Quadrature Error Correction for Wideband Zero-IF Signals

ABSTRACT

This application note describes the quadrature error correction (QEC) for broadband quadrature signal on microwave upconverters and downconverters, such as ADMV1017, ADMV1018, ADMV1128A, and ADMV1139A.

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REVISION HISTORY

5/2023—Revision 0: Initial Version

INTRODUCTION

ADMV1017, ADMV1018, ADMV1128A, and ADMV1139A are microwave upconverters and downconverters that are optimized for 5G radio designs operating in the frequency bands 24 GHz to 29.5 GHz and 37 GHz to 48 GHz. These converters offer two modes of frequency translation: direct-conversion from/to differential baseband in-phase/quadrature (I/Q) input signals to/from RF, as well as single sideband conversion from/to complex intermediate frequency (IF) inputs to/from RF. The baseband (BB) I/Q frequency range of these converters is DC to 1.5 GHz.

The microwave converters are suitable for the fifth generation (5G) applications, which provide Gbps data rates. The direct conversion IQ modulation can provide a good solution for wideband signaling when interfacing the upconverters and downconverters with the analog-to-digital converters (ADC) and digital-to-analog converters (DAC). However, in the direct-conversion architecture, any gain and/or phase mismatch between the in-phase (I) and quadrature (Q) signal results in undesired (image) frequency components to fall onto the signal and therefore causes in-band signal interference, which degrades the error vector magnitude (EVM).

To suppress the image signal, the QEC algorithm is often used. Such algorithm attempts to estimate and correct for the gain and phase imbalances in the I and Q signal paths. The QEC algorithm can either be implemented on analog platform (using gain and phase knobs) or on a digital platform (using any digital-signal processing platform). Digital QEC algorithm is more accurate and can provide large image rejection. Digital QEC algorithm might be particularly useful when the IQ imbalances are frequency-dependent (that is, gain and phase mismatches are not flat across the frequency).

To measure the image rejection of a radio, the image rejection ratio (IRR) in dB is commonly used. IRR is defined as the ratio between the desired signal level at a frequency component and the signal level at the image frequency. Figure 1 shows a desired tone at −500 MHz and an image at 500 MHz, the image rejection ratio is about 40 dB. In a perfect mixer, the image rejection ratio can reach around −78 dBc.

Figure 2 shows the IRR in dB for different values of gain and phase mismatch in the I and Q signal paths. For instance, 1 dB gain imbalance or 6.5º phase imbalance results in −25 dB image rejection.

The upconverters and downconverters include analog knobs to control the gain and phase offsets between the I and Q paths. These knobs can typically achieve 25 dB to 30 dB image rejection. Typical values for image rejection ratio are 40 dBc to 50 dBc. For example, a −40 dBc image translates to an interference or noise level that causes $10^{-40/20} = 0.01$ or 1% EVM.

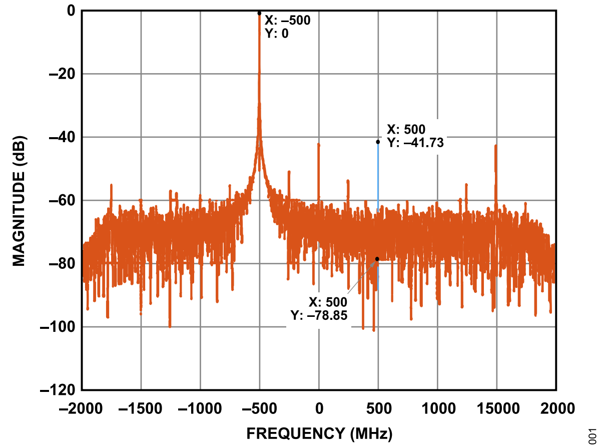

Figure 1. Illustration for the Image Frequency: A Carrier Wave Tone at −500 MHz and Its Image at 500 MHz

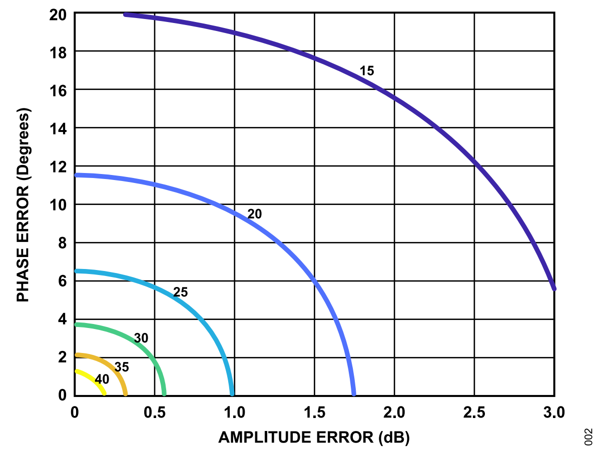

Figure 2. Contours for the IRR (in dB) vs. Gain and Phase Imbalance

TRANSMITTER AND RECEIVER IQ IMBALANCE

The IQ imbalance in the transmitter and receiver paths of the frequency converters can be generally nonidentical. Therefore, QEC algorithm is required to operate for both transmitter and receiver paths. For the receiver path, the received signal can be captured and processed to correct for the IQ imbalance. For transmitter, however, an observation receiver (ORx) path might be needed to capture the transmitted signal and estimate the IQ imbalance in the transmitter path. Once the IQ imbalance is estimated, a precorrected IQ signal is created to precompensate for the (estimated) transmitter IQ imbalance.

The QEC measurements are performed using high-rate data converters AD9988 connected to the frequency converter ADMV1018 on a printed circuit board (PCB). Two transmit channels (DAC) of AD9988 are connected to the two baseband ports of the ADMV1018 (I_{IN} and Q_{IN}), while two receive channels of AD9988 (ADC) are connected to two baseband ports (I_{OUT} and Q_{OUT}) of ADMV1018. The board is designed such that the trace lines between AD9988 and ADMV1018 are balanced in terms of gain and phase.

IQ TESTS ON MXFE BOARD

Zero-IF tests have been conducted on an evaluation board that has AD9988 interfacing with the upconverter and downconverter ADMV1018 (Figure 3). In the transmit mode, the signal is delivered to AD9988 DAC through an FPGA, and then routed to the IQ input of the ADMV1018. The signal is then captured by the analyzer to perform the RF measurements (IQ image, adjacent channel leakage ratio (ACLR), and EVM, …). In the receive mode, an RF signal goes from an external source into the RF input of ADMV1018, which downconverts the signal to baseband (input of the DAC AD9988). Another receiving mode exists on this board, a loopback path from the RF_{OUT} into RF_{IN} of the ADMV1018.

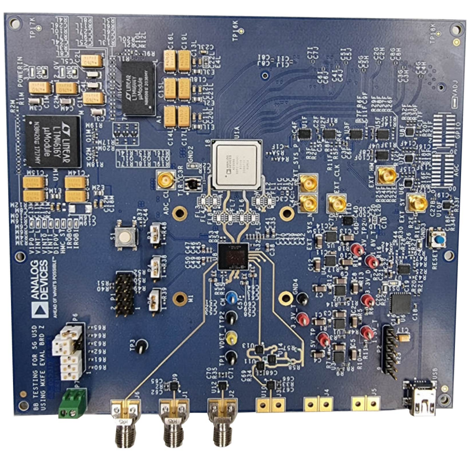

Figure 3. Data Converter (AD9988) + 5G Upconverter and Downconverter ADMV1018 (UDC) Used for ZIF QEC

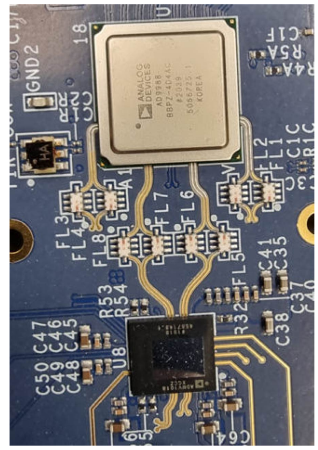

Figure 4. Data Converter (AD9988) + 5G Upconverter and Downconverter Zoomed Photo

QEC ALGORITHM

In the receiver path, the RF signal is downconverted and digitally processed through a complex digital adaptive filtering shown in Figure 5. The number and weight of the filter coefficients can be adjusted to achieve the required image rejection.

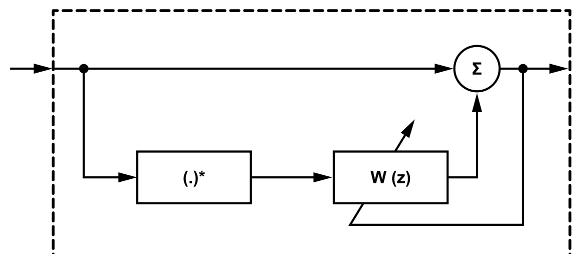

Figure 5. Complex Adaptive Digital Filter Used for QEC

The algorithm uses the circularity-based approach, for more information, refer to the external reference mentioned in the Notes section. This approach uses second-order statistics of the signal. A baseband signal is said to be proper (or circular), when the complementary autocorrelation function vanishes for long observation period. The assumption is valid for signals used in most communication systems. Under IQ imbalance, the signal becomes improper, that is, the complementary autocorrelation function does not disappear. Linear filtering can be used to suppress the mirror-frequency created by the IQ imbalance.

Let $x(n)$ be the discrete-time samples representing the baseband signal that has mirror-frequency interference (that is, IQ imbalance). A complex digital filter can be used to reject, for more information, refer to the external reference mentioned in the Notes section. Let $w(n)$ be the discrete-time filter tap. A simple algorithm to obtain a clean signal, $y(n)$, that has a rejected image is:

$$y(n) = x(n) + \boldsymbol{w}^T(n)x \times (n) \tag{1}$$

$$\boldsymbol{w}(n+1) = \boldsymbol{w}(n) - \boldsymbol{M} \quad \boldsymbol{y}(n)y(n) \tag{2}$$

The vectors $y(n)$ and $x(n)$ are given by Equation 3 and Equation 4 respectively:

$$\boldsymbol{y}(n) = [y(n) \quad y(n-1) \quad ...y(n-N+1)]^T \tag{3}$$

$$\boldsymbol{x}(n) = [x(n) \quad x(n-1) \quad ...x(n-N+1)]^T \tag{4}$$

The filter coefficient vector is given by:

$$\boldsymbol{w}(n) = [w(n) \quad w(n-1) \quad ...w(n-N+1)]^T \tag{5}$$

Complex adaptive digital filter used for QEC.

The step-size matrix ***M** = diag*(μ1, μ2...μN) is a diagonal matrix that controls the convergence rate to the optimal solution. The adaptive algorithm obtains the filter coefficient vector $\boldsymbol{w}(n+1)$ at time $n+1$ by using a reference signal $\boldsymbol{x}(n)$, an observation vector $\boldsymbol{y}(n)$, and the filter vector $\boldsymbol{w}(n)$, at time n. The optimal solution for the filter vector is obtained when $y(n)y(n)$ is minimized. The quantity $y(n)y(n)$ simply represents a sample Pearson correlation coefficient that can be used in this discrete-time model instead of the statistical correlation coefficient $E(y(n)y(n))$. An optimal solution is reached when $E[\boldsymbol{y}(n)y(n)] = \boldsymbol{0}$, or equivalently, when $\boldsymbol{y}(n)y(n)$ is minimized.

Notice that the filter coefficient vector is adapted for every time instant n. Therefore, at every instant n, a new filter coefficient vector, and a new sample of the filter output are obtained, that is, the filter adaptation is done online while the baseband signal is being received and processed. This process is called Receiver QEC.

Unlike the receiver path, the signal coming out from the transmitter path must be preprocessed prior of upconversion process to reject the image frequency. The filter coefficient used for the transmitter can be estimated by first capturing an upconverted signal through an observation receiver. The captured signal can be processed using a digital filter similar to the one given by Equation 1 and Equation 2. Once the filter coefficient vector is obtained, the baseband signal can be prefiltered prior of the transmitter upconversion to obtain a clean RF signal, that is, a signal that has rejected image.

The filter coefficient vector and the weighted step-size matrix can be chosen to control the convergence rate of the algorithm as well as the desired image rejection ratio value. As mentioned before, typical values for image rejection ratio are 40 dBc to 50 dBc.

QEC MEASUREMENTS

Figure 6 shows a capture from the analyzer screen for a 100 MHz new radio (NR) 5G signal centered at 28.150 GHz and an image signal at 27.850 GHz (in the blue trace). The image signal is more than −25 dB below the main (yellow) signal (that is, the image rejection <25 dB). When applying the QEC algorithm, the image signal is suppressed.

Figure 7 shows 400 MHz NR 5G signal centered at 27.8 GHz. The image signal is about 22.6 dBc. When applying the QEC algorithm, the image is suppressed, and the IRR is about 46 dB.

Figure 8 shows 100 MHz NR 5G signal centered at 250 MHz and an image signal at −250 MHz. The signal is processed in baseband using MATLAB. The image is about −20 dB below the main signal before applying the QEC algorithm and goes to −50 dBc after applying the QEC algorithm.

Figure 9 shows 400 MHz NR 5G signal centered at 200 MHz and an image signal at −200 MHz. The image is about −20 dB below the main signal before applying the QEC algorithm and goes to −45 dBc after applying the QEC algorithm.

The upconverters and downconverters (UDC) operate with single local oscillator (LO) source for both transmitter and receiver. When doing transmitter QEC, an external ORx path is used. This ORx path operates with a separate LO source that is used to downconvert the RF transmitter signal into low-IF (not Zero-IF) to estimate the necessary transmitter QEC filter. Low-IF is needed in order not to overlap the ORx image on the transmitter image. Another methodology can be also used to do transmitter QEC using the receiver path of the same UDC chip, as described in the Transmitter QEC Using Transmitter-Receiver Loopback with Same LO section.

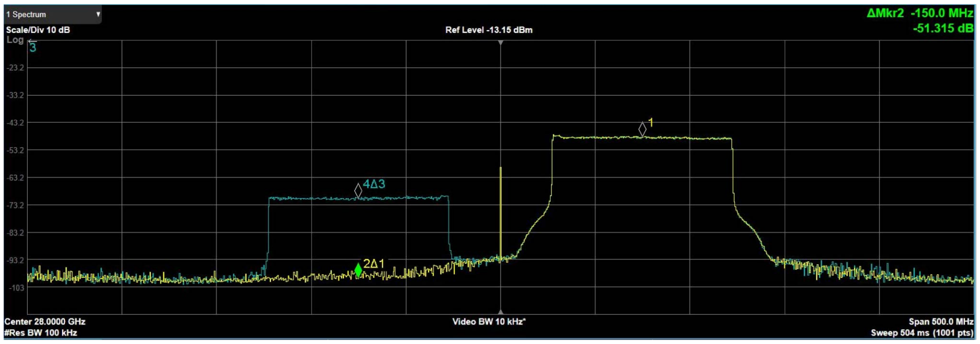

Figure 6. Image Rejection on Upconverter ADMV1018: The Yellow Curve is a 100 MHz NR Signal at 28.150 GHz Captured at the Output of the Upconverter of ADMV1018, the Blue Curve is for the Same Signal When QEC Algorithm is Applied

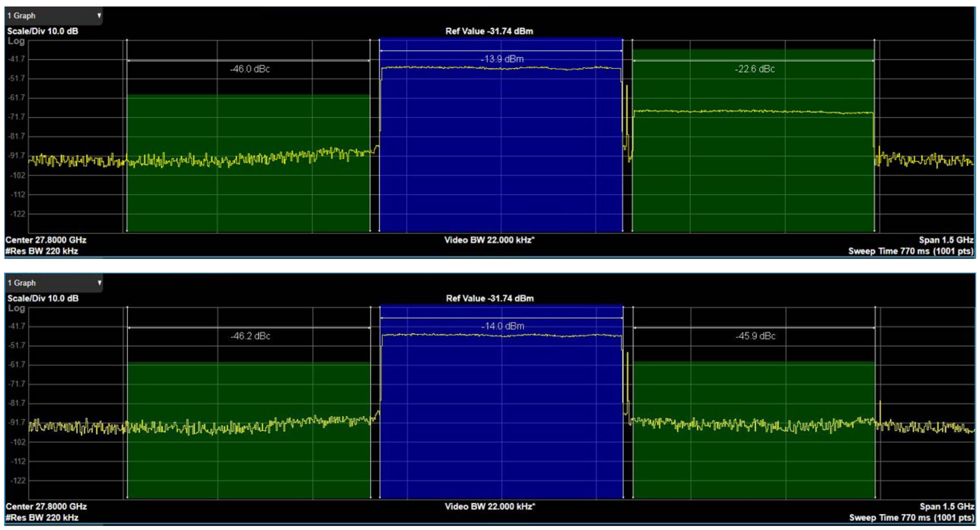

Figure 7. Image Rejection on Upconverter ADMV1018: A) 400 MHz Centered at 27.8 GHz at the Output of ADMV1018 Without Applying the QEC Algorithm, B) the Same 400 MHz After Applying the QEC Algorithm. Note That the Image is Suppressed (IRR is 45.9 dB)

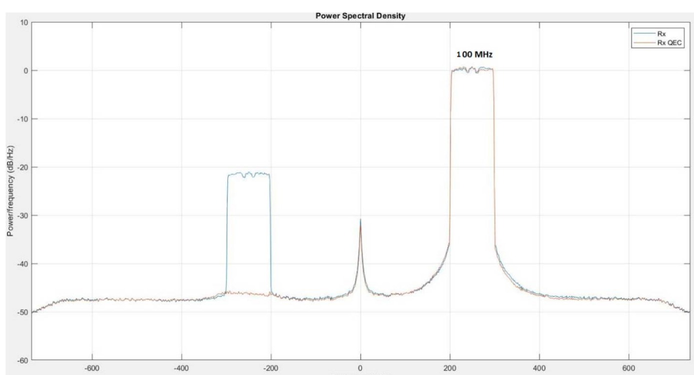

Figure 8. Image Rejection on Downconverter ADMV1018: A) 100 MHz Centered at 250 MHz at the Output of the Downconverter ADMV1018 Without Applying the QEC Algorithm, B) the Same 100 MHz After Applying the QEC Algorithm. Note That the Image is Suppressed (IRR is 50 dB)

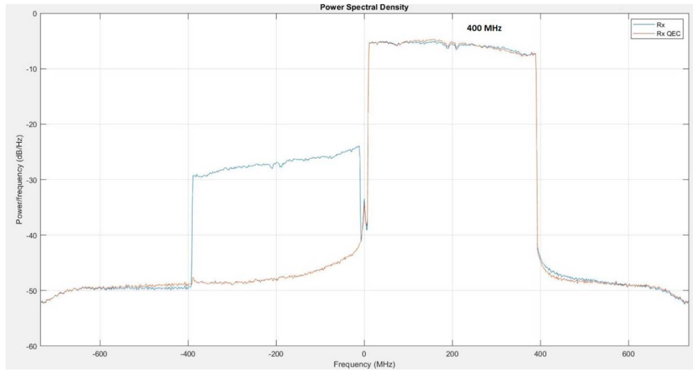

Figure 9. Image Rejection on Upconverter ADMV1018: A) 400 MHz Centered at 200 MHz at the Output of Downconverter ADMV1018 Without Applying the QEC Algorithm, B) the Same 400 MHz After Applying the QEC Algorithm. Note That the Image is Suppressed (IRR is About 45 dB)

TRANSMITTER QEC USING TRANSMITTER-RECEIVER LOOPBACK WITH SAME LO

In some applications, it might be useful to use the receiver path of the same chip, for example ADMV1018, as ORx for the transmitter. In such case, this ORx must be IQ calibrated before doing the transmitter IQ calibration. To calibrate the ORx, an oscillator is needed to generate CW tones at the input of the ORx (to allow for IQ image estimation and cancellation).

This scenario is tested on our MxFE-UDC board: the transmitter and the ORx paths are operating with the same phase locked loop (PLL), the ORx path has been calibrated (with single-tap complex filtering).

Figure 10 and Figure 11 show transmitter QEC using ORx path that has been calibrated with single-tap complex filtering on a 200 MHz signal (to achieve ≥ 40 dB IRR on transmitter).

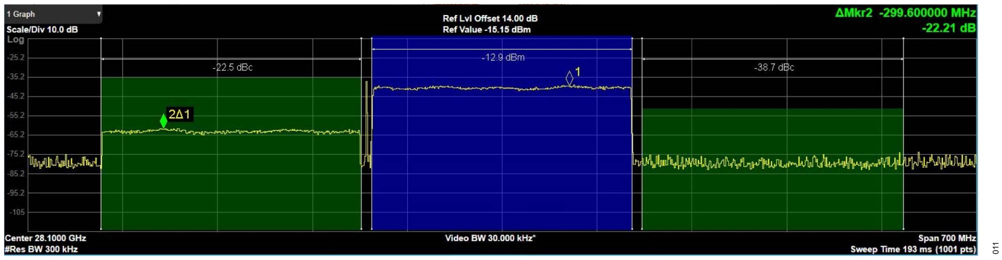

Figure 10. 200 MHz 5G NR Signal on MxFE-ADMV1018 Board. The Image is at −22.5 dBc

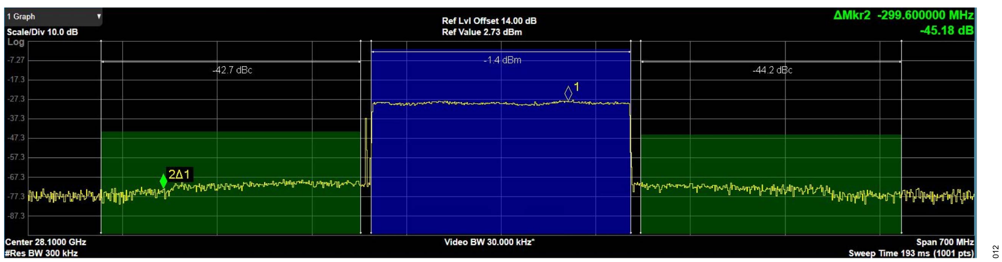

Figure 11. 200 MHz 5G NR Signal on MxFE-ADMV1018 Board. The Image is −42.7 dBc Using ORx Path That has been Calibrated with CW Tones

NOTES

M. V. a. M. R. L. Anttila, "Blind Compensation of Frequency-Selective I/Q Imbalances in Quadrature Radio Receivers: Circularity-Based Approach," 2007.