Hybrid Detection as a Method to Increase Performance of Sensing

Mateusz Kustra, Krzysztof Kosmowski, Marek Suchański, Józef Pawelec
Military Communication Institute
Zegrze, Poland
m.kustra@wil.waw.pl, k.kosmowski@wil.waw.pl, m.suchanski@wil.waw.pl, j.pawelec@wil.waw.pl

***Abstract*—The paper discusses the hybrid sensing method and presents the hybrid detector (HD) which improves the sensing performance. The proposed HD takes advantage of the energy detection (ED) and a method based on the Covariance Absolute Value (CAV). In the paper the system model was described and the simulation results for OFDM signal (Orthogonal Frequency Division Multiplexing) of WiMAX and DVBT systems were presented.**

***Keywords*—hybrid detector; sensing; OFDM; WiMAX; DVBT**

I. Introduction

Cognitive radio systems [1][2] are an effective solution to the problem of spectrum scarcity, mainly owing to Dynamic Spectrum Access (DSA) to bandwidths that are temporarily not used by primary users (PU). Sensing is one of the basic tasks of cognitive radio which must be carried out in order to enable communication. It relies on monitoring broad spectrum bands and detecting the channels not occupied by non-primary (unlicensed) users, which can be used by secondary users (SU). Simon Haykin defines this as "the task of finding the spectrum holes by sensing the radio spectrum in the local neighborhood of the cognitive radio receiver in an unsupervised manner". The term "spectrum holes" means those subbands of the radio spectrum that are not fully utilized at a specified time and place.

The issue of sensing has been theoretically referred to many times. Numerous spectrum scanning techniques have been proposed for cognitive radio systems and the number of publications on this topic is counted in thousands. All of these methods can fall into several basic categories depending on signal characteristics which are used. The most commonly considered methods applied in the spectrum recognition process are energy detection, cyclostationary features detection, matched filter detection and wavelet-based detection [3].

The most commonly used method in spectral scanning is energy detection (ED) [4]. This method is characterized by low computational complexity and simple implementation. ED is a semi-blind detection which requires knowledge of spectral density of noise power for signal detection and as such, ED is sensitive to the uncertainty of its estimation [5][6]. For this reason, in the literature there is also an analysis of the suitability of other sensing techniques that do not require this parameter. These methods most often use distinctive features which let us distinguish noise from modulated signals. However, such detection methods are also not free from disadvantages. They are usually more computationally complex or require a large number of samples to ensure proper detection reliability. The shortcomings mentioned above cause that in the literature on the optimization of sensing methods to improve their efficiency, detectors with hybrid architecture are considered [7][8]. Such detectors are a combination of different detection methods. An additional consideration is the optimization by reducing the number of signal samples (compressive sensing), which also affects computational complexity.

One of the methods which is not sensitive to the uncertainty of noise estimation is the CAV method. This is a blind detection technique which uses the signal time-space-correlation to detect the signal. In this case, no signal or noise level knowledge is required [3]. Although the complexity of CAV is considerably higher than that of ED, CAV is characterized by high accuracy.

Hybrid sensing combines the advantages of each method used and its structure depends on the scenario according to which the spectrum detection is performed. An example of such a solution could be a system which uses energy detection and a method based on detection of signal distinctive features. Energy detection, as the simplest and fastest method of sensing, allows for reliable detection of strong signals, for which a relatively small number of samples allows to detect emissions. And in other cases, if the detected energy level does not allow for accurate estimation using the energy method, another method can be used.

The paper presents a method of hybrid sensing using ED and CAV. The chapters describe the considered hybrid detector, characterize a model of the system for which simulations have been carried out, and then show the results of the study. The presented results are an extension of the results obtained in [9] for the WiMAX system and a comparison with the HD capabilities for the DVBT system. The results demonstrate that the proposed hybrid detector offers better detection properties than ED or CAV.

II. Hybrid Detector

The proposed HD is a two-phase detector taking advantage of both detection methods: ED and CAV. The scheme of the detector is shown in Fig. 1.

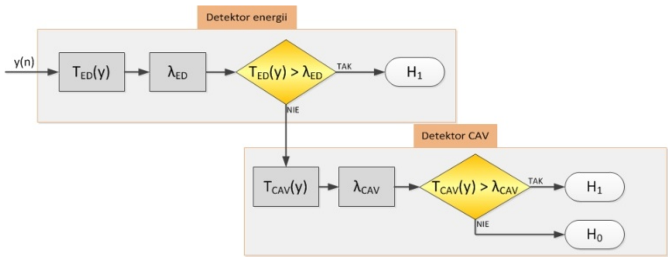

Fig. 1. Scheme of the hybrid detector

For each channel, the presence of PU is firstly determined in the first detection phase in which ED is used. Although this method is sensitive to the uncertainty of noise, its undoubted advantage is the speed of detection and accuracy at high SNR values. Therefore, the decision about PU signal presence will be taken only in unquestionable situations – the energy of the received signal (T_{ED}) will be higher than the ED detection threshold (λ_{ED}) calculated for the assumed probability of a false alarm (P_{fa}).

The decision statistic for the energy detector can be expressed by [3][4]:

$$T_{ED} = \frac{1}{N_s}\sum_{n=0}^{N_s-1}|y(n)|^2 \tag{1}$$

where: $y(n)$ – the received signal; N_s – number of signal samples.

The detection threshold (λ_{ED}) for the assumed constant P_{fa} value is expressed as follows [3][4]:

$$\lambda_{ED} = \sigma_\eta^2\left(Q^{-1}(P_{fa})\sqrt{2N_S} + N_S\right) \tag{2}$$

where: σ_η^2 – noise variance; $Q(t)$ – Q function given by:

$$Q(t) = \frac{1}{\sqrt{2\pi}}\int_t^{+\infty} e^{-\frac{u^2}{2}}du \tag{3}$$

When the decision cannot be made using ED, the second phase of hybrid detection is CAV. It uses the differences between autocorrelation of noise and signal. Autocorrelation of received signal is [10]:

$$\varphi(l) = \frac{1}{N_s}\sum_{n=0}^{N_s-1} y(n) * y(n-l), \qquad l = 0,1 \ldots L-1 \tag{4}$$

where N_s – number of signal samples; L – smoothing factor.

The statistical covariance matrices R_x of the whole signal and noise can be estimated using a matrix $\hat{R}_x$ formed for L consecutive signal samples:

$$\hat{R}_x(N_s) = \begin{bmatrix} \varphi(0) & \varphi(1) & \cdots & \varphi(L-1) \\ \varphi(1) & \varphi(0) & \cdots & \varphi(L-2) \\ \vdots & \vdots & \ddots & \vdots \\ \varphi(L-1) & \varphi(L-2) & \cdots & \varphi(0) \end{bmatrix} \tag{5}$$

This matrix is symmetric and Toeplitz. Based on symmetric property of autocorrelation matrix, two ratios T_1 and T_2 are expressed as follows:

$$T_1 = \frac{1}{L}\sum_{n=1}^{L}\sum_{m=1}^{L}|r_{nm}| \tag{6}$$

$$T_2 = \frac{1}{L}\sum_{n=1}^{L}|r_{nn}| \tag{7}$$

where: r_{nm} and r_{nn} are elements of $\hat{R}_x$ matrix and decision statistic for CAV is expressed as:

$$T_{CAV} = \frac{T_1}{T_2} \tag{8}$$

The detection threshold (λ_{CAV}) is calculated as:

$$\lambda_{CAV} = \left(1 + (L-1)\sqrt{\frac{2}{N_s\pi}}\right)\left(1 - Q^{-1}(P_{fa})\sqrt{\frac{2}{N_s}}\right)^{-1} \tag{9}$$

For the second phase, as in the first phase, the decision about PU signal presence is taken when decision statistic (T_{CAV}) is greater than the CAV threshold (λ_{CAV}). Otherwise, a decision about PU signal absence is made.

For the two-phase hybrid detector, the total probability of a false alarm (P_{fa_HD}) and the total probability of detection (P_{d_HD}) are expressed by:

$$P_{fa\_HD} = P_{fa\_ED} + (1 - P_{fa\_ED})P_{fa\_CAV} \tag{10}$$

$$P_{d\_HD} = P_{d\_ED} + (1 - P_{d\_ED})P_{d\_CAV} \tag{11}$$

where: P_{fa_ED} and P_{fa_CAV} – the probability of a false alarm for ED and CAV, respectively:

$$P_{fa\_ED} = Q\left(\frac{\lambda_{ED} - N_S\sigma_\eta^2}{\sqrt{2N_S\sigma_\eta^4}}\right) \tag{10}$$

$$P_{fa\_CAV} = 1 - Q\left[\frac{\frac{1}{\gamma_{CAV}}\left(1 + (L-1)\sqrt{\frac{2}{N_s\pi}}\right) - 1}{\sqrt{\frac{2}{N_s}}}\right] \tag{11}$$

P_{d_ED} and P_{d_CAV} – the probability of a detection for ED and CAV, respectively:

$$P_{d\_ED} = Q\left(\frac{\lambda_{ED} - N_S\left(\sigma_s^2 + \sigma_\eta^2\right)}{\sqrt{2N_S\left(\sigma_s^2 + \sigma_\eta^2\right)^2}}\right) \tag{12}$$

$$P_{d\_CAV} = 1 - Q\left[\frac{\frac{1}{\gamma_{CAV}} + \frac{\gamma_L \cdot SNR}{\gamma_{CAV}(SNR+1)} - 1}{\sqrt{\frac{2}{N_s}}}\right] \tag{13}$$

where: σ_s^2 – PU signal variance; γ_L – overall correlation coefficient which is defined as:

$$\gamma_L \triangleq \frac{2}{L}\sum_{l=1}^{L-1}(L-l)|\alpha_l| \tag{13}$$

$$\alpha_l = \frac{E[s(n)s(n-l)]}{\sigma_s^2} \tag{13}$$

where $0 \leq |\alpha_L| \leq 1$.

Fig. 2 shows the probability of a false alarm for HD as a function of the ED threshold for different values of CAV threshold. For the CAV threshold ($threCAV = 1{,}1642$) calculated from (9), there is no possibility of reaching $P_{fa} = 0{,}1$. Hence, for HD, the CAV threshold must be changed. Reaching $P_{fa} = 0{,}1$ is possible for $threCAV = \{1{,}19;\ 1{,}21\}$.

III. System Model

The requirements that the cognitive radio must fulfill in sensing of the primary user's signals are strictly connected with the cognitive system scenario. Currently, well known commercial cognitive system standard is the IEEE 802.22 wireless network (this system was launched in the US). Hence,

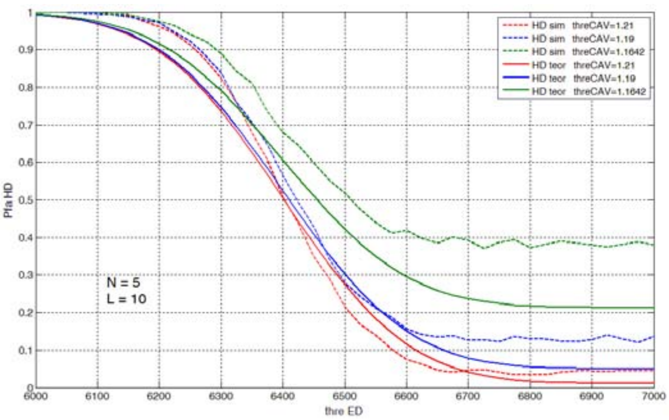

Fig. 2. Probability of false alarm for HD in a ED threshold function for different values of CAV threshold, theoretical (10) and obtained from Monte Carlo simulations

for the purpose of this paper, a work scenario according to this standard is assumed. The cognitive system works outside the area of communication between PUs and a base station of the licensed system (Fig. 3). The cognitive system works in such a distance from the licensed system in order not to introduce additional interference that would result in a deterioration of the sensitivity of PU receivers. For this reason, the cognitive system monitors the spectrum by assuming the following parameters:

- detection sensitivity required: ≤ -10 dB;
- probability of a detection $P_d = 0{,}9$;
- probability of a false alarm $P_{fa} = 0{,}1$;
- uncertainty associated with spectral power density estimation ± 1 dB.

As a licensed system, the WiMAX (IEEE 802.16-2004 [11]) and DVBT (ETSI EN 300 744 V1.6.1 [12] – 2k mode) systems were assumed with the parameters specified in Table I:

IV. Simulation Results

The purpose of the simulations was to check the efficiency of the proposed hybrid sensing method in comparison to other available techniques (ED, CAV). According to the theoretical assumptions, the utilization of HD should significantly increase the reliability of sensing by reducing the probability of false alarms for a specific number of samples and increasing probability of detection.

In order to determine the dependence of the probability of detection on the SNR with the assumed number of samples, the probability of a false alarm was set at 10% ($P_{fa} = 0{,}1$) and for the CAV method the smoothing factor $L = 10$.

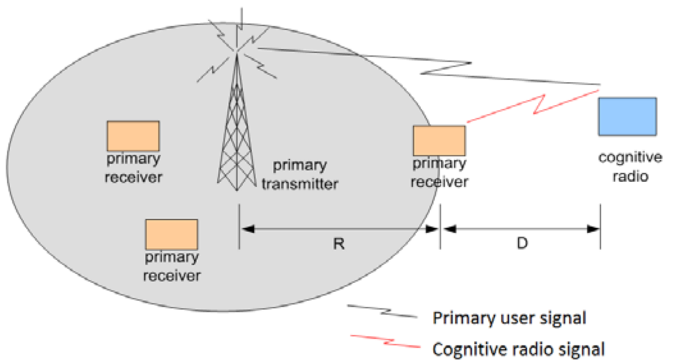

Fig. 3. System model

TABLE I. Parameters of the Licensed Systems

Parameter	Value	
	WiMAX	***DVBT***
Bandwidth	3,5 MHz	8 MHz
OFDM symbol duration	80 µs	280 µs
OFDM useful symbol duration	64 µs	224 µs
Cyclic Prefix ratio	1/4	1/4
FFT size	256	2048

Fig. 4 and Fig. 5 show the comparison of HD performance with ED and CAV for a varying number of OFDM signal symbols (N) depending on SNR values for WiMAX and DVBT systems, respectively. It can be easily concluded that the assumed $P_d = 0{,}9$ is reached at lower SNR values for HD than for the other methods.

For the WiMAX system (Fig. 4) HD reaches $P_d = 0{,}9$ with $SNR = -11$ dB for $N = 5$ and $SNR = -14{,}5$ dB for $N = 25$. In this case, CAV efficiency is worse by {2; 1,5} dB respectively, and ED efficiency is worse than HD by {4,1; 7,2} dB, respectively.

When it comes to the DVBT system (Fig. 5) HD reaches $P_d = 0{,}9$ with $SNR = -14{,}3$ dB for $N = 5$ and $SNR = -18{,}3$ dB for $N = 25$. In this case, CAV efficiency is worse by {1,8; 1,9} dB respectively, and ED efficiency is worse than HD by {7; 10,7} dB, respectively.

In order to compare the detectors under consideration, the ROC (Receiver Operating Characteristic) curves were determined, Fig. 6 and Fig. 7.

It can be noticed that for the signal of the WiMAX system (Fig. 6), HD is characterized by significantly better parameters than the other detectors. HD reaches $P_d = 0{,}9$ at the target $P_{fa} = 0{,}1$ for $SNR = -11$ dB and $N = 5$ and for $SNR = -15$ dB and $N = 25$. With the same parameters, CAV reaches $P_d = 0{,}9$ with the probability of a false alarm $P_{fa} = 0{,}33$ and $P_{fa} = 0{,}35$, respectively. And ED does not reach the assumed probability of detection, with $P_{fa} = 0{,}1$ probability of detection is $P_d = 0{,}6$ and $P_d = 0{,}54$, respectively.

For the signal of the DVBT system (Fig. 7), HD is characterized by significantly better parameters than the other detectors. HD reaches $P_d = 0{,}9$ at the target $P_{fa} = 0{,}1$ for $SNR = -14$ dB and $N = 5$ and for $SNR = -19$ dB and $N = 25$. With the same parameters, CAV reaches $P_d = 0{,}9$ with the probability of a false alarm $P_{fa} = 0{,}27$ and $P_{fa} = 0{,}39$, respectively. And ED does not reach the assumed probability of detection, with $P_{fa} = 0{,}1$ probability of detection is $P_d = 0{,}55$ and $P_d = 0{,}52$, respectively.

In the simulated WiMAX and DVBT systems, the cyclic prefix ratio of the OFDM signal may take one of the following values: 1/4; 1/8; 1/16 or 1/32. An additional aim of the paper is also to estimate the difference in the performance of HD for two different cyclic prefix lenghts (LCP). The following LCP

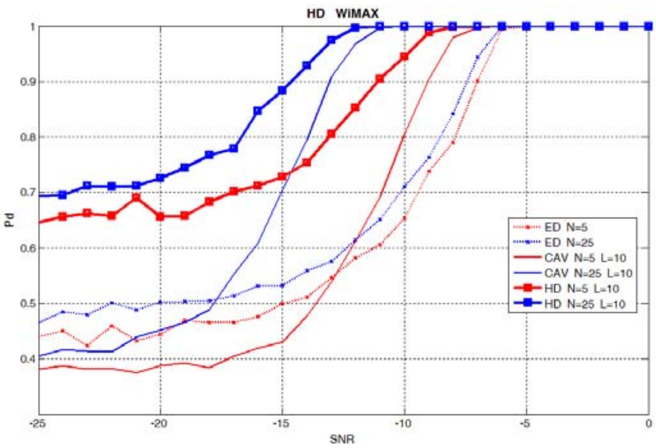

Fig. 4. The probability of detection in a SNR function (ED, CAV, HD) for the WiMAX system

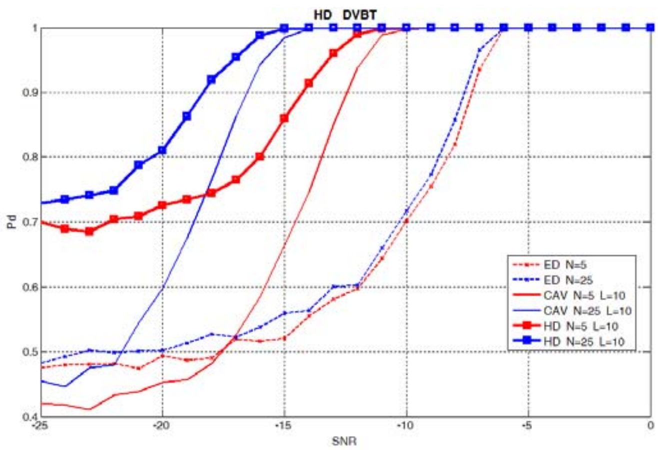

Fig. 5. The probability of detection in a SNR function (ED, CAV, HD) for the DVBT system

a) b)

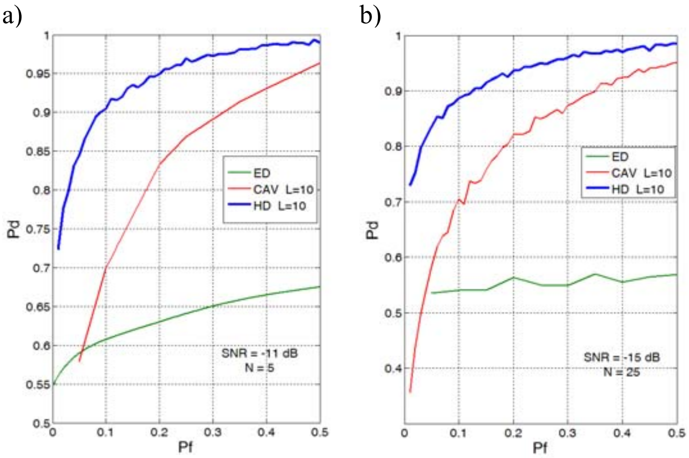

Fig. 6. The ROC curve for ED, CAV and HD detectors for the WiMAX system: a) SNR = -11 dB; b) SNR = -15 dB

a) b)

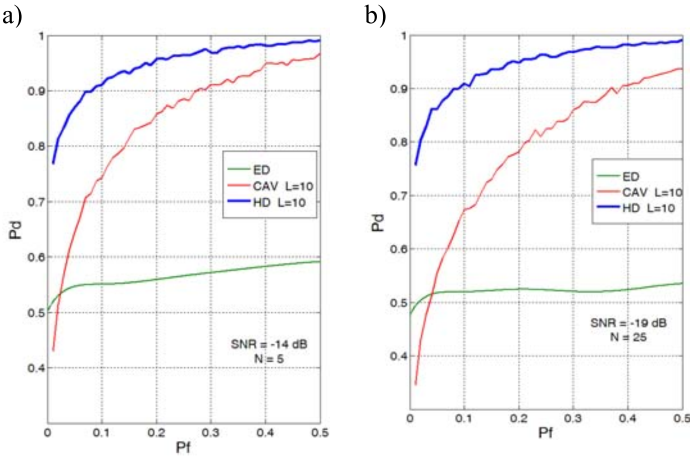

Fig. 7. The ROC curve for ED, CAV and HD detectors for the DVBT system: a) SNR = -14 dB; b) SNR = -19 dB

values were assumed: $LCP = 1/4$ i $LCP = 1/32$. Fig. 8 and Fig. 9 show that there are slight differences between Pd values for varying LCPs, which are the result of different lengths of the received OFDM signal. Depending on the set cyclical prefix (LCP = 1/4 or LCP = 1/32), the received OFDM signal consists of symbols each of which is represented by the number of samples specified in Table II.

TABLE II. THE NUMBER OF OFDM SIGNAL SAMPLES FOR THE WIMAX AND DVBT SYSTEMS

	WiMAX	**DVBT**
OFDM useful symbol length	512	2048
OFDM symbol length with LCP = 1/4	650	2560
OFDM symbol length with LCP = 1/32	528	2112

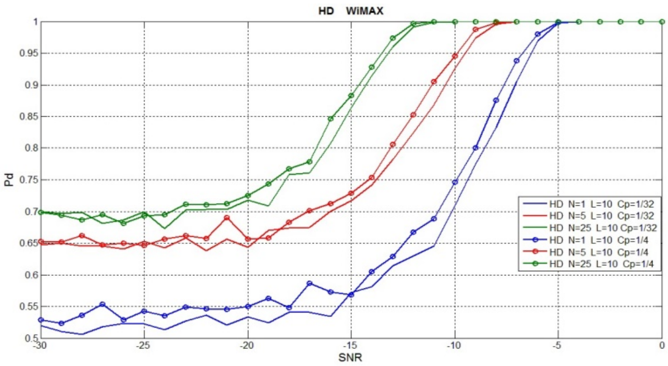

Fig. 8. The probability of detection in a SNR function (HD) for OFDM signal with $LCP = 1/4$ and $LCP = 1/32$ (the WiMAX system)

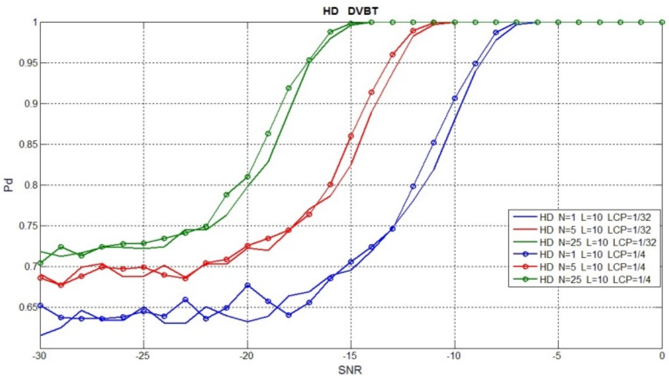

Fig. 9. The probability of detection in a SNR function (HD) for OFDM signal with $LCP = 1/4$ and $LCP = 1/32$ (the DVBT system)

V. CONCLUSION

The paper has presented a hybrid sensing technique and described HD taking advantage of energy detection, as well as CAV methods. In the first phase, the signal is detected via ED, which allows for a quick detection of strong signals. In other cases, when the detected energy level does not allow for making an unquestionable decision about the presence or absence of PU on the channel, the CAV method is utilized.

Then, the results of simulations of the proposed detector for the OFDM signal of the WiMAX and the DVBT systems have been presented. The efficiency of HD has been compared with that of ED and CAV. The simulation results for the assumed system (according to theoretical assumptions) have shown the superiority of the proposed hybrid method over the other ones. While taking into account that the hybrid method significantly minimizes P_{fa} (as indicated by the ROC curves), it can be stated that it is the most effective sensing method for a given length of a received signal.

REFERENCES

[1] Federal Communications Commission, "Notice of proposed rulemaking and order, Facilitating opportunities for flexible, efficient and reliable spectrum use employing cognitive radio technologies," FCC 03-322, 2003.

[2] S. Kapoor, G. Singh, "Non-cooperative spectrum sensing : A hybrid model Approach," 2011 International Conference on Device and Communications (ICDeCom), India 2011.

[3] Y. Zeng, Y.-Ch. Liang, A. T. Hoang, R. Zhang, "Review on spectrum Sensing for cognitive radio: Challenges and Solutions," EURASIP Journal on Advances in Signal Processing, 1-15, 2010

[4] H. Urkowitz, "Energy detection of unknown deterministic signals," Proc. IEEE, vol. 55 : 523–531 1967

[5] D. Cabric, A. Tkachenko, R. Brodersen, "Experimental study of spectrum sensing based on energy detection and network cooperation," Proc. of the ACM International Workshop on Technology and Policy for Accessing Spectrum, Boston, Massachusetts, USA August 2006.

[6] A. Sahai, D. Cabric, "Spectrum sensing: fundamental limits and practical challenges," Proc. of the IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 546-551, Baltimore 2005.

[7] H. Bogucka,. "Technologie Radia Kognitywnego," PWN, Warsaw, 2013.

[8] S. Haykin, D. J. Thomson, J. Reed, "Spectrum sensing for cognitive radio," Proc. IEEE, vol. 97 : 849 -877 2009.

[9] M. Kustra, K. Kosmowski, M. Suchański, J. Pawelec, "Detekcja hybrydowa jakos metoda zwiększająca wydajność sensingu" [in Polish], KKRRiT 2017.

[10] Y. Zeng, Y.-Ch. Liang, "Covariance based signal detections for cognitive radio," DYSPAN07, 202-207., Dublin 2007.

[11] http://ieee802.org/16/pubs/80216-2004.html

[12] http://www.etsi.org/deliver/etsi_en/300700_300799/300744/01.06.01_60/en_300744v010601p.pdf