I-Q imbalance correction in time and frequency domains with application to pulse doppler radar

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Abstract. Digital In-phase(I) and Quadrature phase(Q) imbalance correction schemes are presented for improving the balance between I & Q signals by rejecting the image frequencies due to imbalance. The imbalance errors in the analog and digital demodulation schemes are highlighted. Simplified correction schemes are presented for time and frequency domain imbalances. These correction schemes are useful in radar and communication systems. In this paper, a digital I-Q scheme is also presented for a pulse Doppler radar, along with hardware configuration for implementation.

Keywords. Digital I-Q; quadrature demodulation; pulse doppler radar; time-frequency analysis.

1. Introduction

In a coherent receiver, In-phase and Quadrature (I-Q) phase signals are derived by demodulating the Intermediate Frequency (IF) signal. The I-Q signals should match in gain and in phase by 90 degrees. In the analog schemes, IF signal is demodulated using in-phase and quadrature phase carrier (Goldman 1986; Liu 1989; Tsui 1995) and is sampled in two channels. In the digital schemes (Liu et al 1989, Tsui). IF signal is sampled and demodulated using sampled cosine and sine of the carrier. These I-Q schemes are explained in the literature towards simplification in the implementation (Levanon 1988; Liu et al 1989). However, these schemes tend to develop amplitude and phase imbalances. In this work, we are proposing simplified schemes for correcting the imbalances in time and frequency domains with application to pulse Doppler radar.

In radar and communication systems, signals are sampled for digital processing. As per Nyquist criterion a signal must be sampled at a rate more than twice the bandwidth. In complex (I-Q) sampling, the signals can be sampled minimum at the rate of bandwidth. I-Q signals avoid blind phases in sampling. This complex sampling also improves signal to noise ratio (SNR) by 3-dB compared to the only real (I-channel) signal processing (Levanon 1988).
The analog I-Q detector has a limitation of matching the gain & phase in the I and Q channels which can be achieved only up to a certain level (Goldman 1986). The mismatch creates an unwanted image frequency with an amplitude 24 dB down to the main signal. To achieve further rejection, the penalty in terms of cost is very high (Goldman 1986). Correction algorithms are incorporated in the signal processors to reduce the imbalance.

In the literature (Liu et al 1989; Tsui 1995), digital I-Q schemes are presented. Analog I-Q imbalance corrections are explained by Churchill et al (1981) and Levanon (1988) and the calibration procedure is presented by Pierre & Fuhrmann (1995). Hilbert transform techniques are described by Oppenheim & Schafer (1975). Simplification of digital sampling is available by Brown (1979), Considine (1983), and Frerking (1994). Recent literature (Liu et al 1989; Tsui 1995) on I-Q, stresses the imbalance free demodulation. However, such demodulation creates an additional imbalance due to delay between I-Q samples for Doppler-shifted signals. For example, in radars, the image frequencies have to be rejected up to 50 dB to 60 dB down in severe clutter to signal levels of 30 to 40 dB. From the clutter signal, the image frequencies can be calculated, but ignoring of these image frequencies creates additional blind zones in the Doppler plane. So to avoid blind zones and false target detections, the image frequency level should be brought down to the noise background.

2. Modeling I-Q imbalances

I-Q channels are modeled in four ways depending on the presence of error terms either in I or Q channels. The most commonly used signal with errors is (Churchill et al 1981; Levanon 1988)

\[ x(t) = a(t)[(1 + \varepsilon)\cos(\omega t) + j\sin(\omega t + \theta)] , \quad (1) \]

where \( a(t) \) is the envelope, \( \omega \) is the angular frequency, \( \varepsilon \) is the amplitude imbalance, \( \theta \) is the phase imbalance between I-Q channels and \( t \) is the time. The imbalence ratio is derived for (1). For simplicity \( a(t) \) is taken as amplitude \( A \).

\[ x(t) = A[(1 + \varepsilon)\cos(\omega t) + j\sin(\omega t + \theta)] \]
\[ = A/2 [(1 + \varepsilon)(e^{j\omega t} + e^{-j\omega t}) + (e^{j(\omega t+\theta)} - e^{-j(\omega t+\theta)})] \]
\[ = A/2 [e^{j\omega t}(1 + \varepsilon + e^{j\theta}) + e^{-j\omega t}(1 + \varepsilon - e^{-j\theta})] . \]

The image frequency strength \( X(-\omega) \) to main component strength \( X(\omega) \) is given by

\[ \frac{X(-\omega)}{X(\omega)} = \frac{(1 + \varepsilon - e^{-j\theta})}{(1 + \varepsilon + e^{j\theta})} \]
\[ \approx \frac{1 + \varepsilon - \cos(\theta) + j\sin(\theta)}{1 + \varepsilon - \cos(\theta) + j\sin(\theta)} \]
\[ \approx \frac{\varepsilon^2 + 2\varepsilon + \frac{j\varepsilon}{2}(1 + \varepsilon)\sin(\theta)}{2(1 + \varepsilon + \frac{\varepsilon^2}{2} + \varepsilon\cos(\theta) + \cos(\theta))} \]
\[ \approx \frac{\varepsilon/2 + j\theta/2}{\varepsilon/2 + j\theta/2}, \text{ for small values of } \varepsilon \text{ and } \theta. \]