Leakage Phase Noise Mitigation for Monostatic FMCW Radar Sensors Using Carrier Transmission

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***Abstract*— One common problem of frequency modulated continuous wave radar is leakage from the transmitter to the receiver. The leakage power is orders of magnitude larger than the target return power and appears as a very strong signal in the first few range bins. Additionally, the residual phase noise density of the local oscillator occurs around the leakage signal, which often raises the noise floor and limits the dynamic range of a radar system at the close proximity of the sensor. In this paper a novel system concept that cancels the phase noise around the dominating leakage path is proposed, mathematically derived, and proven by radar measurements with a radar demonstrator at 77 GHz.**

***Keywords*— Millimeter wave radar, FMCW radar, phase noise, leakage cancellation, novel radar system, PLL.**

I. Introduction

Frequency modulated continuous wave (FMCW) radar systems are widely used in industrial, medical, automotive, and consumer goods applications [1].

Although FMCW radar possess a lot of advantages in comparison to pulse radar in terms of power consumption, hardware effort, and minimum detectable range, there is one major drawback, which is the partial leakage of the transmitted signal power to the receiver. This short-range leakage appears as a very strong target in the first few range bins. The leakage in a monostatic FMCW radar mainly occurs due to the non-ideal isolation of the transmit-receive duplexer, wave reflections at a radome or car body, and due to antenna leakage. The typical isolation is at best cases around 30 dB, which denotes that the leakage power in the receiver is orders of magnitude higher than the target return power [2].

The residual phase noise of the local oscillator (LO) occurs around the leakage signal, which usually raises the noise floor and leads to a strong degradation of detection sensitivity, especially for nearby targets [3], [4]. For instance, this is a problem for various industrial or automotive applications, where weak targets like humans might be masked if they are not properly detected.

The effect of leakage in FMCW radars is already well investigated. There are several possiblities to mitigate this loss of sensitivity at the proximity of the radar sensor. One way is to reduce the leakage power, which appears at the intermediate frequency (IF) signal. This was done in [5] with an adaptive vector modulator. These kind of approaches use the fact that a phase shift of 90° at the down-converting mixer cancels the dc signal at the receiver output. Therefore, the phase noise effect around the leakage peak does not reduce the sensitivity performance of the radar.

Other approaches showed that good leakage cancellation can be achieved by an additional delay line generating an auxiliary leakage signal. The delay line is matched to the round-trip delay of the undesired signal reflection [6]. Alternatively, the auxiliary leakage signal can be generated by adaptive nonlinear filtering techniques [7]. Afterwards, the auxiliary leakage signal is subtracted from the target return, which contains the undesired signal reflection.

Another possibility to mitigate the decrease in sensitivity performance is to improve the phase noise of the ramp oscillator (RO), which is usually limited by the phase noise of the frequency synthesizer circuits [8].

In this paper, a new radar concept is introduced, which reduces the phase noise for the dominating leakage path by transmitting a carrier with the same phase noise statistics as the ramp signal. The phase noise cancellation concept is mathematically derived for a typical leakage scenario. Radar measurements verify the effectiveness of the new concept.

II. System Concept

For conventional monostatic FMCW radar sensors with common signal generation, the same LO is used for the transmit and the receive signals. Due to the small channel delay, the phase noise of the transmit and receive signal is partly correlated. Hence, a certain amount of phase noise within the intermediate frequency (IF) cancels out at the down-converting mixer. This well-known range correlation effect was first described in [9] and is given by

$$\mathcal{L}_{\Delta\Phi}(f) = 2\mathcal{L}_{\Phi}(f)\left(1 - \cos(2\pi f \tau)\right), \qquad (1)$$

with $\mathcal{L}_{\Phi}$ as the phase noise density of the transmit signal, f the frequency offset from the carrier, τ the signal delay of the receive signal and $\mathcal{L}_{\Delta\Phi}$ as the resulting phase noise density at the receiver output spectrum.

Additional hardware related path differences in real world radar systems aggravate this effect due to a decrease of the cancellation factor in (1). The phase noise leakage becomes more relevant with increasing leakage delay, which is often fulfilled for a radar mounted behind a radome. The radome increases the additional channel delay and causes a strong signal reflection, which results in residual phase noise locally in the close vicinity of this leakage signal.

The basic principle of the novel system concept including all prevailing leakage paths is depicted in Fig. 1. In this new system concept it is assumed that the linear modulated frequency ramp s_{RO} is generated at a low frequency with

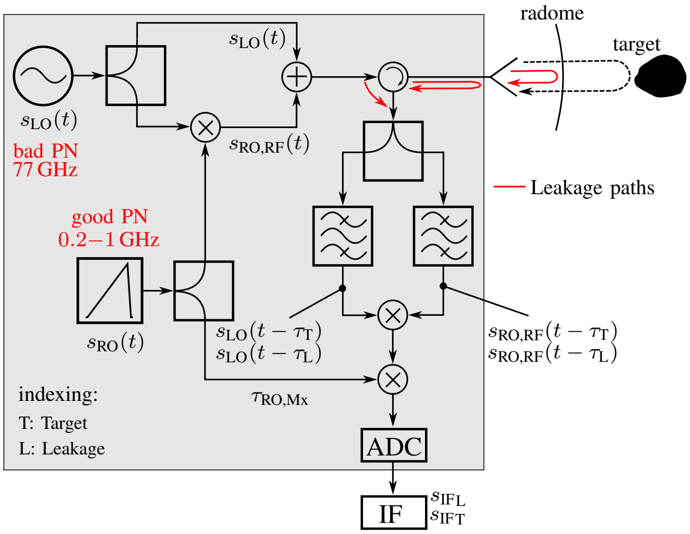


Fig. 1. Novel proposed system setup for a monostatic FMCW radar with carrier transmission to mitigate leakage caused noise floor increase.

superior phase noise characteristics in comparison to the high frequency LO signal s_{LO}, which is used for the up-conversion of the ramp to the mm-wave band.

If the ramp is starting with an offset frequency f_{off}, the carrier and the RF ramp do not overlap in the frequency domain. For the case that the mixer does not add additional phase noise, which is usually fulfilled, the phase noise of both sources is added up at the up-converting mixer. Therefore, the inferior phase noise performance of the LO is dominating and is mainly present at the transmit signal. Consequently, the carrier and the RF ramp contain the same phase noise statistics.

Both signals are combined and afterwards transmitted. Within the radar channel they are affected by the same channel delay for each target. At the receiver both signals are separated from each other by an adequate filtering stage. A practical filter design at high frequencies is usually very challenging. Thus, it can also be realized at a lower frequency by using a heterodyne approach and by down-converting to a mid-band frequency. If a common LO is used, the same phase noise influence is added to the received carrier and the ramp. Afterwards, the received RO signal is down-converted to the IF band using the received carrier. In this mixing step the phase noise cancels out.

The effectiveness of the novel concept and the superiority in comparison to the standard FMCW radar depends on the internal channel delays and the realized LO phase noise. If the round-trip delay including the transmit and receive paths delays is larger than the inter-target delay between radome and target, the novel concept is superior concerning phase noise cancellation.

III. Signal Model

The functional principle of the novel system concept is mathematically derived for a typical leakage scenario, consisting of two targets with large difference in radar cross section (RCS), i.e., one strong target such as a radome and one weak target like a human hand. They are closely spaced to each other. The ramp signal s_{RO} is generated at a low frequency with superior phase noise performance. The ramp starts with an offset frequency f_{off} relative to dc, i.e.,

$$s_{\mathrm{RO}}(t) = \exp\left[\mathrm{j}\left(2\pi\left(f_{\mathrm{off}}t + \frac{B}{2T}t^2\right) + \varphi_{\mathrm{start,RO}}\right)\right]. \tag{2}$$

In (2) $t\in[0,T]$ denotes the continuous time with the chirp duration T, B the sweep bandwidth of the frequency ramp, and $\varphi_{\mathrm{start,RO}}$ the starting phase of the ramp. The baseband ramp signal is assumed to be almost perfect in comparison to the carrier. Thus, a time varying phase noise term is neglected in (2).

The frequency offset f_{off} has to be chosen such that it can be separated by filtering in the RF band. Without loss of generality, the amplitudes of the transmitted signals are set to the value of 1.

The LO is at a high frequency with inferior phase noise performance compared to the baseband ramp. It can be described by

$$s_{\mathrm{LO}}(t) = \exp\left[\mathrm{j}(2\pi f_0 t + \varphi_{\mathrm{start,LO}} + \phi_{\mathrm{LO}}(t))\right]. \tag{3}$$

In (3) f_0 denotes the oscillation frequency, $\varphi_{\mathrm{start,LO}}$ the starting phase, and $\phi_{\mathrm{LO}}(t)$ the phase noise term of the carrier. The signal in (2) is up-converted to the RF band by means of the carrier in (3). This results in

$$\begin{aligned} s_{\mathrm{RO,RF}}(t) &= s_{\mathrm{LO}}(t)s_{\mathrm{RO}}(t) \\ &= \exp\left[\mathrm{j}\left(2\pi\left((f_{\mathrm{off}}+f_0)t + \frac{B}{2T}t^2\right) + \varphi_{\mathrm{start}} + \phi_{\mathrm{LO}}(t)\right)\right], \end{aligned} \tag{4}$$

with $\varphi_{\mathrm{start}}=\varphi_{\mathrm{start,LO}}+\varphi_{\mathrm{start,RO}}$. Due to the frequency offset f_{off}, the RF ramp $s_{\mathrm{RO,RF}}$ and the carrier do not overlap in the frequency domain.

As depicted in Fig. 1, there are different possible leakage paths. In reality usually one leakage path is dominating with respect to phase noise. For instance, the circulator leakage and the leakage due to antenna mismatch have very short delays, which improves the phase noise cancellation of (1). In comparison, the reflection at a radome or plastic plate is also very strong but has much larger delays.

For the following derivations it is assumed that the leakage path across the radome is the dominating path. The received signals of the leakage and the targets after the circulator in Fig. 1 are

$$s_{\mathrm{RX,L}}(t) = A_{\mathrm{L}}\left(s_{\mathrm{RO,RF}}(t-\tau_{\mathrm{L}}) + s_{\mathrm{LO}}(t-\tau_{\mathrm{L}})\right), \tag{5}$$

$$s_{\mathrm{RX,T}}(t) = A_{\mathrm{T}}\left(s_{\mathrm{RO,RF}}(t-\tau_{\mathrm{T}}) + s_{\mathrm{LO}}(t-\tau_{\mathrm{T}})\right), \tag{6}$$

with the leakage signal amplitude A_{L} and the target amplitude A_{T}. The channel delay for the leakage and the target are denoted by τ_{L} and τ_{T}, respectively. For a weak target close to the radome, it can be assumed that $A_{\mathrm{L}}\gg A_{\mathrm{T}}$ and $\tau_{\mathrm{L}}\approx\tau_{\mathrm{T}}$.

Consequently, they are highly correlated. The resulting and filtered carrier can be simplified by

$$
\begin{aligned}
s_{\mathrm{LO,tot}}(t) &\approx A_{\mathrm{L}} s_{\mathrm{LO}}(t-\tau_{\mathrm{L}}) \\
&= A_{\mathrm{L}} \exp\left[\mathrm{j}(2\pi f_0 (t-\tau_{\mathrm{L}}) + \varphi_{\mathrm{start,LO}} + \phi_{\mathrm{LO}}(t-\tau_{\mathrm{L}}))\right]. \quad (7)
\end{aligned}
$$

The signals $s_{\mathrm{RX,L}}$ and $s_{\mathrm{RX,T}}$ in (5) and (6), respectively are now down-converted with the filtered carrier signal $s_{\mathrm{LO,tot}}$ in (7). For the down-converted leakage signal this results in

$$
\begin{aligned}
s_{\mathrm{IF_L}}(t) &= s^*_{\mathrm{LO,tot}}(t) A_{\mathrm{L}} s_{\mathrm{RO,RF}}(t-\tau_{\mathrm{L}}) \\
&= A_{\mathrm{L}}^2 \exp\left[\mathrm{j}\left(2\pi\left(f_{\mathrm{off}}(t-\tau_{\mathrm{L}}) + \frac{B}{2T}(t-\tau_{\mathrm{L}})^2\right) + \varphi_{\mathrm{start,RO}}\right)\right]. \quad (8)
\end{aligned}
$$

The down-converted leakage signal in (8) is unaffected from phase noise. The derivation shows that the phase noise cancellation for the dominating leakage path is improved, which makes the concept and the hardware independent from changing environmental conditions.

The subsequent signal processing steps are the same as for common FMCW radar and can be found in literature [10].

IV. Measurement Setup

To verify the novel system concept and to verify the theory, measurements are conducted in an anechoic chamber. The set-up consists of one plastic plate shortly behind the antennas and one wooden rod as target with low RCS representing a radome scenario and a human hand. A photograph of the measurement setup is shown in Fig. 2.

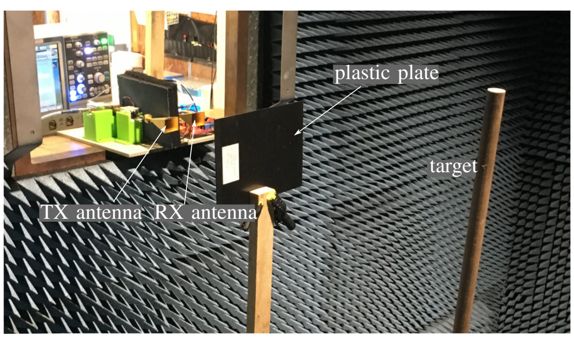


Fig. 2. Photograph of the measurement setup in the anechoic chamber.

In order to setup a radar system with one dominating leakage path and in order to perform all system operations digitally, a digital radar demonstrator with horn antennas at 77 GHz is used. Its block chart is given in Fig. 3.

The signal is generated using Matlab and realized with an arbitrary waveform generator (AWG). In a first step an ideal chirp sequence signal with additional dc content is generated. Additionally, additive spectral phase noise densities $\mathcal{L}(f)$ are added to an ideal LO signal with f_0=3 GHz, see Fig. 4. The modelled phase noise is characterised by the $1/f$-corner frequency f_{c}, the loop filter bandwidth B_{PLL}, the in-band phase noise level $\mathcal{L}_0$, and the thermal noise floor level $\mathcal{L}_{\mathrm{floor}}$, which are defined in frequency domain according to a typical phase noise spectrum $\mathcal{L}(f)$ of a PLL as depicted in Fig. 4 (a).

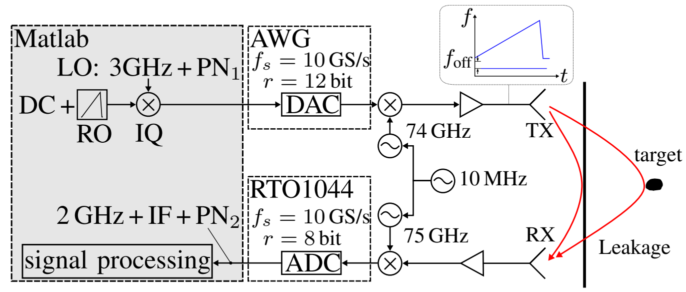


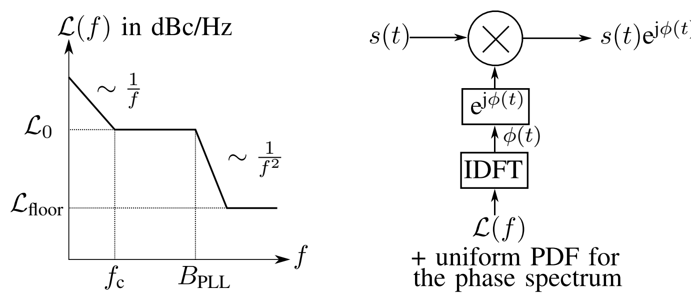
Fig. 3. Block chart of the used measurement setup.

Table 1. Signal and Modulation Parameters for Measurement

Ramp duration T	100 µs
Sweep bandwidth B	800 MHz
Number N of frequency chirps	64
Offset frequency f_{off}	200 MHz
In-band noise level $\mathcal{L}_0$	$-40/-50$ dBc/Hz
$1/f$-corner frequency f_{c}	1 kHz
PLL Loopfilter bandwidth B_{PLL}	1 MHz
Thermal noise floor level $\mathcal{L}_{\mathrm{floor}}$	-150 dBc/Hz

The time-domain jitter can be determined by an IDFT of $\mathcal{L}(f)$ with uniformly distributed randomized phase samples, see Fig. 4 (b). Afterwards, this is numerically added to the time domain samples of the LO signal. For more details the reader is referred to [11].

The used signal and modulation parameters for the measurements are summarized in Table 1.



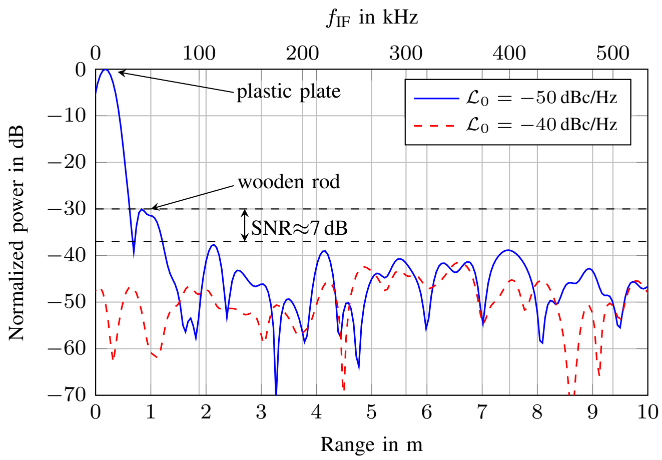
(a) Typical PLL phase noise spectrum (b) Generation of time-domain jitter

Fig. 4. Phase noise modeling of the LO signal according to [11].

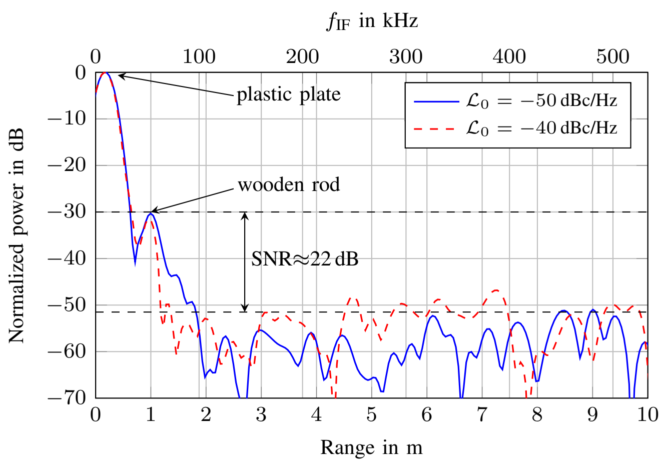
After digitizing the received radar signal, all system operations according to Fig. 1, consisting of appropriate bandpass and lowpass filtering, mixing and FFT are all conducted in Matlab.

V. Measurement Results

The measurements compare the well-known standard chirp sequence approach with the novel system concept in terms of detection performance. In order to minimize the distortion effect in frequency domain close to the carrier due to a nonuniform hardware-related frequency response, special attention is taken to operate all components in their linear regions. Thus, the effect of residual phase noise is dominant. For the standard chirp sequence evaluation, the same signals



(a) Chirp sequence



(b) Chirp sequence with carrier

Fig. 5. Normalized power of the measured and averaged (64 ramps) IF frequency signal of the standard chirp sequence approach (a) in comparison to the novel approach (b) for two differing in-band phase noise density levels $\mathcal{L}_0$. The measurement scenario is a typical leakage scenario consisting of a radome and a weak target with a spacing of $R = 80$ cm behind the radome.

are used, but only the ramp signal is used for evaluation, which can be obtained by a bandpass filtering.

Fig. 5 shows the IF frequency signal in frequency domain after performing an FFT with zeropadding ($\times 3$) for the chirp sequence approach (Fig. 5 (a)) in comparison to the new approach with carrier transmission (Fig. 5 (b)). A Hanning window is used to suppress sidelobes and to facilitate a separation of sidelobes from noise.

The measurements show that for the standard chirp sequence approach no reliable detection is feasible for an in-band phase noise density level $\mathcal{L}_0 = -50$ dBc/Hz, because the SNR is only approximately 7 dB and thus the target cannot be clearly distinguished from the noise. By increasing the in-band phase noise level to $\mathcal{L}_0 = -40$ dBc/Hz no targets are visible anymore as the phase noise cancellation is too bad.

For the novel concept the noise floor is significantly decreased for an in-band phase noise level of $\mathcal{L}_0 = -50$ dBc/Hz by approximately 15 dB, which results in an SNR of approximately 22 dB. By increasing the phase noise level to $\mathcal{L}_0 = -40$ dBc/Hz the targets are still visible with only a slightly increased noise level. This proves that the novel concept allows for a high phase noise correlation, which enables a reliable detection of the wooden rod, even for bad phase noise conditions.

VI. Conclusion

An investigation for a novel system concept using carrier transmission for leakage phase noise cancellation was shown and derived for a typical leakage scenario. The ramp is generated at a low frequency with superior phase noise performance in comparison to the high frequency LO, which is used for up-conversion to the mm-wave band. A mathematical derivation was shown for the typical leakage scenario consisting of one strong and one weak target closely spaced apart.

Radar measurements proved that the novel concept is unaffected from decreasing phase noise performance around the leakage and has superior performance in comparison to the standard chirp sequence approach.

This makes it a good candidate for radar applications requiring a very good detection sensitivity in the vicinity of the sensor such as for short-range automotive or industrial sensors.

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