INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2011, VOL. 57, NO. 1, PP. 43–48
Manuscript received January 19, 2011; revised February 2011. DOI: 10.2478/v10177-011-0006-y

Reconstruction of the Reference Signal in DVB-T-based Passive Radar

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***Abstract*—In the paper the problem of decoding of digital television signal and its reconstruction for the purpose of using it in passive radar is presented. The main focus is the reconstruction of the signal using a general purpose receiver, not dedicated to digital television signal reception. The performance of the proposed method is verified on simulated and real-life signals.**

***Keywords*—Passive radar, passive coherent location, DVB-T.**

I. Introduction

PASSIVE radar, known also as passive coherent location (PCL), is a radar system which uses non-cooperative transmitters as source of illumination of the observed object, and therefore, does not need its own transmitter [1]. It makes such system relatively cheap and difficult to detect, which has led to dynamic growth of this branch of radar technology.

A family of PCL radars exploiting commercial FM radio called PaRaDe (Passive Radar Demonstrator) has been developed at Warsaw University of Technology (WUT) [2]. Those systems were successfully tested in stationary configuration, as well as on moving platforms (car and aircraft). The current research involves extension of the number of types of transmissions used by the system. One of the most popular sources of illumination, apart from FM radio, is digital video broadcasting-terrestrial (DVB-T). It provides good area coverage and high bandwidth, resulting in good range resolution. Additional advantage is that, contrary to FM radio, DVB-T is a digital transmission standard, which is more robust to the external noise.

Target detection in passive radar is based on calculation of a crossambiguity function of a reference and surveillance signals. The surveillance signal is simply a signal received by an antenna directed towards an area of interest. The reference signal is, in theory, a perfect copy of the transmitted signal. Usually, we do not have a direct access to the transmitted signal at the receiver site, therefore, the reference signal has to be obtained remotely. One way of achieving that is by pointing a directional antenna towards the transmitter and receiving the reference signal directly from the transmitter. The main disadvantage of this approach is that the received signal is noisy, which can lead to deterioration of the detection performance. An alternative approach is to recreate the transmitted signal by decoding the received noisy signal to the bit level, and coding it again, thus obtaining a noiseless, and hopefully perfect, copy of the transmitted signal.

The latter approach is the focus of this paper. We present an algorithm for decoding of the DVB-T signal recorded with universal COTS receiver. The performance of the algorithm is assessed from the point of view of clutter removal and crossambiguity function calculation. This paper is extension of work presented in [3].

This work was partially supported by the European Union in the framework of European Social Fund through the Warsaw University of Technology Development Programme.

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II. Signal Processing for Passive Radar

Target detection in passive radar involves processing of signals with very high dynamic range. It is a result of the fact that the echoes of flying targets are much weaker than the direct signal originating from the transmitter and reflections from stationary targets. In addition, the detection of weaker signals is more difficult due to the correlation sidelobes originating from the strong peaks. Those sidelobes can completely mask weak target echoes. For this reason, usually some method for removing unwanted signal components (clutter) is employed. Most often, an adaptive filter is used as a clutter canceler [4]. It removes the target echoes with zero Doppler shift (direct signal and reflections from stationary targets), and thus, the strong echoes do not mask weak target echoes any longer.

After the application of the clutter canceler, the crossambiguity function is calculated according to the following expression [5]:

$$\chi(R,V) = \int_{-T/2}^{T/2} x_r(t) x_s^*\left(t - \frac{R}{c}\right) \exp\left(j2\pi \frac{V}{\lambda} t\right) dt, \quad (1)$$

where $x_r(t)$ is the reference signal, $x_s(t)$ is the surveillance signal (after the application of the clutter canceler), R is the bistatic range (proportional to the time difference of arrival between the direct and reflected paths), V is the bistatic velocity (time derivative of the bistatic range), c is the speed of light, T is the integration time and λ is the wavelength.

After calculation of the crossambiguity the detection is performed by comparing $|\chi(R,V)|$ with a threshold. If the value of $|\chi(R,V)|$ crosses the threshold, a detection is declared. The position of the echo on the bistatic range – bistatic velocity plane indicates the parameters of the echo.

The locus of points with constant bistatic range forms an ellipsoid with the transmitter and receiver at the foci positions. The position of the target in Cartesian coordinates can be found by calculating intersection point of multiple bistatic ellipsoids corresponding to different transmitters or receivers. Another approach is to estimate the direction of arrival of the echo, and calculate intersection point of the bistatic ellipsoid and the direction of arrival.

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In the processing scheme described above, the reference signal is used in clutter canceler and crossambiguity calculation. The quality of the reference signal directly affects the performance of passive radar. As mentioned above, the reference signal can be obtained using a directional antenna or it can be reconstructed from the noisy copy of the reference signal by decoding and coding it again. In this paper we focus on the reconstruction of the reference signal recorded with a universal receiver. Because the receiver is not dedicated to the DVB-T standard, the sampling frequency is not matched to the one used in the standard. Moreover, the mismatch between the carrier frequency in the transmitter and the receiver, so called carrier frequency offset (CFO), has to be corrected.

III. DVB-T Standard

A. Introduction

The main feature of the physical layer of the DVB-T standard is application of the OFDM (orthogonal frequency-division multiplexing) modulation [6]. Furthermore, certain mechanisms for digital protection derived from the digital transmission techniques are used in order to increase the reliability and the transmission quality.

Two modes are used in DVB-T standard: 2k (with 2048 subcarries) and 8k (with 8192 subcarries). In both cases the bandwidth of the signal is the same. The bandwidth can be 6, 7 or 8 MHz, depending on the region. In the 2k mode the spacing between the subcarriers is larger, therefore, this version is more immune to the Doppler effect and more suitable for mobile systems. The subcarriers at the edges of the bandwidth are not used (they are set to zero) to minimize the interference between adjacent frequency channels. In Poland 8k mode with 8 MHz bandwidth is used, and this will be assumed in the rest of the paper.

The standard defines only how input data and all operations applied to them should be organized. The implementation of the transmitter and the receiver is not a part of the standard, and it depends on the producer of the equipment.

Input bit stream is constructed from packages containing 188 bytes. The symbols form the input data. They are grouped in 68-element packages called frames. Frames are grouped in 4-element superframes.

A simplistic generation scheme of the DVB-T signal is shown in Fig. 1. It is composed of the following blocks:

- coding of the DVB-T signal;
- QAM mapping;
- pilots adding;
- signal formatting and guard interval (cyclic prefix) insertion.

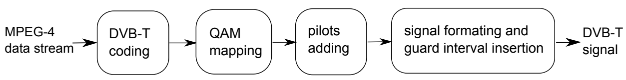

Fig. 1. DVB-T signal generation scheme.

B. OFDM Modulation

In a system with a single carrier frequency the duration of the data symbol has to be short to guarantee required bit rate. They are often shorter than channel impulse response, which leads to intersymbol interference (ISI). On the other hand, in OFDM symbols are transmitted on multiple carriers simultaneously. As a result the symbol duration is longer, but at the same time the bit rate is high. Nevertheless, because the symbol duration is finite, its spectrum has Sinc (sin(x)/x) shape. To overcome this problem, the subcarriers frequencies and the symbol length are matched so that the zeroes of the Sinc function coincide with the other subracarriers.

To eliminate the ISI, a guard interval is used. The guard interval, also called the cyclic prefix (CP), is created by copying the end of the symbol in the time domain in front of the symbol. The length of the CP depends on the expected length of the channel impulse response. Thanks to this approach the ISI is eliminated. The symbol start can be found by cross-correlating signals from two windows spaced according to the CP parameters. When the windows are aligned with the symbol start a correlation peak appears, since the contents of both windows is the same.

The main problem that the engineers designing DVB-T receivers have to solve is to ensure orthogonality between the carriers. In order to achieve this, it is essential to obtain the same sampling and carrier frequency that was used in the transmitter. Since the clocks in both the transmitter and the receiver are not perfectly synchronized and not perfectly stable, continuous synchronization is needed. Mismatch causes a loss of carriers orthogonality and sometimes also a loss of the possibility of correct reception of the signal and decoding of the data stream.

C. Signal Model

The transmitted signal is described by the following expression [6]:

$$x(t) = Re\left\{ e^{j2\pi f_c t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=K_{min}}^{K_{max}} c_{m,l,k} \cdot \Psi_{m,l,k}(t) \right\} \quad (2)$$

where:

$$\Psi_{m,l,k}(t) = \begin{cases} e^{j2\pi \frac{k'}{T_u}(t-\Delta-l\cdot T_s-68\cdot m\cdot T_s)}, \text{when} \ldots \\ \ldots (l+68\cdot m)\cdot T_s \le t \le (l+68\cdot m+1)\cdot T_s, \\ 0,\ \text{otherwise.} \end{cases} \quad (3)$$

where:

- k - carrier number;
- l - OFDM symbol number;
- m - transmission frame number;
- K - number of transmitted carriers;
- T_s - symbol duration;
- T_u - inverse of the carrier spacing;
- Δ - duration of the guard interval;
- f_c - central frequency of the RF signal;
- k' - carrier index relative to the center frequency, $k' = k - (K_{max} + K_{min})/2$;

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- $c_{m,l,k}$ - complex symbol for carrier k of the data symbol no. l in frame number m.

Our task is to estimate the complex symbols $c_{m,l,k}$ from the noisy received signal, and recreate an ideal copy of the transmitted signal $x(t)$ (more specifically, its baseband representation).

IV. Reference Signal Reconstruction

A. Symbol Length Calculation

During the reception of the OFDM signal it is important to know the length of the symbol length expressed in samples. If the sampling frequency in the transmitter and the receiver are equal, the length of the signal in samples is an integer and the reception consists in transforming the signal from the time into the frequency domain using FFT (Fast Fourier Transform).

In the case considered here, the ADC (analog-to-digital converter) in the receiver has a fixed set of sampling frequencies, which do not match the sampling frequency defined by the DVB-T standard (64/7 MHz $\approx$ 9.14 MHz). For this reason, the symbol length is not integer and the spectrum calculated using FFT will be distorted since the transform points do not correspond to the proper subcarriers positions. One of the possible solutions is to perform resampling of the signal by interpolation and decimation. However, when the signal occupies almost the whole bandwidth, the resampling introduces large distortions which may prevent further processing.

In order to overcome this problem, another approach was used in this paper. Instead of FFT, the chirp-Z (CZT) transform was used to demodulate the OFDM symbols. Its proper functioning requires knowledge of the exact length of the symbol. The autocorrelation function is used to estimate exactly the symbol length.

Since the guard interval is the copy of the end of each symbol which is placed at the beginning of the symbol, signal correlates with itself at the point corresponding to the length of the symbol expressed in samples. This value is not known a priori. However, if the clock frequency of the transmitter and the receiver is known, the range in which the symbol length is located can be estimated by the equation:

$$\hat{T}_u \in (L \cdot \frac{f_{s,r}}{f_{s,t}} - n; L \cdot \frac{f_{s,r}}{f_{s,t}} + n), \tag{4}$$

where:

- $\hat{T}_u$ - estimated symbol length without guard interval;
- L - number of subcarriers in the received signal;
- $f_{s,r}$ - receiver sampling frequency;
- $f_{s,t}$ - transmitter sampling frequency;
- n - a constant greater than 0.

The value n determines the range of delays for which the autocorrelation has to be calculated. The wider the interval, the greater the likelihood that the sought symbol length value is in this range. The experiments show that n of a few is enough. In Fig. 2 the autocorrelation function of a real-life signal is shown. The shape of the autocorrelation function is similar to the Sinc function. This corresponds to a rectangular spectrum shape, which can be observed for the DVB-T signal.

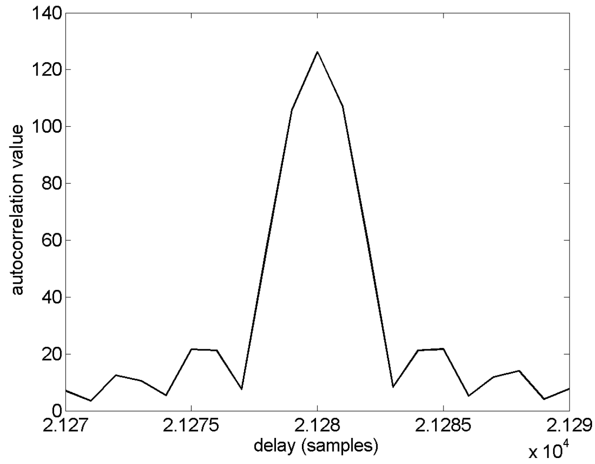

Fig. 2. Autocorrelation function of a real-life signal.

The maximum of the autocorrelation function corresponds to the length of the symbol. In order to exactly estimate the position of the maximum, the correlation peak can be approximated by a parabola and the position of the parabola maximum can be taken as an estimate of the symbol length. That value is used in further signal processing, as well as for signal reconstruction.

The autocorrelation function is also used for correction of the mismatch in the carrier frequency (carrier frequency offset – CFO). The phase of the autocorrelation function corresponding to the maximum is the estimate of the CFO (normalized to the subcarrier spacing). Using this phase the CFO can be corrected by appropriate signal modulation.

B. Symbol Spectrum Evaluation

The next step in the reception of DVB-T signal is OFDM symbol decoding. It is based on calculating the signal spectrum using an operation opposite to the operation applied in the transmitter. Usually it is realized with the FFT. However, as mentioned before, due to the mismatch between the sampling frequencies of the transmitter and the receiver, calculating FFT would result in sampling of the spectrum in incorrect frequency positions. Fig. 3 shows an example of the spectrum of the signal calculated using FFT. The rectangular shape of the OFDM spectrum is visible, however, the spectrum values are spread randomly due to the fact that they do not correspond to the constellation points on the subcarriers.

In the paper the method based on CZT is used for decoding of the OFDM symbol. The CZT enables us to calculate the spectrum value for arbitrary frequency points. In the considered case, using CZT it is possible to calculate the correct spectrum values if the real length of symbol is known. Knowing the real length of the symbol it is possible to calculate the position of the first subcarrier and the difference between two successive subcarriers on the basis of the following dependency:

$$W = e^{-j2\pi \frac{1}{T_u}} \tag{5}$$

$$A = e^{-j\pi \frac{N}{T_u}}, \tag{6}$$

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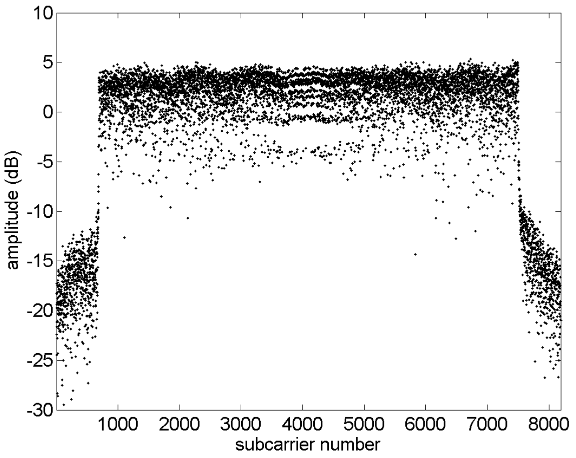

Fig. 3. Symbol spectrum calculated using FFT algorithm.

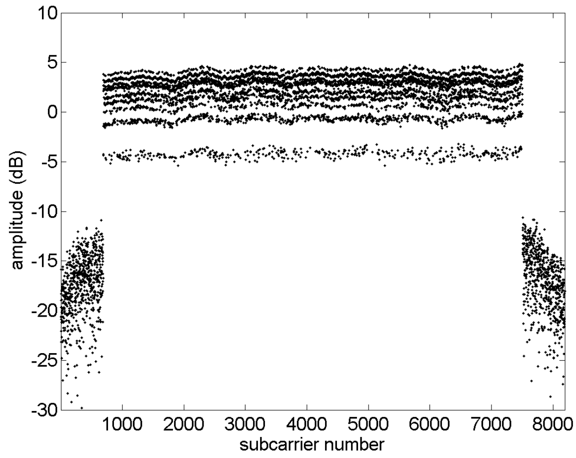

Fig. 4. Symbol spectrum calculated using CTZ transform.

where:

- A - position of the first subcarrier;
- W - difference between two successive subcarriers;
- N - number of subcarriers in the symbol;
- $\hat{T}_u$ - estimated symbol length without the guard interval.

The CZT is calculated by substituting the values of W and A defined by (5) and (6) into the formula:

$$X_i(k) = W^{k^2} \sum_{\theta=0}^{\lfloor \hat{T}_u \rfloor - 1} \{r_{s,i}(\theta) A^{\theta} W^{\theta^2}\} W^{-(k-\theta)^2}, \quad (7)$$

where:

- $X_i(k)$ - symbol number i in the frequency domain;
- $r_{s,i}(\theta)$ - symbol number i in the time domain (without guard interval);
- k - subcarriers numbers, $k = 0, 1, \cdots N-1$.

It is worth noting that the equation (7) corresponds to convolution of two signals in the time domain: $r_s(\theta)A^{\theta}W^{\theta^2}$ and $W^{-\theta^2}$, since their spectra are multiplied in the frequency domain. In Fig. 4 the spectrum calculated using CTZ is shown. It can be seen that compared to the spectrum from Fig. 3, a significant improvement is observed. In the spectrum calculated using CTZ horizontal lines corresponding to different constellation points are visible. The influence of the channels frequency response can also be seen as ripples in the horizontal lines.

The influence of the channel frequency response can be easily eliminated in the OFDM modulation thanks to the pilot subcarriers. The pilots have known values and are included in the signal spectrum. They are used to estimate the channel frequency response by interpolating the values between the pilots. In the presented algorithm, a simple linear interpolation was used. Next, the spectrum of the OFDM signal is corrected by dividing it by the estimated channel frequency response – this process is known as channel equalization.

After the equalization the constellation can be recreated. Fig. 5 shows the constellation diagram obtained from the signal after the application of the CZT. It can be seen that in this case 64-QAM modulation has been applied. The pilots are marked in the figure with circles. From this constellation, the symbols $c_{m,l,k}$ corresponding to individual subcarriers can be obtained.

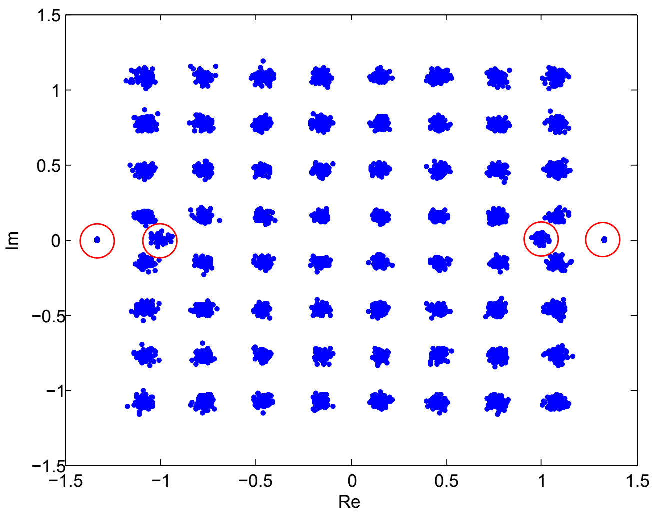

Fig. 5. Symbol constelation diagram.

C. Transformation Into the Time Domain

The next step in the signal reconstruction is to reproduce the transmitted signal without the noise and multipath effect. In order to do this equations (2) and (3) are used. Those equations are slightly modified since the signal is reconstructed in the baseband, not at RF. Moreover, because we analyze each OFDM symbol individually, the symbol number l and frame number m are neglected. The modified equations are as follows:

$$x'(t) = \sum_{i=0}^{\infty} \sum_{k=K_{min}}^{K_{max}} c_{i,k} \cdot \Psi_{i,k}(t), \quad (8)$$

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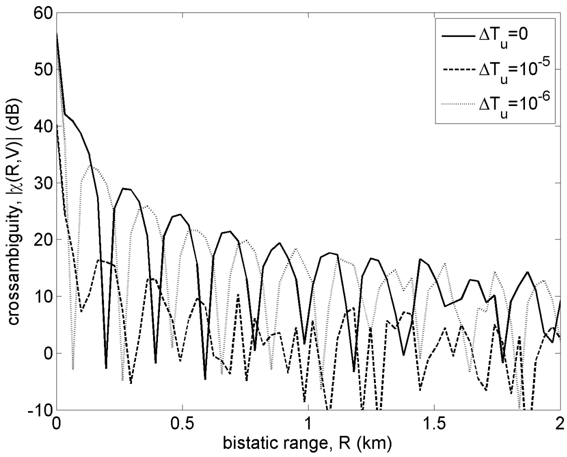

Fig. 6. Slice of the crossambiguity function for zero frequency shift for different symbol length estimation errors.

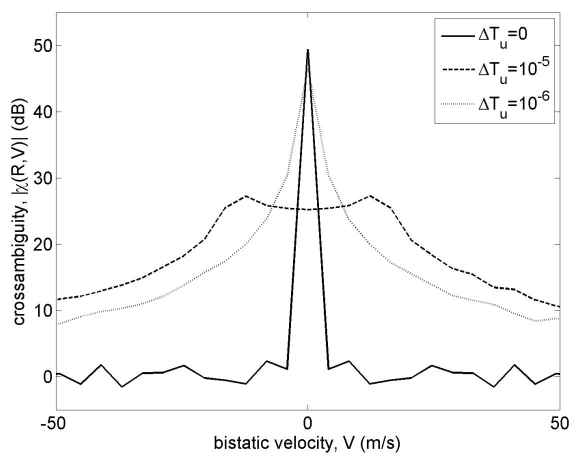

Fig. 7. Slice of the crossambiguity function for zero delay for different symbol length estimation errors.

where:

$$\Psi_{i,k}(t) = \begin{cases} e^{j2\pi\frac{k'}{T_u}(t-\Delta-i\cdot T_s)}, & \text{when } i\cdot T_s \leq t \leq (i+1)\cdot T_s, \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

V. Reconstructed Signal Verification

As already presented, signal reconstruction consists of the estimation of the symbol length, evaluation of the spectrum and transformation to the time domain. First the influence of the symbol length estimation on the crossambiguity calculation was investigated. An ideal OFDM signal $x(t)$ was generated from a random stream of bits. The modulation used here was 64-QAM. In the signal there were 100 OFDM symbols, which corresponded to the total number of samples equal to 870400 with 1/16 cyclic prefix. The reconstructed signal $x'(t)$ was generated with different relative error of the estimated symbol length ΔT_u. The slices of the crossambiguity function calculated according to (1) for the ideal $x(t)$ and reconstructed $x'(t)$ signals are shown in Fig. 6 and 7. The first figure corresponds to the slice for zero frequency shift ($V = 0$ m/s) and the second to zero delay ($R = 0$ km). It can be seen that even the relative error of the symbol estimation error equal to 10^{-6} degrades the crossambiguity function substantially.

In order to asses the influence of the bit error rate (BER) on the quality of clutter canceler, the following experiment was carried out. An ideal OFDM signal was generated. Next a signal $x'(t)$ with certain bit error rate (BER) was generated. The clutter removal was simulated as an adaptive subtraction of the two signals: ideal $x(t)$ and the one reconstructed with certain BER $x'(t)$:

$$z(t) = x(t) - \frac{\langle x(t), x'(t)\rangle}{\langle x'(t), x'(t)\rangle} x'(t). \tag{10}$$

A similar operation is performed on each stage of a lattice filter used as a clutter canceler [4]. The quality of removal was measured as a relative power of the residual signal $z(t)$ to the power of the original signal $x(t)$. The results of the experiment are shown in Fig. 8. It is clear that the BER has great impact

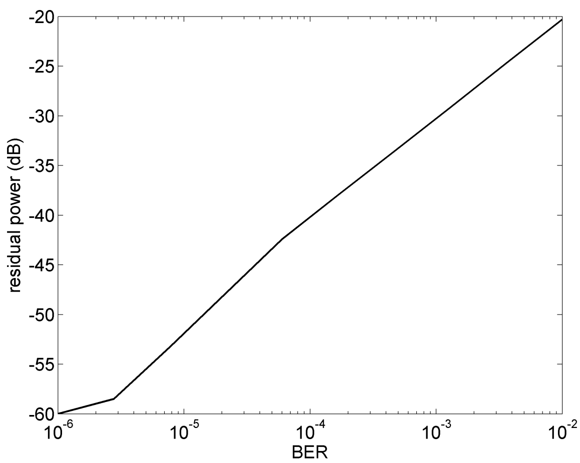

Fig. 8. Residual power after adaptive filtering.

on the signal removal capability. To suppress the signal by 40 dB, BER should be at least 10^{-4}. If 60 dB suppression is desired, BER of the order of 10^{-6} should be provided.

In the next experiment the influence of the BER on the correlation was investigated. The correlation was calculated according to (1) for two scenarios: ideal signal $x(t)$ was correlated with itself, and the ideal signal $x(t)$ was correlated with reconstructed signal $x'(t)$ with BER=10^{-2}. The slices of the crossambiguity function for zero frequency shift ($V = 0$ m/s) and zero delay ($R = 0$ km) are shown in Figs. 9 and 10, respectively. As the figures indicate, even high BER does not influence the crossambiguity function substantially. The only difference is visible in the sidelobes.

The reconstruction algorithm presented in this paper was tested on real-life signals. The signals were recorded using a general purpose signal analyzer. The carrier frequency of the signal was 690 MHz, the sampling frequency was 23.75 MHz, the length of the cyclic prefix was 1/8 of the symbol length, the length of the recording was 1 s, and 64-QAM modulation was used. Figs. 11 and 12 show the slices of the crossambiguity

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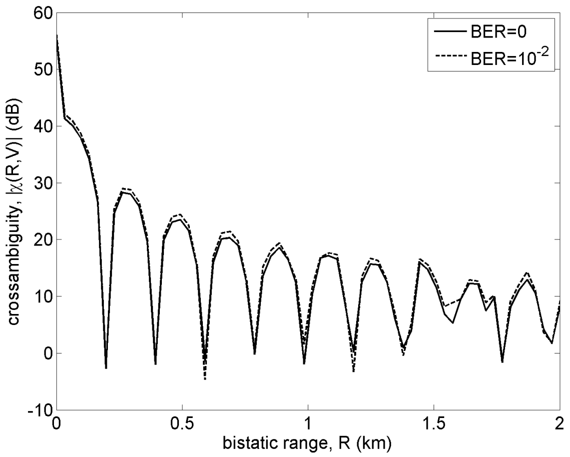

Fig. 9. Slice of the crossambiguity function for zero frequency shift for ideal signal and signal with BER=10^{-2}.

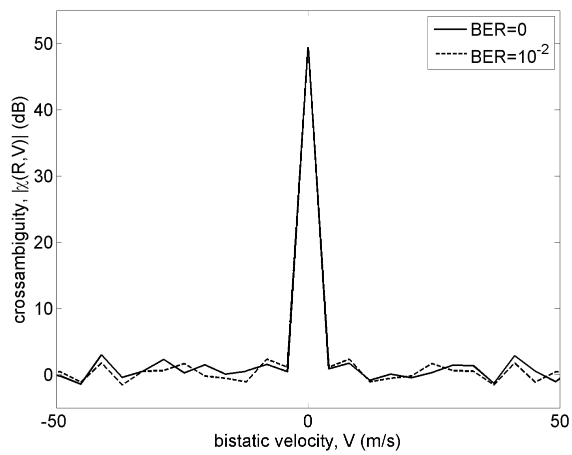

Fig. 10. Slice of the crossambiguity function for zero delay for ideal signal and signal with BER=10^{-2}.

function for zero frequency shift and zero delay, respectively. The crossambiguity functions were calculated for the received signal $x(t)$ and the reconstructed signal $x'(t)$. It can be seen that the slices of the crossambiguity are close to the theoretical ones. This does not provide much information about obtained BER, because the crossambiguity is not very sensitive to bit errors, as shown in Figs. 9 and 10. However, the nearly perfect slices of the crossambiguity prove that the symbol length was estimated with high accuracy. Based on our simulations, we estimate that the error in symbol length estimation was better than $2 \cdot 10^{-8}$. This corresponds to a difference of a fraction of the sampling interval for the whole recording, which was $23.75 \cdot 10^{6}$ samples long.

VI. Conclusion

In the paper a method for reconstruction of the DVB-T signal has been presented. The main difficulty was to develop a method enabling decoding of the signal using universal receiver not dedicated for DVB-T standard. This

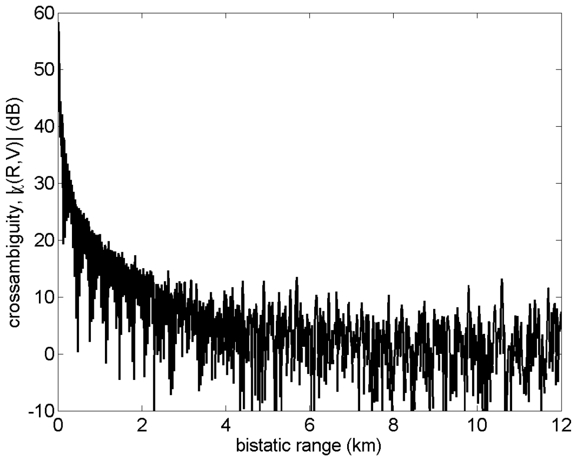

Fig. 11. Slice of the crossambiguity function for zero frequency shift.

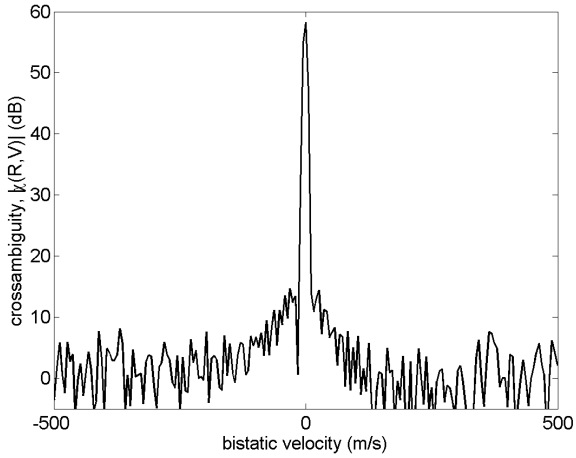

Fig. 12. Slice of the crossambiguity function for zero delay.

was achieved by estimating the length of the OFDM symbol using autocorrelation function and using chirp-Z transform for evaluation of the signal spectrum. The presented method was tested on simulated and real-life signal.

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