Time-frequency based analysis of wireless signals

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Abstract—**This paper deals with signal characterization in communication systems. An algorithm for components separation of highly multicomponent wireless signals has been described. Eigenvalue decomposition method along with time-frequency signal distribution is used. Approach has been tested on synthetic IEEE 802.11b wireless signal. This method can be useful for the elimination of frequency collisions - interferences that occur in wireless network systems, as well as in separation of different types of signals operating in the same frequency band.**

Keywords-eigenvalue decomposition; time-frequency analysis; wireless signals

I. INTRODUCTION

The devices based on radio technology have been intensively developed in recent years. The satellite and broadcast television, wireless computer devices, cellular and portable phones are some examples in which wireless technology has been applied. Radio waves used in wireless technology should satisfy certain conditions such as high speed, transmission over long distances and low power consumption. Achieving all of these conditions simultaneously is difficult, and therefore, several types of wireless networks have been introduced: Wireless Personal Area Network – WPAN (Bluetooth, HomeRF, ZigBee, etc.); Wireless Metropolitan Area Network (WMAN); Wireless Local Area Network – WLAN (IEEE 802.11b, HYPERLAN) and Wireless Wide Area Network - WWAN [1] - [2]. Main differences between these standards are operation distance, data rates and energy consumption. The first group, WPAN, is used for connecting devices over short distances and has maximal signal range up to 10 meters. WLAN standard creates networks for wider range, and enables communication up to 100 meters. WLAN covers wider operational range than WPAN, but has high energy consumption. The Wireless Metropolitan Area Network (WMAN) network has a signal range of approximately 5 km and is used to connect the user to the Internet. WWAN covers much wider area then the previously mentioned networks. In this paper special attention is paid to the IEEE 802.11b standard for wireless communication.

IEEE 802.11b [3] is commonly used standard in wireless technology. This standard operates in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band. ISM band is 83.5 MHz wide, with lower and upper limit of 2400 MHz and 2483.5 MHz, respectively. IEEE 802.11b standard uses one of the 14 overlapping, 22 MHz wide channels. Standard allows the wireless transmission at distances from 10 up to 100 meters, at a transmission speed of approximately 11 Mbps.

In this paper, a procedure for characterization of communication signals in wireless technology is described. It is based on the combined eigenvalue decomposition approach and the time-frequency signal representation. Representation of the signals in the time-frequency domain provides identification of the wireless standards at a particular time instant and at a given frequency [4] - [5]. The S-method is used in order to provide better concentration of the isolated signal components in time-frequency domain. The described procedure is effective when estimating features of wireless signals, such as: frequency of each separated component, inter-carrier spacing and number of signal components [6].

The paper is organized as follows. The theoretical background on used time-frequency distributions is given in Section 2. In Section 3, the eigenvalue decomposition method in combination with time-frequency distribution is described. The modification of the described procedure and the experimental results are given in Section 4. The conclusion is given in Section 5.

II. THEORETICAL BACKGROUND

The most commonly studied nonlinear time-frequency distribution is the Wigner distribution [7] - [10], defined as:

$$W(t,\omega)=\int_{-\infty}^{\infty} s(t+\frac{\tau}{2})s^{*}(t-\frac{\tau}{2})e^{-j\omega\tau}d\tau. \qquad (1)$$

There is a significant drawback of this distribution for the case of multicomponent signals. In fact, the Wigner distribution of these signals consists of the sum of auto and sum of cross-terms. The auto-terms are signal terms, and the cross-terms are artificial terms that do not really exist in the signal. They appear in time-frequency representation of the multicomponent signal due to quadratic nature of the Wigner distribution.

The cross-terms appear at the arithmetic mean of the frequencies of the two auto-term components. Energy of the cross-terms could be so high, to completely cover auto-terms. In order to avoid presence of the cross terms in the Wigner distribution, the S-method is introduced. It has been applied in different applications for analysis and filtering of the multicomponent signals, such as in [11] - [12]. This distribution combines good properties of the spectrogram and the Wigner distribution: reduces the cross-terms and preserves

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the concentration of the auto-terms as in the Wigner distribution. The discrete form of the S-method is defined as [11] - [15]:

$$SM(n,k)=\sum_{i=-L}^{L} P(i)STFT(n,k+i)STFT^{*}(n,k-i), \qquad (2)$$

where n and k are discrete samples in time and frequency, respectively, and STFT denotes Short-Time Fourier Transform. Reduction of the cross-terms will depend on the parameter L. Namely, in order to avoid presence of the cross-terms, the $2L+1$ should be greater than auto-term width and less than the distance between two auto-terms.

III. EIGENVALUE DECOMPOSITION

The eigenvalue decomposition method, combined with the time-frequency distribution [16] - [17], can be efficiently used to separate components of the multicomponent signals. In order to apply the eigenvalue decomposition method, consider the autocorrelation matrix of the signal:

$$R=s(n)s^{*}(n), \qquad (3)$$

where $s(n)$ is column vector whose elements are signal values, and $s^{*}(n)$ is a row vector with the complex conjugate values. The eigenvalue decomposition of the square matrix R could be written as:

$$R=\sum_{i=1}^{N+1}\lambda_i u_i(n)u^{*}_{i}(n), \qquad (4)$$

where λ_i are eigenvalues and u_i are eigenvectors of matrix R. The autocorrelation matrix could be obtained by using the inverse Wigner distribution as follows:

$$s(n+m)s^{*}(n-m)=\frac{1}{N+1}\sum_{k=-N/2}^{N/2} WD(n,k)e^{j\frac{2\pi}{N+1}2mk}. \qquad (5)$$

For the signal that consists of M components, the previous relation becomes:

$$\sum_{i=1}^{M} s_i(n+m)s_i^{*}(n-m)=\frac{1}{N+1}\sum_{k=-N/2}^{N/2}\sum_{i=1}^{M} WD_i(n,k)e^{j\frac{2\pi}{N+1}2mk}, \qquad (6)$$

If the STFTs of the signal components do not overlap in the time-frequency plane, than sum of the Wigner distributions on the right side of (6) corresponds to the S-method of the M-component signal:

$$\sum_{i=1}^{M} s_i(n+m)s_i^{*}(n-m)=\frac{1}{N+1}\sum_{k=-N/2}^{N/2} SM(n,k)e^{j\frac{4\pi}{N+1}mk}. \qquad (7)$$

Introducing the following notation, $\sum_{i=1}^{M} s_i(n+m)s_i^{*}(n-m)=R_{SM}(n+m,n-m)$, we get:

$$R_{SM}(n+m,n-m)=\frac{1}{N+1}\sum_{k=-N/2}^{N/2} SM(n,k)e^{j\frac{4\pi}{N+1}mk}. \qquad (8)$$

Eigenvalue decomposition is applied on matrix (8), resulting in eigenvalues and eigenvectors. Eigenvectors correspond to the signal components, and eigenvalues correspond to the energy of components.

IV. RESULTS

A. Wireless signals

Wireless IEEE 802.11b [5], [18] standard, known as Wi-Fi, allows data exchange through computer network. Wi-Fi is based on spread spectrum modulation technique, which uses narrowband signal and expand it to wideband.

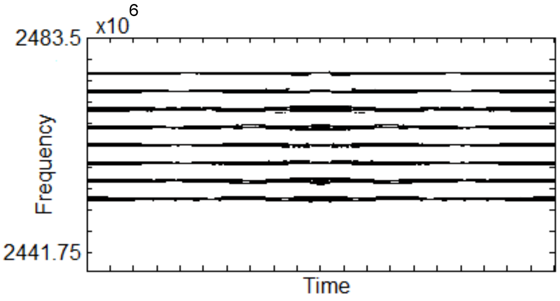

Figure 1. Zoomed region of the S-method of the synthetic IEEE 802.11b signal; frequencies are given in Hz

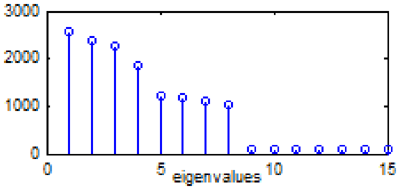

Figure 2. Eigenvalues that correspond to the time-frequency distribution of the observed signal

Therefore, spread spectrum signals use lower power than narrowband signals. IEEE 802.11b standard uses Direct Sequence Code Division Multiple Access (DS-CDMA). Code Division Multiple Access allows multiple signals to occupy same bandwidth at the same time, and thus increases channel capacity.

DS-CDMA signal is generated by multiplying user data signal with code sequence (usually pseudo random code sequence). A single IEEE 802.11b channel uses 22 MHz for transmission.

Components of the synthetic IEEE 802.11b signal are normalized and the S-method is shown in Fig. 1. Fig. 2 shows eigenvalues of the synthetic signal. The first eight eigenvalues correspond to the energy of signal components. The remaining eigenvalues have energy that is dozens of times below the energy of the first eight components. Experimentally is shown that they do not correspond to the energies of the signal components. The first eight eigenvectors correspond to the signal components.

Calculating the S-method of these eigenvectors, we obtain time-frequency representation of each signal component.

As it can be seen from the Fig. 1, the time-frequency representation consists of eight closely frequency spaced components. Separated components are shown in Fig. 3.

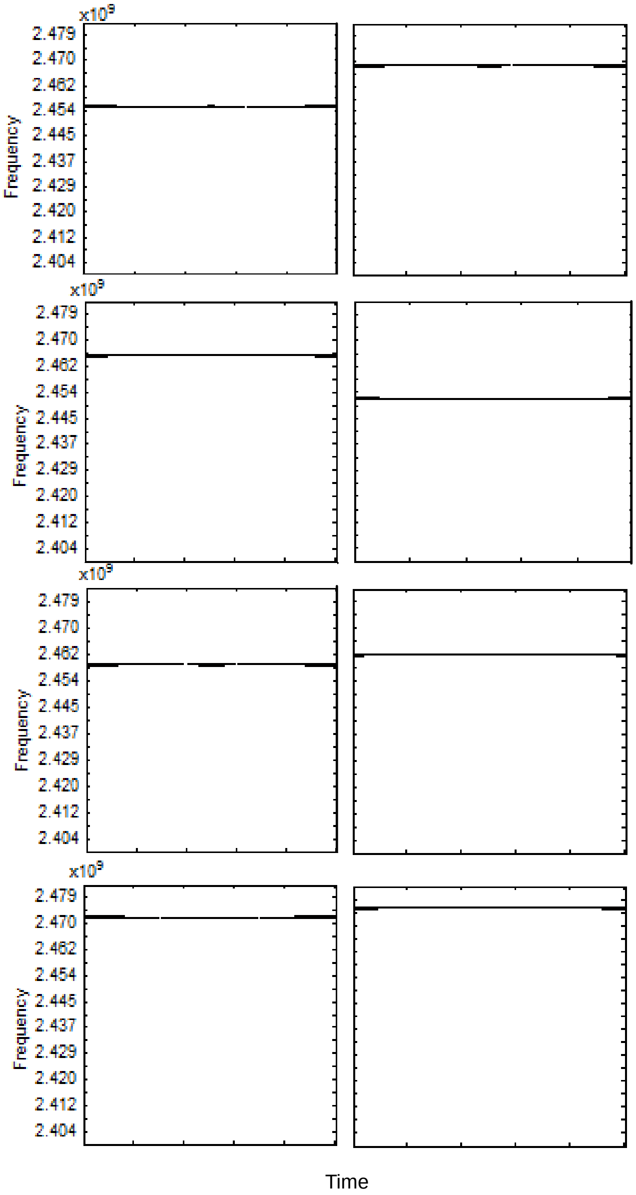

Figure 3. Separated components of the synthetic IEEE 802.11b signal; frequencies are given in Hz

Each separated component shown in Fig. 3 corresponds to the time-frequency distribution of the corresponding eigenvector. Frequencies of the components are obtained as:

$$\omega_i = argmax\left(SM_i\right), \tag{9}$$

where SM_i denotes the S-method of the isolated component.

B. Wireless noisy signal

Consider IEEE 802.11b signal corrupted by Gaussian noise. S-method of the signal is shown in Fig. 4. Fig. 5 shows separated components of the synthetic IEEE 802.11b noisy signal. The signal to noise ratio is -3.5571 dB. It is shown that decomposition procedure works well in the presence of noise.

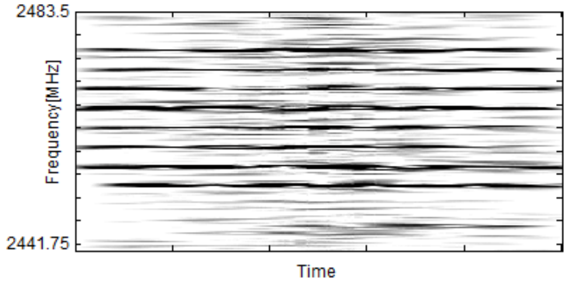

Figure 4. Synthetic IEEE 802.11b signal corrupted by Gaussian noise (Zoomed region of the S-method)

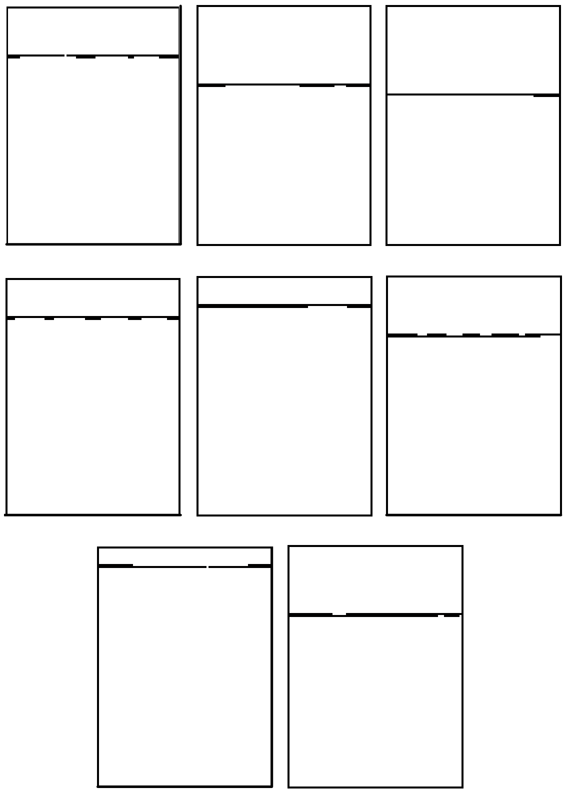

Figure 5: Separated components of the noisy IEEE 802.11b signal; horizontal axis is for time and vertical axis is for frequency

Noise affects all eigenvalues and eigenvectors, but it is spread over different eigenvalues and eigenvectors. By separating eigenvectors that correspond to the signal components, most of the noise from the signal will be eliminated.

CONCLUSION

The paper describes one possible application of the eigenvalue decomposition procedure, based on the S-method. The decomposition procedure is applied on synthetic signals in wireless technology. The signals corresponding to IEEE 802.11b standard are multicomponent. Therefore, the S-method is used for their characterization, as the time-frequency distribution that can produce representation of the multicomponent signal avoiding the presence of cross-terms. It is shown that is possible to separate the components of interest from the observed time-frequency distribution. The time-frequency analysis and the eigenvalue decomposition method allow distinguishing between the wireless standards that use the same frequency band. It is possible to determine central frequency of the signal component, its duration or the number of components in the observed signal. Inter-carrier spacing in Wi-Fi signals may be used for standard identification, since different standards (WiFi, WiMAX, DAB, DVB-T, 3GPP/LTE), have different spacing between subcarriers. Influence of the noise on the decomposition procedure is also considered. It is shown that procedure provides good results in decomposition of the noisy signal, even at low SNR. Most of the noise has been eliminated in the decomposition process. Future work may be focused on removing collisions that occur when two or more users transmit at the same time over the same channel, and they can lead to data loss.

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