A System Analysis of Noise Influences on the Imaging Performance of Millimeter Wave MIMO Radars

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Abstract — In this paper a thorough system analysis to evaluate the overall imaging performance of millimeter wave radar systems is presented. All relevant noise influences and their influence on the system performance are considered. A comparison of two imaging radar systems at 160 GHz with different hardware architectures is discussed, one of which is based on monolithic microwave integrated circuits (MMICs) optimized for low phase noise. Radar measurements are performed to evaluate the achievable imaging performance with both realized radar demonstrators. It is shown that the optimization of the phase noise of a single MMIC is not necessarily advantageous when used for multi-channel radar systems.

Keywords — Accuracy, FMCW radar, Millimeter wave radar, MIMO radar, phase noise.

I. INTRODUCTION

The increasing demand for low-cost and compact imaging radar sensors with high detection performance pushes radar development in the frequency range above 100 GHz [1], [2]. In this frequency range, large absolute bandwidths and large aperture sizes compared to the wavelength are feasible. In order to avoid losses on printed circuit boards (PCBs) above 100 GHz, it is desirable to distribute the frequency modulated continuous wave (FMCW) ramp signal at a lower frequency band and realize the frequency multiplication on-chip [3], [4], [5].

This signal distribution concept requires large multiplication factors. As the phase noise is scaled with the square of the frequency multiplication factor, the noise level is usually increased, which reduces the achievable signal-to-noise ratio (SNR). However, the phase noise optimization of a single MMIC does not necessarily improve the overall imaging performance of a multi-channel system consisting of several MMICs [3]. Thus, a system analysis to evaluate the overall system performance for different hardware architectures used in millimeter wave imaging radars is desirable.

In this paper, a system analysis considering all relevant noise influences and their impact on the imaging performance of millimeter wave multiple-input multiple-output (MIMO) radars is presented. The approach is applied to two 160 GHz radars with different hardware architectures. The first imaging radar consists of 8 coherently coupled MMICs based on the phase noise optimized MMIC as presented in [6]. This system is compared to an imaging radar realized with 8 coherently coupled MMICs using an on-chip frequency multiplier with a factor of 12. The system analysis reveals that with the common multiplier architecture a better overall imaging performance can be achieved. The paper is structured as follows: In Section II both system architectures are described. The noise performance is analyzed for both system realizations in Section III. Afterwards, the angular estimation performance is compared in Section IV by radar measurements.

II. SYSTEM ARCHITECTURES

The block diagrams of the different imaging radar architectures considered in this paper are shown in Fig. 1. Both radio frequency (RF) front-ends are based on a coherent coupling of 8 radar MMICs with integrated antennas arranged in a way to form the same antenna array [3]. The antennas are aligned in a row in the azimuth plane, and a dielectric lens is used to focus the radiation pattern in the elevation plane.

The system architecture in Fig. 1 (a) consists of 8 phase noise optimized MMICs as presented in [6]. The system concept of a single MMIC is based on a low frequency multiplier of factor 4 for the FMCW ramp signal from 8 GHz to 10.5 GHz, which is afterwards up-converted by a low phase noise fixed-frequency PLL at 117 GHz to the RF frequency band from 149 GHz to 159 GHz. The total phase noise of the generated TX signal is only marginally affected by the low phase noise of the fixed-frequency PLL used for up-conversion to the RF frequency band. This architecture is subsequently called mixer architecture. Compared to this architecture, a worse phase noise performance for the generated TX signal of the system in Fig. 1 (b) (multiplier architecture) is expected due to a multiplier of factor 12 instead of 4, and thus, the input phase noise is deteriorated by 21.6 dB instead of 12 dB. The utilized radar parameters are summarized in Table 1.

III. SYSTEM ANALYSIS

The SNR of the intermediate frequency (IF) signal is determined by the received power described by the radar equation and the total noise level. The total noise level is determined by the superposition of thermal noise, phase noise, and quantization noise. The noise contributions for the systems under consideration are as follows:

- Table 1. Overview of the Radar Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp duration $T_{up}$</td>
<td>100 µs</td>
</tr>
<tr>
<td>Ramp repetition time $T_t$</td>
<td>150 µs</td>
</tr>
<tr>
<td>Number of chirps $N_c$</td>
<td>512</td>
</tr>
<tr>
<td>Number of TX / RX channels</td>
<td>8 / 8</td>
</tr>
<tr>
<td>Number of MIMO sequences</td>
<td>64</td>
</tr>
<tr>
<td>RF bandwidth $B$</td>
<td>10 GHz</td>
</tr>
<tr>
<td>Range resolution $ΔR$</td>
<td>15 mm</td>
</tr>
<tr>
<td>Virtual aperture size $A_v$</td>
<td>65λ</td>
</tr>
<tr>
<td>Angular resolution $Δϕ$</td>
<td>1°</td>
</tr>
</tbody>
</table>

...
A. Thermal Noise

The thermal noise $N_{th}$ is given by [7]

$$N_{th} = \omega_n B_n = k_B (F - 1) T_0 G_{RX} \frac{1}{t_{up}},$$  \hspace{1cm} (1)

with the thermal noise power density $\omega_n$, the noise bandwidth $B_n = 1/t_{up}$, the ramp duration $t_{up}$, Boltzmann’s constant $k_B$, the receiver noise figure $F$, the temperature $T_0 = 290$ K, and the receiver gain $G_{RX}$. The receiver noise figure for the MMIC with mixer architecture is $F = F_{Mixer} = 25$ dB [6] and for the multiplier architecture it is $F = F_{Mult} = 16$ dB. The total receiver gain $G_{RX} = G_{IF} G_{MMIC}$ is composed of the receiver gain $G_{MMIC}$ of the MMIC and the gain $G_{IF} = 43$ dB of the baseband amplifier. The receiver gain of the MMIC is $G_{MMIC,Mixer} = -4$ dB and $G_{MMIC,Mult} = 8$ dB for the mixer and the multiplier MMIC, respectively. Using (1), the resulting thermal noise levels are $N_{th,Mixer} = -70$ dBm and $N_{th,Mult} = -67$ dBm.

B. Quantization Noise

Due to the quantization of the signal by an analog-to-digital converter (ADC), an error is introduced. This effect is described by the quantization noise level $N_{qu}$ which is dependent on the number of $k$ bits and the maximum input voltage range of the ADC. It can be calculated for a 50 $\Omega$ system by [8]

$$N_{qu}/\text{dBm} = P_{max}/\text{dBm} - 6.02 \cdot \log_{10} \left( \hat{u}_{ADC} / \sqrt{2} \right) - 10 \log_{10} (50 \Omega) + 30,$$  \hspace{1cm} (2)

with the amplitude $\hat{u}_{ADC}$ of a sinusoidal signal. For the used 14 bit ADC and an input voltage range of $\pm 200$ mV, the quantization noise level is $N_{qu} = -90$ dBm, i.e., $N_{qu} \ll N_{th}$.

C. Phase Noise

If the LO and the RX signal originate from the same frequency source, the phase noise of the RX signal is downconverted mixer is correlated to the LO signal, depending on the time delay $\tau$ of the signal within the radar channel. The phase noise $\ell_\phi$ of the transmitted signal is suppressed and the resulting residual phase noise $\ell_\Delta \phi$ within the IF signal can be calculated analytically by [9]

$$\ell_\Delta \phi(f) = 2 \ell_\phi(f) \left( 1 - 2 \cos(2\pi f \tau) \right).$$  \hspace{1cm} (4)

Fig. 2. Simulated monostatic phase noise levels for both the multiplier and mixer architecture in comparison to the thermal noise level of the used MMICs within the IF spectrum.
However, for the mixer architecture bistatic radar measurements between different MMICs are affected by a decreased SNR. The degradation depends on the amount of power coupling from adjacent TX to the RX antennas and is more severe with closely spaced TX/RX antenna pairs (see Fig. 3 (a)). As it is shown in [3], the phase noise in bistatic measurements is not fully correlated due to the influence of the different on-chip PLL components on the generated TX signal.

For the multiplier architecture in comparison, the TX signal originates from one frequency source. According to (4), a maximum phase noise suppression occurs. Therefore, the noise level in all channels is determined by thermal noise (see Fig. 3 (b)). In conclusion, it should be noted that the phase noise optimized mixer architecture has no advantage when used in multi-channel radars.

IV. MEASUREMENT VERIFICATION

The imaging performance of both radar architectures was evaluated in comparison to each other. The estimation accuracy of the target parameters mainly depends on the SNR of the received signal [10]. Both the direction-of-arrival (DoA) estimation accuracy and the range estimation accuracy depend on an accurate estimation of the phase of the target within the radar response. In the following, only the performance of phase and angle estimation will be discussed.

The range of the target located at an angle $\phi = 10^\circ$ was determined with an accuracy of $5 \mu m$ with both system architectures. Afterwards the phase and amplitude of the target within the radar response was extracted. To conduct a fair comparison between both systems, the RCS was adapted such that the same average SNR of $20 \text{ dB}$ resulted for the evaluation of a single measurement. The corresponding phase and amplitude variations for channels originating from one TX are depicted in Fig. 4. For the mixer architecture, the phase fluctuation is much smaller for the monostatic channel as for the bistatic channels (see Fig. 4 (a)). The deterioration in bistatic channels is caused by the uncorrelated phase noise due to the different PLLs and the decreased SNR, see Section III. As only one frequency source is used for the multiplier architecture, the phase noise is correlated and phase fluctuations are mainly caused by the SNR. Thus, similar phase fluctuations occur for both monostatic and bistatic channels (see Fig. 4 (b)).

The influence of the phase fluctuations on the DoA estimations is now investigated with radar measurements. The
Table 2. Phase and Angle Estimation Accuracy

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\varphi,\text{mean}}$</th>
<th>$\sigma_{\varphi=10^5}$</th>
<th>$\sigma_{\varphi=30^5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixer architecture</td>
<td>$7.4^\circ$</td>
<td>$0.0086^\circ$</td>
<td>$0.096^\circ$</td>
</tr>
<tr>
<td>Mixer architecture (monostatic)</td>
<td>$2^\circ$</td>
<td>$0.007^\circ$</td>
<td>$0.069^\circ$</td>
</tr>
<tr>
<td>Multiplier architecture</td>
<td>$3.7^\circ$</td>
<td>$0.007^\circ$</td>
<td>$0.069^\circ$</td>
</tr>
<tr>
<td>Theoretical lower bound</td>
<td>$-$</td>
<td>$0.006^\circ$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Achievable standard deviation $\sigma_{\varphi}$ of the angle estimation can be determined by [11]

$$\sigma_{\varphi} = \frac{\Delta \varphi_{3\text{dB}}}{1.6\sqrt{2 \cdot \text{SNR}} \cdot \text{PG}} = \frac{1^\circ}{1.6 \sqrt{2 \cdot 100 \cdot 64}},$$

(5)

with the 3 dB-beamwidth $\Delta \varphi_{3\text{dB}}$ of the antenna pattern, and the processing gain PG using 64 virtual channels. The angular spectrum and the mean angle estimation variance of the angles across all virtual channels are depicted in Fig. 5. Mean value and standard deviation were determined with respect to a measurement block consisting of 64 MIMO sequences. The corresponding standard deviation is summarized in Table 2 for the averaged estimated phases $\sigma_{\varphi,\text{mean}}$ and angles $\sigma_{\varphi}$ for two different DoAs. Both systems have similar sidelobe level in the angular spectrum since the antenna array is identical. However, a higher phase and angle estimation accuracy can be achieved with the multiplier architecture (see Fig. 5(b)) than with the mixer architecture (see Fig. 5(c)).

V. CONCLUSION

In this contribution a system analysis to evaluate the overall imaging performance of millimeter wave radar systems is presented. It is applied to two low-cost imaging radars at 160 GHz with different hardware architectures and therefore different phase noise characteristics. All relevant noise influences are analyzed and compared for both system realizations. The multiplier architecture has a worse phase noise performance for the generated TX signals. However, for highly integrated radars, phase noise suppression is sufficiently high to cause the noise level to be determined by thermal noise. Additionally, it is shown that the phase noise optimized mixer architecture is not advantageous for a multi-channel radar, since the noise floor is increased by uncorrelated phase noise in bistatic radar measurements due to the different on-chip PLLs, though all PLLs have the same reference signal. It is shown that for both system approaches it is feasible to achieve a very good angular estimation performance. However, the overall angular estimation accuracy is better for the multiplier architecture.

ACKNOWLEDGMENT

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REFERENCES