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Improving Transmitter Signal Quality by Mitigating Nonlinearities in Power Amplifiers and I/Q Modulators Using UKF

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ABSTRACT

A key challenge in deploying high-speed wireless systems is the presence of hardware-induced impairments that degrade performance. These impairments can introduce both in-band and out-of-band interference, severely affecting system reliability. This study focuses on the nonlinear distortions introduced by transmitter components in full-duplex communication systems, specifically the power amplifier (PA) and the in-phase/quadrature (I/Q) modulator. The nonlinear behavior of these elements is recognized as a major source of signal degradation, leading to increased distortion and reduced efficiency. Through comprehensive simulations, the effects of these impairments are evaluated using critical metrics such as Peak-to-Average Power Ratio (PAPR) and Error Vector Magnitude (EVM). To address these issues, the Unscented Kalman Filter (UKF)—a robust algorithm tailored for nonlinear dynamic systems—is employed to estimate and compensate for these distortions. The results demonstrate that the UKF significantly reduces the adverse impact of PA and I/Q modulator nonlinearities, thereby enhancing transmitter performance and overall signal integrity.

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1. INTRODUCTION

Full-duplex (FD) transmission utilizes the same carrier frequency to simultaneously transmit and receive data signals using a single transceiver. This provides the capability to increase the system capacity by a factor twice when evaluated against a half-duplex (HD) system. An initial effort to implement the FD transmission was detailed in a patent from 1949 (1) and examined in (2). The FD concept was considered unpractical due to challenges associated with its implementation. The factors contributing to the renewed interest in FD include advancements in component and signal processing technologies, along with the rise of short-range radio communication systems, such as femto and other small-cell networks, which operate at significantly lower transmit powers compared to traditional mobile cellular systems characterized by larger cell sizes. The initial realistic implementations of FD concepts were presented in references (3)(4). The implementation of such duplex systems is appealing for widespread deployment but presents significant challenges due to component-related impairments. Among the primary sources of these impairments in high-speed wireless communication systems are the in-phase/quadrature-phase (IQ) imbalance and power amplifier nonlinearities (4–6).

This study highlights the importance of accurate power amplifier (PA) characterization for circuit design, optimization, and troubleshooting, particularly in high-frequency applications. The research evaluates memoryless and polynomial memory models for predicting PA behaviour through measurement-based techniques. Results show that the polynomial memory model outperforms the memoryless model, especially at lower bandwidths, with findings revealing significant memory effects on PA nonlinearity and a moderate influence of bandwidth on model accuracy(7). A study addresses the challenge of nonlinear distortion in multicarrier signals caused by transmitter power amplifiers (PAs), a critical issue in designing energy-efficient wireless systems. To address this, the paper introduces a non-decision-aided Higher Order Combining reception scheme, utilizing machine learning to derive symbol-combining coefficients in the absence of analytical solutions. Simulation results reveal that the scheme outperforms both standard reception and established decision-aided receivers(8).

The authors in (9) investigated the effects of RF distortions in advanced technologies such as MIMO, large MIMO, full-duplex communication, and millimetre waves. Their research primarily focuses on generalized models of impact and compensating methods. The analysis is deficient in its examination of specific distortion characteristics, including IQ imbalance, phase noise, and power amplifier nonlinearity, in relation to certain 5G systems, as well as an evaluation of the impact of these distortions on EVM, a crucial metric for modern networks. In (10), the authors examine the influence of significant distortions in the RF front-end on the performance of wireless communication systems. The emphasis is on nonlinear power amplifier distortions and amplitude-phase inconsistencies in the transmitter. Nevertheless, the study is lacking in a quantitative evaluation of the impact of these distortions on communication quality. An investigation of the combined effects of IQ imbalance and carrier phase/frequency offset is presented in the article (11). In order to examine these impacts, the authors make use of a model that incorporates observations under a variety of local oscillator configurations and analyses dependence on bandwidth and frequency.

This paper (12) evaluated the impact of IQ imbalance on the performance of the Kramers-Kronig receiver. The analysis revealed that amplitude mismatch and time mismatch introduced frequency-independent and frequency-dependent double interference, respectively. These interferences not only compromise receiver sensitivity by disrupting the critical conditions necessary for its operation but also worsen induced RF power fading, further degrading the signal quality. Another paper (13) addressed two key imperfections in wireless systems: frequency offset and in-phase/quadrature IQ imbalance. IQ imbalance in radio frequency direct-conversion systems not only generates undesired in-band image interference but also impairs the accuracy of carrier frequency estimation. To mitigate these effects, a low-complexity nonlinear least squares frequency estimator is proposed, demonstrating robust performance against IQ imbalance. The effectiveness of the proposed method is validated through extensive computer simulations and experimental results across diverse I/Q imbalance conditions. The authors in (14) introduced a novel approach for addressing IQ imbalance in sensing systems. A novel controlled feedback structure for phase demodulation is proposed, utilizing a zero-error closed-loop design. The study focuses on minimizing distortions resulting from IQ imbalance. However, the paper didn't address significant issues, including phase noise and power amplifier nonlinearity. The work presented in reference (15) outlines a method for the characterization of signal distortion induced by amplifiers. The approach involves breaking down the output signal into two components: one that exhibits a linear correlation with the input signal, and another that accounts for nonlinear distortion. however, the integration of methods for compensating IQ imbalance is insufficiently described. Another paper (16) highlighted a significant limitation in high-speed wireless systems, particularly the impairments caused by signal processing imperfections, such as in-phase and quadrature imbalance at multiple transmitters in uplink transmissions of multiuser systems. To address these challenges, the authors propose a widely linear receiver designed to mitigate inter-user interference caused by IQ imbalances. Additionally, a novel subcarrier allocation scheme is introduced, demonstrating high resilience to such distortions, thereby enhancing system performance

This paper focuses on analysing the nonlinearities introduced by the power amplifier and IQ modulator in transmitter systems and explores effective mitigation techniques. To address these impairments, the Unscented Kalman Filter (UKF) was implemented as a robust solution to minimize their adverse effects. The paper is organized as follows: Section 2 introduces the system model and transmitter architecture. Section 3 details the proposed methodology for integrating the UKF into the system. In Section 4, the various impairments representing system nonlinearities are described. Section 5 presents the investigation results and evaluates the system's performance. Finally, the conclusions and key findings are summarized in Section 6.

2. The Proposed System Model

Figure 1 shows the suggested system model for an RF transmitter. This model provides a complete framework for studying how power amplifier nonlinearity, IQ imbalance, and nonlinearity affect 5G networks. The baseband signal generation, the transmitter, and the measurement portion are the three main parts of the system. The methodology corresponds with current developments in wireless communication systems, which focus on processing signals with high accuracy and using trustworthy quality measures. In the modeling framework, the transmitter is in the role of acquiring the baseband signal ready for RF transmission. Figure 1 shows how the transmitter deals with the baseband signal created with 5G NR test models. It does this by employing interpolation and RF modulation. The primary function of the transmitter portion is to transform the baseband signal into a high-frequency RF signal that may be sent over the air. This step is also very important for figuring out transmission problems that have a direct effect on how well the whole system works. The next few sections go into detail on each part, explaining what it does and how it works in the simulation framework.

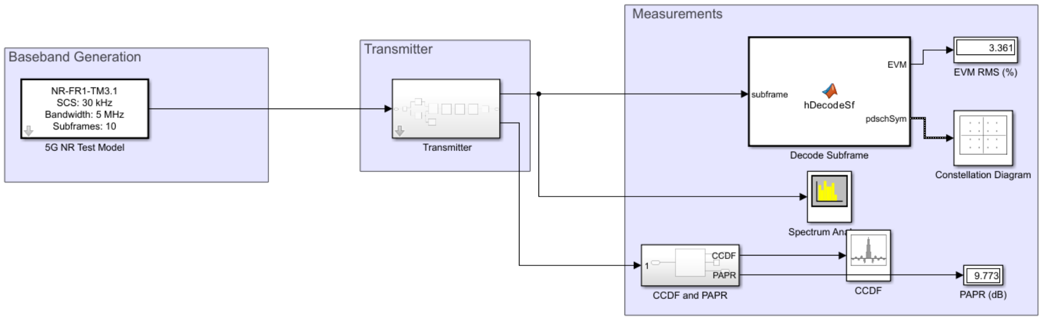


Figure 1 Main Components of the Evaluating System

2.1 Baseband Generation

This block provides the baseband waveform according to 5G standards. The NR-FR1-TM3.1 test model establishes the values for subcarrier spacing (SCS = 30 kHz), bandwidth (5 MHz), and the number of subframes (10). This additionally makes sure that testing and simulation follow 5G NR standards. The RF transmitter subsystem's block outputs.

2.2 Transmitter

The output waveform from the baseband block is bring into the transmission process. It enables data transmission to the RF transmitter. The RF Transmitter block depicted in Figure 2 demonstrates a superheterodyne transmitter configuration (17,18). This architecture upconverts the waveform to the passband frequency, thereafter applying RF filtering and amplification prior to signal transmission (19,20). The up-conversion process converts waveforms into carrier frequencies, and this model incorporates several essential RF components to measure the effects of this change. The standard components of a superheterodyne transmitter include(21–23):

- Mixer
- Phase shifter
- Local oscillator
- Bandpass filter
- Power amplifiers
    - Variable Gain Amplifier (VGA) to regulate the high-power amplifier
    - High-Power Amplifier (HPA).

As can be seen from Figure, the simulated transmitter system begins with the input block, which provides the baseband signal to be processed according to 5G NR standards. The signal is first passed through a "Complex to Real-Imaginary Conversion" block, where it is split into its in-phase (I) and quadrature (Q) components, which are then fed into the IQ modulator. The IQ modulator combines these components to create a modulated RF signal. The modulated signal is passed through a Chebyshev bandpass filter, which isolates the desired frequency band while attenuating unwanted signals, ensuring spectral purity. Following this, the signal is amplified using a Variable Gain Amplifier (VGA), which dynamically adjusts the amplitude to optimize signal strength for further processing. It is then passed through a High-Power Amplifier (HPA), which boosts the signal to the required power level for transmission, ensuring it can travel effectively to the receiver. Lastly the Output Buffer component temporarily stores the transmitted RF signal before passing it to the measurement stages. It converts the envelope voltage to Simulink signal.

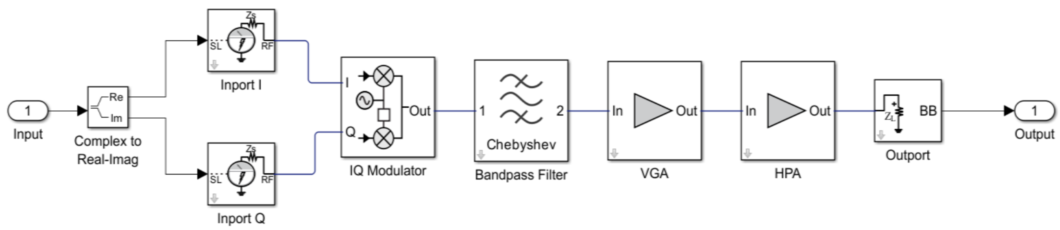


Figure 2 Transmitter components of the system

2.3 Measurements

The Measurements part is all about analyzing and decoding the signal that was received. The Receiver Spectrum Analyzer is one of the tools that looks at the signal's spectrum characteristics. A MATLAB spectrum analyzer tool or function uses the Fast Fourier Transform (FFT) to identify and indicate the frequency spectrum of a signal. This allows users see how the strength of a signal is spread out over different frequencies. Additionally, the CCDF module, which measures the PAPR. The signal is also passed through a decoding block to extract subframes and symbol information, enabling further evaluation of EVM and the generation of a constellation diagram for visualizing the signal's modulation accuracy. These measurements provide critical insights into the quality and performance of the received signal.

3. Kalman filter

The non-linear signal can employ an adaptive filter, such as the Kalman filter, to alleviate signal impairments. The Kalman filter was proposed for adaptive filtering by (24). The filter comprises two primary components: prediction and measurement update. Initially, the Kalman filter forecasts the subsequent state space value for the next time interval, and thereafter, it refines the predicted value using the measured value at each time instance. Thus, the Kalman filter applied to the issue of signal distortions may forecast a canceled signal based on the previously received signal and refine it using the signal of interest, which is recognized on the digital side. The current work concentrates on an unscented Kalman filter (UKF) to address the aforementioned nonlinearity impairments. The unscented Kalman filter algorithm executes real-time estimate of a nonlinear system. The depiction of the nonlinear system with the proposed methods is illustrated in Figure 3.

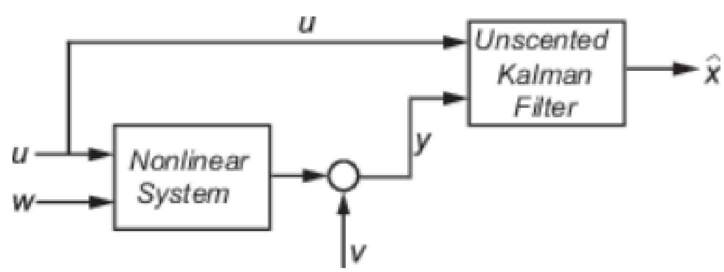


Figure 3 Proposed integration of the Unscented Kalman Filter within the simulated nonlinear transceiver system.

Unlike the conventional Kalman Filter, which depends on linear approximations, the UKF employs a deterministic sampling technique to accurately capture the mean and covariance of the state distribution. This approach excels in handling systems with nonlinear dynamics and measurement processes.

To estimate the signal, the UKF treats the projected signal as a form of noise due to its significantly lower power relative to the distorted signal, in conjunction with noise, and then recovers the signal. The recovered signal is utilized to eliminate the distortions from the total received signal, so obtaining the desired signal. The implementation of the UKF algorithm on the transmitter is executed using simulations in Simulink/Block. The block model defines whether the system operates at a single rate or multi rates. In the realm of NL parameter estimation, a multi-rates model was defined since the system entails varying sampling rates for state transitions and measurements. Together, these parameters ensure that the UKF can effectively capture the non-linearities in the system, leading to accurate nonlinear parameter estimation. Use tuning methods to adjust the process of refining or calibrating the process noise covariance and measurement noise covariance matrices of the Kalman filter to achieve optimal filtering performance.

4. Analysis of Nonlinearities and Impairments in Transmitter Components

In this study, the nonlinearities and impairments of the full-duplex transmitter system were broadly analysed, focusing on critical components; power amplifiers and the IQ modulator. For the power amplifier, key parameters like IP3 (Third-Order Intercept Point), P1dB (1-dB Gain Compression), and Psat (Saturation Power) were examined. IP3 measures the amplifier's linearity and its ability to handle multiple signals without generating intermodulation distortion. P1dB indicates the power level where the amplifier's gain drops by 1 dB, marking the onset of significant nonlinear behaviour. Psat represents the maximum output power achievable before the amplifier saturates and generates severe distortions.

For the IQ modulator, impairments I/Q gain mismatch, I/Q phase mismatch, phase noise, and coherence time were investigated. I/Q gain mismatch occurs when the in-phase (I) and quadrature (Q) components have unequal amplitudes, distorting the signal constellation. I/Q phase mismatch arises when the phase difference between these components deviates from the ideal 90°, causing rotational distortions. Phase noise refers to random fluctuations in the carrier signal's phase, leading to spectral spreading and adjacent channel interference. Coherence time measures the duration over which the channel's characteristics remain stable; a shorter coherence time can result in signal fading and reduced performance.

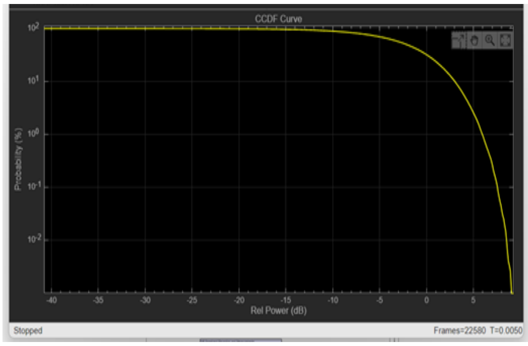
Together, these nonlinearities and impairments significantly affect signal quality, and system efficiency, highlighting the need for mitigation strategies to maintain reliable and high-fidelity operation. Table 1 provides values of the critical nonlinear parameters and impairments that affect the applied to the power amplifiers and IQ modulator.

Table 1: Proposed parameters and values for investigation

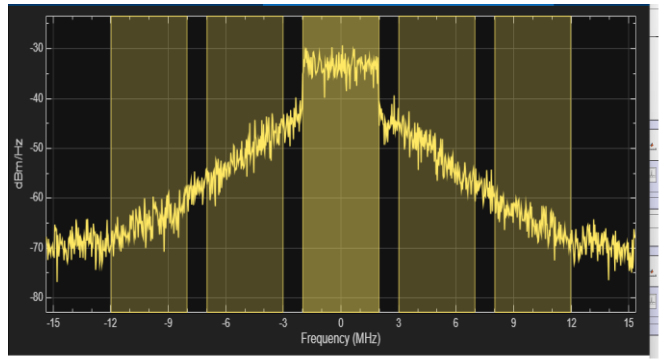
Component	Parameter	Value
Power Amplifier	IP3	45 dBm
	P1dB	40 dBm
	Psat	43 dBm
IQ Modulator (Impairments)	Gain Mismatch	3 dB
	Phase Mismatch	10°
	Phase Noise Level	–105 dBc/Hz @ 1MHz
	Time Duration	100 µs
IQ Modulator (Nonlinearity)	IP3	35 dBm
	P1dB	30 dBm
	Psat	33 dBm

5. Results and Discussion

The investigation of both amplifier and the I/Q modulator is critical for understanding and mitigating signal distortions in communication systems. Nonlinearities in components VGA and HPA can introduce undesired effects, which degrade signal quality and system performance. Similarly, the I/Q modulator is vulnerable to impairments like phase and gain mismatches, which can lead to constellation distortions and increased EVM. Figure 4 displays the behavior of these nonlinearities, quantifying their impact on the key performance metrics. The analysis of both I/Q modulator and amplifier nonlinearities revealed significant performance degradation, as evidenced by the observed results: a PAPR of 27.25 and an EVM of 19.56. The high level PAPR specifies severe power fluctuations, which lead to inadequacies in power utilization and increased risk of signal distortion in power-limited systems. The raised EVM reflects substantial deviations from the ideal signal constellation, signifying a loss of modulation accuracy. The combined impact distorts the transmitted signal, degrading overall communication quality. From the Complementary Cumulative Distribution Function (CCDF) plot, it can be observed that as the relative power increases, the probability decreases sharply, indicating the occurrence of high-power peaks is rare. Moreover, the constellation diagram, which is the difference between the expected (ideal) and actual received signal positions, shows greater the deviation.



(a)



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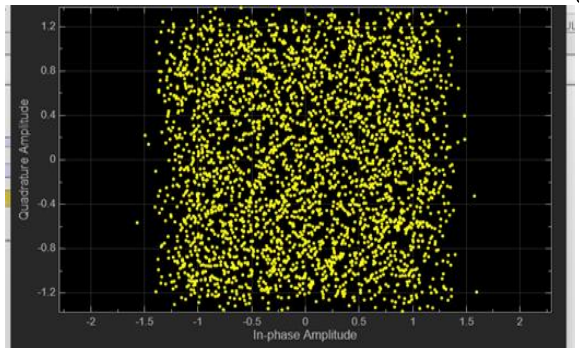
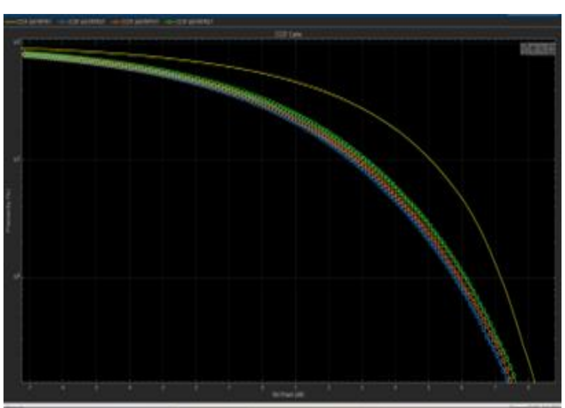


(c)

Figure 4 Results of Simultaneous Nonlinearities in Amplifiers and I/Q Modulator (a) CCDF, (b) ACLR, (c) Noise Constellation.

In the situation where applying the filter against the nonlinearity for both amplifiers and IQ modulator, the ACLR is considerably low compared to the distorted case with impairment the mismatch and phase noise and nonlinearity for both amplifiers and IQ modulator. The PAPR performance in the simulated system has been significantly improved after applying the proposed Filter. At the CCDF, as shown in Figure 5a, the Kalman Filter effectively reduces the curve responses, indicating improved system performance. As can be seen from Figure 5 that the spectrum of ACLR signal across different stages using the filter was improved significantly. The constellation diagram also exhibits noticeable improvement. Furthermore, the PAPR, reduced considerably of approximately 11 dB. Moreover, the Kalman filter reduced the peak EVM to 9.3. In subsequent cases the filter parameters were tuned to enhance its ability to reduce signal distortions, further enhancements were observed. The ACLR decreased further, and both the constellation and EVM metrics improved.



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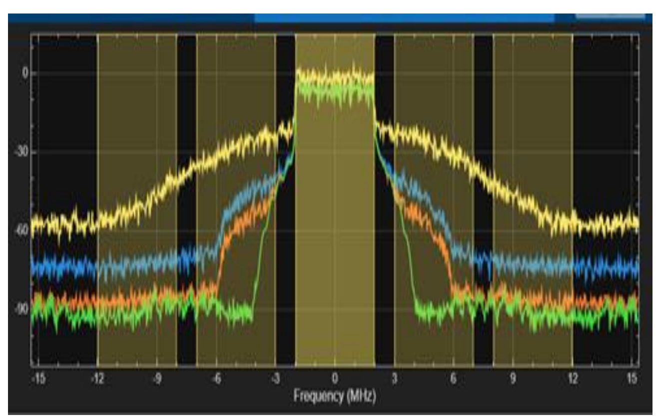

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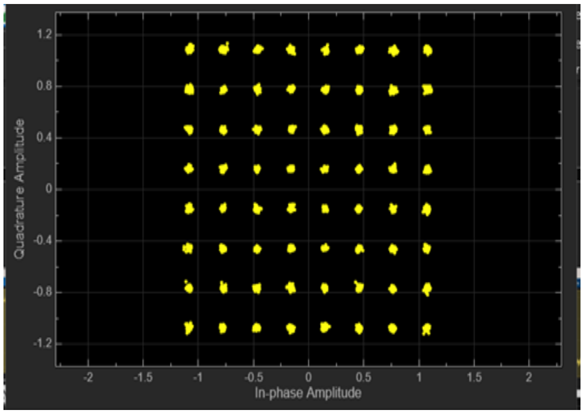

(c)

Figure 5 Results of Mitigating Simultaneous Nonlinearities in Amplifiers and I/Q Modulator Using the Kalman Filter (a) CCDF, (b) ACLR, (c) Noise Constellation.

6. Conclusions

This paper investigates the nonlinearities occurring in the receiver section of a wireless system, with particular attention to distortions introduced by the power amplifier and I/Q modulator. These impairments were found to significantly degrade signal quality and overall system performance. To address this, the Unscented Kalman Filter (UKF) was employed to suppress these effects, showing strong potential in improving signal integrity without adding excessive computational complexity. The results highlight notable enhancements in performance indicators like EVM and PAPR, demonstrating the UKF's effectiveness in compensating for receiver-side nonlinearities. These outcomes support the use of UKF as a reliable approach for improving the performance of full-duplex communication systems.

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The recommended number of authors is at least 2. One of them as a corresponding author.
Please attach clear photo (3x4 cm) and vita. Example of biographies of authors:

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