A new LMS I/Q & LOFT imbalance correction scheme for RF Transmitter

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Block Diagram

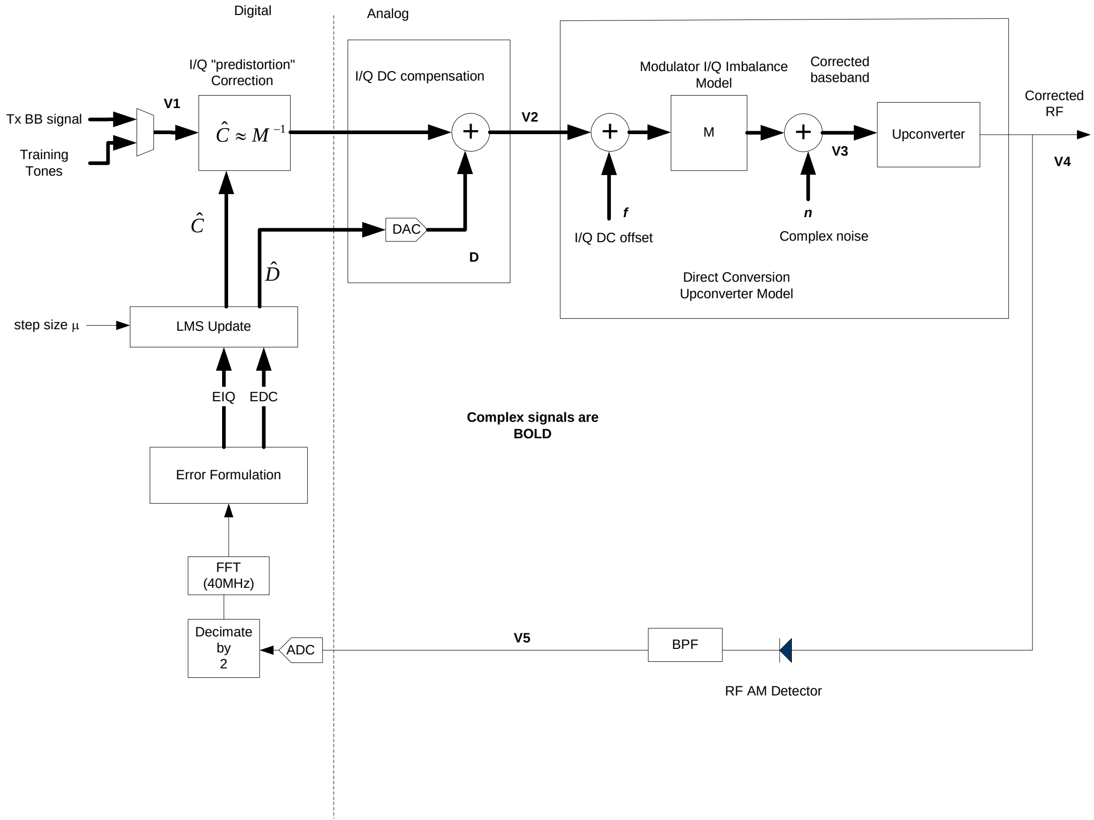

Figure 1. Block diagram of the Transmitter I/Q & LOFT compensation algorithm.

Abstract

The I/Q imbalance and LOFT in a transmitter can be detected in an RF envelope detector and corrected concurrently in a convergent algorithm without the need to individually sweep the DC offsets or gain/phase imbalances. The error signals are obtained by (1) generating fixed tones which have small DC or I/Q offsets added sequentially, (2) detecting the resultant RF signals, and comparing the frequency content *in pairs* to generate a direction and error signal, and (3) applying an LMS update to 4 parameters concurrently.

This new approach has the merit of fast convergence, individual control over when to start/stop the algorithm (convergence vs. tracking), as well as avoiding the misadjustment of parameters that typically occurs with coupled parameters such as I/Q phase, gain and DC leakage when swept individually.

The algorithm is based loosely on reference [1] but with several important changes, specifically,

- An entirely different mechanism for predistortion is used based on adding a small amount of conjugate signal.
- An entirely different set of training tones is used which concurrently steps both DC and I/Q at the same time. These effects can be observed independent of each, but at the same time using an orthogonal transformation such as an FFT.
- An entirely different error formulation based on subtracting out two *pairs* of FFT frequency bin magnitudes from different training tone sets.

Model definitions and equations

Refer to Figure 1.

The I/Q phase/gain compensator "predistorts" the ideal I/Q inputs and adds DC "predistortion" according to the following formula;

$$V_2 = V_1 + C(V_1)^* + D \qquad \textbf{Equation 1}$$

Where

- V_1 is the ideal complex baseband signal,
- V_2 is the "predistorted" complex baseband signal,
- * is the complex conjugate operator
- D is the complex dc offset "predistortion"
- C is a complex multiplier representing the desired leakage in the compensator block from one branch (I or Q) to the other branch, i.e. gain and phase differences between the I/Q paths.

The direct upconverter modulator adds IQ imbalance and LOFT distortion, as represented by the following formula;

$$V_3 = ((V_2 + f) + M(V_2 + f)^*) + n \qquad \textbf{Equation 2}$$

Where

- V_2 is the predistorted complex baseband signal,
- V_3 is the baseband corrected signal after going through the modulator,
- * is the complex conjugate operator
- f is the undesired complex dc offset introduced at the modulator
- n is complex noise with variance σ^2 introduced at the modulator
- M is a complex multiplier representing the undesired leakage in the modulator from one branch (I or Q) to the other branch, i.e. gain and phase differences between the I/Q paths.

The distortion matrix M (or C for that matter) represents the I/Q leakage transformation and is shown in Figure 2.

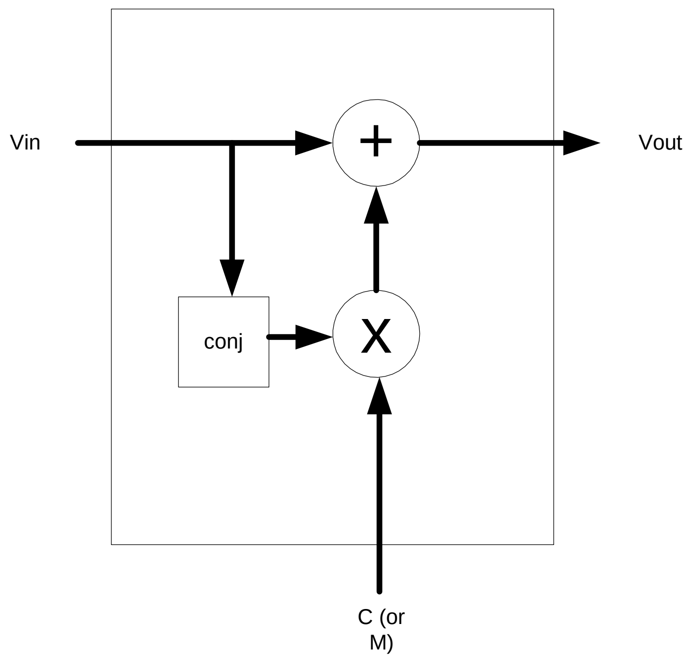

Figure 2 Complex representation of I/Q gain/phase leakage block. C (or M) is usually a small complex number. This structure is used to represent modulator distortion, as well as to represent compensator "predistortion".

The leakage block is analogous to adding differential gain and phase imbalances.

In the algorithm, we attempt to get back the original signal by estimating the inverse $\hat{C} \approx M^{-1}$. We also compute estimates for the complex DC value $\hat{D} \approx -f$ using the LMS update algorithm.

Training Tones

For each iteration a set of training tones must be generated and output to the transmitter modulator.

The training tone set $T(k)$=[$T_1(k)$, $T_2(k)$,$T_3(k)$] is 4.8us long. T_1, T_2 and T_3 are each 1.6us in duration and are applied sequentially. T_1 *(k)* is the "baseline" training tone at iteration *k*. T_2 *(k)* is the same as T_1 *(k)* except that it has a small amount of additional C and D added on the *real* portion only. T_2 *(k)* is the same as T_1 *(k)* except that it has a small amount of additional C and D added on the *imaginary* portion only

The mathematical definition is given below;

$$T_1(k) = S + \hat{C}(k)S^* + \hat{D}(k)$$ **Equation 3**

$$T_2(k) = S + (\hat{C}(k) + \Delta_C)S^* + (\hat{D}(k) + \Delta_D)$$ **Equation 4**

$$T_3(k) = S + (\hat{C}(k) + j * \Delta_C)S^* + (\hat{D}(k) + j * \Delta_D)$$ **Equation 5**

where

- k is the iteration number
- S is a complex 5MHz tone, lasting for 1.6us.
- $\hat{C}(k)$ is the complex "predistorter" estimate at iteration k
- Δ_C is a small scalar (~0.01) representing a small increment to the real portion of the current estimate of $\hat{C}(k)$
- $j*\Delta_C$ is a small scalar (~0.01) representing a small increment to the imaginary portion of the current estimate of $\hat{C}(k)$
- Δ_D is a small scalar (~0.01) representing a small increment to the real portion of the current estimate of $\hat{D}(k)$
- $j*\Delta_D$ is a small scalar (~0.01) representing a small increment to the imaginary portion of the current estimate of $\hat{D}(k)$

An example is shown in Figure 3. Eight cycles of 5MHz tone will fit into 1.6us.

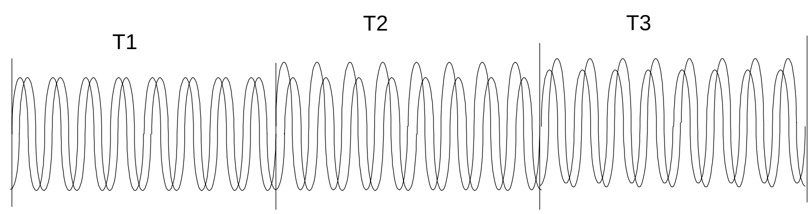

Figure 3. Training tone set for iteration k. T2 has small increases to the real portions of estimates C(k) and D(k). T3 has small increases to the imaginary portions of estimates C(k) and D(k).

Algorithm

Initialization

Set $\hat{C} = 0 + j*0$ (I/Q predistorter estimate)

Set $\hat{D} = 0 + j*0$ (DC offset estimate)

Set $\mu_{IQ} = 0.5$ or some other small value. (I/Q estimate step size)

Set $\mu_{DC} = 0.5$ or some other small value. (DC estimate step size)

Set $\Delta_C = 0.02$ or some other small value (C training tone step)

Set $\Delta_D = 0.02$ or some other small value (D training tone step)

Recursion, iteration (k)

- Generate a set of training tones $T(k)$ using the current estimate of $C(k)$ and $D(k)$. Refer to Equations 3,4,5.
- Apply the three sets of 64 samples of $T_i(k)$, to the RF modulator.
- Apply the RF signal through the RF detector.
- For each subset $T_i(k)$, take 128 samples of the detector output at 80Mhz and decimate to 64 samples at 40MHz.
- Apply the three sets of 64 samples of $T_i(k)$, to the RF modulator.
- 64 point FFT, and output the vectors $FFT_1(b,k)$, $FFT_2(b,k)$, and $FFT_3(b,k)$ for bin b=1,…,64 and iteration k.
- Compute the complex IQ error using

$$E_{IQ}(k) = (|FFT_2(17,k)| - |FFT_1(17,k)|) + j*(|FFT_3(17,k)| - |FFT_1(17,k)|)$$

Equation 6

- Compute the complex DC error using

$$E_{DC}(k) = (|FFT_2(9,k)| - |FFT_1(9,k)|) + j*(|FFT_3(9,k)| - |FFT_1(9,k)|)$$

Equation 7

- Apply the updates

$$\hat{C}(k+1) = \hat{C}(k) - \mu_{IQ} E_{IQ}(k)$$ **Equation 8**

$$\hat{D}(k+1) = \hat{D}(k) - \mu_{DC} E_{IQ}(k)$$ **Equation 9**

- Go back to the beginning

Simulation Results

Parameters

%=========modulator distortion parameters==================
M=0.1+j*-0.2;   %modulator distortion
Mdc=0.1-j*0.5; %DC offset in modulator
AmpNoise=0.01;% (SNR approx 39dB SNR).

%=========LMS parameters==================
muQ=1;
muDC=1;

CStep=0.02;
DCStep=0.02;

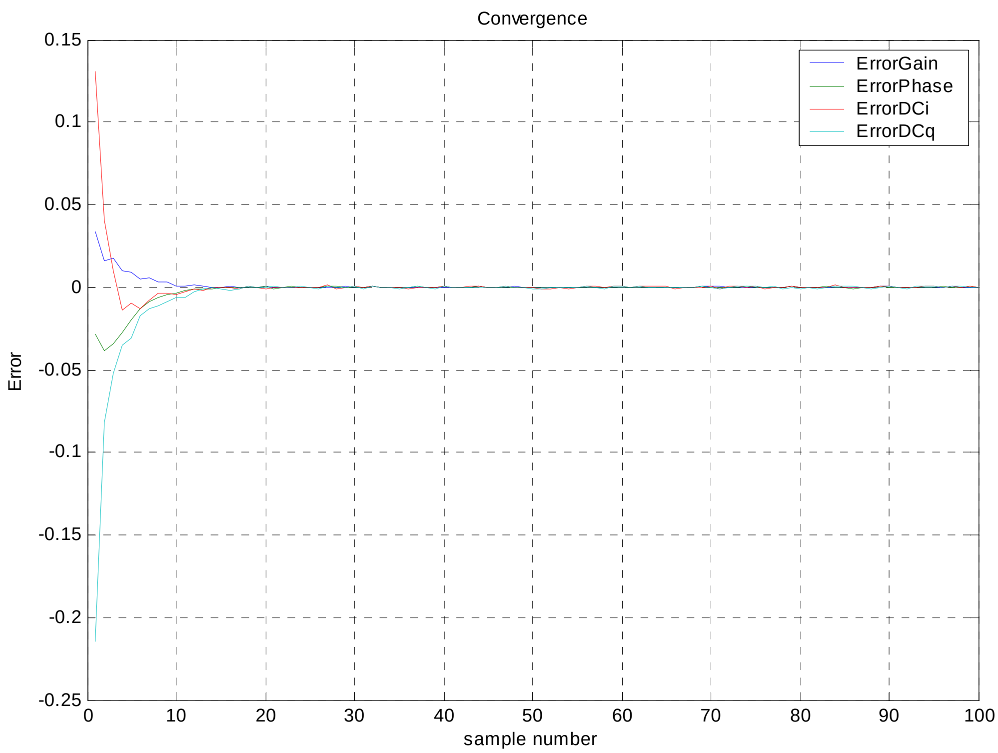

Figure 4 **Convergence curves.**

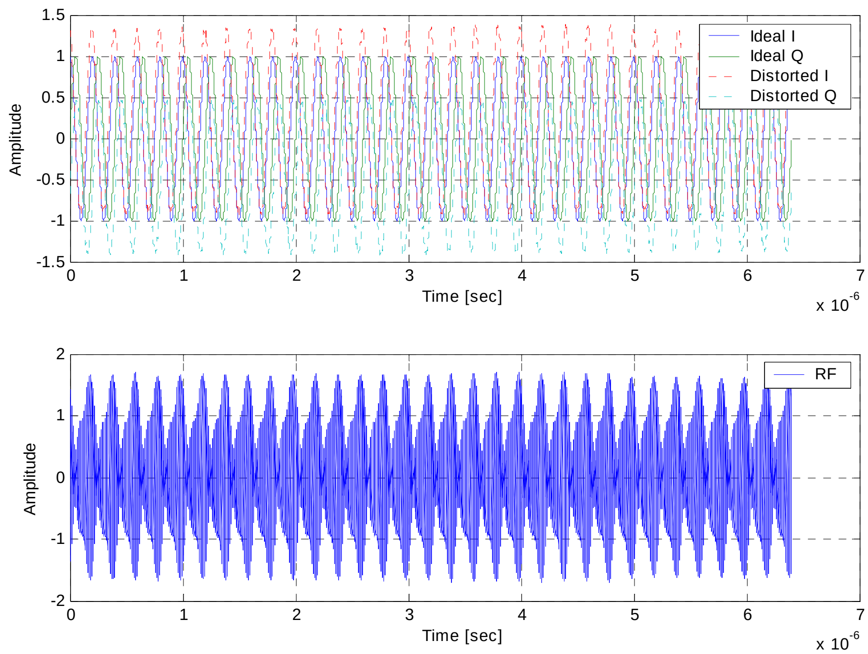

Figure 5. **RF output at start.**

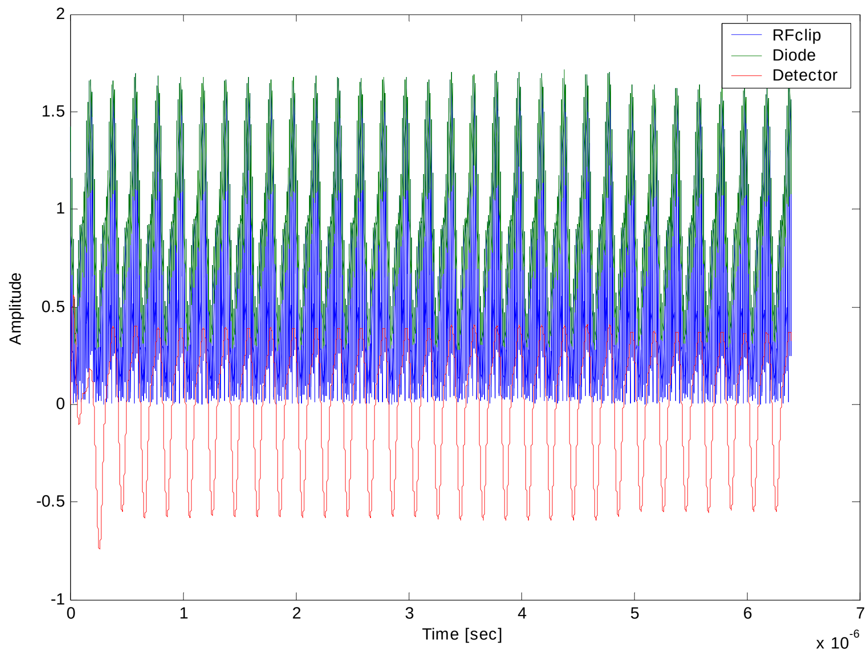

Figure 6 **Detector output at start.**

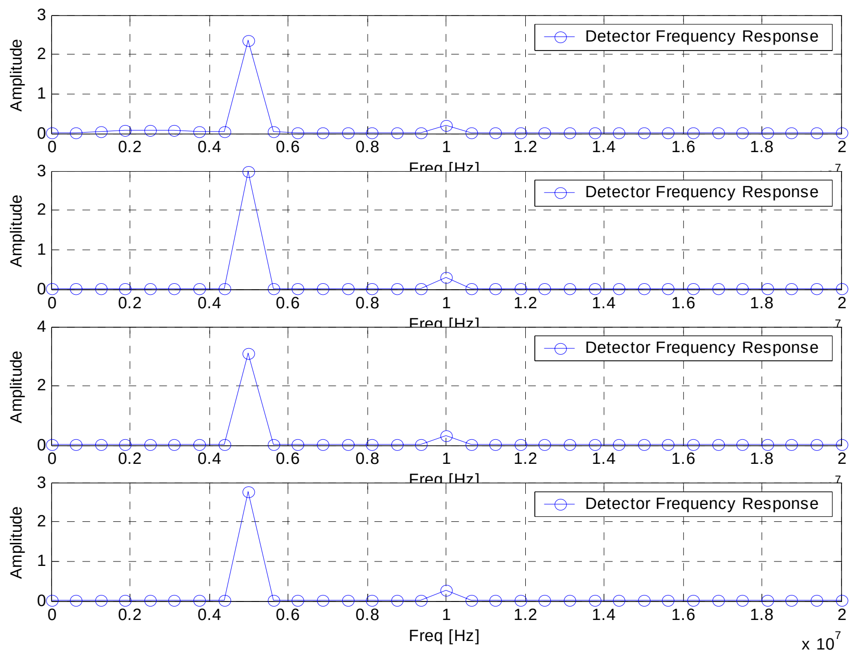

Figure 7 **FFT outputs at start showing 5MHz (DC/LOFT) and 10MHz (I/Q imbalance) effects.**

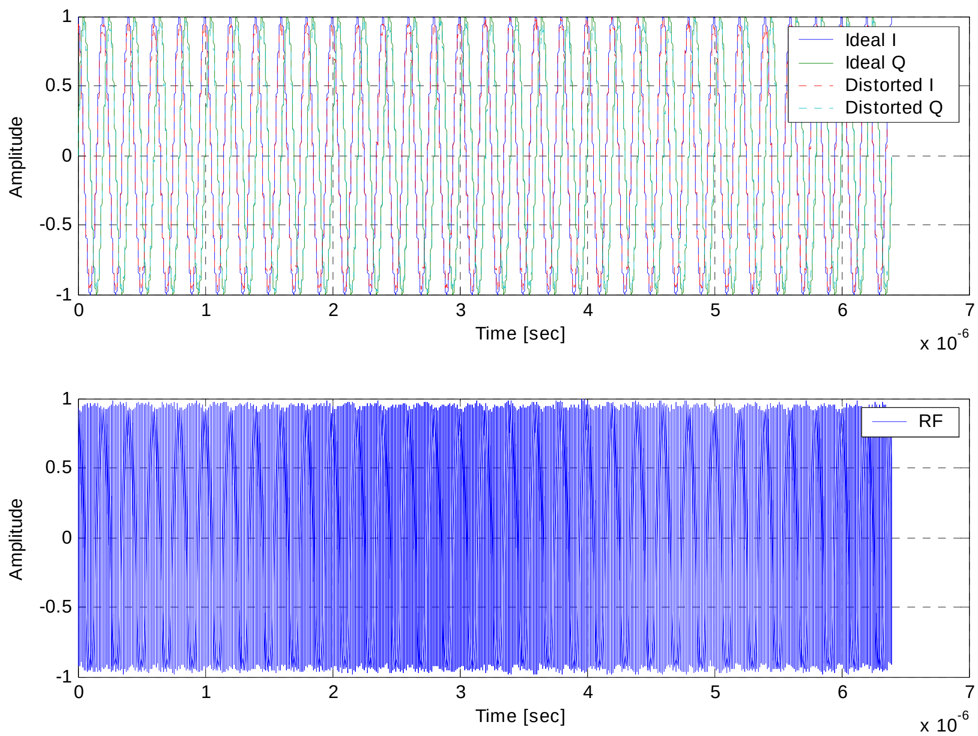

Figure 8. **Tones and RF at end of training.**

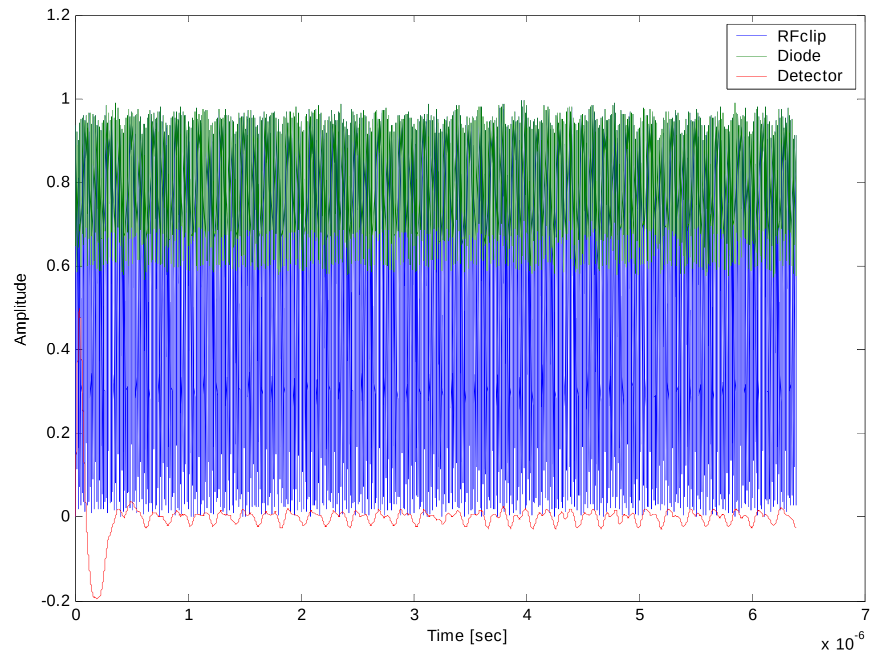

Figure 9. **Detector output at end of training.**

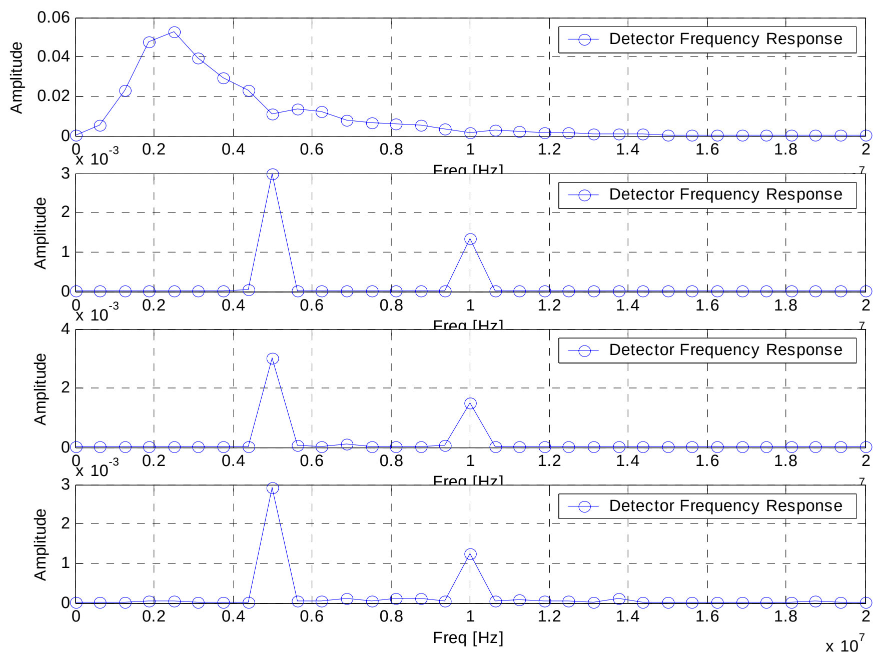

Figure 10 **FFT outputs at end of training shows reduced DC and I/Q error.**

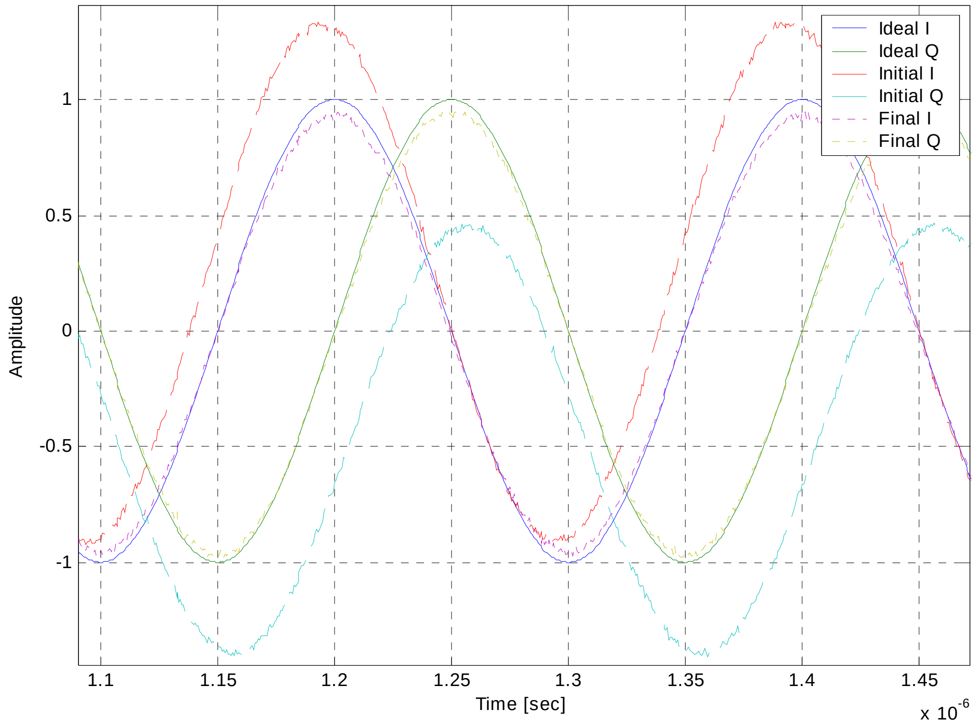

Figure 11 **Initial and final outputs. There is a slight loss of gain in both I and Q, but the balance is better than 45dB.**

References

[1] “Adaptive Compensation for Imbalance and Offset Losses in Direct Conversion Transceivers”, James Cavers, Maria Liao, *IEEE Trans. On Veh. Tech., Vol 42, No. 4, November 1993*, pp. 581-588.