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Evaluation of the Impact of Antenna Parameters on the Performance of Six-Port Radar

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Introduction

Industry requires precise displacement, positioning and vibration sensors for a variety of applications ranging from level metering to the tracking of machinery. In these industrial environments, laser techniques are often not feasible or too expensive and ultrasonic sensors don't feature the required accuracy. Therefore, radar sensors are often employed for those applications. Six-port based sensors have the advantage, that high accuracies in the sub-millimeter range and a precision of some micrometers can be achieved with an ISM frequency band conform Radio Frequency (RF) signal at 24 GHz.

The accuracy of a Six-port radar, which is directly related to the linearity of the measured phase, can be improved by suitable calibration techniques. However, the precision depends on system's parameters like the crosstalk between transmit and receive path. System imperfections primarily lead to offsets as well as amplitude and phase imbalances of the baseband signals. An offset on the baseband signals reduces the available dynamic range of the operational amplifiers and the Analog-to-Digital Converters (ADC). Hence, the offset leads to a reduced precision.

In this work, the impact of the antenna parameters on the baseband signals will be analyzed. Furthermore, the subsequent maximum achievable accuracy and resolution of the Six-port radar will be evaluated for a monostatic (Figure 1) and a bistatic system.

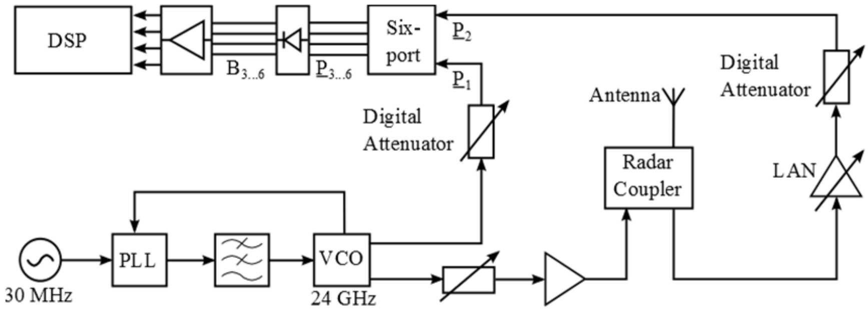

Figure 1: RF front-end of a monostatic Six-port radar sensor.

Theoretical Background

It is very important to know the influence of antenna parameters on the radar's systematical and random errors. With this information, calibration algorithms and digital signal processing can be improved. Furthermore, for given antenna parameters, the layout and system concept of the RF front-end can be optimized.

The baseband voltages $B_{3\ldots6}$ of a Six-port radar (Figure 1) can be interpreted as differential I/Q signals varying with the target's distance $d(t)$:

$$B_3 = A_3 \sin\left(4\pi\frac{d(t)}{\lambda} + \varphi_3\right) + O_3, \quad B_4 = -A_4 \sin\left(4\pi\frac{d(t)}{\lambda} + \varphi_4\right) + O_4,$$
$$B_5 = A_5 \cos\left(4\pi\frac{d(t)}{\lambda} + \varphi_5\right) + O_5, \quad B_6 = -A_6 \cos\left(4\pi\frac{d(t)}{\lambda} + \varphi_6\right) + O_6, \tag{1}$$

where λ is the wavelength of the RF signal, A_i are the amplitudes, O_i the offsets and φ_i the deviations of the ideal phase of the baseband signals. As a measure of the front-end's performance, the ratio between the peak-to-peak values ($2A_i$) and the maximum value ($A_i + O_i$) of the baseband signals is considered (PMR: Peak-to-peak amplitude to Maximum Ratio):

$$\mathrm{PMR_i} = 2A_i/(A_i + O_i), \tag{2}$$

with $i = 3 \ldots 6$. For ideal Six-port radars, $\mathrm{PMR_i} = 1$, leading to an optimal use of the ADC's dynamic range. Hence, with a 12 bit ADC, a maximum theoretical range resolution for each channel of $0.5\,\lambda/2^{12} = 1.52$ µm can be achieved at 24 GHz.

Simulation Results

Figure 2 depicts the impact of the antenna's return loss on the PMR for a monostatic system. The matching of a 14 dBi gain antenna has been varied. The target is a trihedral corner reflector with a radar cross section of 2.7 m^2 at a distance of 1 m. The reflection at the antenna's feed can be interpreted as a crosstalk from transmit to receive path. This leads to a self-mixing at the detectors causing an offset on the baseband voltages. Due to the degradation of the baseband signals, the resolution is reduced in the same way. Hence, a return loss of 15 dB decreases the resolution by 25 %.

In Figure 3 the quadrature component ($B_3 - B_4$) is plotted over the in-phase signal ($B_5 - B_6$) for a 20 dBi antenna and an edge length of the corner reflector of 0.2 m. The center of the ellipse is shifted due to the mismatch, which results in the need of a suitable calibration to compensate this offset.

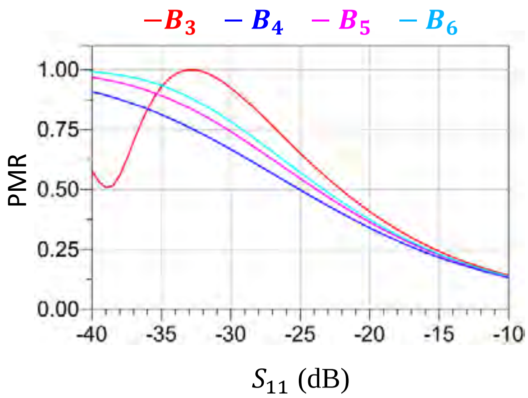

Figure 2: PMR over the matching of the antenna feed

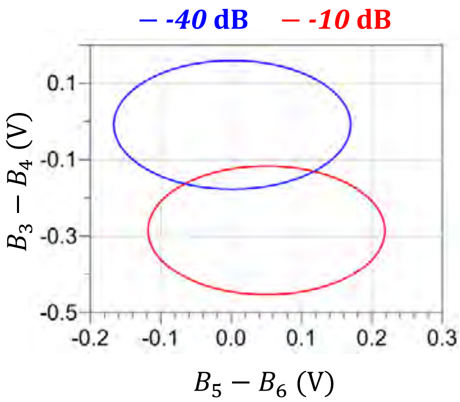

Figure 3: Baseband voltages for $S_{11} = -40$ dB dB and -10 dB