Compressive Sensing for Passive ISAR with DVB-T Signals

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Abstract

As recently demonstrated, ISAR images can be obtained by using DVB-T based Passive radars. When the multichannel DVB-T channels are used for ISAR imaging purposes, the gaps existing between the channels may degrade the image significantly. In this paper the Compressive Sensing (CS) theory is investigated to address this problem. Specifically a 2D-SL0 algorithm is used to solve a sparsity-driven optimization problem.

I. Introduction

Passive radars exploit Illuminators of Opportunity (IOs) to detect and track targets. These types of radar have drawn a lot of attractions all over the world due to the evident advantages with respect to active radar, such as low cost, flexible configuration of the receivers, reduced electromagnetic pollution, and so on [1]. Passive radars often use VHF/UHF bands, which are normally not available for active radars. As a result of the intensive research activities conducted in this field, much progress has been made recently that has improved Passive Coherence Location (PCL) capabilities. One of such is radar imaging [2], which may enable Automatic Target Classification (ATC) capabilities. To obtain effective ISAR images of the radar target, high spatial resolutions should be achieved. Among the analogue and digital IOs, DVB-T signals exhibit a wide bandwidth and thus allow for good spatial resolutions to be achieved. To improve the range resolution, it has been proven in [2] and [5] that multiple adjacent DVB-T channels can be coherently adjoined to form a wide bandwidth signal. However, the VHF/UHF band is not completely filled by the broadcast channels, therefore even if hardware is available which is able to acquire signals over a much wider bandwidth than a single DVB-T channel, the gaps existing between the channels may

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be large. Such gaps in the signal bandwidth are responsible for degradations in the ISAR image, when classical Fourier transform based imaging algorithms are used to form the image of the target. Motivated by the fact that an ISAR image is sparse or compressible in the image domain, as it can be considered composed of few prominent scattering centers, the CS theory [3][4] is investigated in this paper to address the problem of forming an ISAR image when spectrally separated DVB-T channels are available.

This paper is organized as follows: section II provides mathematical details concerning the received signal model. Passive ISAR with DVB-T signals is formulated as a CS problem in section III. Finally, simulation and real data based results are shown in section IV.

II. Signal Model

The mathematical formulation of the signal model for passive ISAR is derived in this section. As a passive radar is intrinsically bistatic (in fact the transmitter and receiver are not co-located), the bistatic configuration can be approximated with an equivalent monostatic configuration with a virtual radar located along the bisector of the bistatic angle, as shown in [7]. In this way, a monostatic ISAR processing can be used to form Bistatic-ISAR (B-ISAR) images.

Firstly, the received signal is match-filtered. Such an operation can be implemented by cross-correlating the received signal with the reference signal within the same sweep. Then, at the output of the matched filter and after Fourier transforming along the delay-time domain, the baseband signal in the frequency/slow-time domain can be obtained. After the motion compensation step, and under certain constraints, the baseband signal can be expressed as follows:

$$S\left(f,n\right) = C \cdot W\left(f,n\right) \cdot \int_{\tau=-\infty}^{\infty} \int_{\nu=-\infty}^{\infty} \alpha\left(\tau,\nu\right) e^{-j2\pi\left(f\tau+n\nu\right)} \ d\tau \ d\nu \tag{1}$$

where C is a constant related to the speed of light, minimum transmitted frequency, effective rotation vector, and bistatic angle factor, τ and ν represent the delay-time and the Doppler axis respectively, $\alpha\left(\tau,\nu\right)$ is the target's reflectivity function, and $W\left(f,n\right)$ is defined as $W\left(f,n\right) = \left|S_T\left(f,n\right)\right|^2 \cdot (u(n) - u(n-N))$, where $S_T\left(f,n\right)$ represents the transmitted signal within the n^{th} sweep and $u(n)$ is the unit step discrete function.

Differently from what happens in the case of active radar systems, for passive radar systems, the transmitted signal changes from sweep to sweep as it depends on the transmitted information content (see eq. (1)). In the case of DVB-T signal, it depends on the transmitted OFDM symbols. Because of that, the received signal cannot be modeled as a deterministic signal but rather as a random signal as it varies among different acquisitions. This could be an issue for the evaluation and the prediction of the algorithm performance. Thus, only the statistical average of the algorithm performance can be estimated. To do that, the statistical average of the received signal will be considered hereinafter as defined in eq. (2):

$$\overline{S}\left(f,n\right) = C \cdot \overline{W}\left(f,n\right) \cdot \int_{\tau=-\infty}^{\infty} \int_{\nu=-\infty}^{\infty} \alpha\left(\tau,\nu\right) e^{-j2\pi\left(f\tau+n\nu\right)} \ d\tau \ d\nu \tag{2}$$

where $\overline{S}\left(f,n\right) = E\left\{S\left(f,n\right)\right\}$, $\overline{W}\left(f,n\right) = E\left\{W\left(f,n\right)\right\}$, and $E\{\cdot\}$ represents the average operator. It can be demonstrated that in the case of DVB-T signals, $\bar{W}(f,n)$ can be approximated as follows:

$$\overline{W}(f,n) \simeq rect\left(\frac{f-f_0}{B}\right)\cdot(u(n)-u(n-N)) \tag{3}$$

Eq. (3) means that the $\overline{W}(f,n)$ acts as an ideal two-dimensional filter in the frequency/slow-time domain which limits the bandwidth of the signal thus determining the spatial resolutions.

In a real scenario, however, both the variables in the frequency/slow-time domain and the image domain are discrete variables. The signal in eq. (2) can then be written in a digitized form as follows:

$$\overline{S}(m,n) = C\cdot\sum_{q=1}^{M}\sum_{d=1}^{N}\alpha(q,d)\,e^{-j2\pi\frac{mq}{M}}e^{-j2\pi\frac{nd}{N}} \tag{4}$$

where $m = 1,2,\cdots,M$, M is the number of transmitted frequency in each sweep, $n = 1,2,\cdots,N$, N denotes the number of sweeps, and $\alpha(q,d)$ stands for the backscattering response from the pixel in the position (q,d). Each non-zero pixel in the image is considered as the contribution from a scattering centre of the target. For ISAR imaging, the whole non-zero pixels occupy only a small part of the imaging plane, which motivates the CS approach to form the ISAR images. In addition, it is worth pointing out that the derived signal model is applicable to all type of transmitted waveforms that satisfy the property in (3). More details concerning the signal model will be provided in the final paper.

III. Passive ISAR Formulation as a CS Problem

CS provides a new sampling paradigm, which can recover a sparse signal using limited measurement via solving an optimization problem constrained by the sparsity of the signal. Let us look at the signal model given in equation (4), which can be further rewritten in a matrix form as

$$\overline{\mathbf{S}} = \mathbf{\Phi}_x\mathbf{\Omega}\mathbf{\Phi}_y^{\mathrm{T}} \tag{5}$$

where $\overline{\mathbf{S}}$ denotes the measurement data matrix, $\mathbf{\Phi}_x$ and $\mathbf{\Phi}_y$ represent the Fourier basis matrices in the frequency and slow-time domains, respectively, and $\mathbf{\Omega}$ is the passive ISAR image. It should be mentioned that in case of passive ISAR with DVB-T signals, since there is no signal transmitted during the bandwidth gaps, the matrix $\mathbf{\Phi}_x$ should be modified by replacing the rows corresponding to the gaps with 0, and we denote the new dictionary matrix as $\mathbf{\Phi'}_x$. Then according to the principle of CS and considering the additive noise, the ISAR image can be reconstructed by solving the following optimization problem as:

$$\min_{\mathbf{\Omega}} \parallel \mathbf{\Omega} \parallel_0 \quad \text{s.t.} \quad \parallel \overline{\mathbf{S}} - \mathbf{\Phi'}_x\mathbf{\Omega}\mathbf{\Phi}_y^{\mathrm{T}} \parallel_{\mathrm{F}}^2 \leq \epsilon \tag{6}$$

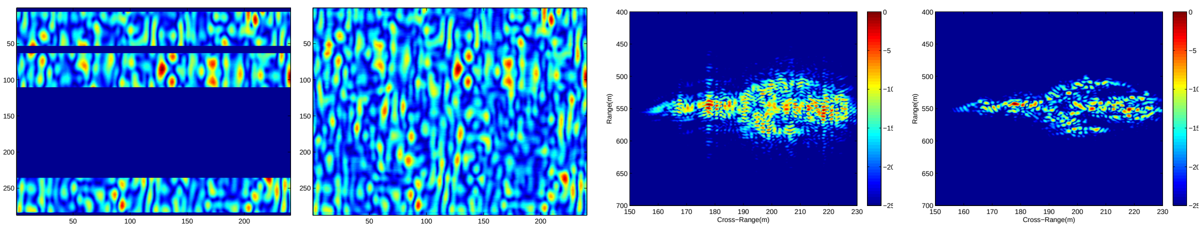
where $\|\cdot\|_0$ denotes the number of non-zero components in $\mathbf{\Omega}$, $\|\cdot\|_{\mathrm{F}}$ represents the Frobenius norm of a matrix, and then ϵ is a small constant. Specifically, a 2D-SL0 algorithm [6] is used to find the solution of (6). Furthermore, the data matrix in frequency/slow-time domain with bandwidth gaps filled is calculated as

$$\hat{\overline{\mathbf{S}}} = \mathbf{\Phi}_x\hat{\mathbf{\Omega}}\mathbf{\Phi}_y^{\mathrm{T}} \tag{7}$$

where $\hat{\mathbf{\Omega}}$ is the estimation of $\mathbf{\Omega}$ from (6). Then a Range-Doppler (RD) algorithm is applied to $\hat{\overline{\mathbf{S}}}$ in order to obtain an ISAR image which is comparable with that one obtained by applying the RD algorithm to the original data.

IV. Results

In this section, simulation results are shown to verify the effectiveness of the proposed method. Additionally, the Image Entropy (*IE*) is introduced to evaluate the quality of the ISAR image. Figure 1 shows the simulation result. By comparing figure 1(a) and 1(b), we can see that the gaps are filled after applying CS and that the grating lobes level has been drastically reduced which can be concluded by comparing figure 1(c) and 1(d). Moerever, the values of *IE* of figure 1(c) and 1(d) are 9.42 and 8.66, respectively, indicating that the latter one is better than the former one. More results based on simulation and real data will be given in the final paper.



(a) (b) (c) (d)

Figure 1. Results (a) simulation data with non-adjacent channels (b) reconstructed full band data (c) ISAR image using RD algorithm (d) ISAR image using the proposed CS-RD algorithm

V. Conclusions

A passive ISAR processing based on compressive sensing with multichannel DVB-T signals has been proposed in this paper. Simulation results show that CS can significantly reduce the grating lobes in passive ISAR imaging in the case of non-adjacent DVB-T channels. Although the passive ISAR images shown are not comparable to active ISAR images in terms of image resolution, they are attractive because 1) they may be improved by using a wider portion of the spectrum by updating the hardware, 2) they provide RCS information of targets at low frequencies where typically active radar cannot transmit, 3) they may be used to stealthy targets detection and imaging.

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