Mitigation of Leakage in FMCW Radars by Background Subtraction and Whitening

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***Abstract*— Leakage in frequency-modulated continuous-wave (FMCW) radar with a homodyne receiver induces strong signal components in the lower frequency parts of the radar observations. There, the dynamic range of the observations has been reduced, such that close and weak targets are hard to detect. In this letter, a signal processing method is proposed to mitigate the leakage. First, background subtraction is applied to cancel the leakage. As the cancellation is imperfect, a noisy signal portion remains: the leakage noise. A statistical model is developed to describe the leakage noise as a colored noise process. This model is parameterized from measurements and used to whiten the observations. As a result, the dynamic range is improved, and the close targets become better detectable.**

***Index Terms*— Frequency-modulated continuous-wave (FMCW) radar, leakage, noise whitening, statistical model.**

I. Introduction

UNWANTED power flux from the transmitter (TX) into the receiver (RX), called leakage, is a severe problem in frequency-modulated continuous-wave (FMCW) radars. Leakage emerges from the limited isolation between TX and RX [1]. Also, static short-range leakage due to undesired targets in the close vicinity of the radar (e.g., the bumper of a car) or reflections at the radar setup (e.g., a radome or lens) can occur too [2]–[4]. Fig. 1 shows the average power spectral density (PSD) of a measurement of a monostatic FMCW radar with homodyne RX. Short-range leakage due to a reflection at a lens [4] occurs as a strong target echo, such that frequencies up to approximately 700 kHz are disturbed. Summarized leakage affects the lower frequencies of the spectrum of the received signal. The dynamic range of the observations is reduced, such that beat frequencies of echos from close and weak targets are hard to detect. Hence, the radar is "blind" with respect to (w.r.t.) such targets. In the literature, hardware [2], [5], [6] or digital preprocessing [3], [7]–[9] based solutions are proposed to reduce the leakage.

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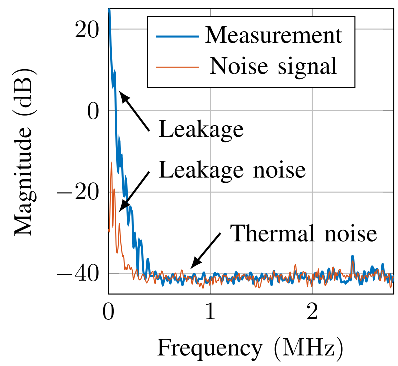

Fig. 1. PSDs (averaged over 32 signal periods, Hann window applied) of a measurement of a monostatic FMCW radar with homodyne RX and no present target. Leakage due to the limited TX-to-RX isolation and short-range leakage from a reflection at a lens occurs. After background subtraction, only the noise signal, consisting of thermal and leakage noise, remains.

In this letter, a signal processing method is proposed to mitigate leakage. The method can be implemented in software and is, therefore, simpler compared with hardware-based solutions. The leakage is assumed as static because the radar setup is nonvarying. Therefore, background subtraction can be applied [10] to remove the static leakage. The static leakage can be extracted from, e.g., a measurement with no present target or a target being far apart and, hence, can be excluded by gating. An exemplary signal after background subtraction, called noise signal, is shown in Fig. 1. Due to noise processes, e.g., phase noise, the background subtraction imperfectly cancels the leakage, and the residuals remain. These residuals will be assumed as a colored noise process, termed leakage noise. In Fig. 1, the leakage noise disturbs frequencies up to approximately 500 kHz. The leakage noise will be treated similar to dense multipath components (DMCs) in channel sounding [11]. A statistical model of the leakage noise will be proposed, which is used for the whitening of this noise. After whitening, close and weak targets become better detectable.

The remainder is organized as follows. A statistical model of the leakage noise process will be developed in Section II. Section III describes the noise whitening. Furthermore, measurements to demonstrate the performance of the proposed approach are shown. The letter is concluded in Section IV.

II. Noise Model

Subsequently, two noise sources will be considered: leakage noise and thermal noise. Quantization noise will be neglected. A statistical model of the noise processes will be developed, which comprises a parametric model of the noise correlation [12]. A parametric model is chosen because much fewer parameters have to be determined compared with a nonparametric description. Hence, fewer measurements are required to get a proper parameterization of the model.

A. Leakage Noise Model

The leakage noise $l(\tau)$ will be modeled as an additive, zero-mean, proper complex normally distributed process

$$l(\tau) \sim \mathcal{CN}(0, \psi_l). \tag{1}$$

The leakage noise is assumed as wide-sense stationary (WSS) in delay domain. Hence, it is uncorrelated among different frequency bins f_1 and f_2 (* denotes the complex conjugate)

$$\mathbb{E}\left\{l(f_1) \cdot l(f_2)^*\right\} = 0 \quad \forall f_1 \neq f_2. \tag{2}$$

The PSD of the leakage noise is exponentially decaying starting from approximately 0 Hz. Taking into account the WSS assumption, a model for the correlation of the leakage noise at frequency bins f_1 and f_2 can be given

$$\Psi_l(f_1, f_2) = \alpha \exp\{-\beta(f_1 - \rho)\} H(f_1 - \rho)\delta(f_1 - f_2) \tag{3}$$

where α is the power, β is the coherence time, and ρ is the frequency offset of the leakage noise. The function $H(f)$ is the Heaviside step function. The delay domain correlation function $\psi_l(\tau_1, \tau_2)$ is given by the inverse Fourier transform of equation 3. Due to the WSS assumption, only the lag difference $\Delta\tau = \tau_1 - \tau_2$ is relevant

$$\psi_l(\tau_1, \tau_2) = \psi_l(\Delta\tau) = \frac{\alpha}{\beta - \jmath 2\pi \Delta\tau} \exp\{\jmath 2\pi\rho\Delta\tau\}. \tag{4}$$

B. Thermal Noise Model

Thermal noise $w(\tau)$ is commonly modeled as additive, zero mean, circularly normal distributed random process

$$w(\tau) \sim \mathcal{CN}(0, \psi_w). \tag{5}$$

Thermal noise will be assumed as WSS and uncorrelated process. The respective correlation function is $\psi_w(\Delta\tau) = \eta \cdot \delta(\Delta\tau)$, with η the noise power.

C. Complete Noise Model

As the leakage noise and thermal noise are additive, an overall noise process $n(\tau)$ can be defined

$$n(\tau) = w(\tau) + l(\tau) \sim \mathcal{CN}(0, \psi_n). \tag{6}$$

Thermal noise and leakage noise are assumed as uncorrelated processes because they are due to independent sources. Accordingly, the autocorrelation function (ACF) of the complete noise process is

$$\psi_n(\Delta\tau) = \frac{\alpha}{\beta - \jmath 2\pi \Delta\tau} \exp\{\jmath 2\pi\rho\Delta\tau\} + \eta \cdot \delta(\Delta\tau). \tag{7}$$

The parameters of the noise model are concatenated in the vector $\boldsymbol{\sigma} = [\eta, \alpha, \beta, \rho]^T$.

Leakage noise and thermal noise are assumed as independent and identical distributed (i.i.d.) and stationary processes. Hence, multiple realizations of the noise process in time domain t, e.g., multiple signal periods, are independent and proper complex normally distributed observations. The respective correlation function is

$$\psi_n(\Delta\tau, \Delta t) = \delta(\Delta t) \cdot [\psi_w(\Delta\tau) + \psi_l(\Delta\tau)]. \tag{8}$$

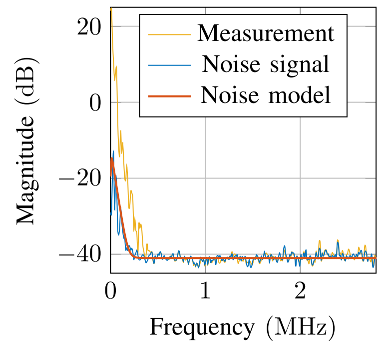

Fig. 2. PSDs (averaged over 32 signal periods, Hann window applied) of an FMCW radar measurement without a target and the resulting noise signal after background subtraction of the leakage. Also, the calibrated model of the PSD of the noise process is shown.

D. Noise Model Calibration

The noise model is calibrated by estimating the parameter vector $\boldsymbol{\sigma}$ from measurements. A maximum likelihood (ML) estimator is used therefor, which is suggested in the literature [12]. Consider a measurement without targets and after background subtraction. Hence, the noise process $n(\tau)$ is observed only. Define matrix $\mathbf{N} \in \mathbb{C}^{K \times N}$, which contains the K measurement samples gathered by sampling with time T_S and N signal periods. Because the noise process is assumed as i.i.d. process over the N signal periods, the ML estimator is

$$\hat{\boldsymbol{\sigma}} = \arg\min_{\boldsymbol{\sigma}} \ \ln\{\det\{\boldsymbol{\Sigma}(\boldsymbol{\sigma})\}\} + \mathrm{tr}\left\{\mathbf{N}^H \boldsymbol{\Sigma}^{-1}(\boldsymbol{\sigma})\mathbf{N}\right\}. \tag{9}$$

Matrix $\boldsymbol{\Sigma}(\boldsymbol{\sigma}) \in \mathbb{C}^{K \times K}$ is the positive definite covariance matrix, which is of the Hermitian Toeplitz structure

$$\boldsymbol{\Sigma}(\boldsymbol{\sigma}) = \begin{bmatrix} [\boldsymbol{\psi}_n]_{(1)} & [\boldsymbol{\psi}_n]^*_{(2)} & \cdots & [\boldsymbol{\psi}_n]^*_{(K)} \\ [\boldsymbol{\psi}_n]_{(2)} & \ddots & \ddots & [\boldsymbol{\psi}_n]^*_{(K-1)} \\ \vdots & \ddots & \ddots & \vdots \\ [\boldsymbol{\psi}_n]_{(K)} & [\boldsymbol{\psi}_n]_{(K-1)} & \cdots & [\boldsymbol{\psi}_n]_{(1)} \end{bmatrix}. \tag{10}$$

The vector entries $[\boldsymbol{\psi}_n]_{(k)}$ are given by sampling the ACF (7)

$$\boldsymbol{\psi}_n(\boldsymbol{\sigma}) = \left[\frac{\alpha}{\beta} + \eta, \frac{\alpha}{\beta - \jmath 2\pi T_S}, \ldots, \frac{\alpha}{\beta - \jmath 2\pi T_S(K-1)}\right]^T. \tag{11}$$

The parameters are estimated from the noise signal using the method in [11] to minimize (9). A calibrated noise model is shown in Fig. 2. A good agreement between the model and the PSD of the noise is obvious. The estimated parameters are $\eta = -41$ dB, $\alpha = -77$ dB, $\beta = 36.8\ \mu$s, and $\rho = 1.51$ MHz.

The ML estimator (9) is the optimal estimator to derive the parameters, but the required optimization is computationally expensive. Hence, estimation during radar operation is not considerable. Further work is required for simpler estimators or optimization methods that have comparable performance. Simpler or computationally more efficient techniques might be more suitable for quasi-real-time operation.

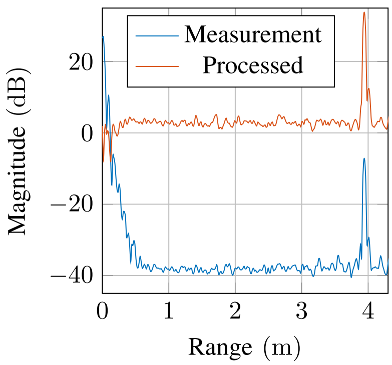

Fig. 3. PSDs (averaged over 32 signal periods, Hann window applied) of an FMCW radar measurement with a static target at approximately 4 m, and the result after processing (background subtraction and whitening).

TABLE I
SETTINGS OF THE FMCW RADAR

Parameter	Value
Bandwidth B	20 GHz
Center frequency	154 GHz
Modulation time T_{M}	250 µs
Sampling time T_{S}	100 ns
No. signal periods N	256

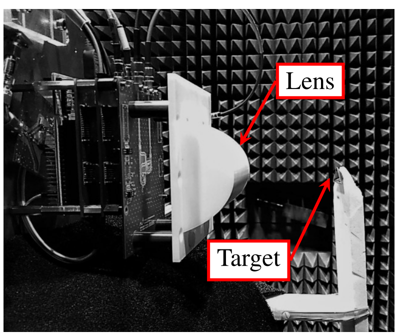

Fig. 4. Measurement setup with the target deployed approximately 7 cm apart from the radar.

III. WHITENING AND MEASUREMENTS

Knowing $\boldsymbol{\sigma}$, the covariance matrix $\boldsymbol{\Sigma}$ can be calculated to whiten the measurements $\mathbf{Y}$ after background subtraction

$$\tilde{\mathbf{Y}} = \mathbf{L}^{-1} \cdot \mathbf{Y}. \tag{12}$$

The matrix $\mathbf{L}$ is the Cholesky factor of the covariance: $\boldsymbol{\Sigma} = \mathbf{L} \cdot \mathbf{L}^{H}$.

In Fig. 3, the average PSD of a radar measurement with a single target is shown, together with the result after processing by background subtraction and whitening. The PSD becomes nearly flat for low frequencies, such that beat frequencies become better detectable in that frequency range.

The improvement in terms of detecting a close target will be demonstrated by a measurement. Fig. 4 shows the measurement setup. A small target has been placed approximately 7 cm apart from the radar. The settings of the FMCW radar are summarized in Table I. The PSD of the measurement and the PSD after processing are shown in Fig. 5. Because the range resolution is finer than the physical size of the radar, short-range leakage due to the radar lens (⋆), leakage due to the limited isolation between TX and RX channel (×), and reflections due to the deployed target (∗) are identifiable. After processing, the close target becomes clearly detectable, whereas the static targets due to the radar setup are suppressed.

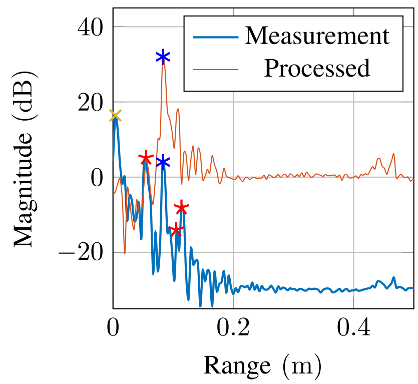

Fig. 5. PSDs (averaged over 256 periods, rectangular window applied) of a measurement with a close target at approximately 7-cm distance, and the result after processing (background subtraction and whitening). Short-range leakage (⋆), leakage between TX and RX channel (×), and the target reflections (∗) can be identified.

IV. CONCLUSION

A novel signal processing method to mitigate static leakage in FMCW radar has been presented. Background subtraction is used to cancel the leakage. After background subtraction, a signal portion remains, which is treated as a colored noise process. A statistical model has been developed, which is used for the whitening of this noise. The whitening improves the dynamic range, such that close targets are better detectable.

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