Target detection for DVB-T based passive radars using pilot subcarrier signal

Osama Mahfoudia[1,2], François Horlin[2] and Xavier Neyt[1]

[1]Dept. CISS,Royal Military Academy, Brussels, Belgium
[2]Dept. OPERA,Université Libre de Bruxelles, Brussels, Belgium

Abstract

Passive coherent location (PCL) radars employ non-cooperative transmitters for target detection. The cross-correlation (CC) detector, as an approximation of the optimum detector, is widely applied in PCL radars: it cross-correlates the reference signal and the surveillance signal. The CC detector is sensitive to signal-to-noise ratio (SNR) in the reference signal and thus a pre-processing of the reference signal is required. DVB-T based PCL radars can benefit from the possibility of reference signal reconstruction for SNR enhancement. The reconstruction process requires an SNR level that allows accurate signal demodulation. Hence, for low SNR values, signal reconstruction performance is limited. In this paper, we present a new approach that employs the subcarrier pilot signal for CC detection in DVB-T based PCL radars. We demonstrate the effectiveness of replacing the noisy reference signal with the a locally generated subcarrier pilot signal for CC detection.

1 Introduction

Passive coherent location (PCL) radars exploit radiations from illuminators of opportunity (IO), non-cooperative transmitter, to detect and track targets in an area of interest. The essential advantages of PCL radars are low cost, interception immunity, ease of deployment, and stealth aircraft detection capability [1, 2]. Several commercial transmitters for communication and broadcasting have been used as IO. For example, FM radio broadcast [3], satellite illumination [4], digital audio and video broadcast (DAB and DVB-T) [5] and Global System for Mobile communications (GSM) base stations [6, 7]. The architecture of PCL radars in the bistatic configuration consists of two receiving channels: a reference channel (RC) and a surveillance channel (SC). The RC captures the direct-path signal from the IO and the SC receives the target echoes.

The majority of existing PCL systems employs a cross-correlation (CC) detector. The CC detection approach is an approximation of the matched filter (MF) where a copy of the transmitted waveform is cross-correlated with the received echo to perform target detection. The exact transmitted waveform employed in MF is inaccessible in PCL radars since the IO is non-cooperative. PCL systems replace the exact waveform used in MF with the reference signal (received through RC). The reference signal is often corrupted by noise and interferences which decreases the coherent integration gain and thus degrades the CC detection performance[8].

PCL systems that exploit the DVB-T broadcasters can benefit from an enhancement of the signal-to-noise ratio (SNR) of the reference signal by demodulating and reconstructing the transmitted data. However, the reference signal reconstruction strategy is limited since it requires an SNR that allows accurate demodulation of the received signal [9, 10].

DVB-T broadcasters have attracted the interest of PCL researchers for their relatively wide bandwidth (8 MHz) allowing good range resolution. In addition, as a digital waveform its spectrum is independent of the signal content. Furthermore, the high radiated power of the DVB-T transmitters permits a considerable detection range. The DVB-T signal consists of two components: a stochastic component that results from the transmitted data randomness and a deterministic one due to the pilot subcarriers.

In this work, we consider a DVB-T based PCL radar and we introduce a new detection strategy. Precisely, we investigate the use of pilot carriers signal for detection as an alternative to the noisy reference signal. In order to do so, we adopt the statistical model developed in [8] and prove that using a locally generated pilot subcarrier signal outperforms employing the noisy reference signal for CC detection.

This paper is organized as follows. Section 2 reviews the DVB-T signal structure and introduces the average power ratio between the stochastic component and the deterministic one. Section 3 introduces the proposed detection strategy and provides the received signals model. In section 4, we derive closed-form expressions for false alarm and detection probabilities. In section 5, the simulation results validate the derived closed-form expression and show that the proposed detection strategy outperforms the use of the full noisy reference signal. Section 6 concludes the paper.

2 DVB-T signal overview

The DVB-T standard adopts the orthogonal frequency division multiplexing (OFDM) encoding method: a large number -K- of equally-spaced orthogonal subcarriers is employed to carry data ($K = 1705$ for $2K$-mode $K = 6816$ for $8K$-mode). The DVB-T signal is organized into symbols, a set of $L = 68$ symbols constructs a frame and a set of four frames composes one super-frame. The DVB-T symbols enclose three types of subcarriers: data subcarriers, transport parameter signalling (TPS) subcarriers and pilot subcarriers. There are two types of pilots: continual pilots (transmitted at known fixed frequencies) and scattered pilots (distributed following a periodic rule) [11]. Pilot subcarriers are transmitted at boosted power compared to data and TPS subcarriers. Figure 1 shows the DVB-T frame structure and emphasizes the patterns of pilot subcarriers.

The DVB-T standard employs a QAM modulation (16-QAM or 64-QAM) where the k^{th} QAM-symbol of value C_k is carried by one subcarrier of frequency f_k. The DVB-T signal s is the result of the summation over K subcarriers:

$$s(n) = \sum_{k=K_{min}}^{K_{max}} C_k e^{-j2\pi f_k n}, \tag{1}$$

where $K_{min} = 0$ and $K_{max} = 1704$ for $2K$-mode or $K_{max} = 6815$ for $8K$-mode.

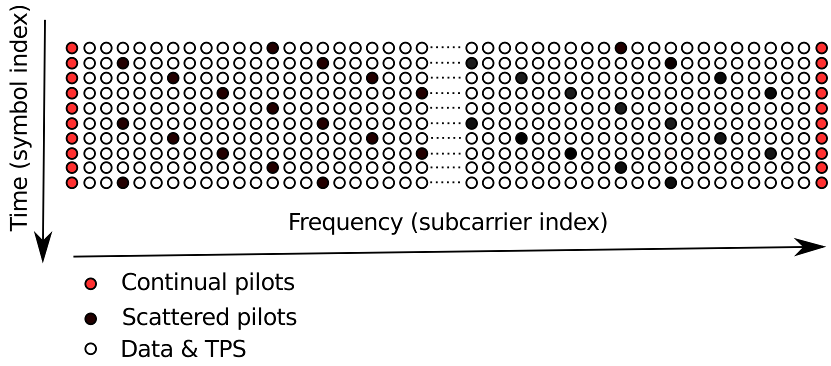

Figure 1: Pilot distribution for DVB-T signal.

The pilots are transmitted with a boosted power: an amplitude of $C_k = \pm 4/3$, thus, an average power of $E_p = 16/9$. The amplitudes of modulated data-symbols and TPS are normalized to achieve an average power of $E_d = 1$. The DVB-T signal samples $s(n)$ follow a normal distribution [12] and it can be considered as the sum of two signals $d(n)$ resulting from data subcarriers and $p(n)$ emerging from the pilot subcarriers signal:

$$s(n) = d(n) + p(n). \tag{2}$$

The data signal $d(n)$ is the sum of independent uniformly distributed QAM symbols carried by orthogonal subcarriers. Thus, the central limit theorem (CLT) leads to consider that $d(n)$ follows a normal distribution, i.e., $d(n) \sim \mathcal{CN}(0, \sigma_d^2)$. The amplitudes of pilot subcarriers ($C_k = \pm 4/3$) are generated by a Pseudo Random Binary Sequence (PRBS) generator. Hence, we consider, applying CLT, that the samples $p(n)$ follow a normal distribution, i.e., $p(n) \sim \mathcal{CN}(0, \sigma_p^2)$. Since $d(n)$ and $p(n)$ are statistically independent, we can write the variance of $s(n)$ as follows

$$\sigma_s^2 = \sigma_d^2 + \sigma_p^2. \tag{3}$$

The power ratio between the data signal and pilot signal can be calculated as follows

$$\rho = \sigma_d^2/\sigma_p^2 = (N_d E_d)/(N_p E_p), \tag{4}$$

where N_d and N_p are the number of data subcarriers and the number of pilots in one DVB-T symbol, respectively.

3 Detection strategy and signal model

In this paper, we propose a new detection approach for DVB-T based passive radars. The proposed approach takes advantage of the DVB-T signal structure that includes a deterministic part formed with pilot subcarriers. Pilot subcarrier signal can be generated knowing the broadcaster parameters such as k-mode and cyclic prefix length. Figure 2 presents the proposed approach for CC detection in noisy reference signal scenario. The received reference signal is exploited for the synchronization of the locally generated pilot subcarrier signal. The pilot signal is generated following the DVB-T standard and with blanking data and TPS subcarriers. The synchronized pilot signal replaces the noisy reference signal for CC detection.

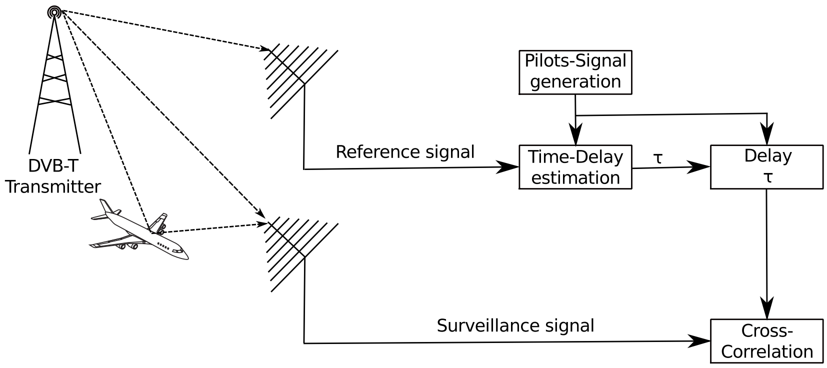

Figure 2: Passive detection employing subcarrier pilot signal.

The RC collects the reference signal formed with the direct-path signal and corrupted by noise. We note x_r the received reference signal and we consider the model in [8]:

$$x_r(n) = \beta s(n) + v(n), \tag{5}$$

where $s(n)$ is the DVB-T signal transmitted by the broadcaster, β is a scaling parameter representing the propagation losses, and $v(n)$ is i.i.d. circular complex Gaussian noise with zero mean and variance σ_v^2. We define the signal-to-noise ratio of the reference signal as

$$SNR_r = |\beta|^2 \sigma_s^2 / \sigma_v^2. \tag{6}$$

As shown in Figure 2, the surveillance signal includes direct-path signal, possible target echoes and noise contribution. We note $x_s(n)$ the received surveillance signal and we write

$$x_s(n) = \gamma s(n) + \alpha s(n-\tau) e^{j\Omega_d n} + w(n) \tag{7}$$

where γ is a scaling parameter representing the propagation losses for SC, $w(n)$ is i.i.d. circular complex Gaussian noise with zero mean and variance σ_w^2 and the target echo is characterized by τ the time-delay, Ω_d the normalized Doppler frequency and the parameter α that expresses the target reflectivity and propagation losses which is assumed to be constant during the integration time. The surveillance signal SNR is defined by

$$SNR_s = |\alpha|^2 \sigma_s^2 / \sigma_w^2. \tag{8}$$

4 Detection statistics

For the purpose of studying the performance of the proposed method, we proceeded to an analytical approach to determine the closed-form expression for the detection probability. In order to do so, the reference signal $x_r(n)$ is replaced by the time-synchronized pilot signal $p(n)$ and we formulate the binary hypothesis test as follows

$$\begin{cases} H_0 : \, x_s(n) = \gamma s(n) + w(n), \\ H_1 : \, x_s(n) = \gamma s(n) + \alpha s(n-\tau) e^{j\Omega_d n} + w(n). \end{cases} \tag{9}$$

Under both hypotheses H_0 and H_1, we calculate the statistics of the cross-correlation detector. For each range-Doppler cell, the reference signal is time-delayed and frequency shifted to match the possible target echo in the cell under test (CUT) and the detection test is given by:

$$T = \left|\bar{T}^2\right| = \left|\sum_{n=0}^{N-1} T_n\right|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda, \tag{10}$$

with λ the detection threshold and T_n is the CC detector result given by

$$T_n = x_s^*(n)p(n-\tau)exp(j\Omega_d n). \tag{11}$$

Under the alternative hypothesis H_1, we calculate the mean and the variance of T_n (to retrieve the statistics for the null hypothesis, we set $\alpha = 0$). The mean value of T_n is

$$E\{T_n\} = \alpha^* \sigma_p^2, \tag{12}$$

and its variance is

$$var\{T_n\} = |\gamma|^2 (\sigma_d^2 + \sigma_p^2)\sigma_p^2 + |\alpha|^2 (\sigma_d^2\sigma_p^2 + \phi) + \sigma_w^2\sigma_p^2, \tag{13}$$

we introduce the pilot-data power ratio (Eq. 4)

$$var\{T_n\} = |\gamma|^2 \sigma_p^4(1+\rho) + |\alpha|^2 (\rho\sigma_p^4 + \phi) + \sigma_w^2\sigma_p^2, \tag{14}$$

with

$$\phi = var\{|d(n-\tau)|^2\}. \tag{15}$$

For a coherent integration time of N samples, the CC output is represented by the quantity $\bar{T}$. It follows a normal distribution with parameters (μ_0, σ_0^2) under the null hypothesis and (μ_1, σ_1^2) under the alternative one:

$$\begin{align}
\mu_0 &= 0, \tag{16}\\
\sigma_0^2 &= N(|\gamma|^2 \sigma_p^4(1+\rho) + \sigma_w^2\sigma_p^2), \tag{17}\\
\mu_1 &= N(\alpha^*\sigma_p^2), \tag{18}\\
\sigma_1^2 &= N(|\gamma|^2 \sigma_p^4(1+\rho) + |\alpha|^2 (\rho\sigma_p^4 + \phi) + \sigma_w^2\sigma_p^2). \tag{19}
\end{align}$$

The statistic $T = |\bar{T}|^2$ under H_0 follows a central chi-squared distribution of two degrees of freedom. Thus, the false alarm probability is calculated as follows

$$P_{FA} = exp\left(-\frac{\lambda}{\sigma_0^2}\right), \tag{20}$$

the detection probability is given by the Marcum Q-function of first order:

$$P_D = Q_1\left(\sqrt{\frac{2|\mu_1|^2}{\sigma_1^2}}, \sqrt{\frac{2\sigma_0^2 ln(P_{FA}^{-1})}{\sigma_1^2}}\right). \tag{21}$$

5 Numerical results and discussion

In order to verify the validity of the detection probability expression in (21), we carried out Monte-Carlo (MC) simulations. Simulation parameters are: signal-to-noise ratio in the reference signal $SNR_r = -10dB$, coherent integration time $N = 10^5$ and false-alarm probability $P_{FA} = 10^{-2}$ (N and P_{FA} are constant for this section). Figure 3 shows the detection probability variation versus the surveillance signal SNR value for MC simulations and expression in (21). As can be seen from this figure, the analytical expression matches perfectly MC results which validates the derived closed-form expressions and the feasibility of pilot subcarrier signal detection for DVB-T based passive radars.

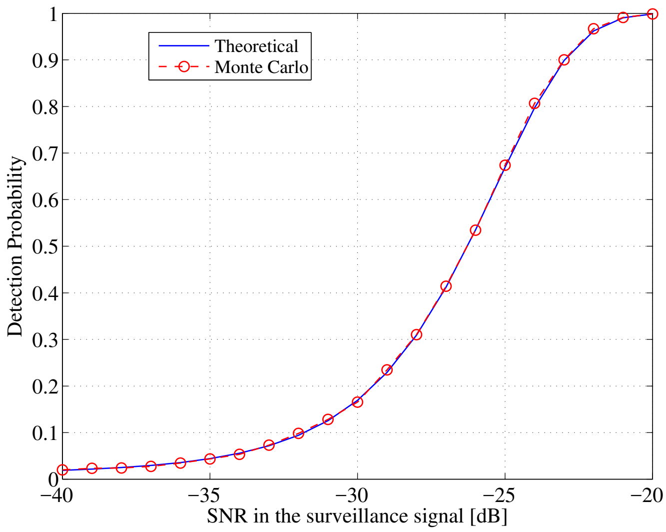

Figure 3: Validation of the detection probability expression.

After validating the feasibility of using pilot subcarrier signal as reference signal for the CC detector, the proposed method is compared to two variants of reference signal: a received reference signal with signal-to-noise ratio $SNR_r = -10dB$ and a reconstructed reference signal. Figure 4 presents the results of MC simulations for detection probability considering two variants of reference signal and the pilot subcarrier signal. For the considered scenario with $SNR_r = -10dB$, CC detection employing pilot subcarrier signal outperforms that using a noisy reference signal. Detection using reconstructed reference signal surpasses slightly that using the proposed method. This is due to the fact that the reconstructed signal contains noise-free pilot subcarriers. In addition, even if the demodulation introduces errors for $SNR_r = -10dB$, the SNR loss in the reconstructed signal is slightly higher than that due to using pilot-only signal.

To investigate the behavior of CC detection employing pilot subcarrier signal, we performed MC simulations for detection probability for a set of SNR_r values and a fixed value of $SNR_s = -30dB$. Figure 5 shows MC simulation results. As the pilot subcarrier signal is unrelated to SNR_r, the detection probability is constant for a given value of SNR_s. For the reconstructed reference signal, the detection probability converges to a non-null value for low SNR_r values. This is due to the fact that signal reconstruction for low SNR_r generates noise (caused by demodulation errors) but provides noise-free subcarrier pilots. Hence, the non-null convergence value of

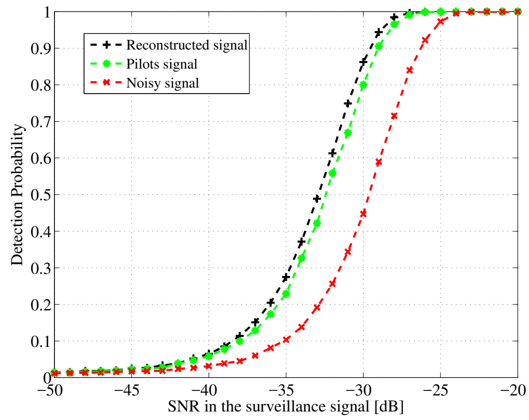

Figure 4: Detection probability for $SNR_r = -10dB$, $N = 10^5$ and $P_{FA} = 10^{-2}$.

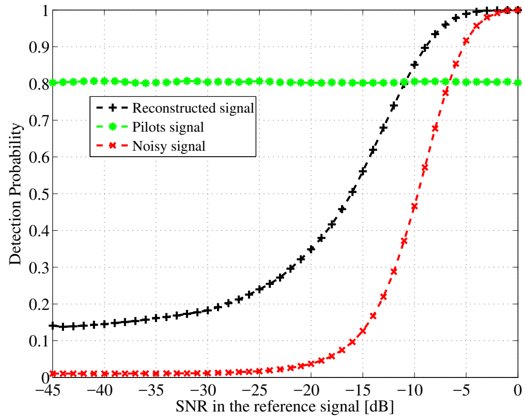

Figure 5: Detection probability for $SNR_s = -30dB$, $N = 10^5$ and $P_{FA} = 10^{-2}$.

the detection probability. For SNR_r values lower than $-11dB$, the proposed method outperforms the two other methods. Starting from $SNR_r = -11dB$, reference signal reconstruction surpasses the pilot subcarrier signal in terms of detection probability. Employing noisy reference signal outperforms the proposed method for $SNR_r = -7dB$.

The results show that the proposed method provides better performances for low SNR_r values compared to the use of noisy received reference signal. Reference signal reconstruction appears to be a solution for CC detection enhancement for noisy reference signal. However, it requires a considerable computation resources for frequency synchronization, demodulation and modulation of the received reference signal. One of the major advantages of the proposed method is that it limits the need of the received reference signal into the time-synchronization of the locally generated pilot subcarrier signal which is a large gain in computation and storage resources. Thus, we suggest employing pilot subcarrier signal for Detection in DVB-T based passive radar for low SNR_r scenario for detection probability enhancement or high SNR_r scenario for resources optimization.

6 Conclusion

In this paper, we introduced a new detection approach for DVB-T based passive radars that employs pilot subcarrier signal to replace the reference signal. We formulated closed-form expression for the detection probability and false-alarm probability and we evaluated CC detector performances analytically and using Monte-Carlo simulations for the proposed approach. We compared the proposed approach with several variants of reference signal to test its performance and limits. Based on the results it can be concluded that the proposed approach provides a solution for CC detector with noisy reference signal. In our future work, we will apply the proposed approach on real measurements.

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