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Uysal, Faruk; Sanka, Sasanka

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Mitigation of Automotive Radar Interference

Faruk Uysal and Sasanka Sanka
Microwave Sensing, Systems and Signals (MS3) group,
Faculty of Electrical Engineering, Mathematics and Computer Science,
Delft University of Technology, Delft, Netherlands.

***Abstract*—This paper presents a new approach to mitigating radar interference and focuses on the application of automotive radar. Traditional interference mitigation techniques in automotive radar depend on detection and identification of the interference. With this paper, we propose a novel method based on advanced signal separation techniques which do not need any prior detection of the interference. The success of the proposed method is demonstrated into simulated and real automotive radar data sets, in the presence of Continuous Wave (CW) and Frequency Modulated Continuous Wave (FMCW) interference. Significant improvement in Signal-to-Interference-plus-Noise Ratio (SINR) is observed after range-Doppler processing.**

***Index Terms*—interference mitigation, signal separation, automotive radar**

I. Introduction

Modern vehicles are equipped with radar systems whose principal goal is to support drivers in driving for increased traffic safety. Moreover, automotive radar is becoming a key element for autonomous vehicles due to its all-weather, day and night capabilities. Recent advancements in the semiconductor industry have made the low-cost mass production of single-chip automotive radars possible. Soon, the coexistence of multiple radars in congested traffic will be an issue with the increasing number of radar-equipped vehicles on the roads. The interference caused by other automobile radars negatively affects the functionality of the radars by decreasing its detection capability [1], [2], [3].

Most of the existing automotive radar interference mitigation techniques rely on detection or identification of interference before mitigating it. The existing state of the art techniques use either detect and avoidance or detect and mitigate techniques to counter the interference effects. [4]. Post detection, interference could be completely avoided by strategically changing the operational frequency [4] [5]. But the probability of another interferer existing at this shifted frequency may not be low. Hence many existing techniques look into mitigating interference by repairing the interfered samples and possibly reconstruct the required signal (such as using sparse sampling signal recovery in [6]).

The knowledge of interferer is essential to mitigate and reconstruct the desired signal. Since a CW or FMCW interference would have a time-varying frequency component after down conversion of the received signal, a short-time Fourier transform (STFT) of the received signal would reveal most of the information regarding the interference in FMCW radar [7]. In this paper, by using compressed sensing, we propose a novel technique to mitigate the interference without detecting or identifying it. Use of compressed sensing techniques for mitigation, [8] and separation of clutter [9], [10], for radar signals without any detection or identification, are proposed in the literature.

In this paper, we propose a novel time-domain solution for the interference mitigation problem by taking advantage of signal separation and signal reconstruction using dual basis pursuit. We show that we can mitigate the interference *blindly* without any detection or identification.

In Section II, we look at a traditional FMCW radar model in the presence of interference. We discuss how the interference is time limited by FMCW system's low-pass Anti-Aliasing Filter (AAF) so that our received signal can be considered as a combination of two distinct time-varying functions. We look at the domains in which these two time-varying functions namely the beat signal and the interference are sparse respectively. Subsequently,

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we propose an algorithm using dual basis pursuit for interference mitigation in Section III. With a description of our experimental setup in Section IV, we discuss the results that were obtained by applying this method to the automotive radar interference problem. Finally, we look into the signal to interference plus noise ratio (SINR) improvement achieved using our algorithm and conclude with a summary and further implementations.

II. FMCW RADAR AND INTERFERENCE

In this section, the system and signal model for a traditional FMCW radar are revisited to describe our approach for interference mitigation.

Let the baseband LFM signal for a single chirp be defined as

$$s_t = e^{j\pi k t^2} \quad \text{for} \quad 0 < t < T \tag{1}$$

where T is the duration and k is the slope of the chirp signal ($k = B/T$ where B is the bandwidth of signal).

In a traditional FMCW automotive radar, the baseband signal is modulated with a carrier signal f_c and transmitted through free space. After free space propagation, return echoes are collected by the antenna(s) and demodulated at the front end. The received signal at the end of the receiver chain $s = s_r + s_i$ is a combination of interference signal s_i and the signal of interest s_r. Explicitly, signal of interest is

$$s_r = P_r e^{j\pi k (t-\tau)^2} e^{-j2\pi f_c \tau}, \tag{2}$$

where τ is the round trip delay of the signal of interest and P_r is the free-space power received by an antenna according to the free-space path loss model. Assuming an interference from a similar type of radar having the same center frequency as that of the transmitted signal, received interferer signal at the end of the receiver chain can be written as

$$s_i = P_i e^{j\pi k_i (t-\tau_i)^2} e^{-j2\pi f_c \tau_i} \tag{3}$$

where k_i is the slope of the interferer P_i is the received power and τ_i is the time delay of the interferer with respect to transmitted chirp. Subsequently, the received signal is mixed with complex conjugate of basebend signal (which also known as dechirping)

$$y = s_r s_t^*, \tag{4}$$

which can be written explicitly as

$$y = P_r e^{j\pi k(\tau^2 - 2t\tau)} e^{-j2\pi f_c \tau} + P_i e^{j\pi\left((k_i-k)t^2 - 2k_i t\tau_i + k_i \tau_i^2\right)} e^{-j2\pi f_c \tau_i} \tag{5}$$

Then, an analog low pass filter (LPF) is applied. The impulse response of the LPF should not produce any unwanted distortion due to the presence of interference. To identify the limits of the interference and for simplicity in derivations, let assume a perfect Brick wall filter which is defined as

$$H(f) = \text{rect}\left(\frac{f}{f_L}\right), \tag{6}$$

where f_L is the cut-off frequency of the LPF.

Note that, in (5), the second part represents the received interference

$$y_i = P_i e^{j\pi\left((k_i-k)t^2 - 2k_i t\tau_i + k_i \tau_i^2\right)} e^{-j2\pi f_c \tau_i}, \tag{7}$$

where the phase change of the received interference signal can be written as

$$\phi(t) = \pi\left((k_i - k)t^2 - 2k_i t\tau_i + k_i \tau_i^2 - 2f_c \tau_i\right). \tag{8}$$

The received interference signal's instantaneous frequency $f_i(t)$ can be computed as

$$f_i(t) = \frac{1}{2\pi}\frac{d}{dt}\phi(t) \tag{9}$$

$$= ((k_i - k)t - k_i \tau_i) \tag{10}$$

which is bounded by the cut-off frequency of the LPF [11],

$$-f_L \leq ((k_i - k)t - k_i \tau_i) \leq f_L. \tag{11}$$

The lower- and upper-bounds of the beat frequencies are illustrated in Figure 1. Considering the fact that the interference is symmetric around the reference signal due to these bounds, the duration of the interference over the beat signal can be re-framed as

$$T_i \leq \left|\frac{2f_L}{k_i - k}\right|. \tag{12}$$

Thus, the received signal post LPF can be written as

$$y_L = \begin{cases} y_r + y_i & \frac{-f_L + k_i \tau_i}{(k_i - k)} \leq t \leq \frac{f_L + k_i \tau_i}{(k_i - k)} \\ y_r & \text{otherwise,} \end{cases} \tag{13}$$

where received signal of interest is

$$y_r = P_r e^{j\pi k(\tau^2 - 2t\tau)} e^{-j2\pi f_c \tau}. \tag{14}$$

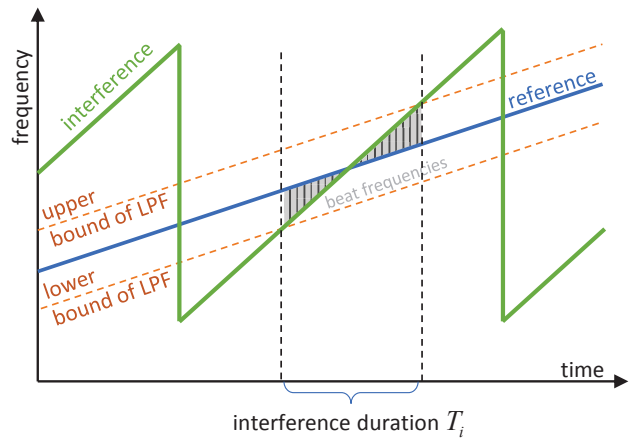

Fig. 1. Illustration of beat frequencies due to the interference in same carrier frequency.

Note that, the interference is time-limited and has an oscillatory behavior (quadratic-phase signal) [12]. Figure 2 shows the behavior of beat and interference signals in time-domain with a dependency of LPF as described in (13).

With information on the time period in which interference is localized, the number of samples that are being interfered is given as

$$N_{int} = T_i f_s \tag{15}$$

To simulate this interference effect, a baseband signal is transmitted at a bandwidth of 1 GHz and 30.6 μs transmit time. This signal is interfered against a CW interferer ($k_i = 0$) having a center frequency of 500 MHz in baseband. The cut-off frequency of the LPF is 20 MHz and the sampling rate is at 40 MHz. Substituting these values in (12), the duration of the interferer is 1.224 μs as shown in Figure 2. The ringing artifacts are observable before and after the time limited interference due to the ideal (brick-wall) low-pass filter.

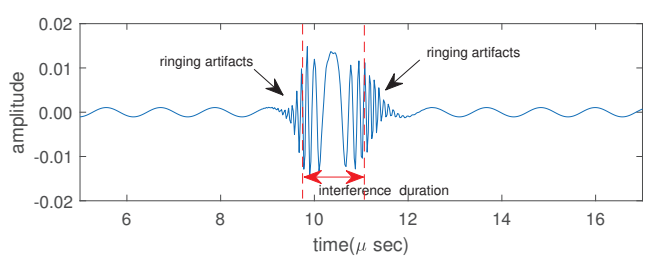

Fig. 2. Simulated received signal consists of interference and beat signal after LPF. Interference is in the form of a time-limited quadratic-phase signal.

III. Algorithm for Interference Separation

The proposed method depends on formulating the interference mitigation as a signal separation problem. We propose to use morphological component analysis (MCA) to decompose received signal into its components, namely the interference and received beat signals.

Let's write the observed signal $\mathbf{y}$ in terms of two components from (5). We consider the two components to be $\mathbf{y}_r$ and $\mathbf{y}_i$ so

$$\mathbf{y} = \mathbf{y}_r + \mathbf{y}_i \tag{16}$$

where $\mathbf{y}_r$ is the beat signal component and $\mathbf{y}_i$ is the interference component.

The morphological component analysis (MCA) approach assumes the two components of the received signal (beat and interference) are sparse in different domains [13]. A particular formulation of MCA aims to find the sparse coefficients with respect to the different transforms. Therefore, instead of finding $\mathbf{y}_r$ and $\mathbf{y}_i$, this formulation of MCA seeks coefficients $\mathbf{c}_1$ and $\mathbf{c}_2$ in different domains (like $\mathbf{A}_1$ and $\mathbf{A}_2$) such that

$$\mathbf{y} = \mathbf{A}_1\mathbf{c}_1 + \mathbf{A}_2\mathbf{c}_2; \tag{17}$$

where $\mathbf{y_r} = \mathbf{A}_1\mathbf{c}_1$ and $\mathbf{y}_r = \mathbf{A}_2\mathbf{c}_2$. This problem is ill-conditioned since there are infinitely many solutions. The separation of $\mathbf{y}_r$ and $\mathbf{y}_i$ from received signal $\mathbf{y}$ can be meaningful if and only if these two components have distinct properties which are known or approximately known. To find a particular solution, MCA follows a variational framework and minimizes a cost function chosen so as to promote sparsity of coefficients.

To promote sparsity, we have considered the beat signal to be sparse in Fourier domain since the spectrum of beat signal represents the range information which is sparse. On the other hand, interference has quadratic-phase so it spans over frequency spectrum and can not be classified as sparse in Fourier domain. As seen from (10), instantaneous frequency of interference is a function of time, thus interference signal can be assumed to be sparse in time-frequency domain. Consequently, the transforms can be selected as a discrete Fourier transform (DFT) $\mathbf{A}_1$ and a short-time Fourier transform (STFT) $\mathbf{A}_2$ to represent the signals sparsely in two different domains. Note that the beat frequencies are also

Algorithm 1: Signal Separation algorithm for automotive radar

Input : y
Initialize: $d_i \geq 0$ for $i = 1, 2$
Repeat until converge:

$$v_1 \leftarrow soft(c_1 + d_1, \tfrac{\lambda_1}{2\mu}) - d_1$$
$$v_2 \leftarrow soft(c_2 + d_2, \tfrac{\lambda_2}{2\mu}) - d_2$$
$$a \leftarrow y - \mathbf{A}_1 c_1 - \mathbf{A}_2 c_2$$
$$d_i \leftarrow \tfrac{1}{2} A_i^H a$$
$$c \leftarrow d_i + v_i$$

where $soft(\mathbf{y}, T) = \mathbf{y} max(0, 1 - T/|\mathbf{y}|)$

sparse in STFT domain. However, beat signal is sparser in DFT domain than the interference signal, which allows the MCA separating these two component successfully. Then, we can define interference mitigation problem as a optimization problem using the ℓ_1 norm of coefficient vectors as follow[1],

$$\begin{aligned} &\arg\min_{\mathbf{c}_1, \mathbf{c}_2} (\lambda_1 \|\mathbf{c}_1\|_1 + \lambda_2 \|\mathbf{c}_2\|_1) \\ &s.t \quad \mathbf{y} = \mathbf{A}_1 \mathbf{c}_1 + \mathbf{A}_2 \mathbf{c}_2 \end{aligned} \tag{18}$$

which is also known as the dual-basis pursuit problem. To solve this optimization problem, we use split augmented Lagrangian shrinkage algorithm (SALSA) [14], which is based on the alternating direction method of multipliers (ADMM) [15]. Note that proximal splitting methods, such as a Douglas-Rachford approach, could be also used to solve this problem [16]. The final algorithm is shown in Algorithm 1 and details of the derivation can be found in [8].

IV. Experimental Setup

We set up an experiment in the presence of continuous wave (CW) interferer to demonstrate the success of proposed algorithm. A new generation NXP Dolphin transceiver chip at a 78.8 GHz center frequency with a bandwidth of 1.0 GHz is set up as an automotive radar. A simple pendulum is used to simulate a moving target. The pendulum, consisting of a 0 dBm^2 (at 77 GHz) trihedral reflector mounted on a swinging arm of 1 m length, is located at 5 m range from the radar unit. The interference source is located at the same range with a 20° degree offset. A 78 GHz CW signal is generated using a Keysight N542A PNA with a WR-10 frequency extension module and is transmitted via a 20 dB standard gain horn (Flann 27240-20).

[1]The ℓ_1 term promotes sparsity in optimization problem. ℓ_1 norm of a vector $\mathbf{x}$ is defined as $\|\mathbf{x}\|_1 = \sum_n |x(n)|$

V. Results and Discussion

To demonstrate the success of the algorithm under worst-case scenario, we select a data where interference and target signature overlaps in range-Doppler (velocity) domain. The time domain snapshot of collected data set is shown in Figure 3a. To minimize the effect of stationary objects (ground clutter) and demonstrate the effect of algorithm clearly, we apply a ground clutter filter as a preprocessing strategy before applying proposed signal separation algorithm.

Figure 3b and Figure 3c show the time domain signature of interference and signal of interest after processing, respectively. Beat signal is separated successfully from the interference signal in the presence of a dominant interferer. The sinusoidal behavior of beat signal can be seen in Figure 3c since there was only one moving target present during the experiment. Figure 4 illustrates the same

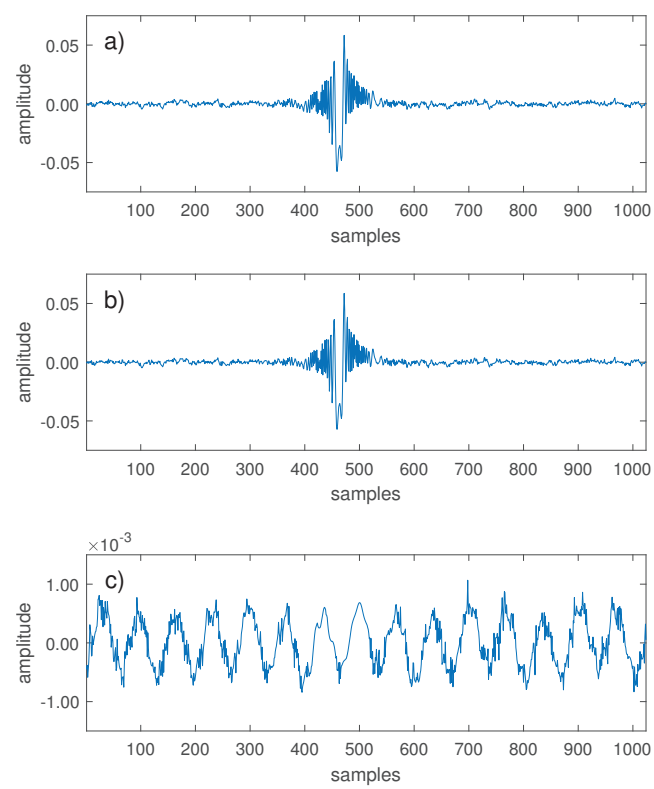

Fig. 3. Real data snapshot: a) Collected signal $\mathbf{y}$, b) separated interference signal $\mathbf{y_r}$ and c) separated beat-signal $\mathbf{y_i}$ after processing.

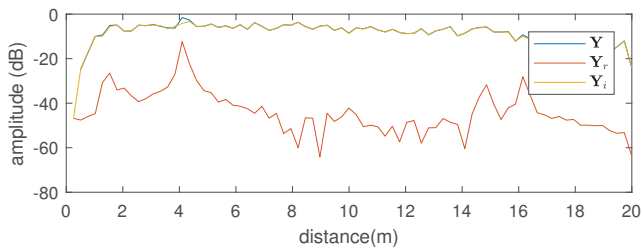

Fig. 4. Received and separated signals in range domain (before Doppler processing). The raise of the noise floor due to the interference is observable. Interference free noise floor is about -50 dB.

signal in range domain where the increase of noise floor due to the interference can be clearly seen.

Figure 5a shows a range-velocity plot of a snapshot of the collected data. As seen from the figure, detection of a target is challenging due to the interference and high side-lobes of ground clutter. Result of ground clutter filter is shown in Figure 5b. Figure 5c shows the signal of interest after applying the proposed algorithm. Similarly, the interference signal after signal separation is illustrated in Figure 5d. Figure 5c shows the success of the proposed method, which works as expected even for the worst-case scenario where the target signature is buried under the interference.

In this example, we compute the SINR only for the interval where there is a presence of interferer as defined by (12). As a result of interference separation, a gain of about 23 dB is observed in SINR as illustrated in Figure 5.

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VI. Conclusion

In this paper, we investigate radar-to-radar interference and its effects on automobile radar. After preprocessing (ground clutter filtering), we proposed to use MCA based signal separation method, which does not need any prior information, to mitigate the interference created by other radars. We demonstrate on real data set that, it is possible to mitigate the interference blindly without any detection or identification, even in a worst-case scenario, to increase SINR of the target of interest.

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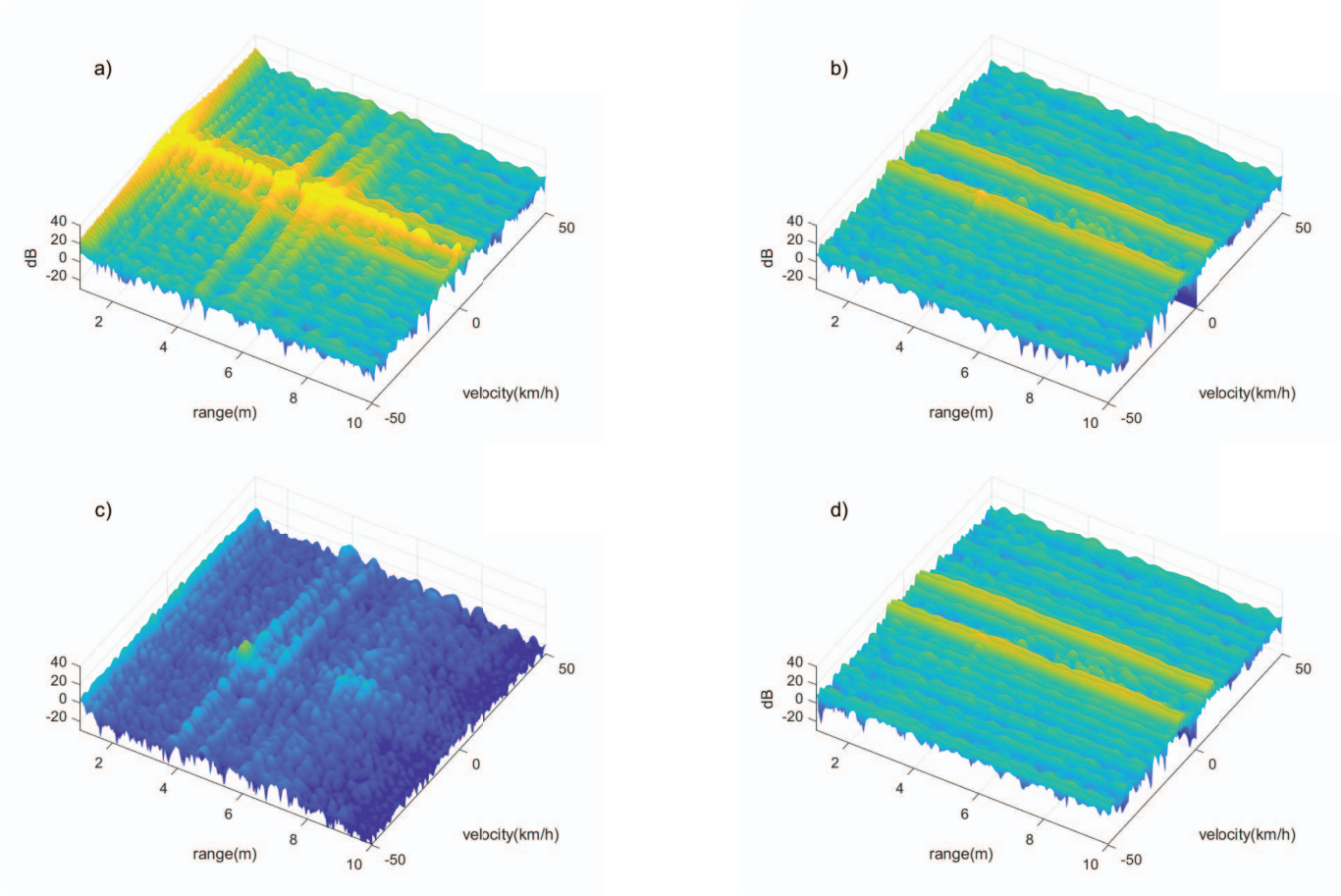

Fig. 5. Real data processing: a) collected signal, b) collected signal after pre-processing c) signal of interest and d) interference after processing.