A Fast LO Leakage Calibration Method for MIMO Transmitter

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Abstract **–** Local oscillator (LO) leakage caused by in-phase/quadrature (I/Q) offsets severely degrades the performance of direct-conversion multiple-input multiple-output (MIMO) transmitters in 5G and emerging 6G systems. Existing LO leakage calibration methods often require many measurements or suffer from slow convergence, making them inefficient for multi-channel and multi-frequency applications. To address this challenge, this paper proposes a fast LO leakage calibration method based on Newton's method. For each channel at each frequency point, the I/Q offset compensation values are determined from only nine groups of I/Q settings and the corresponding LO leakage measurements. Simulations and experiments on an 8-channel MIMO transmitter show that the proposed method achieves an average LO leakage suppression of −55.6 dBc while reducing the number of calibration samples by more than 95% compared with traditional methods, demonstrating its efficiency and practicality for large-scale MIMO transmitters in 5G and 6G communications.

Index Terms **–** Calibration, in-phase/quadrature offset, local oscillator leakage, multiple-input multiple-output transmitter, Newton's method.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) technology is widely regarded as one of the key enabling technologies for 5G and future 6G systems. A MIMO system configured with hundreds or even thousands of antennas can significantly enhance wireless communication performance [1–3]. In MIMO systems, direct-conversion transmitters (DCTs) [4] are commonly employed due to their high integration, low cost, and low power consumption. However, the in-phase/quadrature (I/Q) DC offsets in DCTs cause local oscillator (LO) leakage, which results in transmitter performance degrade [5, 6]. The LO leakage signal cannot be directly eliminated by a filter, since it falls within or near the signal bandwidth in a DCT. Therefore, it is essential to calibrate the I/Q offsets to effectively suppress LO leakage signal.

For large-scale MIMO systems, a key challenge is the trade-off between calibration effectiveness and calibration time. In practical systems, calibration must be performed over multiple transmitter channels and multiple operating frequency points. As a result, the total calibration time scales with channels, frequency points, and measurements required at each frequency point. Although accurate LO leakage calibration is essential, many existing methods require excessive calibration time, which limits their practical applicability in large-scale MIMO systems. Therefore, it is highly desirable to develop a fast calibration method that achieves a favorable trade-off between calibration effectiveness and calibration time.

Existing LO leakage calibration methods can be broadly classified into traversal-based and estimation-based techniques. In traversal-based methods, [7] uses a detector feedback loop to search for proper I/Q offsets, while [5] employs a complex receiver feedback loop with frequency offset for LO leakage calibration. Although effective, such methods usually require

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exhaustive searches over the calibration space, resulting in long calibration time, especially in multi-channel and multi-frequency MIMO systems.

Estimation-based techniques have also been investigated. A blind technique based on higher-order statistics introduced in [4] estimates the calibration parameters using gradient descent, but may suffer from slow convergence and sensitivity to initialization and noise. The method in [8] performs compensation using specially designed training sequences, which limits implementation flexibility. Joint transmitter and receiver calibration is performed in [9, 10] with high computational complexity and unavoidable error propagation. Reference [11] combines least squares and gradient descent methods, but multiple candidate solutions and the need for phase information further increase calibration complexity.

Although these studies provide useful solutions for LO leakage calibration, several limitations remain for large-scale MIMO transmitters. Many existing methods mainly focus on single-channel calibration and do not explicitly consider the stringent calibration-time requirement in multi-channel systems. Moreover, the trade-off among low sample complexity, fast calibration speed, and sufficiently high LO leakage suppression has not been adequately addressed for practical deployment.

To overcome these limitations, this paper proposes a fast LO leakage calibration method based on Newton's method for MIMO transmitter systems. The main contributions of this work are summarized as follows: a fast LO leakage calibration method for MIMO transmitters is developed, which is particularly suitable for systems with numerous channels and frequency points; a Newton-based estimation scheme is developed to determine the I/Q offset compensation values; a nine-point measurement strategy is designed to balance calibration effectiveness and calibration time; experimental results demonstrate the effectiveness and efficiency of the proposed method.

The rest of the paper is organized as follows. Section II introduces the system model and the mechanism of LO leakage. Section III presents the proposed Newton-based LO leakage calibration method. Section IV presents the simulation and experimental results of the LO leakage in an 8-channel MIMO transmitter system. Section V concludes the paper.

II. SYSTEM MODEL

The system model of the LO leakage calibration of DCTs in a MIMO transmitter system is illustrated in Fig. 1. The I/Q signals $I^k(t)$ and $Q^k(t)$ are mixed with the LO signals f_{LO}^k to obtain the RF output signals y_{RF}^k, where k represents the k th transmitter channel, d_i^k and d_q^k represent the DC offsets corresponding to I and Q branch introduced due to the I/Q mixer or I/Q modulator in the k th transmitter channel and, accordingly, $d_{i\_set}^k$ and $d_{q\_set}^k$, generated from digital-to-analog converters (DACs), are the target compensating voltages to the k th transmitter channel for the LO leakage calibration.

The RF output signal of the k th transmitter channel, ignoring the influence of I/Q imbalance, can be expressed as

$$y_{RF}^k(t) = A^k\{[I^k(t) + d_i^k]\cos(2\pi f_{LO}^k t) + [Q^k(t) + d_q^k]\sin(2\pi f_{LO}^k t)\}, \quad (1)$$

where A^k represents the channel gain of the k th transmitter channel.

Ideally, the power of LO leakage signal is

$$P_{LO\_0}{}^k = 10\lg\{(A^k)^2[(d_i^k)^2 + (d_q^k)^2]\}. \quad (2)$$

The simulated variation of the LO leakage level with I/Q offsets is shown in Fig. 2, where I and Q offsets correspond to d_i^k and d_q^k in (2). It is clearly shown that the LO leakage level is minimized when d_i^k and d_q^k are zero. However, d_i^k and d_q^k cannot be equal to zero in practice, and therefore should be compensated by $d_{i\_set}^k$ and $d_{q\_set}^k$ to minimize the LO leakage level. After calibration, equation (2) can be adjusted to

$$P_{LO}{}^k = 10lg\{(A^k)^2[(d_i^k - d_{i\_set}^k)^2 + (d_q^k - d_{q\_set}^k)^2]\}. \quad (3)$$

Obviously, the LO leakage calibration can be completed by finding out the values satisfying $d_{i\_set}^k = d_i^k$ and $d_{q\_set}^k = d_q^k$.

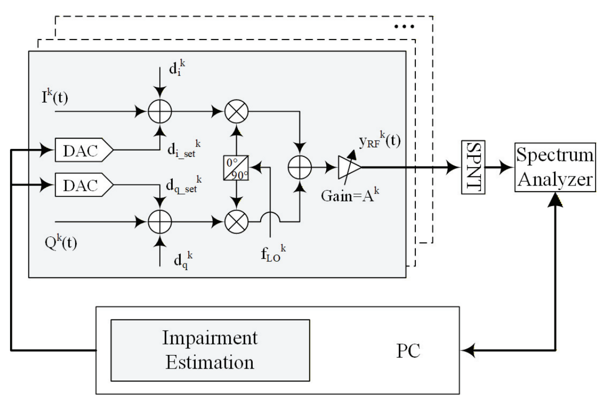

Fig. 1. System model of MIMO DCT system with calibration circuit.

III. CALIBRATION ALGORITHM

As shown in Fig. 1, the PC controls the DACs to generate a set of compensating voltages for various

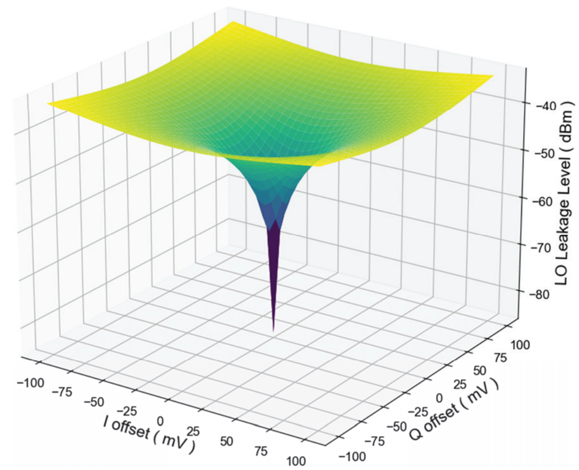

Fig. 2. Simulated LO leakage level versus I/Q offsets.

transmitter channels. The spectrum analyzer measures the corresponding LO leakage levels and reports back to the PC. The proposed calibration algorithm based on Newton's method computes the optimized compensating voltages required to minimize the LO leakage levels.

Taking one transmitter channel as an example, for the nth measurement, $n = 0, 1, \ldots, N$, applying different I/Q offsets $(d_{i\_set\_n}, d_{q\_set\_n})$ and measured LO leakage power P_n, a set of equations can be obtained

$$\begin{cases} P_0 = A(d_i^2 + d_q^2) \\ P_1 = A((d_i - d_{i\_set\_1})^2 + (d_q - d_{q\_set\_1})^2) \\ \qquad \ldots \\ P_n = A((d_i - d_{i\_set\_n})^2 + (d_q - d_{q\_set\_n})^2) \end{cases}, \quad (4)$$

where, for simplicity, the channel superscript k is omitted, and the gain A is a fixed constant for this channel. Set the 0th measurement as the reference, then

$$\begin{cases} \dfrac{P_n}{P_0} = \dfrac{(d_i - d_{i\_set\_n})^2 + (d_q - d_{q\_set\_n})^2}{d_i^2 + d_q^2} \\ \dfrac{P_{n-1}}{P_0} = \dfrac{(d_i - d_{i\_set\_n-1})^2 + (d_q - d_{q\_set\_n-1})^2}{d_i^2 + d_q^2} \end{cases}. \quad (5)$$

Subtracting the two equations in (5), i.e., $\frac{P_n}{P_0} - \frac{P_{n-1}}{P_0}$, yields

$$2\left(\frac{d_{i\_set\_n}}{z_n} - \frac{d_{i\_set\_n-1}}{z_{n-1}}\right) d_i + 2\left(\frac{d_{q\_set\_n}}{z_n} - \frac{d_{q\_set\_n-1}}{z_{n-1}}\right) d_q = \frac{d_{i\_set\_n}^2}{z_n} - \frac{d_{i\_set\_n-1}^2}{z_{n-1}} + \frac{d_{q\_set\_n}^2}{z_n} - \frac{d_{q\_set\_n-1}^2}{z_{n-1}}, \quad (6)$$

where $z_n = 1 - \frac{P_n}{P_0}$ and $z_{n-1} = 1 - \frac{P_{n-1}}{P_0}$.

Under the ideal noiseless model, all $n-1$ lines in (6) will intersect at a single point (d_i, d_q). The target value for the LO leakage calibration can be obtained by determining the intersection point. However, the lines cannot intersect at a single point due to non-ideal physical conditions, such as hardware noise and measurement errors. Instead, an optimization algorithm can be employed to identify a point (d_x, d_y) that minimizes the sum of the squares of the distances from this point to the set of lines. This approach yields the point with the smallest error relative to the theoretical target point (d_i, d_q).

Let $(d_i, d_q) = (x, y)$, equation (6) can be simplified as

$$a_n x + b_n y = c_n. \quad (7)$$

For a candidate point (x, y) as the target point, the square of its distance from the lines in (7) can be expressed as

$$dist_n^2(x, y) = \frac{(a_n x + b_n y - c_n)^2}{a_n^2 + b_n^2}. \quad (8)$$

For convenience, define $w_n = \frac{1}{a_n^2 + b_n^2}, r_n(x, y) = a_n x + b_n y - c_n$, the objective function is the sum of (8)

$$f(x, y) = \sum_{n=1}^{N-1} \frac{(a_n x + b_n y - c_n)^2}{a_n^2 + b_n^2} = \sum_{n=1}^{N-1} w_n r_n^2(x, y), \quad (9)$$

where N represents n set of I/Q offsets, $N-1$ represents $n-1$ lines in (6).

The target point for the LO leakage calibration will be found as soon as the point (x, y) is found which can minimize $f(x, y)$ in (9).

First, the gradient of the objective function is calculated

$$\nabla f(x, y) = \begin{bmatrix} \dfrac{\partial f(x, y)}{\partial x} \\ \dfrac{\partial f(x, y)}{\partial y} \end{bmatrix} = 2 \sum_{n=1}^{N-1} w_n r_n(x, y) \begin{bmatrix} a_n \\ b_n \end{bmatrix}. \quad (10)$$

Second, calculate the Hessian matrix

$$H = \begin{bmatrix} \dfrac{\partial^2 f}{\partial x^2} & \dfrac{\partial^2 f}{\partial x \partial y} \\ \dfrac{\partial^2 f}{\partial y \partial x} & \dfrac{\partial^2 f}{\partial y^2} \end{bmatrix} = 2 \sum_{n=1}^{N-1} w_n \begin{bmatrix} a_n^2 & a_n b_n \\ a_n b_n & b_n^2 \end{bmatrix}, \quad (11)$$

Since $f(x, y)$ is quadratic, the Hessian matrix is constant and positive semidefinite. When the measurement points are chosen such that the resulting lines are not all parallel, the Hessian becomes positive definite, and the minimizer is unique. Therefore, the solution of (9) can be approximated gradually by iteration based on Newton's method. The iterative formula for Newton's method is

$$\begin{bmatrix} x^{(t+1)} \\ y^{(t+1)} \end{bmatrix} = \begin{bmatrix} x^{(t)} \\ y^{(t)} \end{bmatrix} - H^{-1}\nabla f(x^{(t)}, y^{(t)}). \quad (12)$$

The iteration starts from $(x^{(0)}, y^{(0)}) = (0,0)$ as the values of I/Q offsets for LO leakage calibration are usually very small, and stops when the norm of the update falls below a prescribed threshold.

The impact of the number of I/Q offset configurations on LO leakage calibration results under different LO leakage power errors, based on the proposed method, is simulated first. As shown in Fig. 3, the smaller the LO leakage power measurement error (e.g., when $\sigma = 0.1$), the better the LO leakage calibration results. The trend indicates that increasing number of I/Q offset points can improve the LO leakage calibration result. When 8–10 sets of I/Q offset configurations are selected, the calibration performance is about 10 dB worse compared to selecting 20–40 sets. Nine sets of I/Q offset configurations are adopted in this work as a compromise between the LO leakage calibration performance and the total calibration time.

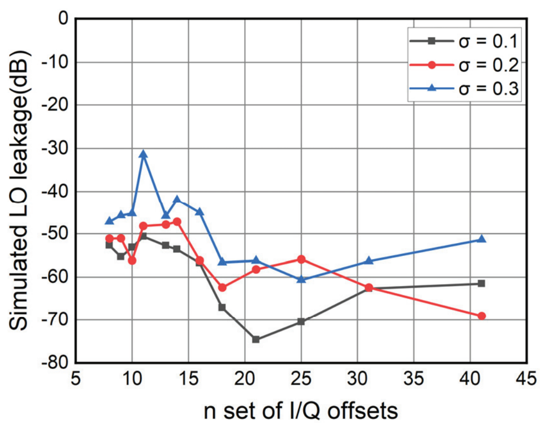

Fig. 3. Simulation of the impact of the number of I/Q offset configurations on LO leakage calibration results under different LO leakage power errors.

The detailed procedure of the proposed LO leakage calibration method for MIMO transmitters is illustrated in Fig. 4. The calibration process is summarized as follows.

S1: Select channel k and the target frequency point. Apply nine sets of I/Q compensation voltages $(d^k_{i\_set\_n}, d^k_{q\_set\_n})$, and measure corresponding LO leakage power P^k_n.

S2: Based on the measured data, derive a set of linear equations according to (4)–(7).

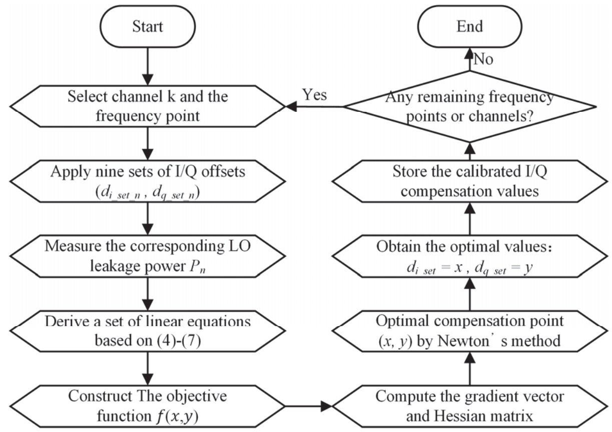

Fig. 4. Flowchart of the proposed Newton-based LO leakage calibration method for the MIMO transmitters.

S3: Construct the objective function $f(x,y)$, which is defined as the sum of the squared distances from a candidate point (x,y) to the derived lines.

S4: Compute the gradient vector and Hessian matrix of $f(x,y)$, and use Newton's method to determine the optimal compensation point (x,y). The obtained result is taken as the optimal compensation values.

S5: The same procedure is repeated for all remaining channels and frequency points until the calibration process is completed.

IV. EXPERIMENTAL RESULTS

Figure 5 shows the experimental scenario for LO leakage calibration, which consists of an 8-channel MIMO transmitter system, a PC running the calibration algorithm, a signal analyzer for measuring LO leakage levels under different I/Q offsets in each channel, and a switching matrix for selecting and switching between different channels.

Table 1 lists the LO leakage levels corresponding to different I/Q compensating voltages $(d_{i\_set\_n}, d_{q\_set\_n})$ in a single transmitter channel. The nine I/Q offset combinations $(0, -0.1, +0.1)$ are carefully chosen to evenly cover the range of possible I/Q offsets, balancing calibration accuracy with calibration time. Following the steps in section III, seven lines are derived, and then the point that can minimize the sum of the squared distances from the seven lines is identified using Newton's method. The seven lines that roughly intersect at one point are depicted in Fig. 6. The point calculated using Newton's method $(-68.70, 19.82)$ is very close to the manually measured point $(-66.10, 17.90)$.

Table 2 compares the I/Q compensating voltages for LO leakage calibration between manually measured and the proposed method for different transmit channels

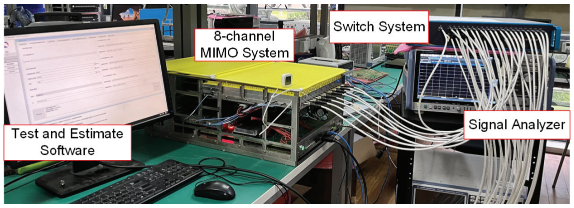

Fig. 5. Experimental scenario.

Table 1: Measured LO leakage level at 9 I/Q offsets

No.	I Offset (mV)	Q Offset (mV)	LO Leakage Level (dBm)
1	0	0	−19.18
2	0	+0.1	−15.54
3	0	−0.1	−13.30
4	+0.1	0	−11.33
5	+0.1	+0.1	−10.88
6	+0.1	−0.1	−9.34
7	-0.1	0	−25.32
8	-0.1	+0.1	−15.71
9	-0.1	−0.1	−15.30

Table 2: Comparison of calculated and manually measured I/Q offsets

Channel	Newton's Method		Manually Test	
	I(mV)	Q(mV)	I(mV)	Q(mV)
1	−68.70	19.82	−66.1	17.9
2	−49.05	−15.78	−51.2	−17.3
3	−57.31	−10.76	−59.3	−12.5
4	−62.16	7.01	−63.7	7.4
5	−54.30	−3.45	−55.7	−3.3
6	−51.10	−10.80	−52.5	−12.3
7	−65.51	32.27	−68.8	31.3
8	−55.29	−3.73	−57.3	−3.3

in the 8-channel MIMO system. The proposed method exhibits high consistency with the manually measured values, with an average error of only 2 mV. The results demonstrate the effectiveness of the proposed calibration technique for MIMO transmitter LO leakage suppression in MIMO transmitter systems.

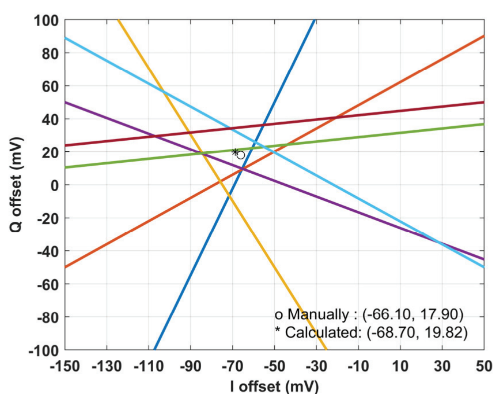

Fig. 6. Calculated and manually measured I/Q compensation values for LO leakage calibration.

The eight I/Q offset calibration values for the 8-channel transmitter, obtained using the proposed method, are applied to the MIMO transmitter system for LO leakage testing. For comparison, the LO leakage without calibration and that with manually calibration are also measured under the same experimental conditions, as shown in Fig. 7.

It can be observed that the proposed method significantly suppresses the LO leakage for all eight transmitter channels compared with the uncalibrated case. Although manual calibration achieves a lower average LO leakage of about −70 dBc, the proposed Newton-based method reduces the average LO leakage of the eight channels to approximately −55.6 dBc, while requiring only nine samples. These results demonstrate that the proposed method provides a favorable trade-off between calibration performance and measurement efficiency in multi-channel MIMO transmitter systems.

Generally, measurement instruments require a signal-to-noise (SNR) in the range of 40 to 52 dBc [12, 13], while the most stringent SNR requirement specified in 3GPP for 5G mobile communication is 35 dBc [14]. Therefore, the calibrated LO leakage level of −55.6 dBc satisfies both instrument-grade SNR requirements and practical communication system requirements.

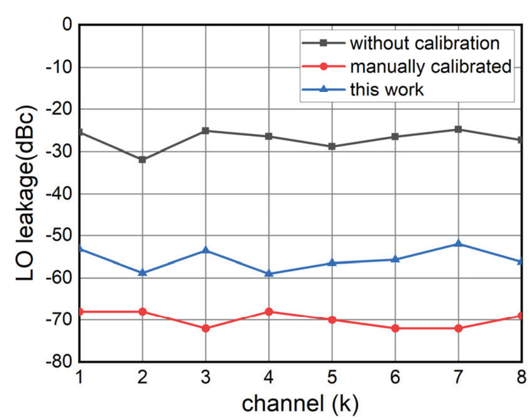

Fig. 7. Measured LO leakage of the 8-channel MIMO transmitter without calibration, with traversal-based and with proposed Newton-based calibration.

Table 3 further compares the proposed method with representative existing methods in terms of LO leakage

Table 3: Comparison of calibration results

Item	Calibration Method	LO Leakage (dBc)	Type	Samples per Frequency Point	Channels	Total Calibration Time* (hour)
[4]	Gradient descent	−52	Chip-level tested	10000	1	1111
[5]	Traversal-based	−100	Simulated	512	1	5.73
[7]	Traversal-based	−45	Chip-level tested	180	1	2
[9]	Least squares	−52	Chip-level tested	1000	1	11.07
[11]	Least squares + gradient descent	−53	System-level tested	40000	1	444
[10]	Joint digital online compensation	−58	Chip-level tested	64	1	/(online)
This Work	Newton's method	−55.6 (average)	System-level tested, 8-channel, RF out	9	8	0.1

*Total calibration time is calculated for an 8-channel system with 100 frequency points per channel, assuming that each set of I/Q compensation values requires 50 ms.

suppression, sample number, applicability, and total calibration time. The proposed method achieves an average LO leakage of −55.6 dBc with only nine samples per frequency point per channel, which is comparable to or better than the reference methods while significantly reducing the sample number by more than 95%. In particular, under the unified assumption of eight channels, 100 frequency points per channel, and 50 ms for each set of I/Q compensation values, the total calibration time of the proposed method is only about 0.1 hour (6 minutes). By contrast, the reported methods cost more than 2 hours due to their much higher sample complexity. This result demonstrates the advantage of the proposed method in achieving a good trade-off between calibration performance and calibration time, especially for multichannel MIMO transmitter systems.

V. CONCLUSION

A novel fast LO leakage calibration technique for the MIMO transmitter system based on Newton's method is proposed in this paper. By measuring nine sets of I/Q offsets and the corresponding LO leakage levels, the I/Q offset values for its LO leakage calibration can be accurately and efficiently computed. Experiments on an 8-channel MIMO transmitter system demonstrate that the proposed method achieves an average LO leakage of −55.6 dBc after calibration, requiring only nine samples per frequency point per channel. These results underscore the method's fast and effective performance, making it well-suited for largescale MIMO systems in 5G and 6G communications.

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