

# An Analytical Technique for Characterization of Transceiver IQ Imbalances in the Loop-back Mode

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**Abstract**— Loop-back is a desirable test set-up for RF transceivers for both on-chip characterization and production testing. Measurement of IQ imbalances (phase mismatch, gain mismatch, DC offset, and time skews) in the loop-back mode is challenging due to the coupling between the receiver (RX) and transmitter (TX) parameters. We present an analytical method for the measurement of the imbalances in the loop-back mode. We excite the system with carefully designed test signals at the baseband TX input and analyze the corresponding RX baseband output. The derived and used mathematical equations based on these test inputs enable us to unambiguously compute IQ mismatches. Experiments conducted both in simulations and on a hardware platform confirm that the proposed technique can accurately compute the IQ imbalances.

## I. INTRODUCTION

As customers demand higher functionality and smaller size communication devices, designs become more complex with higher integration levels. Process variations and complicated layouts cause some system level impairments that degrade the device performance. Characterization of these impairments is necessary not only in context of go/no-go testing but also for the compensation of these impairments to attain adequate product yield. This characterization process often involves high-caliber RF instrumentation and multiple test set-ups, resulting in high production test cost and making on-chip characterization infeasible.

Decreasing production test cost for RF transceivers has been the focus of extensive research lately [1]–[3]. The loop-back configuration wherein the transmitter output is connected to the receiver input is highly desirable as a test venue since it obviates the need for RF instrumentation [4]–[9]. For the same reason, loop-back testing is also desirable for on-chip characterization and compensation. An important challenge in loop-back based testing is the coupling between RX and TX parameters. Several researchers have addressed this problem [2], [4], [6], [7].

In [10], authors present an  $I/Q$  imbalance extraction method that uses a Cholesky decomposition of the received signal's covariance matrix. A frequency offset between LO frequencies of transmitter and receiver is injected to separate the effect of their imbalances in received signal. In some cases, one of the transmitter or the receiver is assumed golden to extract the impairments of the other side. In [11], the transmitter parameters are obtained using constellation analysis assuming

a golden receiver. Also in [12], a step by step approach for a quadrature mixer impairment extraction is presented using an ideal receiver.

An alternate test approach is used in [2], [4], [5]. In this method, a mapping function between the device response to a special test signal and the specification is built to predict the circuit parameters. By exciting various non-linearities in the path using a diverse input stimulus, gain and  $IIP3$  of the RX and TX path can be decoupled. However, linear impairments ( $IQ$  imbalance) are not targeted in [2], [4], [5].

$IQ$  imbalances, namely gain mismatch, phase mismatch, DC offsets, and time skews are several of the most damaging impairments to product performance [13], [14]. These impairments are also most suitable for digital compensation since they can be cancelled out by linear transformations in the baseband [10], [14]–[17].

While some  $IQ$  imbalances have been included as target parameters in prior work [6], [7], [18], extraction of these parameters relies on non-linear estimation where convergence may not always be guaranteed. Moreover, such complex computations are not amenable for on-chip implementation as they require extensive resources. In [19], a method to compute a subset of  $IQ$  imbalances is presented. However, most impairments are assumed to be zero, making the overall model unrealistic. Another step by step technique is presented in [20]. The phase to amplitude conversion concept is used in estimation of a subset of  $IQ$  imbalances. The test is performed for transmitter and receiver separately.

In this work, we develop an analytical technique to measure  $IQ$  imbalances in the loop-back mode. Our model includes all the imbalance parameters we wish to compute as well as other parameters that would alter signal properties. Our technique is based on exciting the system with specialized sinusoidal-based test signals in the baseband TX input and analyzing the signal amplitude at the baseband RX output. By using a programmable delay component in the loop-back path, we base our calculations on the ratio of measured amplitudes rather than their absolute values so as to eliminate dependencies on unknown system parameters. With our technique, each imbalance parameter can be calculated independently and unambiguously without making assumptions on the internal parameters of the system (e.g. path delays). We conduct both simulations and hardware measurements to demonstrate the accuracy of our technique.

The rest of the paper is organized as follows. Section

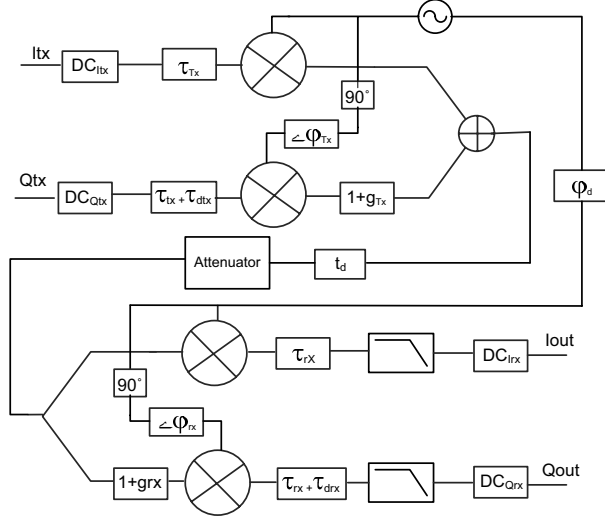


Fig. 1. Transceiver system model

II presents the overall loop-back system model and all the imbalances that have been included. Section III explains the proposed method, the necessary test signals, and the analytical equations that we use for the computations. Results of simulations and hardware experiments are presented in Section IV.

## II. SYSTEM LEVEL MODEL

Since our goal is to compute  $IQ$  imbalances, we use a linear system model shown in Fig. 1 to derive our analytical formulation. Non-linearities in the receive and transmit paths can be ignored by using signal amplitudes well below the 1dB compression points of both paths [19]. The system model includes all  $IQ$  imbalances that we wish to compute: TX and RX gain imbalance ( $g_{tx}$ ,  $g_{rx}$ ), TX and RX phase mismatch ( $\varphi_{tx}$ ,  $\varphi_{rx}$ ), TX and RX time skews ( $\tau_{dtx}$ ,  $\tau_{drx}$ ) and TX and RX DC offsets ( $DC_{I_{tx}}$ ,  $DC_{Q_{tx}}$ ,  $DC_{I_{rx}}$ ,  $DC_{Q_{rx}}$ ). In addition to the desired characterization parameters we include delay parameters in our system model: loop-back time delay ( $t_D$ ), time delay between the TX and RX LO paths ( $\varphi_D$ ) and baseband delays ( $\tau_{tx}$ ,  $\tau_{rx}$ ). Although we are not interested in computing these parameters, the difference between the two RF delays will have a large impact on the output signal amplitude. We will later eliminate this dependency by using multiple measurements. We also include a programmable delay component in the loop-back path to generate the diversity that we need to form linearly independent equations. Deriving the input output relation of the system model in Fig. 1, the baseband receiver outputs can be expressed as Eqn. (1):

$$\begin{aligned}
 I_{out}(t) &= GI(t - t_d - \tau_{tx} - \tau_{rx}) \cos(\omega_c t_d + \varphi_d) \\
 &+ G(1 + g_{tx})Q(t - t_d - \tau_{dtx} - \tau_{tx} - \tau_{rx}) \times \\
 &\times \sin(\omega_c t_d + \varphi_d - \varphi_{tx}) \\
 &+ GDC_{Q_{tx}}(1 + g_{tx}) \sin(\omega_c t_d + \varphi_d - \varphi_{tx}) \\
 &+ GDC_{I_{tx}} \cos(\omega_c t_d + \varphi_d) + DC_{I_{rx}}
 \end{aligned}$$

Parameters	
Gain mismatch	$g_{tx}$ , $g_{rx}$
Phase Mismatch	$\varphi_{tx}$ , $\varphi_{rx}$
TX DC offsets	$DC_{I_{tx}}$ , $DC_{Q_{tx}}$
RX DC offsets	$DC_{I_{rx}}$ , $DC_{Q_{rx}}$
Baseband time skew	$\tau_{dtx}$ , $\tau_{drx}$
Baseband delay	$\tau_{tx}$ , $\tau_{rx}$
Loop-around delay	$t_D$
LO frequency and phase offset	$\omega_c$ , $\varphi_d$
Path gain	$G$

TABLE I  
VARIABLE DEFINITION

$$\begin{aligned}
 Q_{out}(t) &= -G(1 + g_{rx})I(t - t_d - \tau_{tx} - \tau_{rx} - \tau_{drx}) \times \\
 &\times \sin(\omega_c t_d + \varphi_d + \varphi_{rx}) + G(1 + g_{rx})(1 + g_{tx}) \\
 &Q(t - t_d - \tau_{dtx} - \tau_{tx} - \tau_{rx} - \tau_{drx}) \times \\
 &\times \cos(\omega_c t_d + \varphi_d + \varphi_{rx} - \varphi_{tx}) + GDC_{Q_{tx}} \\
 &(1 + g_{tx})(1 + g_{rx}) \cos(\omega_c t_d + \varphi_d - \varphi_{tx} + \varphi_{rx}) \\
 &- GDC_{I_{tx}}(1 + g_{rx}) \sin(\omega_c t_d + \varphi_d + \varphi_{rx}) \\
 &+ DC_{Q_{rx}}
 \end{aligned} \quad (1)$$

Table. I explains all the relevant variables. Where  $I(t)$  and  $Q(t)$  are baseband transmitter inputs. Eqn. (1) suggests that the complete signal output at the receiver involves all of the impairments of the system and a direct calculation based on this signal is not straightforward. In the next section, we discuss specialized test signals that we design to enable decoupling the effect of each of these impairments.

## III. PROPOSED TECHNIQUE

### A. Test Signal Design

From Eqn. (1), we observe that if we eliminate the dynamic signal term,  $Q(t)$ , from the baseband TX input, the dynamic signals at the output of the RX chain only depend on the  $I(t)$  input and a limited number of impairments. The DC term and all the baseband delay terms can be separated out by analyzing the amplitude of these outputs. Similarly, when  $I(t)$  is eliminated, the resulting sinusoidal output signal amplitude is a factor of a different set of impairments and the input signal amplitude  $Q(t)$ . Based on this observation, we first define a sequence of input signals:

$$\begin{aligned}
 I(t) &= I_{DC} + A_I \sin(w_{bb}t) \cdot (u(t) - u(t - T)) \\
 Q(t) &= Q_{DC} + A_Q \sin(w_{bb}t) \cdot (u(t - T))
 \end{aligned} \quad (2)$$

Fig. 2(a) shows the time domain  $I$  and  $Q$  inputs. The key is to not overlap the sinusoidal components of the  $I$  and  $Q$  inputs. Note that  $u(t)$  is the unit step function, while  $I_{DC}$  and  $Q_{DC}$  are not part of the applied input signal but are an artefact of the system. Thus they are impairment parameters that are going to be extracted.

At the output, we divide the  $I_{out}(t)$  and  $Q_{out}(t)$  in the time domain into two parts: one part when  $I(t)$  has a sinusoidal component and one part where  $Q(t)$  has a sinusoidal component. We analyze these two parts separately. In order to

proceed, let us define some of the measured signal amplitudes.

$$\begin{aligned}
I_{out}(t) &= I_{out_I} \cdot (u(t) - u(t - T)) \sin(w_{bb}t + \tau_1) \\
&\quad + I_{out_Q} \cdot (u(t - T - \tau_2)) \sin(w_{bb}(t + T) + \tau_2) \\
&\quad + I_{out_{DC}} \\
Q_{out}(t) &= Q_{out_I} \cdot (u(t) - u(t - T)) \sin(w_{bb}t + \tau_3) \\
&\quad + Q_{out_Q} \cdot (u(t - T - \tau_4)) \sin(w_{bb}(t + T) + \tau_4) \\
&\quad + Q_{out_{DC}} \tag{3}
\end{aligned}$$

Where  $\tau_1, \tau_2, \tau_3$  and  $\tau_4$  are overall baseband delays from Eqn. (1).

Since signals are decoupled in time domain, the amplitudes  $I_{out_I}, I_{out_Q}, Q_{out_I}, Q_{out_Q}, I_{out_{DC}}, Q_{out_{DC}}$  can be measured directly by analyzing the time domain sequence for  $0 < t < T$  and  $T < t < 2T$  where  $2T$  represented the overall signal observation window. Fig. 2(b) shows the output signals based on the defined inputs. Note that both  $I_{out}(t)$  and  $Q_{out}(t)$  have dynamic components for the entire excitation duration  $0 < t < 2T$ . This is due to the fact that RF and LO signals are not fully synchronized as will be the case for any loop-back connection. Thus, one source of the crosstalk between  $I$  and  $Q$  is due to the lack of synchronization. Another source of this crosstalk is due to  $IQ$  imbalances. These amplitudes are related to the system parameters through Eqn. (4), where  $\varphi = \omega_c t_d + \varphi_d$  represents the differential delay between RF loop-back path and internal LO paths of the TX-RX connection. Fig. 2(b) and (c) shows the test response of the same transceiver for different loop-back delays. Although the internal impairments are the same, the amplitudes are different.

$$\begin{aligned}
I_{out_I} &= GA_I \cos(\varphi) \\
I_{out_Q} &= GA_Q \sin(\varphi - \varphi_{tx}) \\
I_{out_{DC}} &= GDC_{Qtx}(1 + g_{tx}) \sin(\varphi - \varphi_{tx}) \\
&\quad + GDC_{Itx} \cos(\varphi) + DC_{Irx} \\
Q_{out_I} &= -GA_I(1 + g_{rx}) \sin(\varphi + \varphi_{rx}) \\
Q_{out_Q} &= GA_Q(1 + g_{rx})(1 + g_{tx}) \cos(\varphi + \varphi_{rx} - \varphi_{tx}) \\
Q_{out_{DC}} &= GDC_{Qtx}(1 + g_{tx})(1 + g_{rx}) \times \\
&\quad \times \cos(\varphi - \varphi_{tx} + \varphi_{rx}) - GDC_{Itx}(1 + g_{rx}) \times \\
&\quad \times \sin(\varphi + \varphi_{rx}) + DC_{Qrx} \tag{4}
\end{aligned}$$

The complete capture window ( $2T$ ) for this test signal can be fit within one frame duration for any given standard. Thus, there is no need to keep the TX or RX active for the extended period of time and the test capture time is in mere microseconds.

From Eqn. (4) we observe that there are 6 distinct measurements we can conduct, whereas the number of unknowns is 9, excluding the time skews (to be addressed later). Thus, one measurement cycle invariably results in linearly dependent equations. In order to solve this problem, we use a programmable delay in the loop-back path and conduct two consecutive measurements with two different delay values. Note that a change in delay in the RF loop-back path is adequate to generate this diversity. The absolute value of this

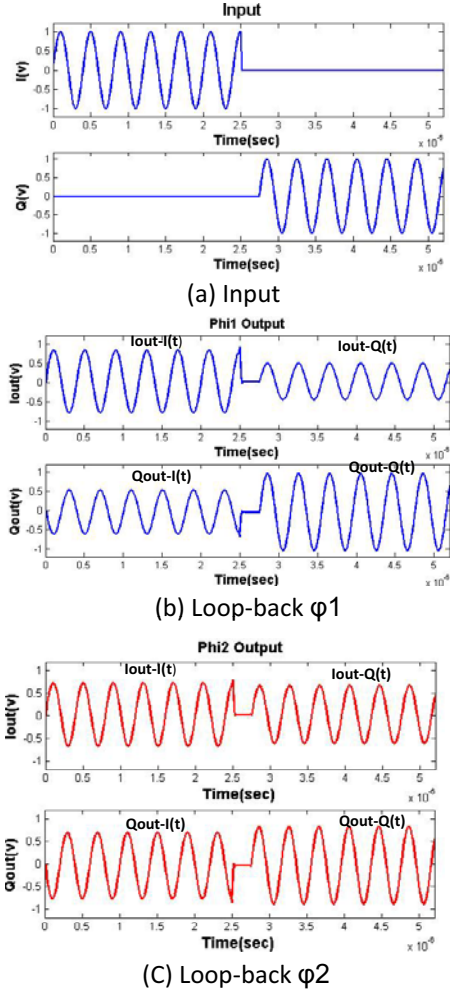


Fig. 2. Device response to designed test signal in two loop-back set-up. (a) Test Signal, (b) Loop-back  $\varphi_1$ , (c) Loop-back  $\varphi_2$

phase is not important as long as the two phases are different and the difference is known. The change in delay will change all the amplitude terms in Eqn. (4). With the second set of measurements, we have 12 measurements and 9 unknowns, which makes our system solvable.

### B. Phase and Gain mismatch calculation

The amplitudes in Eqn. (4) are also a function of  $G$ , which includes the overall path gain as well as all the losses along the measurement path. In order to eliminate these unknowns from the system of equations, we base the rest of our derivations on the ratios of measured amplitudes. Let us define 3 more variables:

$$\begin{aligned}
\frac{I_{out_I}^{\varphi_1} I_{out_Q}^{\varphi_2}}{I_{out_I}^{\varphi_2} I_{out_Q}^{\varphi_1}} &= A \\
\frac{I_{out_I}^{\varphi_1} Q_{out_Q}^{\varphi_2}}{I_{out_I}^{\varphi_2} Q_{out_Q}^{\varphi_1}} &= B \\
\frac{I_{out_I}^{\varphi_1} Q_{out_I}^{\varphi_2}}{I_{out_I}^{\varphi_2} Q_{out_I}^{\varphi_1}} &= C \tag{5}
\end{aligned}$$

Where  $I_{out_I}^{\varphi_1}$  represented the sinusoidal signal amplitude at the  $I$  output of the receiver for  $0 < t < T$  when the loop-back delay is  $\varphi_1$ . Other parameters follow the similar pattern. Plugging Eqn. (4) in Eqn. (5), we obtain:

$$\begin{aligned} \frac{\cos(\varphi_1) \sin(\varphi_2 - \varphi_{tx})}{\cos(\varphi_2) \sin(\varphi_1 - \varphi_{tx})} &= A \\ \frac{\cos(\varphi_1) \sin(\varphi_2 + \varphi_{rx} - \varphi_{tx})}{\cos(\varphi_2) \sin(\varphi_1 + \varphi_{rx} - \varphi_{tx})} &= B \\ \frac{\cos(\varphi_1) \sin(\varphi_2 + \varphi_{rx})}{\cos(\varphi_2) \sin(\varphi_1 + \varphi_{rx})} &= C \end{aligned} \quad (6)$$

Using Eqn. (6), the variables  $\varphi_1$ ,  $\varphi_2$ ,  $\varphi_{tx}$ ,  $\varphi_{rx}$  can be unambiguously determined without making any assumption on their values, as the difference between the loop-back delays is known. Once those variables are determined, overall gain,  $G$ , and gain mismatches can be calculated as in Eqn. (7).

$$\begin{aligned} G &= \frac{2I_{out_I}}{\cos \varphi_1} \\ g_{rx} &= \frac{Q_{out_I}}{\left| \frac{G}{2} \sin(\varphi + \varphi_{rx}) \right|} \\ g_{tx} &= \frac{I_{out_Q}}{\left| \frac{-G}{2} \sin(\varphi - \varphi_{tx}) \right|} \end{aligned} \quad (7)$$

### C. DC offset calculation

From Eqn. (4), we observe that DC offsets are functions of the mismatches that we have calculated so far and the measured DC offsets at the output. Using the 4 measured DC offsets and the values of the mismatches obtained in the previous steps, we can obtain a system of 4 linearly independent equations of the form of Eqn. (8).

$$\begin{aligned} I_{out_{DC}}^{\varphi_1} &= a_1 DC_{Q_{tx}} + a_2 DC_{I_{tx}} + DC_{I_{rx}} \\ I_{out_{DC}}^{\varphi_2} &= a_3 DC_{Q_{tx}} + a_4 DC_{I_{tx}} + DC_{I_{rx}} \\ Q_{out_{DC}}^{\varphi_1} &= b_1 DC_{Q_{tx}} + b_2 DC_{I_{tx}} + DC_{Q_{rx}} \\ Q_{out_{DC}}^{\varphi_2} &= b_3 DC_{Q_{tx}} + b_4 DC_{I_{tx}} + DC_{Q_{rx}} \end{aligned} \quad (8)$$

Solving Eqn. (8), we can determine and decouple all DC offsets.

### D. Time Skews calculation

So far, we have analyzed the baseband sinusoidal signals in terms of amplitude. The phases of these signals are a function of delays in the baseband path. If we measure these delays, the time skews can be calculated simply as the difference between the  $I$  and  $Q$  delays as Eqn. (9):

$$\begin{aligned} \tau_{dtx} &= \frac{\arg(I_{out_I}^{\varphi_1}) - \arg(Q_{out_I}^{\varphi_1})}{2\pi f_{bb}} \\ \tau_{drx} &= \frac{\arg(I_{out_I}^{\varphi_1}) - \arg(I_{out_Q}^{\varphi_1})}{2\pi f_{bb}} \end{aligned} \quad (9)$$

Note that this calculation does not require any synchronization between the RX and the TX side. Any delay that we add

Parameter	RMS Error	Injection Limit
$TXPhase_{MM}$	0.036°	[0°,5°]
$RXPhase_{MM}$	0.0145°	[0°,5°]
$TXgain_{MM}$	0.53%	[-20%,20%]
$RXgain_{MM}$	0.56%	[-20%,20%]
$I_{tx} - DC_{offset}$	2.2mV	[-50mV,50mV]
$Q_{tx} - DC_{offset}$	2.1mV	[-50mV,50mV]
$I_{rx} - DC_{offset}$	10.1mV	[-50mV,50mV]
$Q_{rx} - DC_{offset}$	8.7mV	[-50mV,50mV]
$TXTimeSkew$	0.011ns	[0ns,2ns]
$RXTimeSkew$	0.0084ns	[0ns,2ns]

TABLE II  
SIMULATION RESULTS - RMS EXTRACTION ACCURACY

during the test period will be added to both  $I$  and  $Q$  arms and thus, will not alter  $\tau_{dtx}$  or  $\tau_{drx}$  computation.

### E. Test Time

As we use direct mathematical expressions to compute the impairment parameters, data processing time is dominated by the 128-point FFT that we use to determine the amplitudes. In order to increase accuracy and reduce errors due to noise, we repeat measurements 5 times and average the FFT amplitudes and phase measurements. The total test time for our approach to compute all of these impairments thus is 1.9 ms on a 2.4 GHz computer.

## IV. EXPERIMENTAL RESULTS

### A. Simulation Results

In order to confirm the accuracy of the computation technique, a transceiver system model (Fig. 1) is implemented in MATLAB. All impairments included in the model are injected at once. Table. II shows the impairment injection bounds and the extraction RMS error in 500 Monte Carlo simulations. The sinusoidal test signal frequency is 2.5MHz. Also the loop-back phases and their difference is changing between 5° and 12° randomly.

As it is shown in Fig. 3 (a) the maximum phase mismatch extraction is 0.15°. The maximum error for gain mismatch extraction is 4% Fig. 3 (b). FFT error is the source for this computation error. The error can be decreased by using higher FFT size.

In the simulations, the amplitudes are determined using a 128 point FFT. The extraction error is mainly due to FFT accuracy. DC offsets for the  $RX$  side have higher error as they are calculated in the last step and have the accumulated error from previously calculated parameters.

### B. Hardware Measurement Results

In the simulations, our model is used to both generate the output and perform the calculations. Any modelling error will reduce the accuracy of these computations. Moreover, unmodeled effects may invalidate the mathematical formulations. In order to evaluate the accuracy of our overall model as well as the accuracy of our technique on a hardware platform, we formed the simple transceiver, as shown in Fig. 4 out of

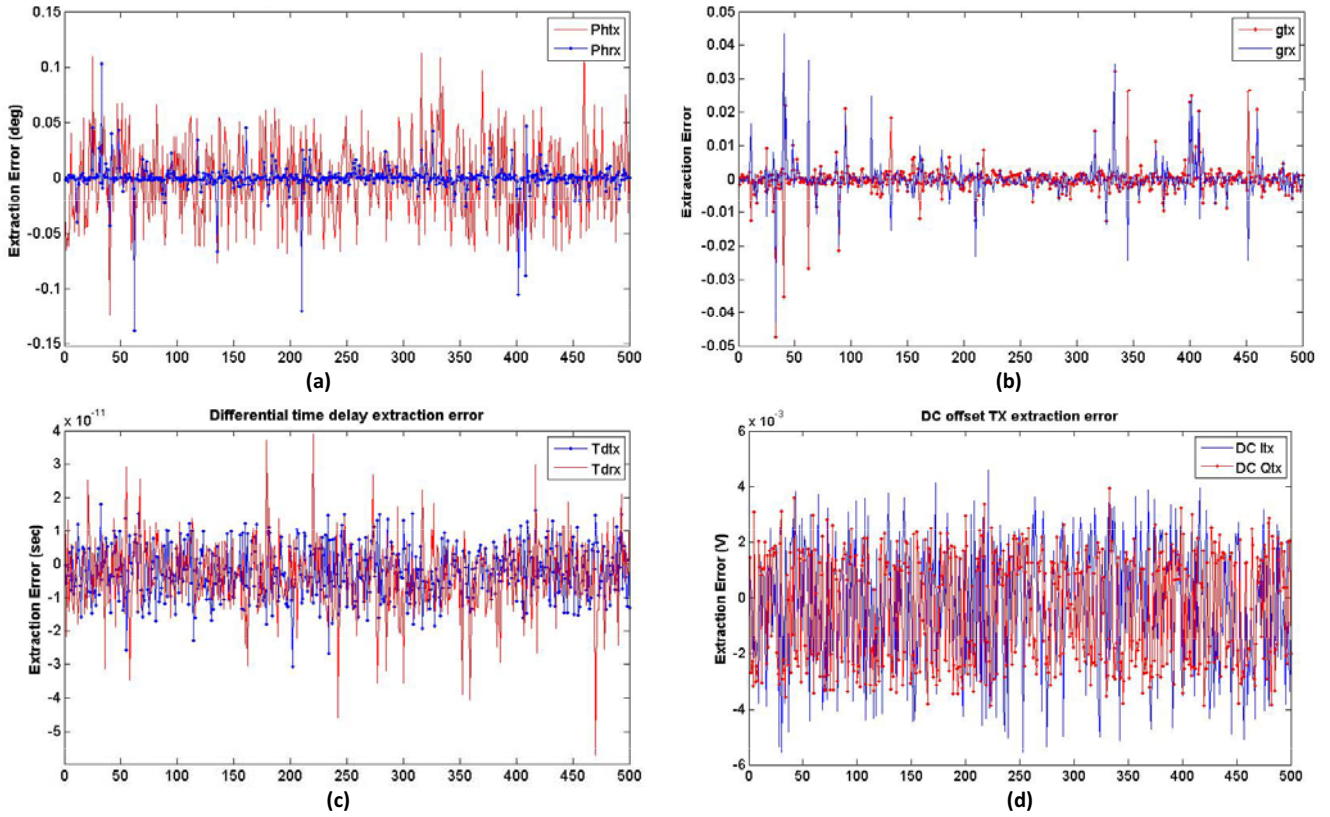


Fig. 3. Simulation Results (a) Phase Extraction Error,(b) Gain Extraction Error,(c) Time skews Extraction Error,(d) TX DC offsets Extraction Error

discrete components (Mini-circuits: Mixer ( $ZFM - 15 - S^+$ , Power splitter/combiner ( $ZFSC - 2 - 4 - S^+$ ),  $90^\circ$  splitter ( $ZX10Q - 2 - 3 - S^+$ ), low pass filter ( $SBLP - 117^+$ )). The picture of this transceiver is shown in Fig. 5.

By using various cables of different length, we are able to generate different delay amounts. We use SONY Tektronix AWG520 arbitrary waveform generator to generate the  $I$  and  $Q$  baseband signals (Fig. 2(a)) and Agilent Technologies DSO6104A oscilloscope to capture the  $I$  and  $Q$  outputs at the end of the receiver chain. The LO signal is generated using a signal generator (Agilent E4432B) and is split using power splitter (Mini-Circuits ( $ZFSC - 2 - 4 - S^+$ ) to generate all the four required LO signals.

Fig. 6 shows a sample capture signal at the  $I$  and  $Q$  output. As we expect the crosstalk between  $I$  and  $Q$  arms results in dynamic signal component at the output even when the corresponding input has no sinusoidal component.

Measurements have been conducted for 3 cases of impairments. The actual impairment values and extraction results are shown in Tables. III, IV, V. As these results show, the analytical computation follows the actual values. Measurements display slightly higher error due to noise in the system, equipment limitations, and potential unmodeled behavioral deviations.

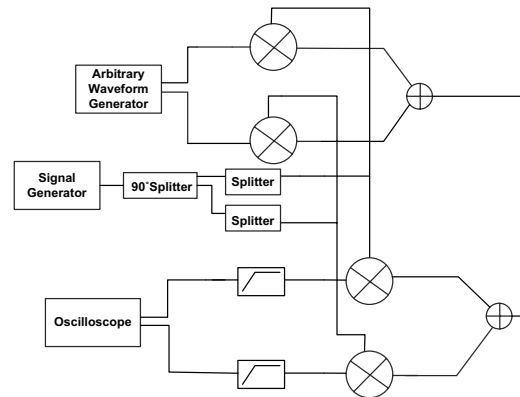


Fig. 4. Hardware Measurement Block Diagram



Fig. 5. Hardware Measurement Set-up

## V. CONCLUSIONS

In this paper, a new analytical technique for  $IQ$  imbalance measurement of RF transceivers in loop-back mode has been

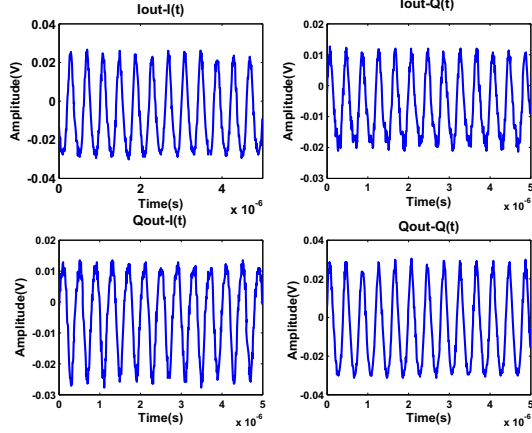


Fig. 6. Measurement Capture Sample

Parameter	Actual	Computed	Error
$TXPhase_{MM}$	1°	1.58°	0.58°
$RXPhase_{MM}$	2°	1.76°	0.24°
$TXgain_{MM}$	10%	10.7%	0.7%
$RXgain_{MM}$	25%	26.7%	1.7%
$I_{rx} - DC_{offset}$	20mV	22.6mV	2.6mV
$Q_{rx} - DC_{offset}$	15mV	12.5mV	2.5mV

TABLE III  
HARDWARE MEASUREMENT RESULTS - CASE 1

proposed. For this measurement, we use a single tone test signal specially designed to separate out impairment terms that we wish to compute. We use ratio based equations based on the signal amplitudes in two consecutive measurements. This proposed technique can compute the  $IQ$  imbalances in mere milliseconds including both test data capture and processing time. This method can be a candidate for on-chip implementation as we only need to analyze the baseband output signal with low computational burden. The accuracy of the method is confirmed in simulations and hardware measurements.

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Parameter	Actual	Computed	Error
$TXPhase_{MM}$	4°	5.87°	1.87°
$RXPhase_{MM}$	2°	1.25°	0.75°
$TXgain_{MM}$	25%	25%	0%
$RXgain_{MM}$	15%	16%	1%
$I_{rx} - DC_{offset}$	-20mV	-18mV	2mV
$Q_{rx} - DC_{offset}$	10mV	9.4mV	0.6mV

TABLE IV  
HARDWARE MEASUREMENT RESULTS - CASE 2

Parameter	Actual	Computed	Error
$TXPhase_{MM}$	3°	5.43°	2.43°
$RXPhase_{MM}$	2°	1°	1°
$TXgain_{MM}$	30%	29.3%	0.7%
$RXgain_{MM}$	15%	14.7%	0.3%
$I_{rx} - DC_{offset}$	-15mV	-14.8mV	0.2mV
$Q_{rx} - DC_{offset}$	10mV	9.4mV	0.6mV

TABLE V  
HARDWARE MEASUREMENT RESULTS - CASE 3

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