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Fast Spectrum Sensing Method for Cognitive Radio

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A key aspect of the functioning of cognitive radio systems is fast and reliable detection of unoccupied channels in cases of dynamic changes of electronic environment. To solve this problem, a fast iterative method based on the coefficient of variation as decisive statistic of the power spectral density (PSD) is proposed. The essence of the method is in comparing the values of the coefficient of variation with the threshold value using the predicted value of the number of signal samples and the method of the golden ratio. The threshold values of the decision statistics were obtained by calculating the vector of PSD, sorting and normalizing it to energy, and calculating the vector of values of the coefficients of variation by sequential removing from the normalized PSD samples with the maximum value. To reduce the number of iterations when calculating the decisive statistics, the predicted value of spectrum occupancy is used. This value is calculated using an empirical formula with the coefficient of variation for the zero iteration as an argument. In practice, the presence of several signals with different powers in the analyzed bandwidth leads to errors in the predicted value of spectrum occupancy. Moreover, the larger the dynamic range and the lower the signal-to-noise ratio, the greater this error will be. The predicted value of the spectrum occupancy is a rough estimate of the number of signal samples in the spectrum, and the golden ratio method was applied to find its true value in fast way. Processing gain in reducing the number of iterations for calculating the decisive statistics depends on the spectrum occupancy prediction error and can reach several tens of times. The proposed method can be used to improve existing and develop new cognitive radio systems based on Software Defined Radio (SDR) technology.

Key words: coefficient of variation; iterative method; cognitive radio; golden ratio; spectrum occupancy; threshold

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Introduction

Radio systems based on SDR technologies have become widely used due to providing flexible management of radio frequency spectrum [1–3]. A key aspect of the functioning of cognitive radio is fast and reliable sensing of unoccupied frequencies in case of dynamically changed electronic environment [4,5]. The solution of this problem is complicated by a priori unknown and time-varying noise variance, number and dynamic range of signals in the analyzed bandwidth. Also, when scanning wide frequency bands, the noise level at different frequencies can change significantly. In addition, using of various SDR transceivers, amplifiers and switching antennas requires ongoing estimation of noise power, which in an unknown signal environment is associated with significant difficulties.

In unknown and dynamic signaling environment, estimation of noise variance for threshold calculation will be performed with errors. Increasing the noise variance by only 20% of the estimated leads to an increasing in the probability of false alarm by an order and even more. In such conditions, there is a need to develop a fast spectrum sensing method with noise-independent characteristics of detection spectrum holes.

1 Review of related works

A significant number of scientific publications is devoted to the radio frequency spectrum sensing in cognitive radio systems. In [6] proposed an adaptive spectrum sensing algorithm for a dynamic signaling environment using estimates of noise variance obtained from autoregressive model. However, the proposed threshold adaptation procedure uses slow and complex gradient methods. In [7] for signals detection was proposed calculation the wavelet transform of spectrum and compute the discrete cosine transform from the low- and high-frequency wavelet coefficients. But it is not specified how the threshold is calculated and whether it depends on the noise level. In [8] proposed threshold adaptation in the frequency domain using a set of bandpass filters. But the adaptation algorithm requires knowledge of noise and signal power. In [9] for detection and accurately estimation signals parameters in frequency domain, first calculate the spectrum on a short time window and roughly estimate the occupied frequency bands. In the second stage, using the Goertzel algorithm, accurate estimates of the signal parameters are obtained. However, the threshold value does not adapt to changes of noise variance. In the multi-channel method of signal detection proposed in [10], the noise power is estimated at unoccupied parts of the spectrum, which requires a preliminary analysis of the analyzed frequency band. Limitation of proposed in [11] method for detecting occupied frequency bands is its performance only on signals with a rectangular spectrum. The closest to the proposed method is described in [12]. But the computational complexity of this method increases with increasing spectrum occupancy. Thus, the problem of fast spectrum sensing under conditions of noise variance uncertainty remains unresolved.

2 Purpose and objectives of research

The aim of the article is to provide the possibility of fast and reliable detection of unoccupied spectrum channels for cognitive radio systems in conditions of dynamic change of noise variance.

3 Methodology of spectrum sensing acceleration

To solve the problem of spectrum holes' detection fast iterative method based on decisive statistics is proposed. The Welch method, which is based on the calculation of the Fast Fourier transform (FFT) and has a low variance of spectral estimates, is used to estimate the PSD. This method is based on the division of input sequence of samples of length M into K segments of length N with overlapping L samples, calculation modified periodogram for each segment and averaging of the obtained periodograms.

According to [12], the coefficient of variation of the PSD samples Q, which has a much smaller variance than the variance of PSD samples themselves, is chosen as the decisive statistics. The essence of the proposed method is to compare the values of the coefficient of variation of the spectrum with the threshold value for each iteration.

The threshold values of the decisive statistics are obtained by calculating the vector of the PSD samples for noise, its sorting and normalization to energy and computing the vector of values of the coefficients of variation by sequential removing from the normalized PSD vector sample with the maximum value. The length of the coefficients of variation vector is equal to the length of the vector of spectral samples. After processing a large number of noise realizations (determined by the required accuracy of the threshold calculation) for each iteration is calculated the threshold value of the coefficient of variation $Q_{tr}[i]$ for a given probability of false alarm in the frequency domain P_F. It was experimentally found that for a given quantile of the probability density distribution of the decisive statistics Q_{tr} of the level α is performed the approximate equality $P(Q_{tr}[i]) = 1 - \alpha \approx 1 - P_F$.

Fig. 1 shows the dependence of the threshold value of the decisive statistic Q_{tr} via iteration number for $P_F = 10^{-3}$ and for different values of the FFT window length. At low spectrum occupancy levels, which is equivalent to a small value of the iteration, the threshold value of the decisive statistics increases with increasing length of the FFT window.

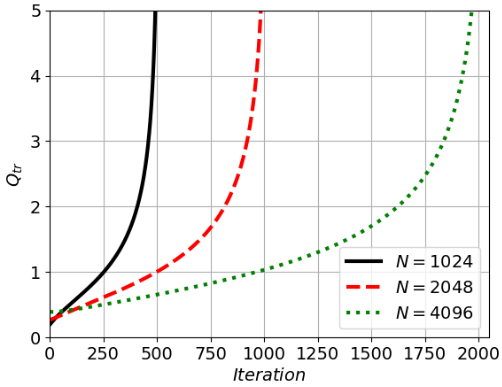

Fig. 1. Threshold values of decisive statistics Q_{tr} via iteration

At large N and high bandwidth occupancy η described in [12] iterative algorithm requires significant computational resources. To reduce the number of iterations for the calculation of the decisive statistics in the detection of spectrum holes, the predicted value of spectrum occupancy level (number of signal samples) is used. This value is calculated by the empirical formula using the coefficient of variation of the PSD for zero iteration of decisive statistic Q_0. The formula for predicting the spectrum occupancy is obtained by approximating the experimental dependence of the coefficient of variation via spectrum occupancy for the value of the signal-to-noise ratio (SNR) of 10 dB and the same power of all signals in the sensing bandwidth. For a real signal, the predicted value of the number of signal samples can be calculated by the following empirical formula:

$$J_{pred} \approx 0.5N \left(182e^{-0.89Q_0} + 2.15\right). \qquad (1)$$

This expression gives an accurate value of the spectrum occupancy, if the dynamic range of the signals does not exceed 10-12 dB. The dependency of the predicted spectrum occupancy η via calculated value of

Q_0 for zero iteration at SNR 10 dB is shown in Fig. 2. At other values of SNR there is an ambiguity concerning the predicted spectrum occupancy because Q_0 can have identical values for high spectrum occupancy and high SNR and low spectrum occupancy and low SNR.

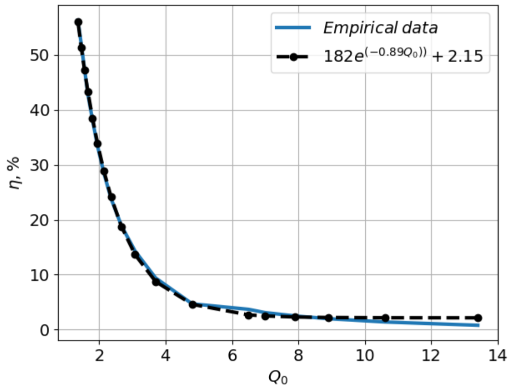

Fig. 2. Predicted spectrum occupancy level via Q_0

In general case, small values of Q_0 indicate high spectrum occupancy or a low occupancy at a low SNR value. Large values of Q_0 indicate low occupancy or high occupancy with a significant dynamic range of signals. Therefore, in most cases, the predicted spectrum occupancy value will be calculated with errors. The error value increases with increasing dynamic range of the signals in analyzed bandwidth.

In practice, the values of SNR and dynamic range can change significantly, which leads to errors in the predicted value of the spectrum occupancy. If there are several signals with different powers in bandwidth of the analysis, the predicted value of the occupancy will be underestimated, and for one signal with less than 10 dB SNR – overestimated. Moreover, the larger the dynamic range and the smaller the SNR, the greater the error in the spectrum occupancy prediction. The value of error can be estimated by the following expression:

$$\varepsilon_\eta = \frac{2\,(J_{estim} - J_{pred})}{N}\,, \qquad (2)$$

where J_{estim} is the estimation of the number of signal samples; J_{pred} is the predicted value of the signal samples number.

Predicted spectrum occupancy value is a rough estimate of the number of signal samples in the spectrum, and the golden ratio method was used to reduce time for finding its true value J_{estim}. Golden ratio method was chosen due to its' asymptotic effectiveness in realization of minimax strategy of extreme search.

The algorithm of the proposed fast spectrum sensing method is implemented using Python, so when describing further material, the peculiarities of this language are taken into account. The essence of the method is to sequentially perform the following steps.

1. Set the parameters of the Welch periodogram M, K, N, L, type of window function and the probability of false alarm and calculate the vector of threshold values of the decisive statistic $Q_{tr}[i]$, $i = 0 \ldots 0.5N-1$.

2. Calculate the PSD P_{xx}, its energy-normalized value X and form two auxiliary vectors: a descending array of frequency samples $P = sort(X, reverse)$, which will be followed by signal samples (in case of presence) and then noise, and the array of indices of the vector P – $Y = argsort(X, reverse)$.

3. Calculate the coefficient of variation of the PSD $Q_0 = variation(P)$.

4. Check if there is signal in given realization of PSD – $Q[0] \geq Q_{tr}[0]$.

5. If condition 4 is fulfilled, it is necessary to calculate the predicted spectrum occupancy value, which will correspond to some signal samples number J_{pred} in the vector P according to (1).

6. If because of approximation errors and noise influence the calculated value of J_{pred} is more than $0.5N$, it must be replaced by $0.35N$, and if less than 0 – by 0.

7. Calculate the new value of the decisive statistics $Q = variation(P[0 : J_{pred}])$.

8. Check the condition $Q[J_{pred}] = Q_{tr}[J_{pred}]$ and in case of its validation the vector of values of signal bins can be found as $Freq = Y[0 : J_{pred}]$, and the threshold value will be equal to the minimum value of the signal bin $Threshold = P[J_{pred}]$. The number of signal samples will be $J_{estim} = J_{pred}$, and the spectrum occupancy level will be $\eta = 2N^{-1}J_{estim}$.

9. If condition 8 is not fulfilled, and condition $Q[J_{pred}] < Q_{tr}[J_{pred}]$ is fulfilled, then the search of J_{estim} must be performed in the interval [1: J_{pred}]. To do this, the specified interval is divided into 3 segments in the proportion of the golden ratio. Dividing points have the following coordinates:

$$J_1 = B - \frac{B-A}{\varphi}\,, \quad J_2 = A + \frac{B-A}{\varphi}\,, \qquad (3)$$

where $A = 1$, $B = J_{pred}$ and $\varphi \approx 1{,}618$.

For these points, the values of the decisive statistics are calculated and are compared with the threshold values. The division of the segment in the proportion of the golden ratio continues until the difference between the calculated value of the decisive statistics at a given point and the threshold value becomes less than certain value. The point found will correspond to the required number of signal samples J_{estim}.

10. If conditions 8 and 9 are not fulfilled, the search for the number of signal samples J_{estim} is performed in the interval [J_{pred} : $0.35N$] similarly to the procedure described in 9.

4 Spectrum sensing performance

The predicted spectrum occupancy value in the vast majority of cases will deviate from the actual. The occupancy level may be lower than the predicted because of SNR value below 10 dB or higher due to the high dynamic range at high occupancy level or higher than 10 dB SNR at low occupancy.

Fig. 3 shows a variant of the underestimated predicted value of the spectrum occupancy due to the high dynamic range of signals. As can be seen from this figure, the error in predicting the number of signal samples is about 2 times. At Fig. 4 is shown results of proposed method performance for a spectrum occupancy of about 20%. The parameters of the Welch periodogram have the following values: $M = 16384$, $K = 16$, $N = 1024$, $L = 512$, the type of window function – Hamming. The probability of false alarm was chosen as 0.01. As you can see, the method is suitable to determine occupied channels and signal powers, as well as frequencies that can be used by cognitive radio systems. The dynamic range of signals in this case is at least 30 dB. In general case, the dynamic range of signals, in which the method allows to accurately determine the spectrum holes is limited by the maximum level of the side lobes of the window function.

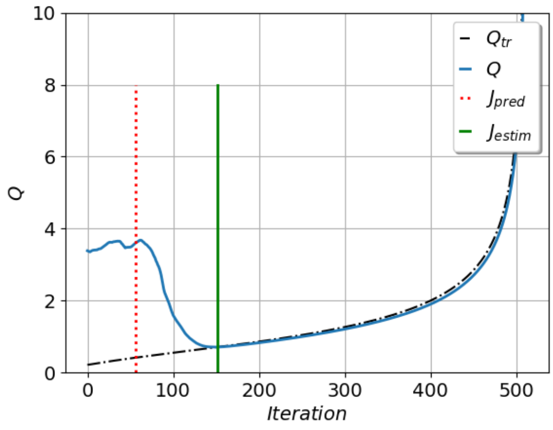

Fig. 3. Underestimated spectrum occupancy

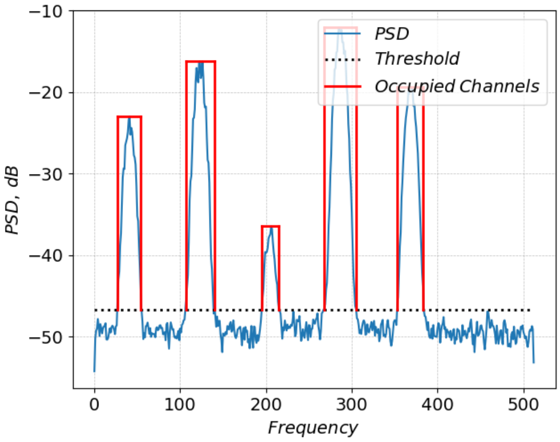

Fig. 4. Results of proposed method performance

5 Simulation results

Now we compare the speed of spectrum sensing using the developed method and the iterative method proposed in [12]. The processing gain G is calculated as the ratio of the number of iterations of decisive statistics computation for the method [12] and the proposed method.

Processing gain depends on several factors: spectrum occupancy and prediction errors, dynamic range and SNR. But due to the uncertainty of noise, even with the same SNR and spectrum occupancy level for different signal realizations and the same error in the prediction of the occupancy, processing gain in reducing the number of iterations can differ significantly.

Fig. 5 shows the average under the influence of all factors dependence of the processing gain G in reducing the number of iterations via spectrum occupancy prediction error ε_η (calculated according to equation (2)). At low spectrum occupancy of analyzed bandwidth (up to 10%), which corresponds to a value of ε_η less than 0, the average gain is only a few times. This can be explained by a poor approximation of the predicted occupancy at large values of the decisive statistics (Fig. 1). With increasing spectrum occupancy, the gain increases linearly and is several tens of times, although the forecast error modulo does not exceed the forecast error for small occupancy levels.

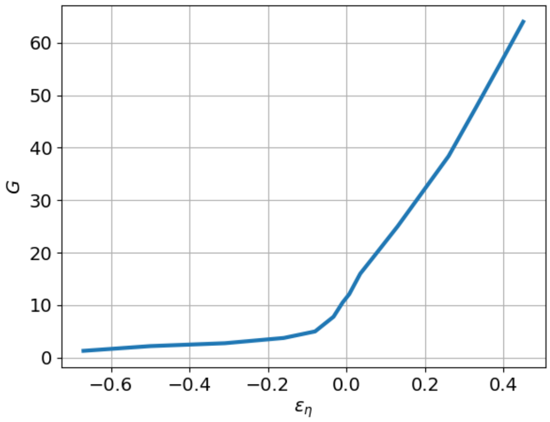

Fig. 5. Processing gain via error of predicted spectrum occupancy

Conclusions

The proposed fast spectrum sensing method allows finding unoccupied bands of the radio frequency spectrum under conditions of dynamic change of the electronic environment at unknown noise variation and the dynamic range of signals that can be processed is limited only by the level of the side lobes of the window function. Processing gain in reducing the number of iterations of calculation the decisive statistics depends on the error of the predicted spectrum occupancy and can reach several tens of times. The proposed method can be used at improvement of existing and development of new cognitive radio systems based on SDR technology. Prospects for further research in this area are associated with the development and study of similar methods for detecting broadband signals.

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Швидкий метод аналізу радіочастотного спектра для когнітивних радіосистем

Бугайов М. В.

Ключовим аспектом функціонування когнітивних радіосистем є швидке та надійне визначення вільних ділянок частот при динамічній зміні радіоелектронної обстановки. Для вирішення даного завдання запропоновано швидкий ітеративний метод із використанням коефіцієнта варіації спектральної щільності потужності (СЩП). Сутність методу полягає в порівнянні значень коефіцієнта варіації спектра прийнятої реалізації з пороговим значенням із використанням прогнозованого значення кількості сигнальних відліків та методу золотого перетину. Порогові значення вирішуючої статистики отримано шляхом розрахунку вектора відліків СЩП, його сортування і нормування до енергії та розрахунку вектора значень коефіцієнтів варіації при послідовному відкиданні від нормованого вектора СЩП відліка з максимальним значенням. Для зменшення кількості ітерацій розрахунку вирішуючої статистики при виявленні вільних ділянок у смузі частот аналізу використовується прогнозоване значення завантаженості (кількості сигнальних відліків). Дане значення розраховується за емпіричною формулою із використанням в якості аргументу коефіцієнта варіації для нульової ітерації. На практиці наявність в смузі частот аналізу кількох сигналів з різними потужностями призводить до появи помилок прогнозованого значення завантаженості. Причому чим більшим є динамічний діапазон і менше відношення сигнал-шум, тим більшою буде дана помилка. Прогнозоване значення завантаженості є грубою оцінкою кількості сигнальних відліків у спектрі і для швидкого пошуку її істинного значення застосовано метод золотого перетину. Виграш у зменшенні кількості ітерацій обчислення вирішуючої статистики залежить від помилки прогнозу завантаженості і може досягати кількох десятків разів. Запропонований метод може бути використаний при удосконаленні існуючих та розробленні нових когнітивних радіосистем на основі SDR технології.

Ключові слова: коефіцієнт варіації; ітеративний метод; когнітивне радіо; метод золотого перетину; завантаженість спектра; поріг

Быстрый метод анализа радиочастотного спектра для когнитивных радиосистем

Бугаёв Н. В.

Ключевым аспектом функционирования когнитивных радиосистем является быстрое и надежное определение свободных участков частот при динамическом изменении радиоэлектронной обстановки. Для решения данной задачи предложен быстрый итеративный метод с использованием коэффициента вариации спектральной плотности мощности (СПМ). Сущность метода заключается в сравнении значений коэффициента вариации спектра принятой реализации с пороговым значением с использованием прогнозируемого значения количества сигнальных отсчетов и метода золотого сечения. Пороговые значения решающей статистики получено путем расчета вектора отсчетов СПМ, его сортировки и нормирования к энергии и расчета вектора значений коэффициентов вариации при последовательном отбрасывании от нормированного вектора СПМ отсчета с максимальным значением. Для уменьшения количества итераций расчета решающей статистики при обнаружении свободных участков в полосе частот анализа используется прогнозируемое значение загруженности (количество сигнальных отсчетов). Данное значение рассчитывается по эмпирической формуле с использованием в качестве аргумента коэффициента вариации для нулевой итерации. На практике наличие в полосе частот анализа нескольких сигналов с разными мощностями приводит к появлению ошибок прогнозируемого значения загруженности. Причем чем больше динамический диапазон и меньше отношение сигнал-шум, тем большей будет данная ошибка. Прогнозируемое значение загруженности является грубой оценкой количества сигнальных отсчетов в спектре и для быстрого поиска ее истинного значения применен метод золотого сечения. Выигрыш в уменьшении количества итераций вычисления решающей статистики зависит от ошибки прогноза загруженности и может достигать нескольких десятков раз. Предложенный метод может быть использован при совершенствовании существующих и разработке новых когнитивных радиосистем на основе SDR технологии.

Ключевые слова: коэффициент вариации; итеративный метод; когнитивное радио; метод золотого сечения; загруженность спектра; порог