EXPERIMENTAL EVALUATION OF RADIO FREQUENCY SPECTRUM SENSING DETECTORS IN TV BANDS

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Abstract: This paper deals with real time experiments with spectrum sensing in TV bands. First, different spectrum sensing algorithms suitable for fast signal detection of digital TV signals are reviewed. The performance of several selected detectors has been evaluated on data of real TV transmission in Brno region. Three different implementations have been setup – first using the Universal Software Radio Peripheral device, second using PC with data acquisition card sampling the DVB-T tuner intermediate frequency output and the third based on the implementation of energy detector in Xilinx Virtex IV FPGA. Moreover the experiments with decision fusion from heterogeneous detectors have been performed.

1 INTRODUCTION

The requirements on current radio communication technologies are significantly increasing in order to provide high reliable high speed communications. The user desires are often in contrast to technological limits like spectrum availability. Cognitive radio (CR) has been introduced as a promising technology to effective spectrum utilization in wireless communication (Quan, 2008). All the cognitive radio users are divided into the primary (licensed) and secondary users. In a CR network secondary users scan the frequency spectrum (try to detect a spectrum holes in time or frequency domain) and adapt transmission parameters to actual available communication channel. The work described hereinafter has been focused on the detection of licensed users in TV bands. Digital Video (DVB-T) and analogue broadcasting belong to primary users. The main goal of the spectrum sensing device is to distinguish between two basics hypothesis:

$$\begin{aligned} &H_0: x(n) = v(n) \\ &H_1: x(n) = v(n) + s(n), \qquad n = 1, 2, \dots, N, \end{aligned} \tag{1}$$

where H_0 stands for the absence and H_1 for the presence of primary user signal. In the case of valid H_0 the channel is unused and contains only noise term $v(n)$. The hypothesis H_1 represents the case of primary user presence, where $s(n)$ is the primary user's signal and $v(n)$ is the additive noise term.

The paper is structured as follows. The section 2 reviews the basic spectrum sensing detectors and presents their brief comparison. Section 3 is devoted to the overview of possible methods for decision fusion from various devices. In section 4, the setup for experiments in TV band is presented, while the measurement results are summarized in section 5.

2 SPECTRUM SENSING ALGORITHMS

Many spectrum sensing detectors have been proposed for the use in cognitive radio applications. There are several criteria like the simplicity, robustness, sensing time and application range, helpful for the appropriate choose of the detector. Below the three main families of different algorithms for sensing will be briefly reviewed.

2.1 Energy Detection

Energy detector is the most common way of spectrum sensing because of low computational and implementation complexities (Shankar, 2005), (Yuan, 2007). It decides about the data occupation by simple estimation of the energy in the channel. The receivers do not need any knowledge about the primary users. The received signal is detected by

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comparing the output of the energy detector with a threshold. The threshold λ depends on the noise floor and is compared with test statistic $T(x)$given by 0):

$$T(x) = \sum_{n=1}^{N} |x(n)|^2. \tag{2}$$

Some of the energy detector disadvantages can be characterized as: bad performance under low signal to noise ratio values, poor detecting of spread spectrum signals and problems with selection of the threshold for detecting users. Many methods of energy detection are based on the periodogram principle or its modifications. Some of the approaches will be further discussed in next section.

2.2 Matched Filtering

Matched filtering is considered as convenient method for detection of primary users if the transmitted signal is known a priori (Cabric, 2006). It is also called as coherent detector. The method requires good knowledge about primary user signal such as modulation type, bandwidth, carrier frequency, etc. The test statistic is compared with threshold and in the discrete form is defined by (Quan, 2008):

$$T(x) = \sum_{n=1}^{N} x(n)s^*(n), \tag{3}$$

where $s(n)$ denotes known signal.

2.3 Cyclostationary Sensing

It is also called Feature Detection. Cyclostationary based sensing uses the unique pattern of the signal to detect its presence (Gardner, 1991). Major primary signals are modulated by the sinusoidal carriers or have cyclic prefixes. Periodic correlation function is used for detecting signals in a frequency spectrum. The feature detection belongs to more difficult implementations. The method is described in detail in (Quan, 2008). It is sensitive to the impairments between the cyclic frequency, carrier frequency and sampling frequency.

3 DECISSION AND ITS FUSION

One of the main problems related with the correct decision about the spectrum usage is the appropriate threshold setting. This problem is frequently solved by empirical methods based on measurement from real environment. In this case the assumption of free channel with white noise only is deployed for all above-mentioned methods of spectrum investigation.

The performance of the detectors can be well characterized using the ROCs (Receiver Operation Characteristics). During the estimation of ROCs, the decision threshold is moved along the probability of false alarm P_{fa} and the real probabilities of correct incumbent's signal detection (detection probability) are computed.

In order to improve the reliability of decision about channel utilization it is possible to fuse decision results from more than one detector (Kattepur, 2007). These detectors can be located at one place or the spatial distribution of them can be employed. Currently, the most of the research in this domain employs the detectors of the same type (mostly energy detectors). Essentially each detector can be of different type than others. We consider that every detector gives Boolean result for every channel at every decision period. The fusion of these results can be performed by one of the basic rules: AND, OR, majority, eventually more sophisticated rules using weighting and statistical models.

4 EXPERIMENTAL SETUP

This section is devoted to the description of individual spectrum sensing methods selected for the experiments and three different experimental implementations.

4.1 Used Sensing Methods

Four different spectrum sensing methods has been used thorough the experiments. First two of them correspond to the energy detection family (see section 2.1), other two uses either some statistical properties of signals (key features) or the cyclic prefix property of DVB-T OFDM signal.

4.1.1 Welch Periodogram

Let's assume signal $\{x[n]\}_0^{N\text{-}1}$ with length of N samples. The Welch spectrum estimate can be obtained using the equation (Madisetti, 1998):

$$P_{\mathrm{W}}(f) = \frac{1}{K}\sum_{k=1}^{K}\frac{1}{L}\left|\sum_{n=0}^{L-1} w(n)x_k(n)e^{-j2\pi fn}\right|^2, \tag{4}$$

where $x_k(n)$=x(n+(k-1)D), L is the length of segment, K stands for number of segments. The Welch's method is similar to Bartlett periodogram, the difference lies in using D samples overlap of segments and multiplying every segment by window function $w(n)$. Typical overlap values are 25%, 50% or 75% of segment length L.

4.1.2 Multi Window Spectral Estimation

This method (sometimes called Multi tapper method) uses the set of orthogonal sequences as the windows applied to the periodograms. Final spectrum estimate is given as the average of all particular periodograms. The discrete prolate spheroids - Slepian sequences are often used as the windows.. The corresponding power spectrum estimate is given as (Thomson, 1982):

$$P_{\mathrm{MW}}(f) = \frac{1}{m}\sum_{i=0}^{m-1}\frac{1}{\lambda_i}\left|\sum_{n=0}^{N-1} w_i(n)x_k(n)e^{-j2\pi fn}\right|^2 \qquad (5)$$

Where m represents number of used windowing sequences, w_i and λ_i are the i-th sequence and its eigenvalue respectively.

4.1.3 Signal Key Features

This method initially proposed for the modulation type classification has been proposed in (Ulovec, 2008). In that paper, several features (most of them statistical moments) have been defined. During our experiments, we have used mainly the feature denoted $A_{S.}$ More informations about the method can be found in the original paper. Defined signal key features can be used also for modulation type recognition. In TV bands, the classification into 3 classes – DVB-T, analog TV or noise is possible in the assumption of sufficiently high *SNR*.

4.1.4 Cyclic Prefix Correlation

The correlation algorithm generally defined as:

$$R_{fg}(n) = \sum_{m=-\infty}^{\infty} f^*(n)g(n+\mathrm{m}) \qquad (6)$$

can be used for signal presence detection. There are several possible alternatives of signals f and g assignment (autocorrelation, correlation of received signal with known preamble etc.). We have used the special property of the OFDM signal used for DVB-T (ETSI, 2009) broadcasting – cyclic prefix. Sliding correlation of two signals with duration of cyclic prefix length and time separation corresponding to the length of OFDM symbol useful part has been used. Because both signals actually present in the windows are almost identical, the peaks in the correlation function will occur. The correlation peak and average values have been measured and compared with selected threshold.

4.2 Experimental Implementations

4.2.1 Sensing Device in Universal Software Radio Peripheral

In this first described implementation, the radio frequency signal has been received by the Universal Software Radio Peripheral (USRP) device equipped with TV tuner TVRX, both commercially available from Ettus Reseach company. The received complex baseband signal has been acquired to Simulink environment, where the above mentioned sensing methods have been tested. The issue of this implementation for the use in European countries is in different bandwidth of TV tuner developed for US use.

4.2.2 PC-based Sensing Device by Sampling DVB Tuner Output

This implementation has been based on the sampling of the intermediate frequency output of commercially available Humax F3-FOX T DVB-T receiver. The received signal has been digitized by Gage CompuScope 12400 card. The sampling frequency of 100MHz with 12 bit resolution has been used. The data have been subsequently converted into baseband with the use of Hilbert transformer and downsampled by factor of 10 in order to relax the processing complexity.

4.2.3 FPGA Sensing Device by Sampling DVB Tuner Output

The energy detector based on the periodogram was synthesized for FPGA Virtex IV (device xc4vsx35) device with use of the Xilinx System Generator environment. For the real time implementation the Memec Virtex IV MB Development Kit with analogue module P240 was chosen (Memec design, 2005). Hardware details are described in the following paragraph. The analogue module provides dual channel analogue inputs and outputs. The A/D converters are 14 – bits up to 125 MSPS. Similarly to the previous case, the intermediate frequency signal from DVB-T receiver has been sampled by the A/D converters in analog module as is shown in Figure 1.

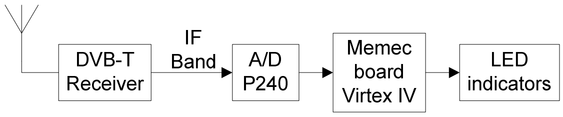

Figure 1: The block diagram of spectrum sensing chain with FPGA Virtex IV device.

The band from 32 MHz to 40 MHz, corresponding to one TV channel around the 36MHz IF has been used for the energy detection. Simplified block schematic prepared in Xilinx System generator is shown in Figure 2. Two LED diodes were used as signal present/absent indicator. The power is computed at the output of FFT block with possibility to average the individual periodograms. Computed power in the band of interest is compared with the threshold determined in order to guarantee desired false alarm/correct decision probability. If the detected power is higher than threshold level it is signalized by green LED indicator inversely by red LED indicator. The device utilisation is summarized in Table 1.

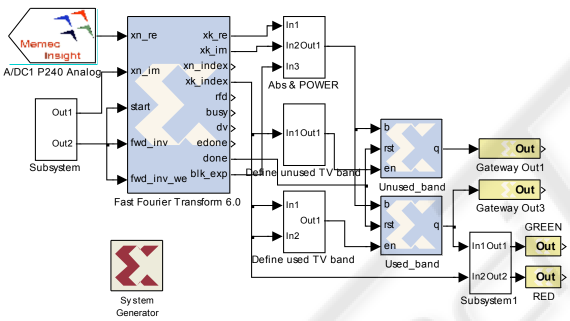

Figure 2: Simplified block diagram of the FPGA implementation (created in Xilinx System Generator).

Table 1: Device Utilization of the Virtex IV xc4vsx35.

Logic type	Utilization [%]
Number of Slice Flip Flops	14
Number of 4 input LUTs	16
Number of occupied slices	25
Number of DSP48 slices	32

5 RESULTS

The test statistics (detector outputs) calculated from 1000 realizations for used detectors are shown in Fig. 3. Each measurement has been performed for three channels – one used by DVB-T multiplex, one occupied with analog TV and one channel with no transmission (noise and outside band interferences only). It is evident, that for the presented situation (relatively high SNR), the detectors can more or less distinguish between the case of present DVB –T signal, present analogue TV signal and no signal. The method based on the cyclic prefix correlation is, from its principle, suitable only for DVB-T signal detection.

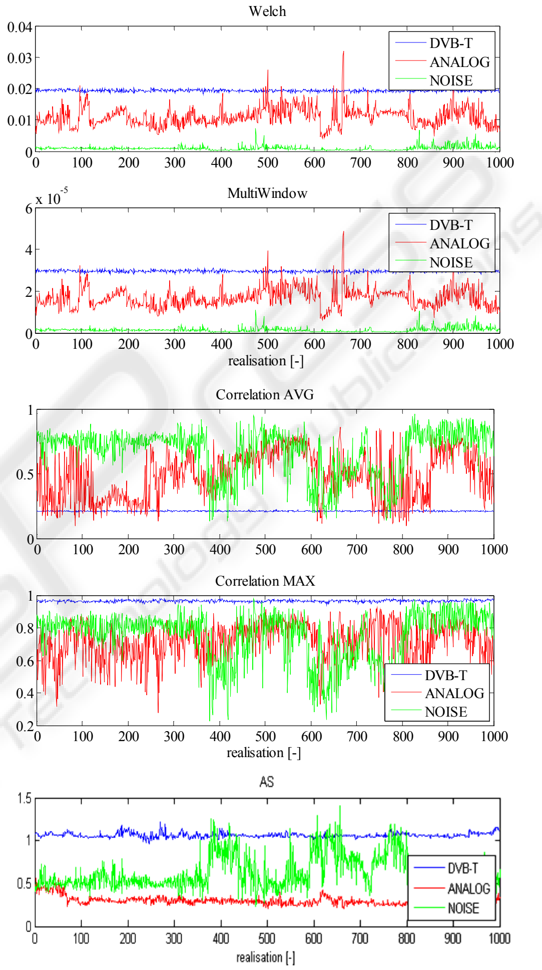

Figure 3: Test statistics for various detector types . From top to bottom: Welch periodogram, MultiWindow, Correlation (average value), Correlation (max value), key feature AS.

The corresponding ROC curves for channels occupied with digital TV, analog TV (PAL) and no signals for Multi Window, key feature AS and correlation detectors are presented in Fig. 4. Note that the presented performance corresponds to the situation of relatively strong received useful signal and that the detector’s performance for low Signal to Noise Ratios (SNR) will differ. It is expected that a correlation detector would outperform both energy based detectors in low SNR situation.

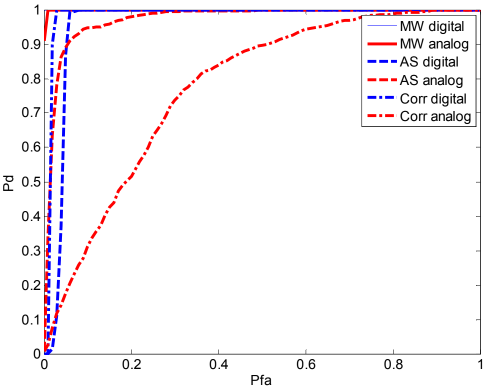

Figure 4: ROC curves for Multi Window (MW), key feature AS and correlation (Corr) detectors for both digital and analog TV signals sampled at DVT-T receiver IF output.

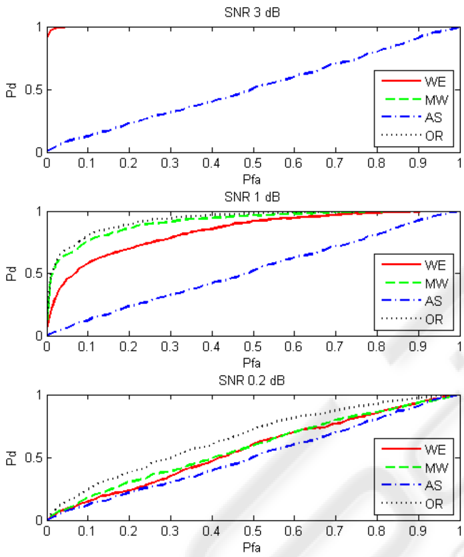

Figure 5: ROC curves for three investigated detectors – Welch (WE), MultiWindow (MW), key feature AS, together with OR fusion of Welch's and Multi Window in various SNR.

In order to obtain the ROC curves for lower SNR, the Additive White Gaussian Noise has been added in MATLAB to signals sampled at DVB-T receiver IF output. The estimated ROC curves for three SNR values and three selected detector types computed in MATLAB are shown in Fig. 5. The fourth ROC in the graph denoted OR corresponds to decision fusion of results provided by Welch's and Multi Window method with logical function OR. It is evident that this method improves the ROC shape, hence the quality of detection method is increased. As the situations with considerably low SNR have been assumed, the key feature based method AS does not perform well for such low SNR's. The performance of other methods for 3dB SNR is almost perfect. For SNR equal to 1dB, it is possible to distinguish different performance of each method. For very low SNR of 0.2 dB, the performance is highly degraded. It can be improved using OR or any other form of decision fusion.

The last figure – Fig. 6 shows an example of power spectrum estimate from the FPGA implementation. The case corresponds to the channel occupied by the DVB-T multiplex signal. The channel centered at IF frequency is marked by the red box.

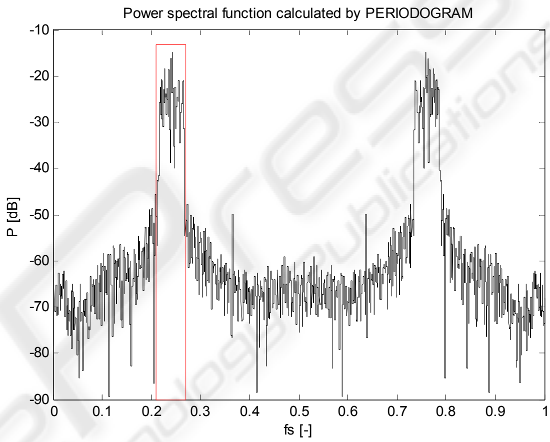

Figure 6: Power frequency spectrum estimation computed by the FPGA based sensing device (DVB-T transmitting in the tested channel).

6 CONCLUSIONS

The experimental verification of four various spectrum sensing detectors in TV bands has been presented. The three experimental implementations have been briefly described and the results obtained by the measurement and analysis of real TV channels in Brno region have been presented. The results have been presented in form of test statistics for 1000 consecutive measurement realizations and the corresponding ROC curves have been calculated.

During the experiments, the channels with high signal quality resulting in high signal to noise ratio has been measured. The performance of three detectors (Welch periodogram, Multi Window method and key feature) for low SNR has been further evaluated by the computer simulation with the added AWG noise.

Further work will be directed towards incorporating more advanced type of detectors, their evaluation for a network of several mobile sensing devices and towards to integration of the sensing process together with the adaptive multicarrier cognitive radio system.

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