Analysis of Direct Signal Recovery Scheme for DVB-T Based Passive Radars

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Abstract

In this work, a directed signal reconstruction scheme for Digital Video Broadcast Terrestrial-based passive radars is assessed. The direct signal reconstruction provides a noiseless and multipath-free estimate of the reference signal which improves the static clutter rejection (SCR) efficiency. The direct signal recovery is performed by demodulating and remodulating the base-band received signal. The recovery process induces errors leading to a mismatch between the estimated and the true copies of the reference signal. The impact of this mismatch on the SCR is studied and an expression is derived to evaluate the degradation of the SCR efficiency.

1 Introduction

Passive radars perform target detection using signals from non-cooperative sources of illumination in the environment. Target detection in passive radars requires reference and surveillance signals. On the principle, the reference signal is obtained by an antenna directed towards the transmitter and the surveillance signal is received by an antenna directed to the area of interest. In addition to the target echo, the surveillance signal contains direct path signal and multipath echoes which decreases the detection performances. To cope with this issue, undesirable echoes removal is performed using an adequate filter, this operation is named the static clutter rejection (SCR) [1].

The SCR process requires a noiseless multipath-free template of the reference signal to achieve the total undesirable echoes removal. However, the received reference signal is affected by reception noise and multipath fading which decreases the SCR efficiency. DVB-T based passive radars benefit of the reference signal reconstruction possibility; it is performed by demodulating and remodulating the received signal which increases the SCR efficiency. The process of the reference signal reconstruction and the encountered issues are detailed in the next sections.

This paper is organized as follows, section 2 presents the system model and details the demodulation/remodulation task. Section 3 treats the SCR operation and proposes an expression for SCR efficiency degradation. In the section 4, the simulation scheme is presented and simulation results are given to validate the derived expression. Section 5 concludes the paper.

2 DVB-T direct signal recovery

2.1 System model

Considering the DVB-T based passive radar presented in figure 1, we denote the received reference signal by $x_{ref}(n)$ and the surveillance signal by $x_s(n)$ [2]. The received reference signal $x_{ref}(n)$ is given by

$$x_{ref}(n) = \alpha_0 x(n-\tau_0) + \sum_{i=1}^{K-1} \alpha_i x(n-\tau_i) + \xi_r(n), \tag{1}$$

where, $x(n)$ is the transmitted signal after undergoing the effects of a frequency-selective channel H, α_0 is the complex gain of the direct path signal, the coefficient α_i represents the complex gain of the i^{th} static scatterer, τ_i is the delay corresponding to the i^{th} range-cell, K is the number of range-cells and $\xi_r(n)$ is the additive white Gaussian noise (AWGN) for the reference channel.

The surveillance signal $x_s(n)$ includes target returns in the form of delayed, attenuated and Doppler-shifted versions of the transmitted signal. In addition, it contains static clutter, noise and possible direct path signals. The surveillance signal model is

$$x_s(n) = \sum_{i=1}^{N} \beta_i x(n-\tau_i) + \sum_{l=1}^{M} \gamma_l x(n-\tau_l) exp(j\omega_l n) + \xi_s(n), \tag{2}$$

with β_i represents the scattering coefficient at the i^{th} static scatterer, N is the number of the considered range-cells, γ_l is the reflection coefficient for the l^{th} moving target, M is the moving targets number, ω_l the shift caused by the Doppler effect for the l^{th} moving target and $\xi_s(n)$ is the AWGN for the surveillance channel. If we note $z(n)$ the sum of the noise and the target echoes signal in the surveillance signal, we may write

$$x_s(n) = \sum_{i=1}^{N} \beta_i x(n-\tau_i) + z(n) \quad with \quad z(n) = \sum_{l=1}^{M} \gamma_l x(n-\tau_l) exp(j\omega_l n) + \xi_s(n). \tag{3}$$

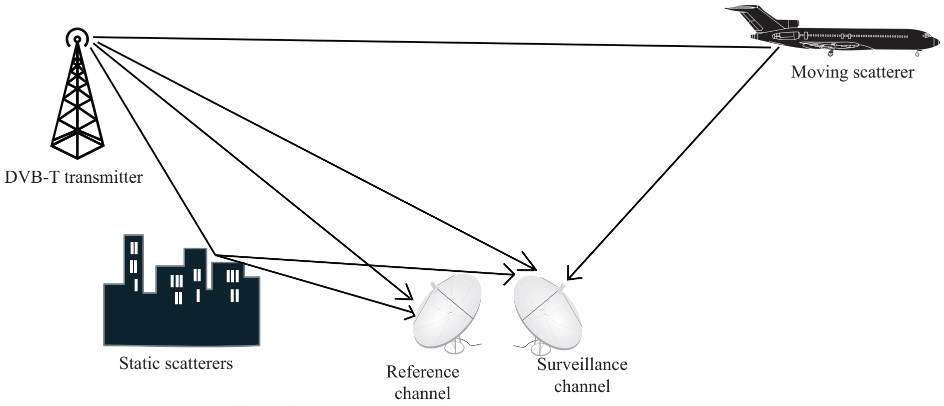

Figure 1: Configuration of a DVB-T based passive radar.

2.2 Synchronization

The demodulation of the base-band received reference signal is preceded by the transmitter-receiver synchronization. The synchronization is achieved by the estimation of the following parameters: the coarse time delay, the fractional frequency offset (FFO), the integer time delay and the integer frequency offset (IFO).

- The coarse time synchronization aligns the FFT window with the received DVB-T symbols by estimating the beginning of the DVB-T symbol.
- The integer time synchronization estimates the order of each DVB-T symbol.

- The frequency synchronization compensates the transmitter-receiver frequency offset, it consists of two steps: FFO and IFO compensations.

Coarse time and FFO estimation exploits the cyclic nature of DVB-T symbols; a cyclic prefix (called also the guard interval) is inserted at the beginning of each DVB-T symbol. The cyclic prefix is formed by the last N_g samples of the DVB-T symbol, with N_g the length of the guard interval. In the present work, an autocorrelation-based method is applied for coarse time and FFO estimation [3].

The subcarrier pilots (continuous pilots and the scattered pilots) are one type of the transmitted subcarriers, they are modulated by a known Pseudo-Random Binary Sequence (PRBS) with a boosted amplitudes compared to other subcarriers ($\pm 4/3$). In addition to the use for synchronization, subcarriers pilots are used for channel estimation and equalization [7].

After coarse time correction and FFO compensation, a pilot-aided method is applied for IFO and integer time estimations [4]. IFO compensation is required to align each subcarrier with the corresponding FFT bin and integer time synchronization estimates the scattered pilots pattern for the first symbol. The received reference signal synchronization is achieved by the frequency offset compensation (FFO and IFO) of the time synchronized signal (after considering the coarse time delay).

2.3 Demodulation

The demodulation of the synchronized signal is performed by removing the cyclic prefix from each DVB-T symbol and applying an FFT on the useful samples. The result for each DVB-T symbol is a constellation of coded symbols (64-QAM in our case). The received constellation is affected by propagation channel effect, noise and synchronization imperfections. The k^{th} coded symbol($k_{max} = 1705$ for the 2k-mode and $k_{max} = 6817$ for the 8k-mode) from the l^{th} DVB-T symbol is given by

$$X_{ref}(l,k) = H(l,k)X_t(l,k) + W(l,k), \tag{4}$$

where $H(l,k)$ is the channel weight, $X_t(l,k)$ is the exact transmitted QAM symbol and $W(l,k)$ includes the AWGN and the multipath.

The transmitted coded symbols for subcarrier pilots are known, which allows the channel response estimation over pilot subcarriers bins. Then, the resulting estimate is interpolated to obtain the channel response for the remaining subcarriers. In this work, the least-squares (LS) estimator is used for channel estimation [6]. The LS estimator ignores the effect of the noise $W(l,k)$ and gives the channel estimate for subcarrier pilots by

$$\hat{\boldsymbol{H}}_{\boldsymbol{p}}(l) = \boldsymbol{X}_{\boldsymbol{t,p}}^{\boldsymbol{-1}}(l)\boldsymbol{X}_{\boldsymbol{ref,p}}(l), \tag{5}$$

with $\boldsymbol{X}_{\boldsymbol{t,p}}$ is a matrix with the known transmitted pilot amplitudes on its diagonal ($\pm 4/3$) and $\boldsymbol{X}_{\boldsymbol{ref,p}}$ represents the array of the received symbols $X_{ref}(l,k)$ at the pilot subcarriers, i.e., $k \in P$ with P indicates the pilot subcarriers positions.

The channel response for the l^{th} DVB-T symbol, $\hat{\boldsymbol{H}}(l)$, is obtained by the interpolation of the pilots response $\hat{\boldsymbol{H}}_{\boldsymbol{p}}(l)$. After the channel estimation, the equalization of the received symbols is performed by

$$X_{ref,eq}(l,k) = X_{ref}(l,k)/\hat{H}(l,k). \tag{6}$$

The transmitted symbols, $\hat{X}_t(l,k)$, are estimated by approximating the equalized symbols, $X_{ref,eq}(l,k)$, to the nearest QAM symbol. The LS estimator is characterized by its simplicity and its sensitivity to noise. One can reduce the noise effect by averaging the channel response for pilot subcarriers $\boldsymbol{X}_{\boldsymbol{ref,p}}(l)$ over L DVB-T symbols.

2.4 Remodulation

It has been proven that remodulating the recovered QAM symbols without the reintroduction of the channel effects and the frequency offsets creates a mismatch between the reconstructed and the true reference signals [2]. Therefore, The channel effect is reintroduced as follows

$$\hat{X}(l,k) = \hat{H}(l,k)\hat{X}_t(l,k). \tag{7}$$

The channel estimate $\hat{H}$ is affected by errors caused by zero-forcing (LS estimator), interpolation of the subcarrier pilots channel response and synchronization imperfections. If we note the estimation error e, the channel estimate is

$$\hat{H}(l,k) = H(l,k) + e(l,k). \tag{8}$$

We define the normalized estimation error variance $\sigma^2_{\Delta H}$ as

$$\sigma^2_{\Delta H} = \sigma^2_e/\sigma^2_H = SNR_H^{-1}, \tag{9}$$

where σ^2_H is the channel variance, σ^2_e represents the channel estimation error variance and SNR_H is the signal-to-noise ratio for the channel estimate. We use (8) in (7), we get

$$\hat{X}(l,k) = H(l,k)\hat{X}_t(l,k) + V(l,k) \quad with \quad V(l,k) = e(l,k)\hat{X}_t(l,k). \tag{10}$$

The SNR for the symbols $\hat{X}$ is

$$SNR_{\hat{X}} = (\sigma^2_H\sigma^2_X)/(\sigma^2_e\sigma^2_X) = \sigma^2_H/\sigma^2_e = (\sigma^2_{\Delta H})^{-1}. \tag{11}$$

The noiseless multipath-free estimate of the reference signal, $\hat{x}(n)$, is obtained by applying an IFFT on the symbols $\hat{X}(l,k)$ [7]. The remodulation result is given by

$$\hat{x}(n) = x(n) + v(n), \tag{12}$$

with $x(n)$ is the true multipath-free estimate of the reference signal and $v(n)$ represents the estimation error.

If we consider $v(n)$ (with variance σ^2_v) as a noise uncorrelated with $x(n)$ (with variance σ^2_x), the SNR for the estimated signal $\hat{x}$ is determined by

$$SNR_{\hat{x}} = \sigma^2_x/\sigma^2_v. \tag{13}$$

Since $\hat{x}$ is the time-domain version of $\hat{X}$, we may write $SNR_{\hat{x}} = SNR_{\hat{X}}$. Using the SNR equality with (11) leads to

$$\sigma^2_{\Delta H} = SNR_{\hat{x}}^{-1}. \tag{14}$$

If we consider a channel response averaging along L DVB-T symbols, the channel estimate is

$$\hat{H}_{av}(k) = \frac{1}{L}\sum_{l=1}^{L}(H(l,k) + e(l,k)), \tag{15}$$

the averaging process reduces the estimation error variance by a factor of L, we may write the normalized estimation error in (9) as

$$\sigma^2_{\Delta \hat{H}_{av}} = \sigma^2_{\Delta H}/L. \tag{16}$$

Thus, equation (14) becomes

$$SNR_{\hat{x}} = L\,(\sigma^2_{\Delta H})^{-1}, \tag{17}$$

where, $SNR_{\hat{x}}$ is the SNR of the estimated reference signal, $\sigma^2_{\Delta H}$ is normalized estimation error variance and L is the channel averaging length.

3 Static clutter rejection

The static clutter rejection removes zero-Doppler echoes form the received signal, which allows the detection of targets with weak echoes. The SCR efficiency is evaluated with the residual power P_r, it is the power of the post-SCR signal [5]. For a perfect SCR, P_r represents the power of targets echoes and surveillance channel noise. Poor SCR leads to a P_r with residual static clutter. The SCR is performed using an adequate filter which requires a reference signal to operate. One of the SCR efficiency degradation factors is a noisy reference signal. The recovery of the reference signal provides a noiseless multipath free reference signal increasing the SCR efficiency. In practice, even the recovered signal is affected by channel estimation errors among other factors. In this section, a theoretical approach is applied to retrieve an expression relating the channel estimation errors to the post-SCR signal power. We consider a finite impulse response (FIR) Wiener filter [8] for the SCR, the filter weights, $\boldsymbol{w}$, are defined by

$$\boldsymbol{w} = \boldsymbol{R}_{\hat{\boldsymbol{x}},\hat{\boldsymbol{x}}}^{-1} \boldsymbol{r}_{\hat{\boldsymbol{x}},\boldsymbol{x_s}}, \tag{18}$$

with $\boldsymbol{R}_{\hat{\boldsymbol{x}},\hat{\boldsymbol{x}}}$ is the autocorrelation matrix of $\hat{x}$ and $\boldsymbol{r}_{\hat{\boldsymbol{x}},\boldsymbol{x_s}}$ is the cross-correlation of $\hat{x}$ and x_s. The values of the previous quantities can be approximated as follows

$$\begin{cases} \boldsymbol{R}_{\hat{\boldsymbol{x}},\hat{\boldsymbol{x}}} = diag(\sigma_x^2 + \sigma_v^2) \\ \boldsymbol{r}_{\hat{\boldsymbol{x}},\boldsymbol{x_s}}(i) = \beta_i \sigma_x^2 \end{cases} \tag{19}$$

Hence, using (19) in (18) yields to relate Wiener filter weights to the exact multipath coefficients;

$$w_i = \beta_i / (1 + SNR_{\hat{x}}^{-1}). \tag{20}$$

The SCR output signal is denoted by $y(n)$, it is given by subtracting the Wiener filter output $\hat{x}_s(n)$ from the surveillance signal $x_s(n)$;

$$y(n) = x_s(n) - \hat{x}_s(n) \quad with \quad \hat{x}_s(n) = \sum_{i=1}^{N} w_i \hat{x}(n - \tau_i). \tag{21}$$

After replacing $x_s(n)$ and $\hat{x}_s(n)$ by their values, we get

$$y(n) = \sum_{i=1}^{N} \beta_i x(n - \tau_i) + z(n) - \sum_{i=1}^{N} w_i \hat{x}(n - \tau_i), \tag{22}$$

where $z(n)$ includes targets echoes and surveillance channel noise; it is the residual signal after a perfect SCR (equation 3). It follows that

$$y(n) = \sum_{i=1}^{N} (\beta_i - w_i) x(n - \tau_i) + z(n) - \sum_{i=1}^{N} w_i v(n - \tau_i). \tag{23}$$

The difference $(\beta_i - w_i)$ can be defined from (20) as $\beta_i - w_i = w_i SNR_{\hat{x}}^{-1}$, this yields to

$$y(n) = SNR_{\hat{x}}^{-1} \sum_{i=1}^{N} w_i x(n - \tau_i) + z(n) - \sum_{i=1}^{N} w_i v(n - \tau_i). \tag{24}$$

The post-SCR signal power can be approximated by

$$P_y = SNR_{\hat{x}}^{-2} \sigma_x^2 \sum_{i=1}^{N} \mid w_i \mid^2 + P_z + \sigma_v^2 \sum_{i=1}^{N} \mid w_i \mid^2 . \tag{25}$$

Therefore,

$$P_y = (SNR_{\hat{x}}^{-2}\sigma_x^2 + \sigma_v^2)\sum_{i=1}^{N} \mid w_i \mid^2 + P_z, \tag{26}$$

we get

$$P_y = \sigma_x^2(SNR_{\hat{x}}^{-2} + SNR_{\hat{x}}^{-1})\sum_{i=1}^{N} \mid w_i \mid^2 + P_z. \tag{27}$$

We denote the static clutter power by P_{sc}

$$P_{sc} = \sigma_x^2 \sum_{i=1}^{N} \mid \beta_i \mid^2 . \tag{28}$$

To represent P_y as a function of P_{sc} and $SNR_{\hat{x}}$, the value of w_i in (27) is replaced by (20):

$$P_y = (SNR_{\hat{x}}^{-2} + SNR_{\hat{x}}^{-1})(1 + SNR_{\hat{x}}^{-1})^{-2}\sigma_x^2 \sum_{i=1}^{N} \mid \beta_i \mid^2 + P_z. \tag{29}$$

The post-SCR signal power is summarized by writing

$$P_y = P_z + P_{sc}/(1 + SNR_{\hat{x}}). \tag{30}$$

Finally, we replace (17) in (30)

$$P_y = P_z + P_{sc}/(1 + L(\sigma_{\Delta H}^2)^{-1}). \tag{31}$$

Thus, equation (31) gives an estimate of the residual static clutter power. It proves the impact of the channel estimation error on the SCR performances; the SCR efficiency decreases significantly for high channel estimation error.

4 Simulation

4.1 Simulation scheme

Figure 2 illustrates the simulation scheme. The reference signal is formed by a strong line of sight signal, multipath components and additive white Gaussian noise (AWGN). The surveillance signal comprises multipath returns, moving targets returns and AWGN. In the reference signal reconstruction stage, an estimate of the propagation channel is used: $\hat{H} = H + e$ with H denotes the exact channel and e represents the estimation error. The SCR stage is performed using a FIR Wiener filter.

To investigate the impact of the channel estimation error e on the SCR performances, the residual power for different values of e is calculated. The channel estimation error is modeled by a zero-mean complex Gaussian noise with variance σ_e^2. The channel H is considered time-unvarying during the observation time.

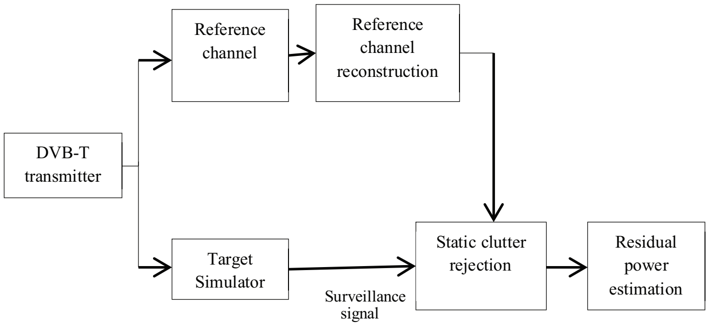

Figure 2: Simulation scheme.

4.2 Simulation results

Figure 3 is a comparison of the simulation results and the results from the model 31 for the case $L = 1$ (no channel averaging). We notice that the model fits perfectly the simulation. The results show the sensitivity of the SCR performances for channel estimation error. For large channel estimation errors (≥ 10 dB) the SCR effect vanishes.

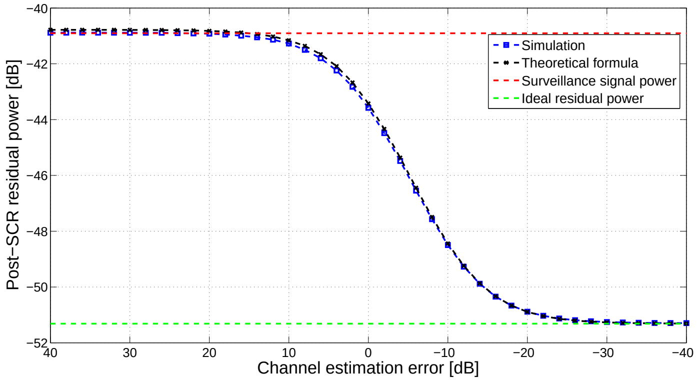

Figure 3: Validation of the theoretical formula.

To reduce the impact of the channel estimation errors, we perform an averaging of the subcarrier pilots response for L DVB-T symbols. Figure 4 shows the impact of channel response averaging ($L = 100$) on the SCR efficiency; a considerable improvement can be noticed.

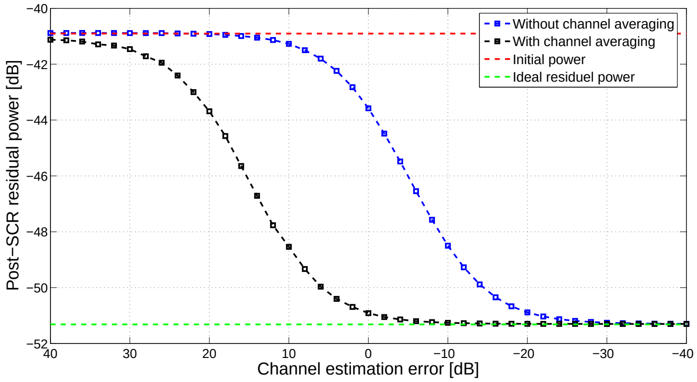

Figure 4: Averaging channel response impact on SCR efficiency.

5 Conclusion

In this paper, a reference signal recovery method is analyzed. The methods applied on the synchronization, demodulation and remodulation are tested on real-world data proving their efficiency. A theoretical analysis led to the expression for the post-SCR signal power. Simulation results proved that the channel estimation errors effect can be reduced by an averaging of the pilots channel response.

References

[1] D. Poullin, "Passive detection using digital broadcasters (DAB, DVB) with COFDM modulation," Radar, Sonar and Navigation, IEE Proceedings, vol 152 .number 3 pages 143-152, June 2005.

[2] J.E. Palmer, H.A. Harms, S.J. Searle and L.M. Davis, "DVB-T Passive Radar Signal Processing," Signal Processing, IEEE Transactions,vol. 61, pages 2116-2126, April 2013.

[3] S.H. Chen et al., "Mode detection, synchronization, and channel estimation for DVB-T OFDM receiver," Global Telecommunications Conference,GLOBECOM '03. IEEE, vol. 5, pages 2416-2420, December 2003.

[4] Peng Liu, Bing-bing Li, Zhao-yang Lu and Feng-kui Gong, "A new frequency synchronization scheme for OFDM," Consumer Electronics, IEEE Transactions on, Vol. 50, pages 823-828, August 2004.

[5] M.K. Baczyk and M. Malanowski, "Decoding and reconstruction of reference DVB-T signal in passive radar systems," 11^{th} International Radar Symposium(IRS), pages 1-4, June 2010.

[6] A.M. Khan V. Jeotiet and M.A. Zakariya, "Improved pilot-based LS and MMSE channel estimation using DFT for DVB-T OFDM systems," Wireless Technology and Applications, 2013 IEEE Symposium on, pages 120-124, September 2013.

[7] European Telecommunications Standards Institute (ETSI), "Digital Video Broadcasting (DVB); Framing Structure, Channel Coding and Modulation for Digital Terrestrial Television," June 2004.

[8] S. Haykin, "Adaptive Filter Theory - Third Edition," Prentice Hall Inc., pages 194-235, 1996.