I/Q Imbalance Modeling of Quadrature Wireless Transceiver Analog Front-Ends in SIMULINK

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Abstract-**Quadrature transceivers utilize complex signal processing in the analog front-end (AFE) to tackle the image problem in frequency up/downconversion. The image-rejection performance is limited by the unavoidable *I/Q* imbalance throughout the AFE. In this paper, an in-depth analysis and modeling of *I/Q* mismatch effects in 3 different AFE frequency up/downconverters in SIMULINK are presented to better illustrate their image-rejection performance and to establish the most effective solution to improve it. The modeled AFEs include the conventional quadrature up/down-converter, double-quadrature up/downconverter with passive quadrature generator and the analog-double quadrature sampling (A-DQS) scheme for IF-to-baseband downconversion in complex-IF receiver path.**

***Keywords*-Analog front-end, analog-double quadrature sampling, image-rejection, I/Q imbalance, quadrature transceiver**

I. INTRODUCTION

Explosive growth of mobile and wireless communications drives the developments for low-power consumption, high-integration and small form factor wireless transceiver systems. Recent published works proved that quadrature transceiver architectures, as shown in Fig. 1, are the most fitted to achieve those goals simultaneously [1-3]. Such kind of transceiver architectures employ two parallel channels *I* (in-phase) and *Q* (quadrature) to perform complex signal processing, thus no off-chip components are required once the *I* and *Q* channels are well-matched. Regrettably, this parallel operation in the transceiver analog front-end (AFE) suffers from the inevitable *I/Q* mismatch resulting in unrecoverable image interference distortion. In order to improve their image-rejection performance to fulfill the stringent requirements from today's communication standards, an in-depth perception of quadrature transceiver AFE *I/Q* mismatch issues should be robustly mandatory. This work presents a systematic high-level modeling of three different AFE frequency up/downconverter *I/Q* mismatch issues. The SIMULINK macro-model includes the quadrature up/downconverter with quadrature local oscillator (LO) [1-3], double-quadrature up/downconverter with passive quadrature generators [4-5] and the analog-double quadrature sampling (A-DQS) scheme [6], which mainly can be utilized in low-IF receiver path.

First, in section II, the *I/Q* mismatch issue and the image problem will be briefly reviewed. Then, theoretical analysis and *I/Q* mismatch macro-models of 3 different AFE frequency up/downconverters will be presented in section III. Finally, the conclusions will be drawn in section IV.

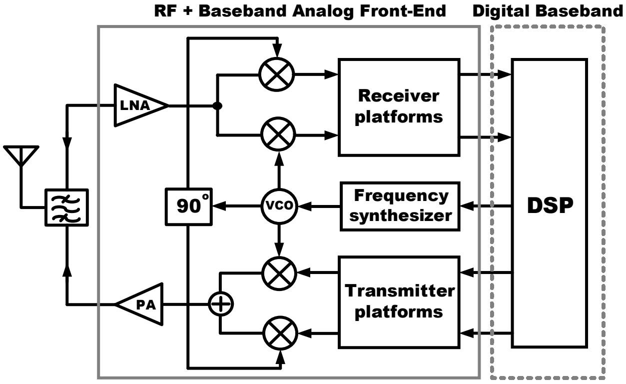

Figure 1. A typical quadrature wireless transceiver system

II. *I/Q* MISMATCH AND THE IMAGE PROBLEM

Wireless transceivers employ complex signal (*I/Q*) for frequency up/downconversion to avoid the crosstalk from the image interference, which is original located two IF apart from the desired signal. Fig. 2a and 2b show the examples of ideal frequency downconversion and with *I/Q* mismatch, respectively. The level of imbalance determines the image rejection capabilities and its figure of merit is the image-rejection ratio (IRR) given by:

$$\mathrm{IRR} = \frac{\text{Signal power}}{\text{Image(s) power}} \tag{1}$$

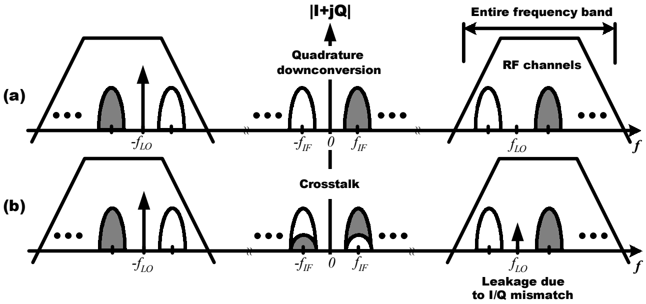

Figure 2. Quadrature downconversion with (a) ideal (b) *I/Q* mismatch

The image-rejection requirement depends on the selection of the IF and the applications. For instance, the image-rejection requirement in a narrowband 2nd-generation (2G) GSM receiver is approximately 32dB [2] when the IF is equal to half-

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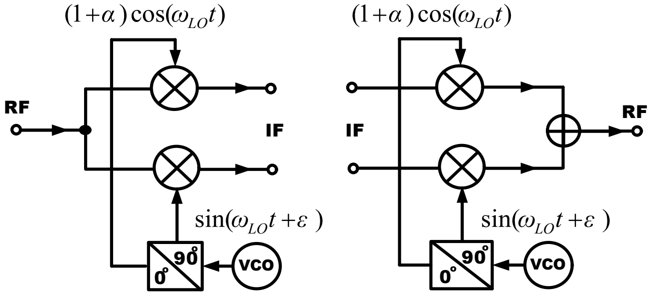
channel spacing. However, the IRR requirement increases to approximate 80dB when the IF is set between 100MHz to 200MHz since the blocking signals and adjacent channels power values increase with the frequency they stay apart from the desired channel. On the other hand, for the wideband 3rd-generation (3G) systems like WCDMA, the IF is conveniently set to zero [7-8] to minimize the IRR requirement, since the down-converted co-channel interference is relatively low and their wideband natures are insusceptible to the low frequency noise and DC-offset.

III. ANALYSIS AND MODELING OF AFES *I/Q* MISMATCH

Three different AFEs are presented in this section. The modeled architectures are mainly focused on the *I/Q* matching imperfection. Other random implementation faults are ignored since they exist in both channels, resulting in insignificant influence to the image-rejection performance.



(a) (b)

Figure 3. *I/Q* mismatch model of (a) quadrature downconverter (b) quadrature upconverter

A. Quadrature up/downconverter

As shown in Fig. 3, the two kinds of real-to-complex up/downconversion presented are the simplest approaches that could be employed in zero-IF, Weaver and Hartley receiver architectures. Their performances are governed by the matching precision between the *I/Q* mixers and the quadrature accuracy of the local oscillator signals. Without loss of generality, the relative gain and phase mismatch between the *I* and *Q* channels can be modeled into the local oscillators by

$$\mathrm{I}: (1+\alpha)\cos(\omega_{LO}t) \quad \text{and Q: } \sin(\omega_{LO}t+\varepsilon)$$

Where α and ε are the relative gain and phase mismatch, respectively. Then the IRR can be given by

$$IRR=\frac{1+2(1+\alpha)\cos\ \varepsilon\ +(1+\alpha)^2}{1-2(1+\alpha)\cos\ \varepsilon\ +(1+\alpha)^2} \tag{2}$$

As shown in Fig. 4, the IRR is limited to 32dB (34dB) for 0.025 (0.02) gain mismatch when combined with 2.5° (2°) phase mismatch. Thus, a downconverter SIMULINK macro-model with the correspondent filtering stages placed ahead in the chain is shown in Fig. 5 and it can be utilized to determine a better and practicable combination of mismatches. The macro-model of the upconverter can be similarly constructed and it is consequently omitted here. The highest possible IRR is around 44dB, which implies that such architectures are only appropriate for zero-IF [8] or very low-IF operations [2].

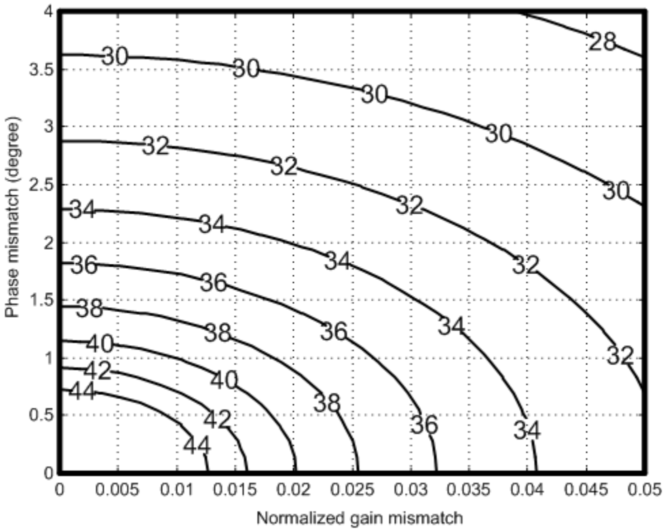


Figure 4. IRR versus amplitude and phase mismatch of the quadrature local oscillator signals

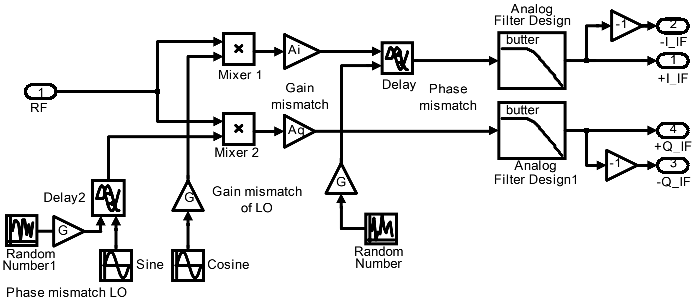
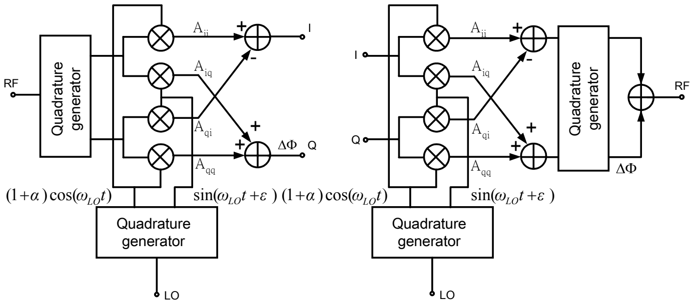


Figure 5. SIMULINK macro-model of quadrature downconverter AFE



(a) (b)

Figure 6. *I/Q* mismatch model of (a) double quadrature downconverter (b) double quadrature upconverter

B. Double-quadrature up/downconverter with quadrature generator

To improve image-rejection the double-quadrature architecture shown in Fig. 6 is a sensible alternative. By suppressing the image using the quadrature generator first, the matching precision between the mixers can be highly relaxed. Thus, the reported IRR can achieve 30dB [4] over a 200MHz bandwidth in up-conversion and 46dB in downconversion [5] without external trimming and tuning. The main advantage results from the doubled image-suppression obtained by using the quadrature generator and quadrature downconverter. The IRR of an individual quadrature generator is given by

$$IRR = \frac{1}{\Lambda^2} \tag{3}$$

where Λ is the half-band rejection. The quadrature generator with the respective input sources can be modeled as shown in Fig. 7 (where Del=Λ).

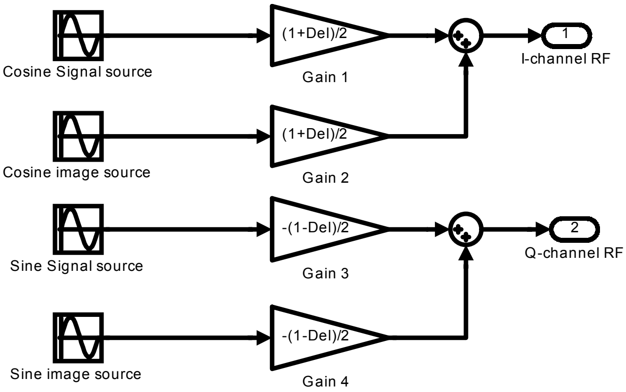


Figure 7. SIMULINK macro-model of a quadrature generator

Combining such generators with the double-quadrature mixers, the IRR can be theoretical improved and given by

$$IRR = \frac{1}{\Lambda^2}\frac{1+2(1+\alpha)\cos\ \varepsilon\ +(1+\alpha)^2}{1-2(1+\alpha)\cos\ \varepsilon\ +(1+\alpha)^2} \tag{4}$$

The *I/Q* mismatch can be alternatively modeled in the signal paths by assuming A_{xx}, $x=ii,iq,qi,qq$ as the gain mismatches between the four paths, then the IRR will result in [6]

$$IRR = \frac{(A_{ii}+A_{qi}+A_{iq}+A_{qq})^2}{(A_{ii}-A_{qi}-A_{iq}+A_{qq})^2} \tag{5}$$

For the signal paths phase mismatch, the IRR will be [4]

$$IRR = \tan(\Delta\Phi) \approx \frac{\omega_{LO}}{\omega_{BW}}\cdot\frac{\Delta\omega_{BW}}{\omega_{BW}} \tag{6}$$

Where $\Delta\Phi$ is the phase mismatch, ω_{BW} is the input bandwidth of the mixers and ω_{LO} is the frequency of the local oscillator. Obviously, the phase mismatch can be highly reduced as long as the mixers are designed with a large input bandwidth. On the other hand, the mismatches of the following summation, subtraction and amplification functions are relatively uncritical for two reasons: 1) the image is already suppressed twice in the RF, first by the quadrature generator and second by the double quadrature mixers, 2) Those functions are operating at the IF, a relatively low frequency, which means that high precision matching is simpler to be achieved by enlarging the size of the components and symmetric layout in the implementation. The possible SIMULINK model of a fully-differential double quadrature downconverter with the respective filtering stages is shown in Fig. 8.

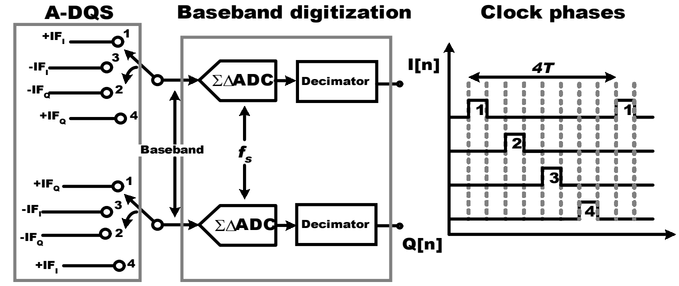


Figure 9. A-DQS scheme for IF-to-baseband frequency downconversion

C. Analog-double quadrature sampling

In the low-IF receiver path, the final frequency downconversion from IF-to-baseband can be effectively performed by the analog-double quadrature sampling (A-DQS) scheme, as shown in Fig. 9. If f_s = 4 IF, such A-DQS can operate as a complex-to-complex frequency downconverter and channel selector [9] with the advantage of requiring only unity

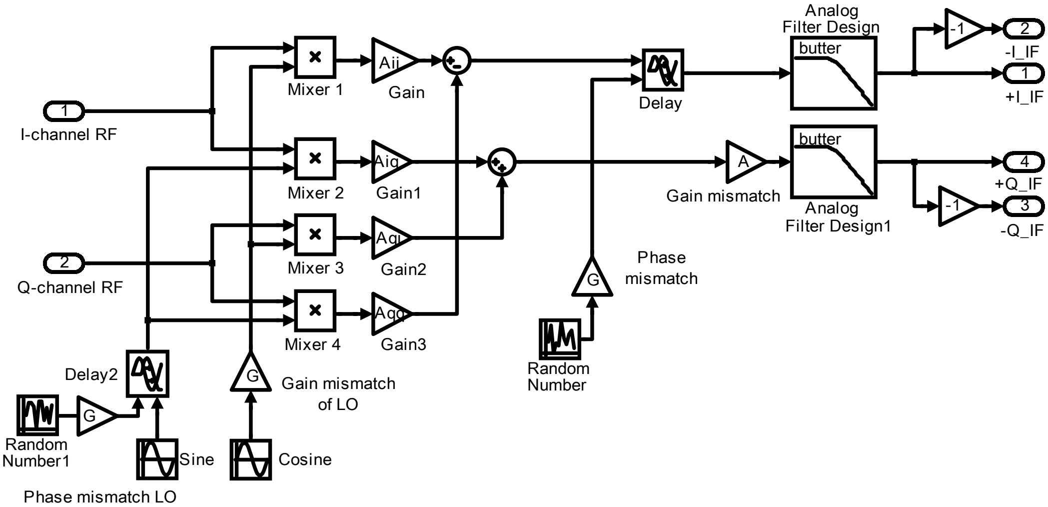


Figure 8. SIMULINK macro-model of double quadrature downconverter AFE

multiplications. Thus, prior to the A/D conversion, the signal is shifted to the baseband through complex sampling in order to employ only lowpass noise-shaping sigma-delta (ΣΔ) A/D converters that highly reduce circuit complexity and power consumption. Regrettably, such analog circuits also suffer from the image problem due to *I/Q* mismatch. The non-ideal model of the A-DQS scheme is shown in Fig. 10 where P_I and P_Q are the complex samplers. Denoting the amplitude mismatch in the four paths as G_{ii}, G_{iq} G_{qi} *and* G_{qq} the IRR will be given by [6]

$$IRR = \frac{(G_{ii} + G_{qi} + G_{iq} + G_{qq})^2}{2(G_{ii} - G_{qi})^2 + 2(G_{iq} - G_{qq})^2} \qquad (7)$$

With 1% amplitude mismatch, the IRR is limited to around 40dB. The phase mismatch will be approximately

$$IRR = \frac{1}{\tan^2(\theta/2)} \approx \frac{1}{(\theta/2)^2} \qquad (8)$$

Where θ is the phase mismatch in radian. For 1° phase mismatch, the IRR is limited to 41dB. The possible SIMULINK model associated is given in Fig. 11. The phase mismatch generated from the sampling phases jitter and the gain mismatches are also included in this model.

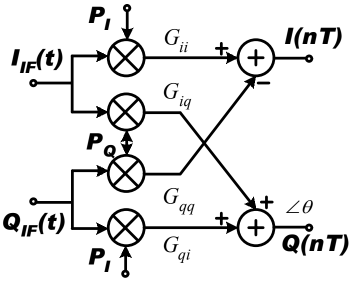


Figure 10. *I/Q* mismatch model of the A-DQS scheme

A front-to-back end modeling of a complex-IF receiver, based on the proposed macro-model for GSM application, is presented in [10] achieving realizable combinations of allowable *I/Q* mismatch in each of the functional blocks. In general, the proposed models can also be utilized in the design of other quadrature transceiver AFEs with some slight modifications.

IV. CONCLUSIONS

The *I/Q* mismatch problem of 3 different quadrature wireless transceiver analog front-ends have been studied and modeled in this paper. The limitations of their image-rejection and some improvement methods were investigated through a better understanding of those mismatch sources and their correlations. The SIMULINK macro-models that were provided can be utilized for system-level modeling and image-rejection budget distribution, which are the essential considerations in the design of high-performance quadrature transceiver systems.

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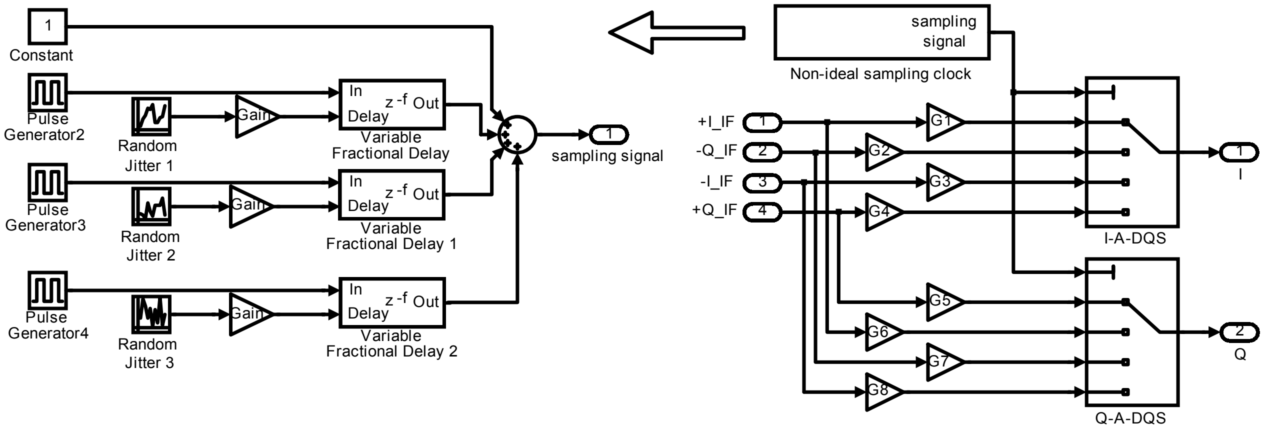

Figure 11. SIMULINK macro-model of A-DQS scheme