On the feasibility of DVB-T based passive radar with a single receiver channel

Osama Mahfoudia[*,†], *François Horlin*[†], *Xavier Neyt*[*]

[*]*CISS Department, Royal Military Academy, Brussels, Belgium*
[†]*OPERA Department, Université Libre de Bruxelles, Brussels, Belgium*

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Abstract

The DVB-T signals are an attractive source of illumination for the passive radars due to their wide bandwidth and signal structure. The DVB-T standard permits the reconstruction of the received reference signal to enhance its signal-to-noise ratio (SNR). The signal reconstruction possibility allows the use of a simplified configuration of the radar by employing a single receiver. In this paper, we propose an optimized processing scheme for the single receiver DVB-T passive radar. We carry out Monte-Carlo simulations to assess the performances of the single receiver configuration, and we present real-data results to validate the proposed scheme.

1 Introduction

Passive radar systems employ signals from non-cooperative transmitters for target detection and tracking. Their major advantages are low cost, intercept immunity, and ease of deployment. The employed non-cooperative transmitters, called also illuminators of opportunity, can be dedicated for radar applications (radar transmitters), or designed for commercial use and exploited for passive detection due to their attractive features. Telecommunication and broadcasting signals are widely employed as illuminators of opportunity for passive radars [1–3].

The classical architecture of passive radars involves two receiving channels: a reference channel for the reception of the direct-path signal and a surveillance channel for the reception of the target return signal [3]. In addition to the target return, the surveillance channel collects reflections from the static scatterers (static clutter), and a direct-path signal. The direct-path signal is the most significant part of the surveillance signal, which may mask the target return and reduces the detection dynamic range [1, 4].

DVB-T signals as an illumination source for the passive radars have been the subject of a growing interest [4]. This is due to the suitable characteristics of the DVB-T waveform (wide bandwidth and data-independent spectrum), the high radiated power of the transmitters, and the possibility of reconstructing the reference signal [4–7]. The DVB-T standard allows the reconstruction of the received reference signal to enhance its signal-to-noise ratio (SNR), which provides an improved reference signal template. Therefore, it is possible to exploit the direct-path signal included in the surveillance signal to estimate a synthetic reference signal. The estimated signal can replace the received reference signal, and thus, a specific channel to acquire the reference signal is unnecessary, which reduces the system cost. Such configuration is called single receiver passive radar [8].

The single receiver DVB-T based passive radar approach has been initiated in [8, 9]. In this paper, we consider a single receiver DVB-T passive radar and we propose an optimized processing scheme. The proposed scheme includes an optimum signal reconstruction method [7] and an efficient static clutter suppression approach [10, 11]. We employ Monte-Carlo simulations to assess the performance of the single receiver configuration and we present real-data results to validate its feasibility.

This paper is organized as follows. Section 2 presents the signal model and the signal processing scheme. Section 3 assesses the performance of the proposed method for signal extraction. Section 4 shows the real-data results. And Section 5 concludes the paper.

2 Signal processing

2.1 Signal model

Figure 1 illustrates the configuration of a single receiver passive radar. The received signal is formed by the direct-path signal, the static clutter resulting from the reflections by the static scatterers in the surveillance area, possible target echoes, and a receiver thermal noise. We adopt the following model for the received signal

$$x(n) = \sum_{l=0}^{L-1} h_l s(n-l) + \alpha s(n-\tau) e^{j2\pi f_d n} + v(n) \qquad (1)$$

where L is the number of the considered static scatterers with reflection coefficients h_l, $v(n)$ is a thermal noise modeled as a Gaussian noise with zero mean and variance σ_v^2. The target return is a time-delayed (τ), frequency-shifted (f_d), and attenuated (with a coefficient α) copy of the transmitted signal $s(n)$. The clutter parameters (h_l) and the target echo parameters (α, f_d, and τ) are assumed to be invariant over the coherent processing interval. We define the direct-path-to-noise ratio (DNR) as

$$\mathrm{DNR} = |h_0|^2 \sigma_s^2 / \sigma_v^2, \tag{2}$$

where σ_s^2 is the variance of the transmitted signal. And the target signal-to-noise ratio (SNR) is defined as follows

$$\mathrm{SNR} = |\alpha|^2 \sigma_s^2 / \sigma_v^2. \tag{3}$$

The DVB-T standard employs the orthogonal frequency division multiplexing (OFDM) modulation scheme, where each DVB-T symbol is formed by K orthogonal subcarriers as follows

$$s(n) = \sum_{k=0}^{K-1} C_k e^{j2\pi f_k n}, \tag{4}$$

where f_k is the frequency of the k^{th} subcarrier and C_k is the k^{th} quadrature amplitude modulation (QAM) symbol. Among the K subcarriers, there are pilot subcarriers which are employed for signal synchronization and propagation channel estimation.

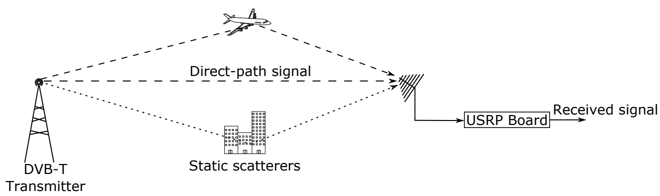

Fig. 1: DVB-T based passive radar with a single receiver.

2.2 Signal synchronization

The reference signal extraction is performed by demodulating the received signal and reconstructing the retrieved symbols [4]. And since the DVB-T signal demodulation is based on symbol structure [12], an accurate synchronization of the received signal is required. The synchronization aim is the knowledge of the arriving time of the DVB-T symbols, and the compensation of the possible carrier frequency offset (CFO). The arriving time synchronization exploits the guard interval correlation to estimate the beginning of the DVB-T symbols, which allows an accurate positioning of the FFT window [13]. The CFO is caused by the mismatch between the local oscillator and the received signal carrier, which results in the loss of subcarrier orthogonality. The CFO estimation is performed in two steps: the first one employs the guard interval correlation to estimate the fractional part of the CFO [13], and the second step uses the pilot subcarriers to estimate the integer part of the CFO [14]. The compensation of the CFO maintains the subcarrier orthogonality and thus reduces the QAM symbol detection error.

2.3 Signal demodulation

Figure 2 presents the proposed scheme for reference signal and target signal extraction from the synchronized signal. The direct-path signal is the dominant part of the received signal [4], which allows to neglect the clutter and target components during the demodulation. Thus, the reconstructed signal based on the received signal demodulation can be considered as an estimate of the transmitted signal. The transmitted signal estimate is then employed for static clutter suppression and target detection.

The synchronized received signal is divided into blocks of DVB-T symbols. Next, the guard interval is removed from each DVB-T symbol. Then, the useful parts of the DVB-T symbols are Fourier-transformed, which results in the following result for each subcarrier

$$X(k) = H(k)C_k + X_t(k) + V(k), \tag{5}$$

where $H(k)$ is the coefficient of the frequency-domain propagation channel for the k^{th} subcarrier, C_k is the transmitted QAM symbol, $X_t(k)$ is the target return contribution at the k^{th} subcarrier, and V is the Fourier-transform of the noise v.

2.4 Propagation channel estimation

An estimate of the frequency-domain propagation channel ($\mathbf{H}$) is required to equalize the received $X(k)$ symbols; it can be obtained by exploiting the pilot subcarriers [15]. The least square (LS) method is widely used for propagation channel estimation; knowing the frequency and the amplitude for the pilot subcarriers, the LS channel estimate at those subcarriers is given by

$$\hat{H}(p) = X(p)/C_p, \tag{6}$$

where C_p is the amplitude of the pilot subcarrier. For the DVB-T standard, the pilot subcarriers are spaced by 12 ΔF with ΔF represents the subcarrier spacing; and four overlapping pilot patterns are employed in a periodic manner [12]. The full response of the propagation channel is obtained by interpolating the responses at the pilot subcarrier locations. To reduce the noise effect, an averaging of the resulting channel estimates is performed. Obviously, the accuracy of the channel estimation affects the precision of the QAM symbol detection since it influences the equalization. To provide a more accurate channel estimate, the method in [11] reduces the interpolation errors by concatenating the pilot responses for each four consecutive DVB-T symbols. As a result the interpolation is performed over 3 ΔF instead of 12 ΔF in the conventional LS method. Consequently, a more accurate QAM detection is expected, which improves the quality of the extracted reference signal.

2.5 Reference signal extraction

The detection of the equalized QAM symbols provides an estimation of the transmitted QAM symbols $\hat{\mathbf{C}}$. The classical approach for reference signal reconstruction is performed by

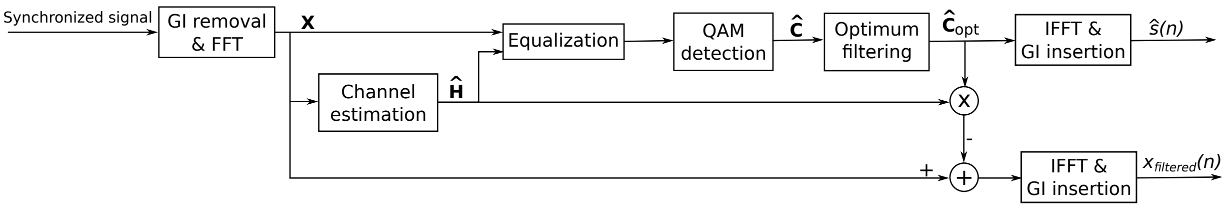

Fig. 2: Signal processing scheme.

modulating the detected QAM symbols ($\hat{\mathbf{C}}$), applying an inverse Fourier-transform, and inserting the guard interval [5,6]; we note the resulting signal as $\hat{s}(n)$. For low DNR values, the QAM symbol detection error is considerable, which creates a mismatch between the estimated signal and the transmitted one [7]. The resulting mismatch degrades the performance of the classical approach for reference signal extraction [5,6], and thus, limits the feasibility of the single channel DVB-T passive radar by requiring a high DNR level.

An optimum reference signal reconstruction method is proposed in [7]; it minimizes the mean square error (MSE) between the transmitted signal and the estimated one. The estimated signal is formed by optimally weighted QAM symbols $\hat{\mathbf{C}}_{\mathrm{opt}}$ which extends the feasibility of the reference signal reconstruction for low DNR values. The optimum QAM symbol calculation is performed as follows

$$\hat{\mathbf{C}}_{\mathrm{opt}} = h_{opt}\hat{\mathbf{C}}, \tag{7}$$

where the weight h_{opt} is a function of the DNR level. Such a performance is useful for the single channel configuration, where the direct-path signal can be received by the antenna sidelobes. In this work, we adopt this optimum reconstruction method for reference signal extraction.

2.6 Static clutter suppression

The masking effect of the static clutter can be mitigated by applying an adaptive or sequential static clutter suppression method [16–18], where the estimate of the reference signal and the synchronized received signal are employed. These methods induce high computational load, which increases the system complexity. For DVB-T signals, the possibility of estimating the propagation channel can be exploited for the static clutter suppression. In fact, the propagation channel estimate summarizes the multipath components of the received signal, which form the static clutter. Thus, an estimation of the static clutter can be obtained by multiplying the propagation channel estimate $\hat{\mathbf{H}}$ and the detected QAM symbols [10, 11]. A simple subtraction of the static clutter estimate from the synchronized signal leads to the clutter-free signal; for the k^{th} subcarrier, we can write

$$X_{filtered}(k) = X(k) - \hat{H}(k)\hat{C}_{opt}(k). \tag{8}$$

The clutter-free signal $x_{filtered}(n)$ is obtained by inverse-Fourier transforming $X_{filtered}$ (the frequency-domain filtered signal) and inserting the guard interval. Clearly, the performance of this method depends on the accuracy of the propagation channel estimate. And since the method in [10] employs a conventional channel estimation (the interpolation gap is $12\ \Delta F$), we propose to employ the estimate of the propagation channel that results from the method in [11] for the static clutter suppression.

2.7 Detection

In passive radars, the range-Doppler profile of the received signal is extracted by cross-correlating the reference signal and the surveillance signal. In this work, we employ the synthetic reference signal $\hat{s}(n)$ and the filtered signal $x_{filtered}(n)$ to calculate the range-Doppler diagram as follows

$$\chi(\kappa, \nu) = \sum_{n=0}^{N-1} \hat{s}^*(n-\kappa)x_{filtered}(n)e^{-j2\pi\nu n}, \tag{9}$$

where κ is the time delay, ν is the frequency shift, and N is the length of the coherent integration interval which determines the Doppler resolution and the coherent processing gain [4].

3 Performance evaluation

In this section, we compare the performances of two methods for reference signal and target signal extraction: a proposed method and a conventional one. The proposed method refers to the method presented in figure 2, where an optimum signal reconstruction [7] and an improved static clutter suppression method [11] are employed. The conventional method uses a conventional signal reconstruction scheme [5, 6] and the static clutter suppression method proposed in [10].

3.1 Qualitative evaluation

Firstly, we compare the static clutter suppression capability; we consider the direct-path suppression level as a metric [17]. Figure 3 presents a cut of the range-Doppler diagram at zero range for $\mathrm{DNR} = 20$ dB and a coherent processing interval of length $N = 10^6$. We notice that the conventional extraction achieved a direct-path suppression of about 20 dB, and that the proposed method performed a full suppression of the direct-path signal. Clearly, the proposed method for static clutter suppression outperforms the conventional one due to the accurate propagation channel estimation, which permits the detection of low magnitude slow target echoes.

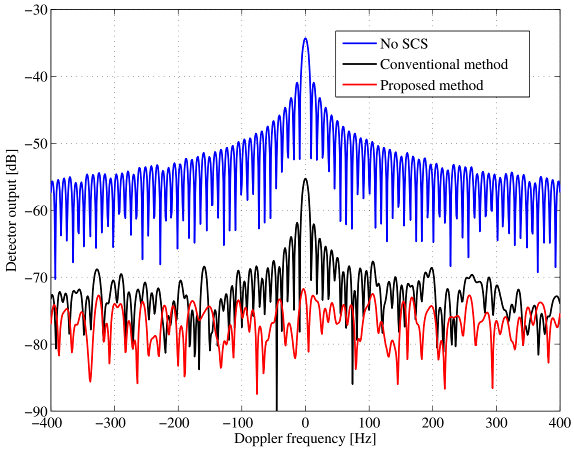

Fig. 3: Cut of the range-Doppler diagram at zero range for $N = 10^6$ and $\text{DNR} = 20$ dB.

Secondly, we assess the impact on target detection probability by considering the resulting noise-floor level [19]. Figure 4 shows a cut of the range-Doppler diagram at the target range for $\text{DNR} = 20$ dB and $N = 10^6$. The target echo has a Doppler shift of $f_d = 200$ Hz and a signal-to-noise ratio of $\text{SNR} = -30$ dB. We notice that the noise-floor level for the proposed method case is considerably lower than that for the conventional extraction method. In addition, we remark a difference of the coherent integration at the target location, which is due to the reference signal extraction quality. In fact, although the DNR level is high, the accuracy of the channel estimation affects the equalization of the received symbols, and thus controls the reference signal quality. Consequently, the reference signal obtained through the conventional channel estimation will lead to a higher noise-floor and a degradation of the coherent integration gain.

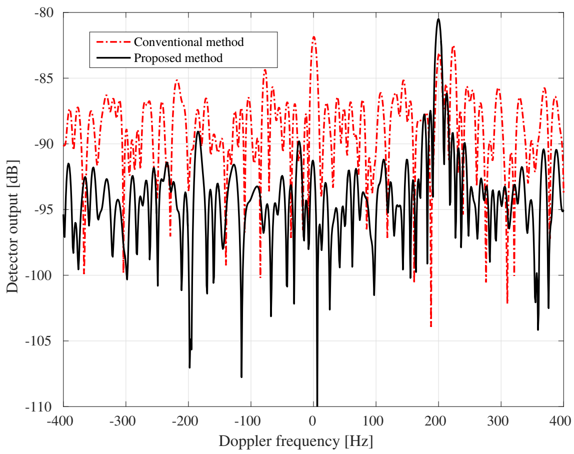

Fig. 4: Cut of the range-Doppler diagram at the target range for $N = 10^6$, $\text{DNR} = 20$ dB, $f_d = 200$ Hz, and $\text{SNR} = -30$ dB.

3.2 Quantitative evaluation

In order to obtain a clearer insight about the performance of the proposed method for signal extraction, we consider the detection probability as function of DNR and SNR values. Figure 5 presents Monte-Carlo simulation results for the detection probability as a function of the target signal-to-noise ratio (SNR) for two DNR values. Two reference signal and target signal extraction methods are employed: the conventional approach and the proposed one. The false-alarm probability was fixed at $\text{P}_{\text{FA}} = 10^{-3}$ and the length of the coherent processing interval at $N = 10^5$. Firstly, we notice that the DNR level affects the detection probability since it controls the quality of the extracted reference signal. It follows that a high DNR level implies an accurate reference signal estimation, which improves the detection probability. Secondly, we remark that the proposed signal extraction method outperforms the conventional method for both DNR values. However, for $\text{DNR} = 10$ dB, the advantage of the proposed method is reduced.

The advantage of the proposed method results from two factors: the optimum reference signal reconstruction and the efficient static clutter suppression. The optimum reference signal reconstruction reduces the mismatch between the reconstructed signal and the exact one, which decreases the noise-floor level and thus increases the detection probability. Similarly, the improved static clutter suppression allows low magnitude target detection through the suppression of the direct-path signal and multipath components. We note that the impact of the optimum reference signal reconstruction can be significant for low DNR values; for high DNR values, both reference signal extraction methods provide the same results and the advantage of the proposed method is due to the improved channel estimation method.

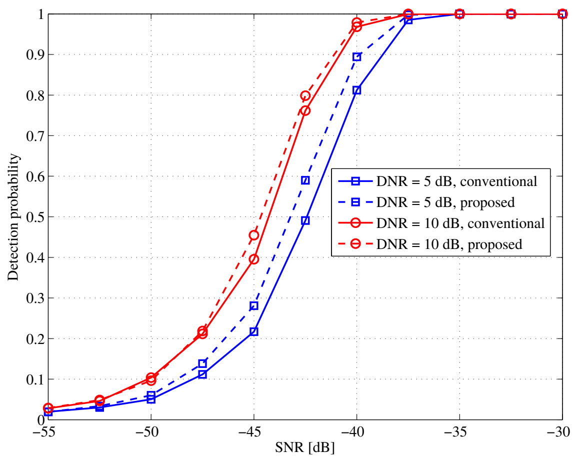

Fig. 5: Detection probability as a function of the target echo SNR for $N = 10^5$ and $\text{P}_{\text{FA}} = 10^{-3}$.

4 Real-data results

The measurement campaign was performed in Brussels at the Royal Military Academy. We considered the DVB-T transmitter which is on the top of the Finance Tower (located at 2.5 km from the receiver) as the illuminator of opportunity. The nearby Zaventem airport (BRU) provides the opportunity of having low altitude targets during landing and taking off manoeuvres. Table 1 summarizes the measurement campaign parameters. The receiver includes a commercial Yagi antenna (dedicated for the domestic reception of DVB-T broadcasting) and a USRP B100 device. The recorded signals are stored in a host computer and processed with Matlab.

Acquisition device	USRP B100
Sampling frequency	8 MHz
ADC resolution	12 bits
Carrier frequency	482 MHz
DVB-T mode	8k-mode
Guard interval (GI)	1/4
Transmitter radiated power	10 kW
Antenna gain	11 dBi
Transmitter-receiver distance	2.5 km
Integration time	0.1 s

Table 1: Parameters of the measurement campaign.

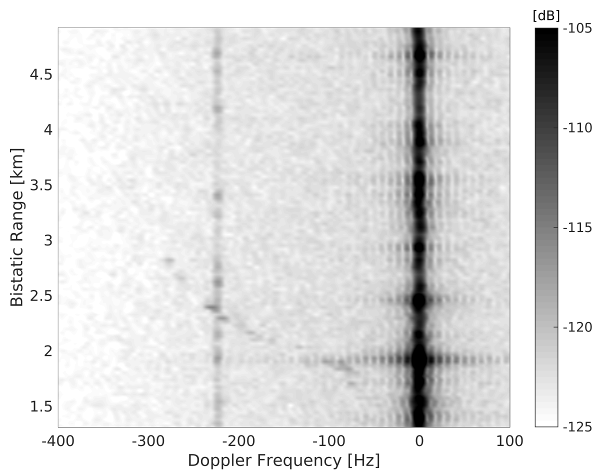

Fig. 6: Real-data results for the conventional method.

Figures 6 and 7 present the range-Doppler detection results for one data set of 10 s duration; the received signal is divided into frames of 0.1 s duration. Each frame is processed by two methods: the conventional method and the proposed one. The resulting range-Doppler diagrams for the frames are summed to provide the full track of the airplane. The used data corresponds to an airplane during the taking off manoeuvre with a bistatic range that varies between 2 km and 4 km, and a Doppler shift from 0 Hz to -350 Hz. The estimated DNR of the received signal is about 20 dB; it follows that the optimum weight employed in equation (7) tends to 1. Thus, the improvement due to the optimum reconstruction are insignificant for this data set. Therefore, the obtained results will emphasis the impact of the propagation channel accuracy on the detection performance.

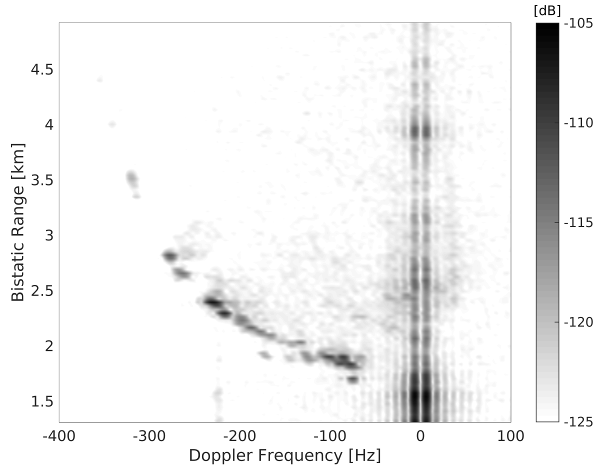

Fig. 7: Real-data results for the proposed method.

Figures 6 represents the results for the conventional method. We notice that the airplane track is not clear, the noise-floor level is relatively high, and the static clutter suppression is inefficient. The employed channel estimation method [10] provided an inaccurate channel estimate, which from one side affects the QAM detection accuracy and thus the reference signal reconstruction, and from the other side failed to suppress the static clutter. In contrast, for the results of the proposed method (figure 7), the airplane track is clear with a lower noise-floor level and more efficient static clutter suppression than the conventional method. This illustrates the impact of the proposed channel estimation method [11] that provided an accurate channel estimate, which allowed a precise QAM symbol detection and an efficient static clutter estimation. The clutter around -220Hz corresponds to ambiguities due to the pilot signal in the DVB-T signal itself. As can be seen in figure 7, the static clutter removal indeed suppresses it.

5 Conclusions

The single receiver configuration is feasible thanks to the possibility of reconstructing the transmitted signal based on the received signal which includes multipath and target echoes. Employing a single receiver to build a DVB-T based passive radar reduces the system cost and requirements. The proposed processing scheme includes an optimum reference signal reconstruction method and an improved frequency domain channel estimation method. Both lead to an improved static clutter suppression method as is shown in this paper. The system characterization through Monte-Carlo simulation has provided an insight about the system performances for different DNR values.

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