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DVB-T SIGNAL DETECTION FOR INDOOR ENVIRONMENTS IN LOW-SNR REGIME

Abstract: **The problem of coexistence between the primary (licensed) and secondary (non-licensed) users can be solved in various ways. One of them assumes the application of the detailed Radio Environment Maps being a kind of database, where some crucial information about the licensed transmission can be stored. In this paper we propose the new methods for signal detection in low signal-to-noise regime and compare it through hardware experiment with other known techniques used for spectrum sensing.**

1. INTRODUCTION

The concept of intelligent and adaptive usage of available frequency spectrum and resources, known as cognitive radio, has attracted researchers in numerous academic and research centres for many years, starting mainly from the publications of the diploma thesis (and the preceding papers) by J. Mitola III [1]. In such an approach the mobile terminal is able to recognize the currently vacant (not-used) frequency fragments and adapt its transmission parameters accordingly. Utilization of the vacant frequency subbands will be possible only under the assumption that the signal reception of the licensed (known also as primary) user will not be disturbed by the non-licensed (called secondary) user. In order to achieve this goal advanced spectrum sensing algorithms have been proposed in the literature [2] focusing on detection of specific features or parameters of the searched signal.

The simplest solution, i.e. the one that bases on energy detection, is characterized unfortunately by high inaccuracy, whereas the most accurate algorithms (e.g. the one that bases on matched filtering) assumes full knowledge about the sensed signal. Since pure single-node spectrum sensing algorithms appeared to be not reliable enough to be applied in practice, other approaches have been proposed. One of the most promising techniques is the application of the geolocation databases, referred also as Radio Environment Maps (REMs) [3], [4]. Such entities will contain various information on surrounding primary users and available frequency channels (e.g. the accurate location of the primary transmitters and receivers, their transmit power, the list of available vacant channels and interference that can be allowed by the primary user etc.) enabling the efficient coexistence between the primary and secondary users. Various tests and initial trials of the REM-based cognitive radio system have been carried out in selected countries all over the world (see e.g.[5]). In most cases, however, REM-based solution concentrate on the outdoor cases, and little has been said on the indoor REM applications. In that paper we would like to address some problems related to deployment of REMs for indoor environments in order to allow reliable signal transmission by the secondary users.

It has to be noticed that although the cognitive radio idea can be theoretically applied to any frequency band, the most promising range of frequencies where the non-licensed transmission could be realized is the TV band. It is due to the fact that after the digital switch-off (i.e. the transition from the analogue to digital terrestrial television) significant number of 8MHz wide TV channels has been vacated. Although a portion of the freed spectrum has been devoted to the so-called digital dividend (first, and maybe second), the remaining fragments of the unused spectrum could be utilized in a cognitive manner. Thus, in our work, we intentionally concentrate on utilization of that frequency band (from 470MHz to 790MHz). Such an approach has some significant benefits comparing to the other possible frequency bands (like the high frequencies around 2-3GHz). First, the frequencies in TV band are relatively low, thus in consequence lower power can be used in order to transmit the signal in the same range when compared to high frequencies. Moreover, TV towers are rather stable (i.e. it is very rare situation, like big mass events, when the mobile TV towers are deployed by the broadcasters), and their transmission parameters rather do not change in time. Thus, it should be possible to create stable characteristics of the TV signal observed in almost every point of the considered building. In our previous paper [6] we have proved the aforementioned assumptions by empirical observations. Although we have proved that the observed signal can be treated as stable at some level of uncertainty, the accuracy of the possible entries to the REM will highly depend on the reliability of detection of the TV signal inside the premises.

Thus, in this work we have verified selected spectrum sensing algorithms from the context of their possible application for establishing the entries to the indoor databases. In particular we would like to be able to detect the presence of the DVB-T signal in low signal-to-noise (SNR) regimes as well as to estimate the value of observed SNR. This task is of high importance since the measured value of the received energy defines the limits on the allowable transmit powers of the secondary user at the neighbouring frequency channels. It is worth mentioning that the observed power is influenced by the attenuation of the outside and inside walls as well as by the inside obstacles and people.

In that context it is worth reminding the particular parameters of the DVB-T signal, defined in [1], that can be broadcasted in Poland, where the experiments have been carried out. The DVB-T channels have bandwidth of 8 MHz and are distributed in band 490-790MHz. Each channel uses OFDM modulator of FFT size set to 8192. In this case 6817 subcarriers are modulated and the duration of main part of OFDM symbol (i.e. without cyclic prefix) equals 896μs .While the QAM constellation size is constant and equals 64, there are two possible cyclic prefix lengths: 1/8 and 1/4 of OFDM symbol length at the output of IFFT block. The convolution code rate is then 3/4 and 5/6 respectively.

As already mentioned in our work we decided to compare the efficiency of the energy-detector, selected algorithms that base on the derivation of the covariance matrix of the received signal. We also propose a new feature detector algorithm that relies on the knowledge of the parameters of the DVB-T signal parameters (such as duration of OFDM signal, carrier frequency, sampling frequency and range of possible cyclic prefix (CP) lengths). In particular we propose to make use of autocorrelation properties of OFDM modulation used in DVB-T system in order to detect the signal in low-SNR regimes.

The rest of the paper is organized as follows: first, in Section 2 we present the channel model that has been considered in the simulation. Then, Section 3 presents the selected spectrum sensing algorithms and describes the new solution proposed in this paper. Section 4 contains the performance evaluation, and finally Section 5 summarizes the paper.

2. CONSIDERED CHANNEL MODEL

In our experiment we would like to verify the efficiency of the selected spectrum sensing methods putting the particular attention on the low-SNR regime. Moreover we would like to check the accuracy of signal-to-noise estimation in the considered simulation schemes. Although energy detection based algorithms are based on simple independence of signal and noise signals, the proposed feature detection has to take into account distortion introduced by wireless channel and transmitter/receiver imperfections. At the design phase such effects like white noise, multipath propagation or non-zero Carrier Frequency Offset (CFO) has to be considered Thus, let us then define the observed signal in the mathematical form as follows. The receiver willing to detect DVB-T signal obtains a complex signal, whose n-th sample can be defined as y_n. When the DVB-T signal is present in the received signal it can be written as

$$y_n = \left(\sum_{l=0}^{L-1} h_l x_{n-l}\right) e^{j2\pi\nu n} + w_n \qquad (1)$$

where the multipath channel of L paths is considered and the complex channel coefficient of the l-th path is denoted as h_l. x_n refers to the n-th sample of transmitted OFDM signal (please note that OFDM symbols in DVB-T are transmitted continuously), and ν stands for the value of CFO, while and w_n for the complex sample of Additive White Gaussian Noise (AWGN) of power σ_w^2. As the detection of DVB-T channel will be limited in time (the decision has to be made in finite time after collection of e.g. N samples) we assume that multipath channel coefficients and CFO do not change over the observation period. Assuming normalized transmit power, the observed Signal-to-Noise-Ratio (SNR) of DVB-T signal can be described as

$$SNR = \frac{\sum_{l=0}^{L-1} |h_l|^2}{\sigma_w^2}. \qquad (2)$$

3. CONSIDERED DETECTION METHODS

3.1. Energy detector

The simplest spectrum sensing strategy is to analyze the amount of the energy measured in the considered frequency band and compare it with a pre-calculated decision threshold ζ_{ed}. The test statistic T_{ed} can be defined as:

$$T_{ed} = \frac{1}{N}\sum_{i=0}^{N-1} |y_n|^2 \qquad (3)$$

When $T_{ed} \geq \zeta_{ed}$ the decision on the presence of DVB-T signal should be made, whereas in the opposite case the channel can be stated as vacant. The decision threshold is defined as:

$$\zeta_{ed} = \sigma_w^2\left(1 + \frac{Q^{-1}(P_{fa})}{\sqrt{0.5N}}\right), \qquad (4)$$

where P_{fa} stays for probability of false alarm, and Q^{-1} defines the inverse Q-function. In the case of perfect knowledge of noise variance the reliability of the energy detector can be improved by increasing the observation time (number of collected samples N). However, when the noise power has to be estimated and some inaccuracy will be present it will not be possible to improve the energy-detection efficiency even for infinite number of collected samples. This phenomenon is known in the literature as SNR wall [10], [11]. In our paper we assume perfect knowledge of the noise variance in order to compare the performance of the proposed method with the best situation from the energy-detection point of view.

3.2. The proposed CP-based (feature) detector

The considered feature detector utilized the auto-correlation property of main part of OFDM symbol and its CP. Although such an approach has been considered previously e.g. in [9], our approach takes into account periodicity of OFDM symbols increasing rapidly signal detection quality. The proposed method is depicted in Fig. 1. In that scheme we utilize the facts that are known about DVB-T signal broadcasted in Poland, i.e. N=8192 samples of main part of OFDM symbols are transmitted during 896μs. Each OFDM symbol is preceded by CP of $N_{CP} = \frac{N}{4}$ or $\frac{N}{8}$ samples. First, incoming signal (of sampling rate 9.14286MSps) is correlated with its part delayed by N samples over correlation window of N_{CP} samples as

$$R(n) = \sum_{k=0}^{N_{CP}-1} \overline{y_{n+k}}\, y_{n+k-N}\ , \qquad (3)$$

where $\bar{y}$ denotes complex conjugate of y.

The expected value of (3) assuming, for simplicity, single tap channel, no noise and alignment in time (n) with CP is

$$E[R(n)] = E\left[\sum_{k=0}^{N_{CP}-1} \overline{h_o x_{n+k}} h_0 x_{n+k-N} e^{-j2\pi\nu N}\right] = |h_0|^2 N_{CP} e^{-j2\pi\nu N}. \quad (4)$$

If the samples x_{n+k} and x_{n+k-N} are not the same (i.e. x_{n+k-N} does not belong to CP) the expected value will equal 0. In the situation when only some components of the sum in (4) have values of x_{n+k} and x_{n+k-N} the same, the absolute value of $E[R(n)]$ will be proportional to number of identical samples, i.e. lower than $|h_0|^2 N_{CP}$. It means that the higher the peak, the more probable detection of the DVB-T channel.

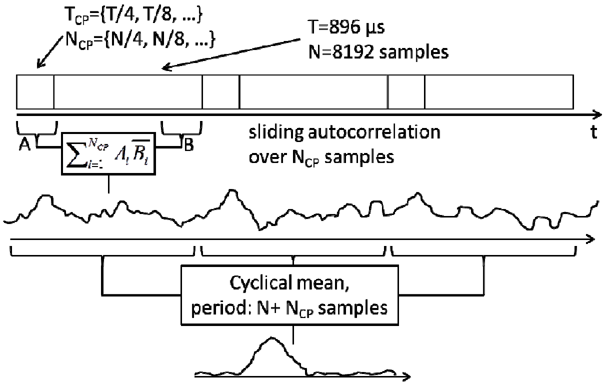

Fig. 1 Scheme of the proposed CP-based detector.

In (4) we assumed that the influence of noise is negligible, though in the measurement environment of interest the noise power can be even higher than the useful signal power. In such a case the variance of metric (3) will be dominated by noise variance that can produce high amplitudes of $R(n)$ even when OFDM signal is not aligned/available. In order to counteract this phenomenon the arithmetical mean with periodicity of N+N_{CP} samples over G periods is proposed in this paper:

$$\hat{R}(\hat{n}) = \frac{1}{G}\sum_{g=0}^{G-1} R(\hat{n} + g(N + N_{CP})) \quad (5)$$

for $\hat{n} = \{1, \ldots, N + N_{CP}\}$ and assuming that $G(N + N_{CP})$ autocorrelation results are available. One can observe that the maximum of the expected value presented in (4) is independent from the complex symbols modulating a given OFDM symbol. As for G consecutive OFDM symbols channel paths coefficients $h_l$and CFO ν can be treated as quasi-constant, the expected value in (4) will not be changed by (5). However, using the properties of arithmetic mean it can be observed that the variance of $\hat{R}(\hat{n})$ will decrease G times in comparison to (3) enabling DVB-T signal detection even under severe noise.
Importantly, the proposed scheme does not require time or frequency synchronization. Unknown time shift will cause the position of peak in $\hat{R}(\hat{n})$ to be unknown. However, by using max operation the estimate of the $\hat{R}(\hat{n})$ peak value caused by DVB-T signal can be found i.e.

$$\widehat{R_{est}} = max_{\hat{n}}\left|\hat{R}(\hat{n})\right|. \quad (6)$$

The CFO can be tolerated as long as OFDM subcarrier frequencies are within the bandwidth covered by the receiver sampling frequency i.e. maximum CFO of (9.14286/2-7.61/2)MHz≈770kHz can be tolerated without detection quality degradation.

Interestingly, the averaging in (5) allows for detection of correct values of the cyclic prefix length N_{CP}. If the incorrect one is chosen, the periodicity of (4) will be different than the one assumed in (5) and the detection metric peaks will be misaligned leading to low values of (6). Therefore, for each value from the set of possible cyclic prefix lengths calculation of (6) should be done. For the value of estimated CP length (N_{CP} in (5))being the same as CP length in the received signal, (6) will obtain higher value than in all other cases. As such, it will point at the correct CP length.

As the value obtained by (6) is hard to be interpreted, a transformation proposed in [12] can be used. Let us define the metric *M* as:

$$M = \frac{\widehat{R_{est}}}{\frac{N_{CP}}{G(N+N_{CP})}\sum_{k=0}^{G(N+N_{CP})}|y_k|^2} \quad (7)$$

where the denominator represents the mean power of the signal received over N_{CP} samples. Then q defined as

$$q = \frac{\sqrt{M}}{1-\sqrt{M}} \quad (8)$$

is an estimate of the received DVB-T signal SNR that will be used in order to evaluate the performance of the proposed method.

4. PERFORMANCE EVALUATION

Performance evaluation of the proposed algorithms was carried on hardware testbed depicted in *Fig. 2*. It is composed of a R&S vector signal generator SMBV100A responsible for DVB-T signal generation in the presence of AWGN with a given power. Unfortunately, that device does not possess the ability for multipath channel generation. The generator is connected via low-loss cable (around 1dB in the considered TV channel) to the R&S spectrum analyzer FSL6. Such a setup allows us for the acquisition of complex IQ samples at a given radio frequency up to the bandwidth of 28MHz. In the first step of the experiment, only white noise samples have been collected (DVB-T modulator turned off) in order to estimate the probability of false alarm (i.e. treating noise as DVB-T signal) associated with the proposed method.

As both devices have separate clocks and they start their operation in different time instances, non-zero timing and frequency error occurs. The spectrum analyzer is connected via Ethernet cable to a laptop computer where MATLAB with Instrument Control Toolbox runs. Main parameters of the testbed are listed below:

- SMBV carrier power: -30dBm (fixed)
- Carrier frequency: 498 MHz
- DVB-T OFDM size: 8192 subcarriers
- Cyclic prefix length: 8192/8 samples
- Modulation: 64QAM
- Sampling frequency: 64/7 MHz
- Input SNR (set at SMBV) was measured over 7.61 MHz (i.e. occupied subcarriers bandwidth)

- Bandwidth of FSL: 10 MHZ (resampled to 64/7 MHz in MATLAB)
- Noise power: varies in the range from -5 to -60dBm.

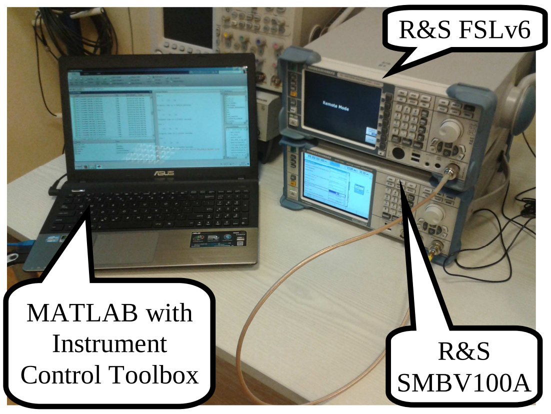

Fig. 2 Picture of the used testbed.

4.1. Performance analysis of the Energy detector

In order to analyze the performance of the pure energy detection in the ideal condition (i.e. the noise variance is perfectly known) the received samples have been processed in Matlab for different number of collected samples *N*. It can be observed that the higher the number of samples, the better the performance. However, it has to be clearly stated that in presence of some noise variance the obtained results will be much worse. In this paper we intentionally limit our analysis to the ideal case, and we encourage interested readers to focus on rich literature on energy-detection performance.

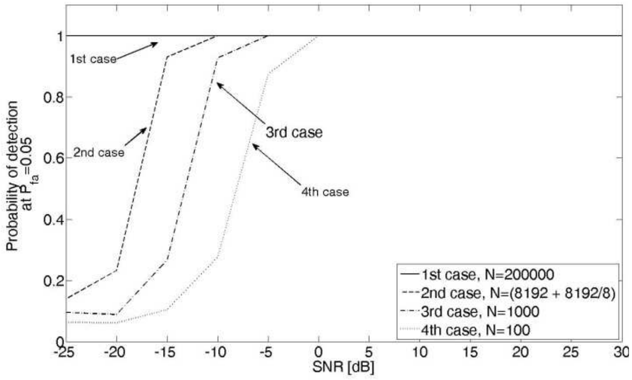

Fig. 3 Probability of detection of the pure energy detector as a function of SNR and the duration of observation N.

So far we have assumed the perfect knowledge on the noise variance estimation (i.e. since the signal and noise have been generated in the signal generator we know their exact values in advance), thus the influence of duration of sensing time has been showed in Fig. 3. However in order to make the results closer to reality let us consider more pragmatic case, where some uncertainty of noise variance estimation has been taken into account. In particular, based on [11] we have included the noise estimation error that will degrade the probability of false alarm. In other words, we have added the estimation error to the previously perfectly known noise power. Two values of estimation errors have been selected, δ=0.2dB and δ=0.5dB, i.e. if the ideal and real noise variance was equal to *x*, the shift of δ dB has been added. The efficiency of the energy detector that takes into account the effect of noise uncertainty has been shown in Fig. 4. One can observe the presence of the so-called SNR-wall, i.e. such value of SNR related to the give noise uncertainty below which the probability will of detection will be always zero regardless of the observation time.

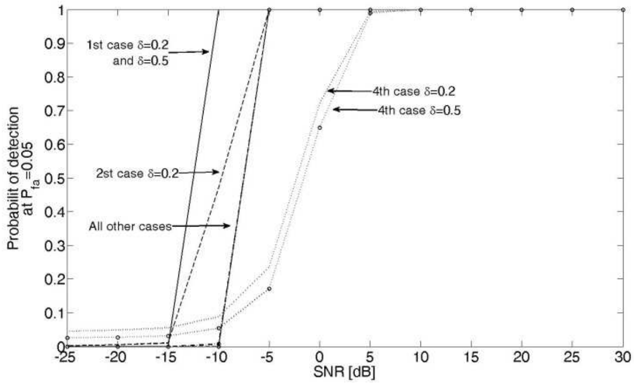

Fig. 4 Probability of detection of the pure energy detector as a function of SNR and the duration of observation N – influence of estimation error.

4.2. Performance analysis of the CP-based detector and analysis of the SNR estimation

Although for every spectrum sensing methods we have dealt with the same signal samples, in the case of the CP-based detector it is worth dividing the whole experiment in two consecutive and disjoint parts.

First phase of the experiment

In this part we will investigate the performance of the proposed feature detector under white noise. It will allow us to define susceptibility of the proposed algorithm to false alarm i.e. detecting noise as DVB-T signal. Threshold will be given that can be used in the next experiment phase, when DVB-T signal is present in the received signal. In *Fig. 5* it is visible that white noise gives SNR estimate of about -11dB (without averaging, i.e. for one OFDM symbol) although in theory SNR of -∞dB should be detected. However, thanks to the proposed averaging scheme the estimated SNR can fall by about 8dB (with averaging over 50 OFDM symbols).
We can use directly the 5th percentile curve in order to obtain the threshold for the probability of false alarm 5%. For each averaging length at least 15 independent results were obtained. Based on the presented results it can be concluded that for the system without proposed averaging the DVB-T signal can be detected down to SNR=-9.8dB, i.e. estimated SNR higher than that has probability of being caused by noise of only 5%. For estimated SNR values lower than -9.8dB it can be either noise or DVB-T signal that is detected. In practice the worst case has to be considered. It means that from the perspective of the secondary user, the estimation of SNR at the level -9.8dB should be classified as the presence of

DVB-T signal. However, due to the proposed averaging operation this threshold can be decreased, e.g. to -15dB for 10 consecutive OFDM symbols and to -18.62dB for 50 symbols.

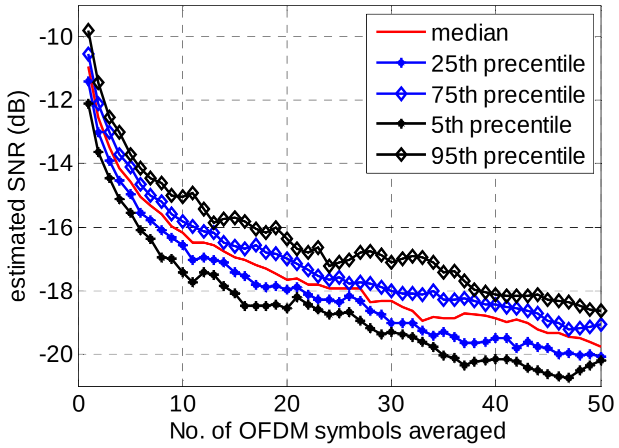

Fig. 5 Result of processing white noise with CP-based detector while increasing averaged symbols number.

Second phase of the experiment

In the second phase of the experiment, the measurements were carried out while changing the SNR of transmitted DVB-T signal (at SMBV) in a range from -25 to 30dB (with step of 5dB). Such an operation is equivalent to changing the noise variance from -60 to -5dB while keeping the signal power constant.

In case of CP-based feature detector boxplots in *Fig. 5*-*Fig. 8* show that the proposed detector works best when SNR is around 0dB (accurate estimation and small deviation). For both high and low SNRs the detector loses its accuracy. As this phenomenon at low SNR was characterized while describing *Fig. 5*, the inaccuracy at high SNR was described in [12] and is observed when *M* in (8) is close to its maximum value of 1. Comparing *Fig. 6*-*Fig. 8* it is visible that the correct estimation range can be increased by utilizing the proposed averaging process.

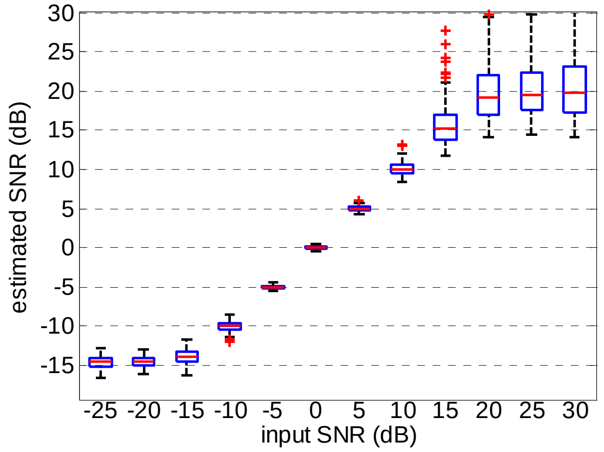

Fig. 6 Estimated DVB-T signal SNR with CP-based detector vs input SNR when no averaging applied

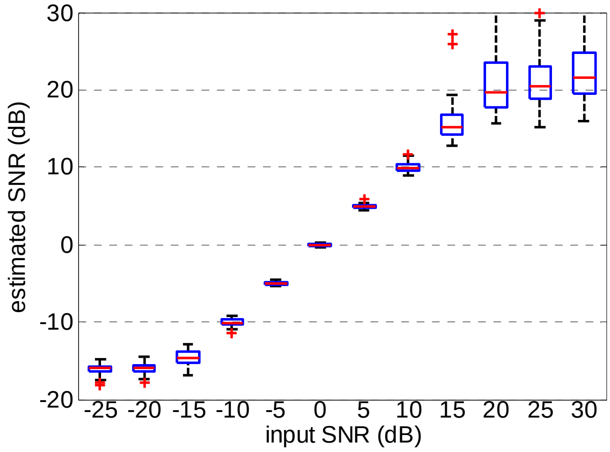

Fig. 7 Estimated DVB-T signal SNR with CP-based detector vs input SNR when averaged over 10 periods.

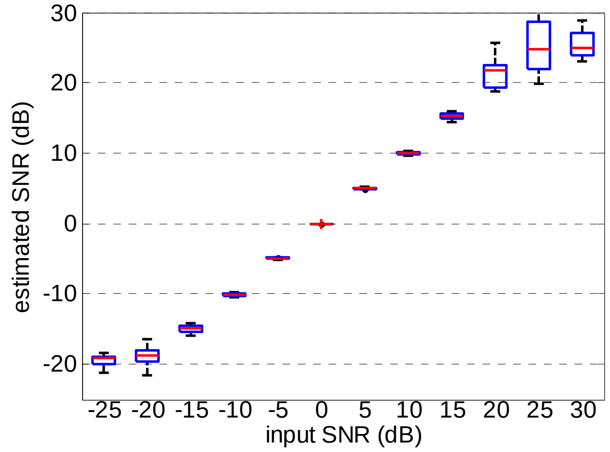

Fig. 8 Estimated DVB-T signal SNR with CP-based detector vs input SNR when averaged over 50 periods.

Based on the results obtained in *Fig. 6*-*Fig. 8* and for the thresholds obtained in the first phase of the experiment (see *Fig. 5* and the curve for P_{fa}=0.05), the values of the probability of DVB-T signal detection has been achieved and shown in Fig. 9. It can be noted that the proposed averaging scheme increases the probability of correct detection. However, it has to be kept in mind that the averaging can be make only as long as CFO and channel taps can be treated as constant (as assumed in Sec. 3.2).

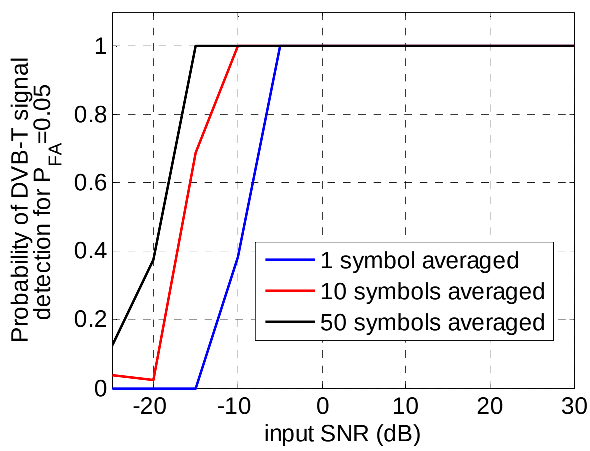

Fig. 10 Probability of DVB-T signal detection for CP-based detector.

5. CONCLUSIONS

The main goal of the paper was to discuss some aspects of obtaining data for the Radio Environment Maps that can be used for cognitive systems deployed inside the buildings. It has been presented that the entries of the REM databases should be characterized by by the highest possible level of accuracy and reliability. In order to fulfil such requirement sophisticated spectrum sensing methods should be applied that will be able to detect the presence of the primary user signal (DVB-T in the considered case) at low SNR levels. In the paper we have compared the well-known energy detector with the new Based on the presented results it can be concluded that the simple energy detection does not provide sufficient efficiency since for quite number of observed samples (one OFDM symbols) and perfect knowledge of the noise variance the primary user signal can be detected at SNR around -15dB achieving probability of detection around 0.9. Although similar results can be obtained for the proposed CP-based method it has to be highlighted that the real accuracy of the energy detector will be much worse due to the inaccuracy of the noise variance estimation. It further means that the application of the feature-detection based spectrum sensing methods for signal detection should be applied in low-SNR regimes which are characteristic for the indoor environments. Moreover, the CP-based method offers a quite reliable method for SNR estimate that can be used as additional information stored in the indoor REMs.

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