A,\pm}(n)$  can be estimated using the LMS method. The recursive relationships for  $\hat{h}_{M,+}$ ,  $\hat{h}_{M,-}$ ,  $\hat{h}_{A,+}$ , and  $\hat{h}_{A,-}$  are expressed as follows:

$$\begin{aligned} \hat{h}_{M,+}[n+1] &= \hat{h}_{M,+}[n] + \mu \cdot e[n] \cdot x_M[n-l] \\ \hat{h}_{M,-}[n+1] &= \hat{h}_{M,-}[n] + \mu \cdot e[n] \cdot x_M^*[n-l] \\ \hat{h}_{A,+}[n+1] &= \hat{h}_{A,+}[n] + \mu \cdot e[n] \cdot x_A[n-l] \\ \hat{h}_{A,-}[n+1] &= \hat{h}_{A,-}[n] + \mu \cdot e[n] \cdot x_A^*[n-l] \end{aligned} \quad (4)$$

### B. Compensation for Nonlinear PA Response

A PA is a crucial component of a transmitter, and it must achieve high efficiency and linearity. Nonlinearity in the PA

response can cause spectral regrowth, leading to interference in neighbouring channels. Such nonlinearity can be represented using a memory polynomial (MP) model [10], which is expressed as follows:

$$y(n) = \sum_{k=1}^K \sum_{m=0}^M b_{km} x(n-m) |x(n-m)|^{k-1} \quad (5)$$

where  $k$  is the polynomial order,  $m$  denotes the memory depth,  $b_{km}$  represents the parameters of the MP model (nonlinear channel),  $x(n)$  denotes the original signal source, and  $y(n)$  is the nonlinear output signal of the PA. The MP model described in Equation (5) and an indirect learning architecture (ILA) are employed for DPD. According to the ILA, Equation (5) can be reformulated as follows:

$$x(n) = \sum_{k=1}^K \sum_{m=0}^M a_{km} y(n-m) |y(n-m)|^{k-1} \quad (6)$$

where  $a_{km}$  is a DPD parameter. This parameter can be derived using the least squares method as follows:

$$\mathbf{a} = (\mathbf{Y}^H \mathbf{Y})^{-1} \mathbf{Y}^H \mathbf{x} \quad (7)$$

where  $\mathbf{Y}$  is the matrix of basic functions for the received signal  $[y(n)]$  computed using the MP model and  $\mathbf{y}_{kp}$  is the vector of  $[y(n)]$ . This matrix is defined as follows:

$$\mathbf{y}_{kp} = [y_{kp}(0), \dots, y_{kp}(N-1)]^T \quad (8)$$

$$\mathbf{Y} = [\mathbf{y}_{10}, \dots, \mathbf{y}_{K0}, \dots, \mathbf{y}_{1P}, \dots, \mathbf{y}_{KP}]^T$$

The dimensions of  $\mathbf{Y}$  are  $N \times L$ , where  $N$  is the signal length and  $L$  represents the number of DPD parameters.  $\mathbf{a}$  and  $\mathbf{x}$  in Equation (7) are expressed as follows:

$$\mathbf{a} = [a_{10}, \dots, a_{K0}, \dots, a_{1P}, \dots, a_{KP}]^T \quad (9)$$

$$\mathbf{x} = [x(0), \dots, x(N-1)]^T$$

A distinctive feature of the proposed DPD technique is that it requires prior compensation of the IQ imbalance.

### C. Active RF Preprocessing Techniques for Addressing Multiantenna Self-Interference

This section focuses on the self-interference encountered in multiantenna systems by describing advanced compensation techniques for improving the overall transmission performance of multiantenna communication systems.

Figure 5 displays the architecture of a generalized linear cancellation filter for the pre-compensation parameters, i.e., and  $w_2(n)$  in the auxiliary path.

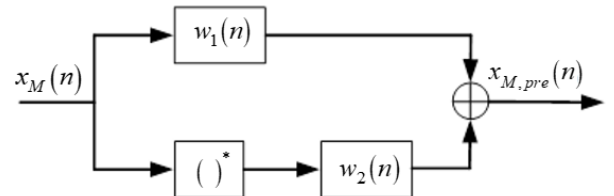


Figure 5. Block diagram of a generalized linear cancellation filter for the pre-compensation parameters

The main and auxiliary paths contain the same signal  $x_m(n)$ ; however, the pre-compensation parameters  $w_1(n)$  and  $w_2(n)$  must be determined for the signal transmitted through the auxiliary path to generate the reconstructed inverse signal. The parameters  $w_1(n)$  and  $w_2(n)$  are determined through the least squares method by using a pseudoinverse matrix as follows:

$$\begin{bmatrix} w_1(n) \\ w_2(n) \end{bmatrix} = -(\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \begin{bmatrix} h_{M,+}(n) \\ h_{M,-}(n) \end{bmatrix} \quad (10)$$

where  $\mathbf{H} = \begin{bmatrix} \mathbf{H}_{A,+} & \mathbf{H}_{A,-} \\ \mathbf{H}_{A,-}^* & \mathbf{H}_{A,+}^* \end{bmatrix}$ . Moreover,  $\mathbf{H}_{A,+}$  and  $\mathbf{H}_{A,-}$  are the Toeplitz matrix forms of  $h_{A,+}(n)$  and  $h_{A,-}(n)$ , respectively.

### III. SIMULATION AND EXPERIMENTAL VERIFICATION OF THE PROPOSED METHOD

#### A. Simulation Verification of the Elimination of RF IQ Imbalance

The first simulation scenario addressing the IQ imbalance issue corresponds to the process shown in Figure 2. In the first stage, the PA operates in its linear region, where the IQ imbalance parameter estimation and pre-compensation are performed. The condition assumed a phase imbalance of  $2^\circ$  and an amplitude imbalance of 2 dB. The simulation results for the four IQ imbalance parameters (as defined in Equation (4)) are shown in Figure 6.

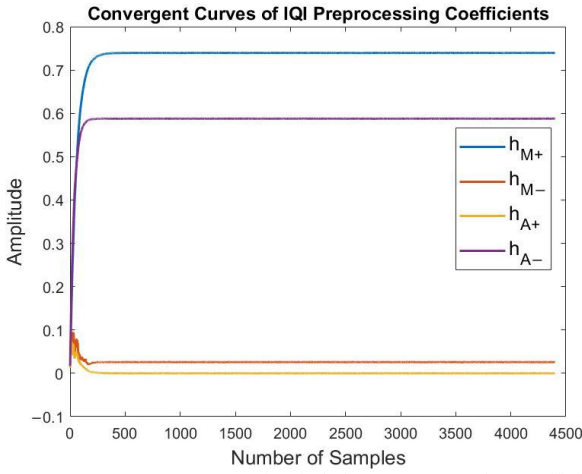


Figure 6. Convergent curves of IQ imbalance preprocessing coefficients.

The four IQ imbalance parameters converged after approximately 300 samples. As shown in Figure 7, after applying IQ imbalance pre-compensation, the image tone of the single-tone signal was suppressed by about -61 dB, with its amplitude reduced from 6546.76 to 5.83. The above simulations confirm the excellent IQ imbalance suppression performance achieved in Step 1 of Figure 2.

(a)

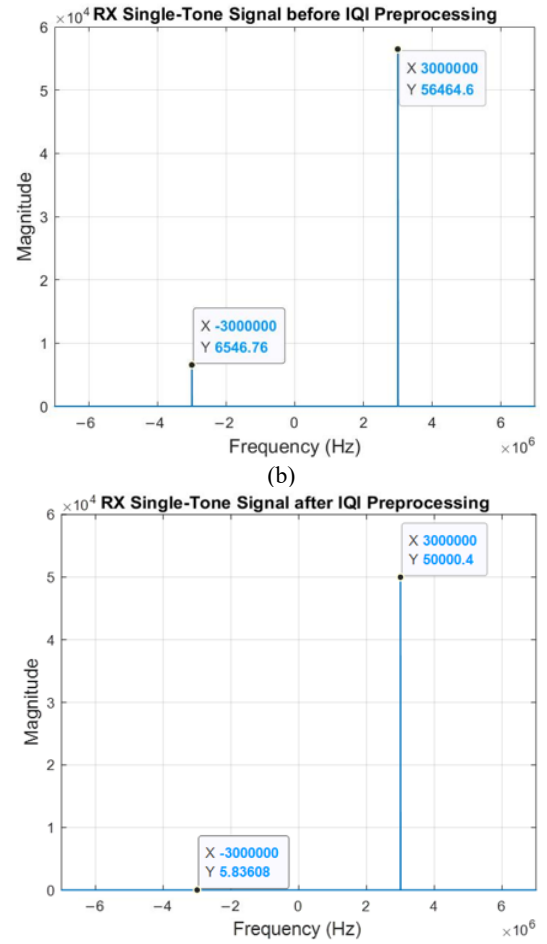


Figure 7. With phase imbalance of  $2^\circ$ , (a) RX single-tone signal before IQ imbalance preprocessing. (b) RX single-tone signal after IQ imbalance preprocessing.

#### B. Experimental Verification of the Compensation for Nonlinear PA Response

The second simulation investigated the combined effects of IQ imbalance and nonlinear PA distortion. This scenario corresponded to the integrated process of Step 1 and Step 2 in Figure 2, where IQ imbalance pre-compensation was first applied, followed by nonlinear PA pre-compensation. The spectra before and after IQ imbalance/DPD preprocessing are presented in Figure 8.

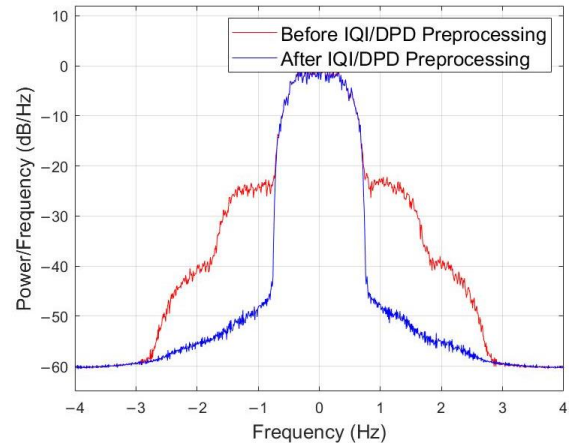
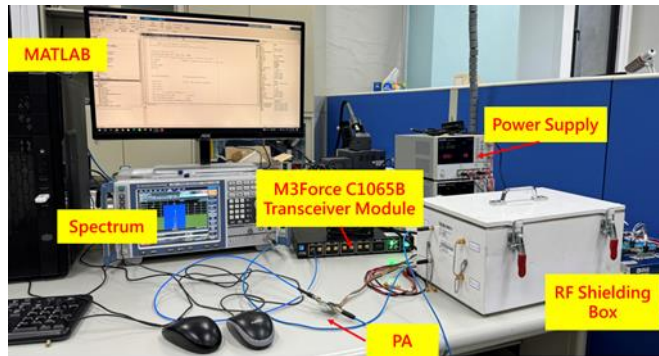
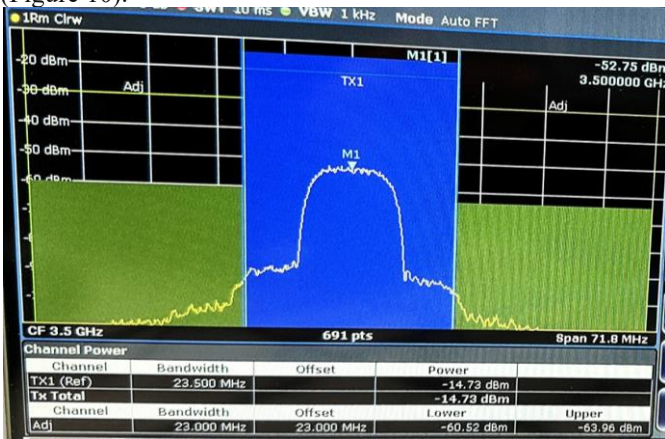


**Figure 8.** IQ imbalance/DPD preprocessing simulation comparison.

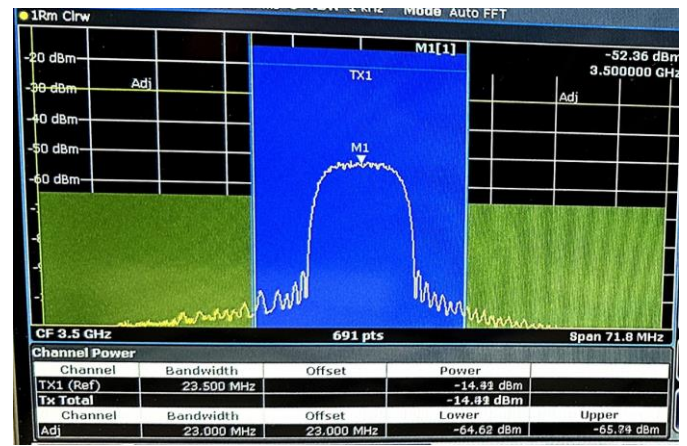
To validate the proposed method, we used a software-defined radio (SDR) platform. The signal modified based on the compensation parameters was transmitted through the M3Force C1065B transceiver module to the spectrum. The experimental setup is depicted in Figure 9.

**Figure 9.** Experimental setup for validating the proposed method.

Step 2 (Figure 2) of the proposed method was conducted using Equations (6) and (7) to compute the DPD response parameters. First, an original 16-QAM signal with an IQ imbalance was generated using MATLAB. This signal was transmitted through the M3force C1065B transceiver module, including the PA, to introduce a nonlinear PA response into it (Figure 10).

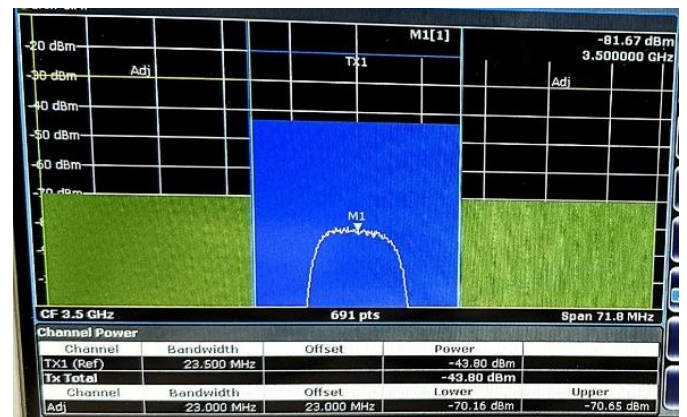
**Figure 10.** Spectrum plot of a 16-QAM signal with a nonlinear PA response.

Second, a 16-QAM signal that was pre-compensated for IQ imbalance was generated. This signal was then passed through the DPD block of the PA DPD to obtain DPD coefficients. Third, the signal with DPD coefficients was transmitted through the M3force C1065B transceiver module, including the PA, to add a nonlinear PA response to it. The compensation effects were then analyzed using a spectrum analyzer. The results (Figure 11) reveal a reduction of approximately 4 dB in adjacent channel power (compared with Figure 10). This finding demonstrates the effectiveness of the proposed method in addressing a nonlinear PA response.

**Figure 11.** Spectrum analysis results obtained after adding a nonlinear PA response to the signal with DPD coefficients.

### C. Experimental Verification of the Compensation for IQI, Nonlinear PA Response and MIMO Linear Self-Interference

Step 3 of the proposed method (Figure 2) was performed using Equation (10) to acquire the channel response parameters for the main and auxiliary transmission paths. Compensation values for the widely linear filter were then derived, given that the IQ imbalance had already been compensated. MATLAB was used to generate two output signals, one each for the main and auxiliary paths. The main path contained a 16-QAM signal with an IQ imbalance that was corrected for the IQ imbalance and pre-compensated for a nonlinear PA response. A nonlinear PA was then introduced into this signal by transmitting it through the adopted PA. The auxiliary path contained the 16-QAM signal with a different training code. Both signals were simultaneously transmitted through the transceiver module (Figure 12), with the coupled signal affected by self-interference.

**Figure 12.** Spectrum analysis results for a receiver signal affected by self-interference

The coupled signal was received by the transceiver module at the receiver end, and MATLAB was used to calculate the preprocessing parameters for self-interference compensation. It means the values calculated using the widely linear filter (Figure 3) for the processing parameter for self-interference compensation ( $w_1$ ). The aforementioned filter began

computation after the switch was activated to enable the cancellation function. Moreover, the switch function “clear” in Figure 3 was changed to “cancellation.”

MATLAB was employed again to generate two signals, one each for the main and auxiliary paths. The main path contained a 16-QAM signal with IQ imbalance, compensation parameters for the IQ imbalance, and pre-compensation parameters for the nonlinear PA response. This signal was passed through the PA to introduce a nonlinear PA response into it. The auxiliary path contained the 16-QAM signal with a preprocessing parameter  $w_1$  for self-interference compensation. The signals from both paths were combined using the coupler, and the combined signal was examined using the spectrum analyzer (Figure 13).

The preprocessing parameters for the self-interference compensation reduced the power of the coupled signal by 34 dBm. This result confirms that self-interference can be eliminated through direct RF reception after transmission.

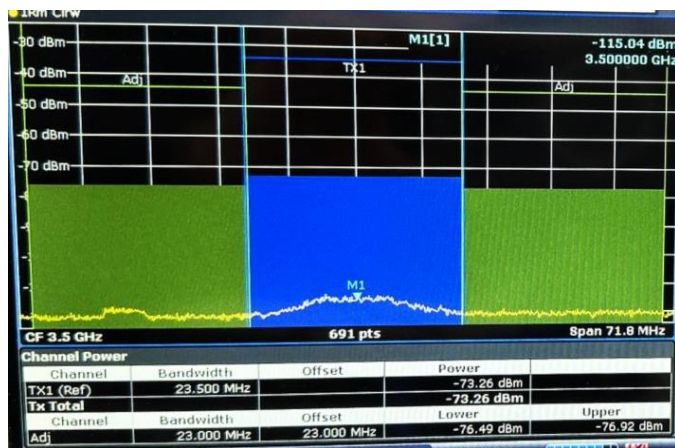


Figure 13. Spectrum analysis results for a receiver signal affected by self-interference

#### IV. CONCLUSIONS

This study developed a method for eliminating distortion arising from IQ imbalance, a nonlinear PA response, and MIMO self-interference in wireless RF signal transmission. In this method, a precoding signal is generated through digital signal-processing techniques and then transmitted through an auxiliary signal transmission path. This signal is designed to be the inverse of the main path signal; thus, the auxiliary path signal suppresses the self-interference at the analogue front end. The proposed method involves three steps, with each step sequentially addressing the aforementioned distortion factors without requiring complex mathematical modelling of distortion components. The proposed method also ensures that signal saturation does not occur, thereby preventing the generation of nonlinear components. This study developed an integrated full-duplex communication technology to effectively suppress various distortion interferences, encompassing IQ imbalance calibration, PA nonlinearity compensation, and self-interference elimination. The proposed distortion cancellation method was experimentally validated

on a soft-ware-defined radio platform. The experimental results suggested that the proposed method reduced the distortion by approximately 20 dBm, thus demonstrating excellent performance. Reference [11] also proposed a similar theoretical concept; however, the method presented in this study offers a more simplified approach and further verifies the self-interference issue associated with dual-data transmission by integrating a millimeter-wave array with an SDR platform. The proposed method can be employed in full-duplex communication technology to effectively suppress the distortion caused by IQ imbalance, nonlinear PA responses, and self-interference in multiple channels.

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**Keng-Hwa Liu** was born in Taichung, Taiwan, in 1989. He received the B.S. degree in electrical engineering from the Yuan Ze University, Taiwan, in 2013, and the M.S. degree in communication engineering from the Yuan Ze University, Taiwan, in 2015. He is currently working in National Chung Shan Institute of Science and Technology, and part-time working

toward the Ph.D. degree in the Department of Communication Engineering at the Yuan Ze University. His current areas of interest research include RF impairment cancellation in wireless communications, space-time signal processing for wireless communication.



**JUINN-HORNG DENG** (Member, IEEE) received the Ph.D. degree in Communications Engineering from National Chiao Tung University, Taiwan, in 2003. In 2008, he joined the Faculty of Yuan Ze University, Chungli City, Taiwan. From 2020 to 2024, he served as the Chairman, Group B, Department of Electrical Engineering, YZU, where he is currently a Professor and the Vice Director of the Communication Research Center. He was a recipient of the Best Track Paper Award of Practical and Experimental Systems at IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) in 2022. He was also a recipient of the Gold Medal Award at Taiwan Innotech Expo Invention Contest in 2018, 2019, and 2021. His research interests include mmWave active phase array design, communication signal processing, RF impairment calibration, model-based communication baseband design, MIMO techniques for wireless communications, and Radar signal processing.



**Min-Sion Yang** was born in Changhua County, Taiwan, ROC in 1999. She received a bachelor's degree in electrical engineering at Yuan Ze University, Chungli City, Taiwan, ROC in 2022. She is pursuing on the Master's degree in Institute of Electrical and Communication Engineering at the Yuan Ze University. Her current research interests include signal preprocessing, mmWave array antennas, and RF circuit and antenna design.