Journal of Communications Vol. 11, No. 3, March 2016

Spectrum Sensing Schemes for Dynamic Primary User Signal Under AWGN and Rayleigh Fading Channels

Wasan Kadhim Saad[1, 2], Mahamod Ismail[1], Rosdiadee Nordin[1], and Ayman A. El-Saleh[3]
[1]Department of Electronics, Electrical and System Engineering, Faculty of Engineering and Build Environment,
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Dept. of Communications Engineering, Najaf Technical College, Foundation of Technical Education, Baghdad, Iraq
[3]Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor, Malaysia
Email: {wasan, mahamod, adee}@eng.ukm.my; ayman.elsaleh@mmu.edu.my

Abstract —In this paper, the performance of spectrum sensing is analysed while taking into account the effect of Primary User (PU) activities. A PU work period is defined and formalized to practically realize the PU activities when dynamically changing between ON and OFF transmission scenarios. In reality, it is important to consider such work period as the PU will only active for certain fraction of the total frame time. A new sensing model, namely, Constant False Alarm Rate-Dynamic Energy Detection (CFAR-DED) is introduced for *dynamic*-PU signal state scenario. The CRAF-DED model is then further categorized into three scenarios; Dynamic Threshold (DT), Two-Stage (TS), and Adaptive Two-Stage (ATS) detection algorithms. Closed-form expressions for the average detection probability have been mathematically derived when the PU is partially present within the observed period under AWGN and Rayleigh fading environments. Simulation results show that the proposed algorithms provide detection improvement as compared with conventional energy detection. In particular, ATS represents the most effective sensing algorithm of the CFAR-DED model. In addition, the results show that the probability of detection degrades severely when the PU work period and sensing time are reduced regardless of the method of detection used. Furthermore, it has been found that the detection performance of the proposed algorithms under Rayleigh fading with low-*SNR* is significantly deteriorated.

Index Terms—Dynamic Energy Detection (DED), Constant False Alarm Rate (CFAR), work period, AWGN channel, rayleigh fading channel, dynamic threshold

I. INTRODUCTION

IEEE 802.22 is seen to be the first international standard process for a Cognitive Radio (CR) to operate in the underutilized TV bands. In this context, Secondary Users (SUs) need to sense TV transmissions as low as 116 dBm [1], [2]. Nevertheless, to ensure non-intervention with potentially hidden primary receivers whose channels are deeply faded of, the SU detectors are required to decide on the existence or absence of very weak PU signals [3]-[5]. Spectrum Sensing (SS) ensures the protection of the PU against harmful interference from SU [6]. Energy Detection (ED) is a popular choice for the SS because of its simplicity and unnecessary knowledge of any prior information. However, it is not robust to noise uncertainty [7].

In practical situations, noise is not completely Gaussian distributed due to channel fading. This makes it hard for the SUs to get complete noise information. Thus, consideration should be given for noise uncertainty in each detection decision for the SUs which can be a severe impairment for CR detection at low Signal to Noise Ratio (SNR). In addition, the important effect of noise uncertainty concept exists because the noise power may marginally vary with location and time as in [8]. The noise variance in [8] is assumed to be limited to a specific time interval while it is unknown otherwise. Therefore, it is always difficult to attain reliable detection performance over the whole sensing time duration due to inaccurate received power estimation. If sensing has been performed at the beginning or at the end of the PU transmission, the PU signal will be present only through the first or last fraction of the observed signal, respectively. Therefore, the probability of the existence of the PU signal for a portion of the observed signal increases. In addition, a general approach is to look at the PU traffic as a random process, where the PU is able to change the state between idle and busy throughout the observation period [9]. Based on this, the activity cases of the PU may change repeatedly throughout the sensing time duration. Thus, this activity pattern of PU is referred to as the *dynamic*-PU. This model is becoming popular in SS studies as it is more realistic in practical CR models. However, a dynamic signal of the PU that changes its state during the sensing period will be influenced by the *work period* (W), thus a creating new test statistic that are different from traditional test statistic. Hence, PU signal work period (PU-W) is defined as the portion of the observation window where the PU signal exists.

The traditional detectors of SS are formulated for *static*-PU signals and cannot detect *dynamic*-PU signals accurately. These detectors are unaware of the PU activities during the work period, thus, computed detection results do not reflect the actual performance investigated. In other words, in traditional SS, it is assumed that the PU will be *static* and continues as such

---

Manuscript received November 8, 2015; revised March 1, 2016.
This work was supported by Ministry of Higher Education Malaysia, with Grant No. ERGS/1/2013/ICT03/UKM/02/1

Corresponding author email: was_basher@yahoo.com

doi:10.12720/jcm.11.3.231-242

either totally present or fully absent (i.e., there is no changing in the PU state) during the observed period. But in a practical case, it is possible to change the state of the PU and become *dynamic* through the period of observation without knowledge of SU, also the detector signal model no longer reflects the realistic behavior of the PU. This constitutes a major threat to the safety of SS as the signal model becomes imprecise. Accordingly, all applications that rely on the calculated detection performance be at risk. Hence, in the framework of this research, work period is performed to allow SS to become aware of PU traffic. For instance, the performance of detection of SS detectors can be analyzed with regard to the Primary User Work period (PU-*W*), which shows the change in the probability of detection when PU exhibits a work period.

In an effort to solve the above issues related to the ED-based spectrum sensing, the main objective of the current study is to discuss the case of a *dynamic*-PU signal, which is modelled as a process of random and changes in the state of the PU activity within the observed duration. This work period will be modelled and incorporated in all the formulated algorithms based on CFAR-DED models to enhance the performance of detection. However, DED refers to the ED scheme which can be modified to include the effect of PU-*W* into the model according to the decision threshold modes to detect *dynamic*-PU signal based on three scenarios, which includes DT, TS and ATS detection algorithms. Thus, DED technique is utilized to calculate the detection performance by considering the effect of the PU-*W*, and it is considered as one of the most commonly used blind detection techniques which do not require any prior information about the PU signal and channel.

Consequently, three main stages of investigations are carried out in this work. In the first stage, analyses of the performance of the SS due to PU-*W* using the new CFAR-DED model with three new detection algorithms, namely, DT, TS and ATS are carried out. This is used to guarantee the reliability of the SS for accurately detecting the activities of the *dynamic*-PU signals through the observation period, and to improve the SS performance in the CRN. In the second stage, the performances of the proposed detectors are evaluated when the PU changes states and shows an unknown *W* within the observed period. Finally, the detection performances of the proposed detectors algorithms using CFAR approach for accurately detecting the activities of the *dynamic*-PU signal within the observed period are carried out. Closed-form expressions for the average detection probability with regard to the PU-W and when PU exhibits *static*-W over AWGN and Rayleigh fading channels are derived.

The remainder of this paper is organized as follows. In Section II, the related works are highlighted and followed by the CFAR-DED scheme description in Section III. Description for CFAR-Dynamic Energy Detection (DED) model with analyses of these proposed schemes from the viewpoint of detection performance over AWGN and Rayleigh fading channels are presented in Section IV. The simulation results and discussion with a comparison on the performance of the CFAR-DED model are presented in Section V. Finally, the concluding remarks of this study are drawn in section VI.

II. RELATED WORKS

Only a few scenarios are studied in the literature where the PU signal is dynamic and changes its states within a sensing cycle. In addition, the change of the PU signal is assumed to mainly occur during the transmission duration and very few studies take into account the possibilities of changing the state of the PU signal during the observed period. The authors in [10]-[12] have recognized this fact and used the activity pattern of the PU to improve some aspects in the performance of spectrum management, spectrum sensing and sensing optimization.

In [13], [14], the authors showed that the traditional detector developed for *static*-PU show a degradation of performance when detecting a *dynamic*-PU signal, where the attained detection rate is less than the computed detection rate. This is because of the traditional detector is developed assuming that the PU signal to be either fully exist or completely non-exist through the observed period [15], [16], while a dynamic-PU exhibits a work period and it only exists for a fraction of the observed period.

Different traffic models are proposed and the detection performance of ED is evaluated in [17]. The results showed that incomplete monitoring will reduce the chances of detection due to the rapidly changing traffic models. However, no suggestion was made for of any solution to this problem. In this paper, we examine the effect of several proposed new SS algorithms on the detection performance by using CFAR method so as to select the detection threshold of the received signal when there is a partial PU signal in case of AWGN and Rayleigh fading channels. In this case, we presume a general situation and carry out an analysis while ignoring the location of the PU signal.

III. CFAR-DYNAMIC ENERGY DETECTION (DED) MODEL DESCRIPTION

In a traditional spectrum sensing, it is assumed that the PU is “static” and its activity remains unchanged, i.e. PU is either fully exist or completely does not exist within the sensing duration [16]. Therefore, the binary hypothesis to decide the absence or presence of the PU signal can be represented based on the observed signal model $Y(k)$ as in the following form,

$$Y(k) = \begin{cases} n(k) & H_0 \\ s(k)h + n(k) & H_1 \end{cases} \tag{1}$$

where $s(k)$ is the PU signal to be detected. $n(k)$ is a zero-mean additive white Gaussian noise (AWGN), and it is Gaussian distributed for the limited sample size used in sensing, i.e. $n(k) \sim N(0, \sigma_n^2)$. $h(k)$ is the amplitude gain of the channel between the PU and SU that which presumed to be 0 under hypothesis H_0 and 1 under hypothesis H_1, respectively.

On the other hand, there is a growing research trend to view the PU as "dynamic", where the PU signal going through changes in its state between ON and OFF through the sensing duration with work period (*W*), which can be defined as a small portion of the sensing duration occupied through the PU signal. In other words, the SU senses a PU channel through the sensing duration, where the dynamic-PU signal can occupy a small portion of the observed signal irrespective of any hypothesis. However, the signal model for the dynamic-PU is dependent on the period and the location of the PU signal, and since it is unknown to the SU, thus W is too unknown. The *SNR* for the PU signal include the effect of W, thus PU-*W* represent a segment of the observed signal, where the PU signal exists, and can be expressed as the total duration of the ON state, T_{on}, divided by the total observed period, *T*, i.e. $(W = T_{on}/T)$, takes a value between $(0 \le W \le 1)$ under H_0 and H_1 [18]. For example, (W = 0.5) means that the PU signal was present during half of the observed period. However, under the special cases, when the (W = 0), the signal of the PU is not exists and the received signal is made up of noise alone as per H_0 of (1). On the other hand, when the (W=1), the signal of the PU is completely existent and the received signal similar to H_1 of (1).

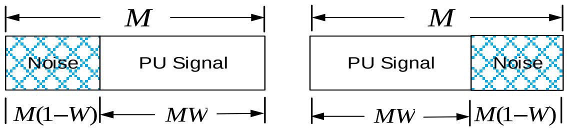
According to the PU-*W* model in this paper, and when $(0<W<1)$, the conventional detection hypothesis will no longer be applicable when there are several ON and OFF states of the PU through sensing duration. Consequently, the new detection hypothesis of the *dynamic*-PU signal model has been proposed depending on the state of the PU at the ending of the sensing duration and the duration of the PU signal. However, assuming that the PU occupies the same fraction of the sensing duration for each proposed scenarios (i.e. work period is equal) with differing the location of PU signal. Thus, two possible scenarios of PU-*W* corresponding to the detection hypotheses (H_0 and H_1) are illustrated in Fig.1, have been proposed in this work, which represents two possible combinations PU initially (ON and OFF) states. The SU estimates PU's behavior according to the sensing duration, thus the detection hypothesis is redefined depending on the state of the PU at the ending of the sensing duration, which represents closely the state of the PU at the start of the transmission duration.

Fig. 1 (a), show the initial state of the PU when sensing begins as OFF state, and PU is changing between ON state and OFF state through the sensing duration. However, when the sensing ends with PU in ON state and (W<1), then H_1 is declared, which means that the PU will be in ON state when the transmission duration starts, where the SU must not transmit. This figure explains a simple example to analysis the DED when the received signal comprises a portion containing only noise with length $M(1-W)$, which is a Gaussian distribution with zero mean and variance σ_n^2. Eventually, the user can provide detection nearly perfect if M is made large enough even at very low-SNR, but practically, the estimation will be only for σ_0^2, and this is referred to as noise uncertainty. Another portion consists of a PU signal that is distorted by noise with length MW is a Gaussian distribution with zero mean and variance $\sigma_s^2 = \sigma_n^2(1+\eta)$. Therefore, for a simple example where the PU is present at the end of observed signal, thus the received signal is defined for *k*th sample, $1 \le k \le M$, and has the following structure:

$$Y(k) = \begin{cases} n(k) & 0 \le k \le M(1-W)-1 \\ s(k)h + n(k) & M(1-W) \le k \le M-1 \end{cases} \tag{2}$$

Thus, the complete received signal $Y(k)$ corresponds to the two linked portions is remains Gaussian distributed with zero mean and variance $\sigma_W^2 = W[\sigma_n^2(1+\eta)] + \sigma_n^2(1-W)$ using the central limit theorem due to simplicity of calculation and sufficient accuracy.

This is the opposite for the case in the Fig. 1 (b), wherein, if the sensing ends with PU in OFF state and (W>0), thus H_0 is declared, which means that the PU has been in OFF state when starts the transmission duration where the SU can transmit. Consequently, since the PU signal and noise are present under both hypothesis, the above signal structure in (2) is applied to both H_1 and H_0.



(a) Initial OFF, H_1 (b) Initial ON, H_0

Fig. 1. Structure of the observed signal model

Therefore, a general scenario of this paper conducted the analysis of detection for the proposed models which ignores the location of the PU signal. However, a *dynamic*-PU signal that alters its state during the sensing period will display *W* and thus produce a new test statistic is the total energy of the two portions, and it is different from that of a conventional test statistic. Therefore, according to the same approach as in [19] for definition the test statistic, we can define $T_W(Y)$ as the test statistic of the received signal with the effect of PU-$W, Y(k)$, with the following distribution

$$T_W(Y) \sim \aleph \begin{pmatrix} \varepsilon_1 = (\eta W + 1)\sigma_n^2 \\ \delta_1^2 = \dfrac{2}{M}(\eta W + 1)^2 \sigma_n^4 \end{pmatrix} \tag{3}$$

where η is the local SNR at the SU. As a result, the new test statistic of the observed signal with the impact of PU signal *work period* $T_W(Y)$ come close to the Gaussian distribution for the binary hypothesis, and thus each SU calculates a summary statistic over a detection interval of M samples which can be represented as:

$$T_W(Y)=\sum_{k=0}^{M(1-W)-1}|n(k)|^2+\sum_{M(1-W)}^{M-1}|s(k)+n(k)|^2 \qquad (4)$$

The test statistic is calculated by using the whole M samples of the observed signal, and the location of the PU signal does not influence the test statistic distribution. The calculation of W depends on the whereabouts of the PU signal, thus varies for H_0 and H_1. However, a correctly designed sensing duration should guarantee W_1 noticed under H_1 is high, while W_0 noticed under H_0 is small. However, in conventional ED algorithm, the threshold is fixed and it has been established that the performance is lower under noise uncertainty. This indicates that the selection of a fixed threshold is no longer appropriate when there is noise uncertainty and a flexible threshold should be selected instead where necessary.

The traditional detector computes a decision threshold and compares it to a test statistic engendered from the *static*-PU signal which stays in the same state through sensing duration. Thus, the typical approach to formulate a decision threshold of the PU-*W* that used in this paper is CFAR approach for a signal detection-based model. General, CFAR detection principle means that when the probability of re-using spectrum of the unused spectrum is targeted, the false alarm probability is fixed to a small value and the detection probability is maximized. However, CFAR approach is more commonly implemented since the decision threshold, γ, is set in accordance to the characteristics of the detector in the case of noise only H_0, and it is dependent on a constant noise variance, σ_n^2. Based on the above, the decision threshold is calculated as a function of a targeted probability of false alarm, P_F, and variable detection rate, while the SNR for the PU is unknown [9, 15, 20], in order to ensure the CFAR property, and given as follows:

$$\gamma=\sigma_n^2\left(\frac{2}{\sqrt{M}}Erfc^{-1}(2P_F)+1\right) \qquad (5)$$

When a PU signal with a work period is detected, the W are introduced into the distribution for the hypotheses H_1 for the DED (3). Thus, the updated probability of detection performance of the proposed models with the effect of PU-*W* can be computed in closed form by comparing the cumulative distribution function of the test statistic (4) generated from a *dynamic*-PU with the decision threshold calculated in (5), which formulated for *static*-PU, because of the detector is unaware of PU-*W* when PU exhibits a *static*-*W* through the sensing duration.

The main objective from this paper is to explain how the unknown W exhibits by the PU through sensing duration affects the performance of detection through derivation of the proposed detection model with regard to the PU-W for performance the SS in CR system. The analysis process is illustrated in three steps as follows: Firstly, the decision threshold is calculated by using DED scheme based on the test statistic produced from the received signal $Y(k)$, assuming *static*-PU. Secondly, new test statistic $T_W(Y)$ of the DED models is derived with the effect of the PU-*W*. Finally, a new detection performance $P_{D|W}$ is produced, which is different from the traditional detection performance through comparison the $T_W(Y)$ with the predetermined decision threshold when detecting the *dynamic*-PU exhibiting work period. The PU is said to be presence if $T_W(Y)>\gamma$, wherein this procedure is carried out several times in order to produce an average detection performance to be calculated in closed form. Since the probability of false alarm is not influenced by the PU-*W*, the probability of detection is taken into consideration. In addition, a *dynamic*-PU will increase the W under H_1, resulting in a longer observed period and increases the detection probability because of bigger sample size. In actual fact, even though the location of the PU signal is not known, the same analysis applies, notwithstanding the location of the PU signal [18], [21]. The algorithm that explains this process to calculate the detection performance of the proposed models can be described as shown in Algorithm 1.

Algorithm 1: Analysis process to calculate the detection performance of the proposed CFAR-DED model

```
1) For $0 \le W \le 1$
2) Calculate the conventional decision threshold for the CFAR
3) Generate the distribution of the new test statistic conditional to $W$
4) Compare the new test statistic of the DED with the decision threshold for CFAR to compute the performance of detection conditional to $W$ using theoretical expressions for the CFAR-DED model over AWGA and Rayleigh fading channels
5) End
```

However, the performance of the underlying system significantly degrades when considered the incomplete sensing for the *dynamic*-PU; thus, there is an urgent need for proposed a new reliable SS schemes to improve the overall quality of detection compared with the conventional scheme. Consequently, the main objective in this paper is to investigate how the unknown W exhibits by the PU through sensing duration affects the performance of detection through mathematical formulations of the proposed CFAR-DED sensing model. This is investigate the performance of detection through used the proposed (DT, TS, and ATS) SS scenarios that are used as examples to explain how the detection performance are influenced by the PU-*W* in the CRNs when these detectors utilize to detect a PU signal exhibiting a work period are unknown over AWGN and Rayleigh fading channels. As this model is built on different scenarios, the correlation is also different between the probability of detection and the PU-*W*.

The detection performance for the proposed model is calculated based on the theoretical expressions, which are derived and given in detail in the following section and supported through simulations. This study assumes that all parameters and assumptions necessary for the proposed detectors are available and fully known, while the variable unknown to the detector is the work period of the PU. Furthermore, regardless of the number of PU status changes at any time instant during the sensing duration, the received sample has two possibilities: it either contains noise only, or contains signal plus noise.

IV. PROPOSED DYNAMIC ENERGY DETECTION UNDER CFAR MODE

The AWGN channel does not take into account the impacts of inevitable fading, thus the DED scheme make a decision on the presence of the signal $s(k)$ in (2) according to the decision variable in light of noise uncertainty. This section provided an explanation of the dynamic CFAR-DED spectrum sensing models that is used to calculate the detection performance in the CRNs when PU displays a fixed W under three scenarios including DT, TS and ATS detections to enhance the detection performance over AWGN and Rayleigh fading channels.

A. Mathematical Formulation of Dynamic Threshold Based CFAR-DED Model

Noise Uncertainty (NU) decreases sensing sensitivity, which causes a sharp decline in the detection accuracy of CR. In such a case, introducing cognitive users will cause harmful interference with the PUs. Conventional ED algorithm is based on a fixed threshold and it is very sensitive to NU, thus it decreased the detection performance under NU environments. However, since the fixed threshold is no longer valid under NU, thus it is important to propose a Dynamic Threshold (DT) scenario as an effective approach to address NU and enhance detection sensitivity. Thus, the new detection performance of the proposed CFAR-DED model based on DT scenario when PU exhibits an unknown-work period through the sensing duration is $P^{*}_{(D|W)}$. This can be calculated in closed form over AWGN channel through finding the cumulative distribution function of the test statistic (4) that matches the decision threshold computed in (5) [22], and given as follows,

$$P^{*}_{(D|W)} = \frac{1}{2} Erfc\left(\frac{\frac{2}{\sqrt{M}} Erfc^{-1}\left(2P_F\right) - dW\eta + 1 - d}{\frac{2}{\sqrt{M}} d\left(W\eta + 1\right)} \right) \tag{6}$$

where $P^{*}_{(D|W)}$ is the approximation expression for the detection probability in closed form of the DED scheme based on dynamic threshold over AWGN channel when the PU exhibits *W*. It can be assumed that the dynamic threshold coefficient $(d \geq 1)$ and set the DT values range as $\left[\gamma/d\,,d\gamma\right]$. Thus, $P^{*}_{(D|W)}$ can be utilized to analyze both probabilities of detection and false alarm under H_1 and H_0, respectively. Therefore, for Special situations when $W = 0$ and $W = 1$, $P^{*}_{(D|W)}$ is equivalent to the traditional probability of false alarm (PU signal is absent) and the traditional probability of detection (PU signal is present), respectively. However, when the PU exhibits *W* and the PU exists for a small portion within the observed period under $H_0(W > 1)$, then $P^{*}_{(D|W)}$ will be equal to the traditional probability of false alarm. Also, if the PU is partially non-existent within the observed period under $H_1(W < 1)$, then, $P^{*}_{(D|W)}$ will be equal to the traditional probability of detection P_D. Therefore, by solving (6) we can get the signal to noise ratio (η) required to attain $P_D \geq P^{*}_{(D|W)}$ as follows,

$$\eta = \frac{\frac{2}{\sqrt{M}}\left[Erfc^{-1}\left(2P_F\right) - d\, Erfc^{-1}\left(2P_D\right)\right] - d + 1}{d\,W\left[\frac{2}{\sqrt{M}} Erfc^{-1}\left(2P_D\right) + 1\right]} \tag{7}$$

However, the probability of false alarm does not change since CFAR model is assumed, and therefore it is independent of the *SNR* [23]. Unlike AWGN environment, the distributions and subsequent probabilities in a fading environment do not follow the formulae given earlier because the *SNR* has different distributions. Furthermore, when the channel is varying due to fading impacts, the probability of detection equation given earlier represents conditional probability of detection on the instantaneous *SNR*. Therefore, we can get the closed form expression for detection probability in a fading channel by calculating the average probability of detection conditioned through the *SNR* fading distribution. However, if the signals from PUs experience independent and identical distributed (i.i.d.) Rayleigh fading, the probability of distribution function (PDF) of the *SNR* at CR node under Rayleigh fading has an exponential distribution. Therefore, a closed form formula for the average probability of detection, P^{*}_{D}, of the CFAR-DED scheme based on the dynamic threshold when the PU exhibits a *work period* over Rayleigh fading channel can be determined by statistically averaging $P^{*}_{(D|W)}$ in (6) over the PDF of *SNR* [eq. 2.8.9.1 in; 24] through some algebraic processes, and it is given as follows,

$$P_D^* \approx \frac{1}{2} Erfc\left(Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}(1-d) \right) + \exp\left[\frac{1}{M\, d^2 W^2 \bar{\bar{\eta}}^2} - \frac{2\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}\,(1-d) \right]}{\sqrt{M}\, d\, W\, \bar{\bar{\eta}}} \right] \quad (8)$$

where $\bar{\bar{\eta}}$ is the average *SNR*. In fact, although $\bar{\bar{\eta}}$ is relatively small, the practically-required large M for a low $\bar{\bar{\eta}}$ can boost $\sqrt{2M\bar{\bar{\eta}}}$ to a relatively high value to satisfy (8). By solving the quadratic equation in (8) to get the required $\bar{\bar{\eta}}$ with the desired performance pair of probability of detection and probability of false alarm, and for $M >> 1$, we can get the expression of $\bar{\bar{\eta}}$, as follows,

$$\bar{\bar{\eta}} \approx \frac{-2\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}(1-d) \right]}{\sqrt{M}\, d\, W \ln\left[P_D - 0.5\, Erfc\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}(1-d) \right] \right]} \quad (9)$$

B. Mathematical Formulation of Two-Stage Based CFAR-DED Model

The SS performance studies are often carried out based on the assumption of perfect knowledge of noise power. Nevertheless, in practical cases, the noise power level could vary dramatically over time, and also noise uncertainty should be taken into account. In this case, it is assumed that the real noise power is changing randomly from one detection cycle to another with a regular distribution given by $\sigma^2 \in [\sigma_n^2/\varpi, \varpi\sigma_n^2]$, and it is unchanging through the detection period [25], where ϖ denotes the noise power uncertainty coefficient in dB, which takes the values $\varpi > 1$, and σ_n^2 is the average noise power. Hence, with the increase of noise uncertainty factor, the detection performance of the system is largely degraded and the required value of detection probability cannot be achieved [4]. Noise uncertainty may cause a severe impairment to the performance of different SS methods used for PU detection at low-*SNR*. This paper has shown that this effect can be overcome by proposing new two-stage and adaptive two-stage detection methods based that take into account noise uncertainty and dynamic threshold. Thus, the detection performance of the two-stage CFAR detector for a PU signal under *work period* based on noise uncertainty and dynamic threshold can be computed in closed form by finding the cumulative distribution function of the test statistic of the DED of (4) for a *dynamic*-PU signal that matches the detection threshold calculated in (5) as follows,

$$P_{(D|W)}^{**} = \frac{1}{2} Erfc\left(\frac{\frac{2}{\sqrt{M}} Erfc^{-1}(2P_F) - d\,W\eta + \frac{\varpi - d}{\varpi}}{\frac{2}{\sqrt{M}} d\,(W\eta + 1)} \right) \quad (10)$$

where $P_{(D|W)}^{**}$ is the approximation expression for the probability of detection in the closed form of the DED based on the two-stage scenario with the effect of PU signal *work period*. Thus, by solving (10) for η, we can get the minimum η required to attain $P_D \geq P_{((D|W)}^{**}$ as follow,

$$\eta = \frac{\frac{2}{\sqrt{M}}\left[Erfc^{-1}(2P_F) - d\, Erfc^{-1}(2P_D) \right] + \left(\frac{\varpi - d}{\varpi} \right)}{d\, D\left[\frac{2}{\sqrt{M}} Erfc^{-1}(2P_D) + 1 \right]} \quad (11)$$

If the PU signal is subject to flat Rayleigh fading channel, the closed-form expression for the average probability of detection of the CFAR detector based on TS scenario, P_D^{**}, becomes,

$$P_D^{**} = \frac{1}{2} Erfc\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}\left(\frac{\varpi - d}{\varpi} \right) \right] + \exp\left[\frac{1}{M\, d^2 W^2 \bar{\bar{\eta}}^2} - \frac{2\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}\left(\frac{\varpi - d}{\varpi} \right) \right]}{\sqrt{M}\, d\, W\, \bar{\bar{\eta}}} \right] \quad (12)$$

By solving the quadratic equation in (12) for $\bar{\bar{\eta}}$, the required average *SNR* for the desired performance probability of detection and probability of false alarm is given. Thus, for $M >> 1$, we get the average *SNR*, $\bar{\bar{\eta}}$, as follows,

$$\bar{\bar{\eta}} \approx \frac{-2\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}\left(\frac{\varpi - d}{\varpi} \right) \right]}{\sqrt{M}\, d\, W \ln\left[P_D - 0.5 Erfc\left[Erfc^{-1}(2P_F) + \frac{\sqrt{M}}{2}\left(\frac{\varpi - d}{\varpi} \right) \right] \right]} \quad (13)$$

C. Mathematical Formulation of Adaptive Two-Stage Based CFAR-DED Model

The detection performance can be improved by proposed a new adaptive two-stage (ATS) detection scheme, taking into account produce the adaptive method based on noise uncertainty and dynamic threshold spectrum sensing. Initially, the SU estimates the *SNR* of the channel and based on the *SNR* information, the SU will pick one of the sensing methods (i.e., DED based on noise uncertainty or DED based on a dynamic threshold) when PU exhibits static *work period*. It is expected that the DED based on noise uncertainty scheme has performed very badly with a low-*SNR*. As such, this sensing method cannot precisely detect the channels if the *SNR* is lower than the threshold, and thus, the DED based on dynamic threshold sensing method will be performed to detect the channels.

Furthermore, the DED based on dynamic threshold cannot precisely detect the channels if the SNR is greater than or equal to the threshold, and thus, the DED based on noise uncertainty detection will be performed to detect the channels. Therefore, the average detection probability of these proposed method when PU exhibits static work period is computed in closed form as follow:

$$P^{\wedge\wedge}_{(D|W)} = P\,P^{\wedge}_{(D|W)} + (1-P)P^{*}_{(D|W)}$$

$$= P\left[\begin{array}{l} 0.5\,Erfc\left[\dfrac{Erfc^{-1}(2P_F)-\dfrac{\sqrt{M}}{2}\left[W\eta-\left(\dfrac{\varpi-1}{\varpi}\right)\right]}{\left(W\eta+\dfrac{1}{\varpi}\right)}\right] \\ -0.5\,Erfc\left[\dfrac{Erfc^{-1}(2P_F)-\dfrac{\sqrt{M}}{2}\left[dW\eta-1+d\right]}{d\,\left(W\eta+1\right)}\right] \end{array}\right] + 0.5\,Erfc\left[\dfrac{Erfc^{-1}(2P_F)-\dfrac{\sqrt{M}}{2}\left[dW\eta-1+d\right]}{d\,\left(W\eta+1\right)}\right] \quad (14)$$

where $P^{\wedge}_{(D|W)}$ and $P^{\wedge\wedge}_{(D|W)}$ the probability of detection of the DED based on noise uncertainty and the new actual probability of detection based on ATS, respectively, when PU exhibits static *work period*. If P is the probability that a channel would be reported to a DED based on noise uncertainty detector as the second stage, then (1 – P) will be the probability that a channel would be reported to a DED based on DT detector. Furthermore, P is determined by the *SNR* of the channels to be detected, and on the whole $P^{\wedge}_{(D|W)}$ is determined directly by P. The SU will carry out a DED based on dynamic threshold method in order to detect most of the channels for $(0 \le P < 0.5)$, where the majority of the channels are very noisy. Furthermore, the detector will take a longer time than the DED based on noise uncertainty method to detect more channels. Meanwhile, the SU will perform DED based on noise uncertainty method in order to detect most of the channels for $(0.5 \le P \le 1)$, where most of the channels have a very good *SNR* because of the performance of the DED based on noise uncertainty method is outstanding with a good *SNR*.

If the PU signal is subject to flat Rayleigh fading channel, the closed-form average probability of detection, $P_D^{\wedge\wedge}$, of the CFAR-DED based on adaptive two-stage scenario for a PU signal with *work period* is becomes

$$P_D^{\wedge\wedge} \approx \frac{1}{2}\,Erfc\left(Erfc^{-1}(2P_F)+\sqrt{\frac{M}{2}}(1-d)\right) + \exp\left[\frac{1}{M\,d^2W^2\,\overline{\overline{\eta}}^{\,2}} - \frac{\sqrt{2}\left[Erfc^{-1}\left(2P_F\right)+\sqrt{\dfrac{M}{2}}\,(1-d)\right]}{\sqrt{M}\,dW\,\overline{\overline{\eta}}}\right] \quad (15)$$

The average detection time of the proposed CFAR-DED model based on ATS scenario equal to the total of the sensing time of CFAR-DED model based on the NU and DT scenarios, respectively, and given by:

$$T_{average} = T_{NU} + T_{DT} \quad (16)$$

However, $T_{NU} = NPT_1$, where NP is the average number of channels reported to the NU detection scenario, and $T_1 = M_{NU}/2B$ is the average sensing time for each channel for NU scenario. In addition $T_{DT} = N(1-P)T_2$, where $N(1-P)$ is the average number of channels reported to the DT detection scenario, and $T_2 = M_{DT}/2B$ is the average sensing time for each channel in case of DT scenario. Thus, the average detection time of the proposed model based on ATS detection scenario is given by:

$$T_{average} = N\left[\frac{P}{2B}\left(M_{NU}-M_{DT}\right)+\frac{M_{DT}}{2B}\right] \quad (17)$$

where N is the number of channels to be detected, B is the channel bandwidth, M_{NU} and M_{DT} are the number of samples during the observation period for each CFAR-DED model based on NU and DT detection scenarios, respectively. Thus, for the worst case scenario when $(P \approx 0)$, the probability of detection and the total average detection time become:

$$P^{\wedge\wedge}_{(D|W)} \approx P^{*}_{(D|W)} \quad \& \quad T_{average} \approx \frac{NM_{DT}}{2B} \quad (18)$$

While, for the best case scenario when $(P \approx 1)$, the probability of detection and the total average detection time become:

$$P^{\wedge\wedge}_{(D|W)} \approx P^{\wedge}_{(D|W)} \quad \& \quad T_{average} \approx \frac{NM_{NU}}{2B} \quad (19)$$

TABLE I: SIMULATION PARAMETERS

Parameter	Values
Probability of false alarm, P_F	0.1
Noise power, δ_n^2	1
Probability of channel, P	$0 \le P \le 1$
Work period, W	$0 \le W \le 1$
SNR (dB)	-6, -8, -10, and -12
Bandwidth	6 MHz
Noise uncertainty factor ϖ	1.03
Dynamic threshold coefficient, d	1.01

We set the CRN parameters in our simulation scenarios as listed in Table I.

V. SIMULATION RESULTS AND DISCUSSIONS

This paper presented a simulation results to evaluation the proposed CFAR-DED models when PU exhibits *static-W* through developing a detection threshold is dynamically adapted to noise levels based on the CFAR method and it does not need to know the SNR of the PU signal. These schemes improve the SS performance in the CRN through providing a very low missed detection rates at low-SNR, thus the negative effect to the existing PUs for a portion of the observed signal negligibly. The effect of the PU-*W* is analysed on the assumption that the PU signal is always present at a particular *work period* ($W > 0$). Since the PU-*W* does not affect the probability of false alarm, therefore only the probability of detection needs to be taken into consideration. Also, the assumption is made that all the channels are subjected to the same SNR and that the probability of false alarm is fixed to a minimum to ensure high utilization of the unused licensed spectrum.

Fig. 2 explains the impact of the PU-W on the resulting detection performance of the CFAR-DED based on TS scenario for different values from SNR and various W under AWGN channel. The detection performance for the CFAR-DED model is evaluated using the analytical expression (9), and validated through simulation from the random noise samples PU signal. From this figure, we can see that the probability of detection drops drastically from ($W = 1$) due to a slight decrease in the *W* for all different *SNR* values. Also, this figure explained that we can get a maximum probability of detection for different SNR values (0 and -6) dB when the PU-*work period* ($W = 1$), which mean that the PU signal is completely existent. While for the case W<1, the probability of detection falls considerably for low-SNR values.

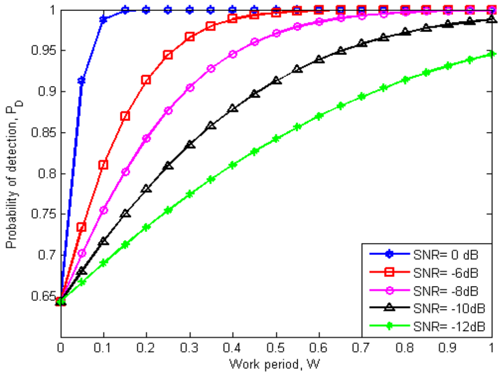


Fig. 2. Detection performance versus *work period* for CFAR-DED based on the two-stage scenario for different *SNR* values over AWGN channel

Fig. 3 explain the impact of various detection periods on the probability of detection for different *SNR* values for CFAR-DED model based on TS scenario for AWGN and Rayleigh fading channels. The detection period varies from zero to the maximum duration of (0.5 ms). From this figure, we can see that the probability of detection gradually decreases with reducing the sensing duration for different values from SNR. Therefore, a higher SNR produces a more powerful signal energy, and thus an improved detection performance.

For instance, when the SNR is -12 dB, a lower detection probability can be achieved and vice versa. However, by using the optimum value for the detection probability, the minimum value of the detection period at point A is 0.033 ms with a SNR of -6 dB, while the minimum value of the detection period at points B and C are 0.073 ms and 0.158 ms when the SNR values are (-8 and -10) dB, respectively. Also, at point D, the minimum value of the detection period is 0.3 ms with an SNR of -12 dB. Furthermore, we notice that there is a significant impact on the detection performance of Rayleigh fading channel gets clearer which will lead to poor spectrum usage, thus the probability of detection for the AWGN channel investigated better performance comparison with the Rayleigh fading channel. In addition, the CFAR-DED sensing detector can attain arbitrary detection requirements by increasing number of samples *M* due to increase sensing time which in turn improves detection performance.

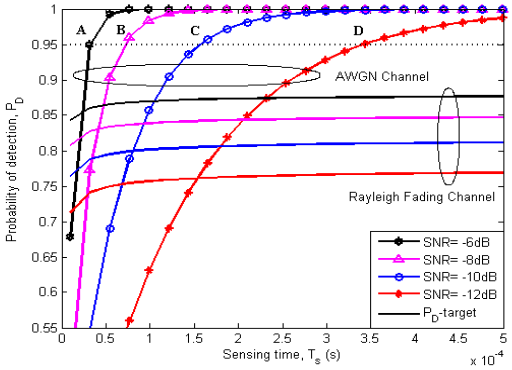


Fig. 3. Detection performance versus sensing time for CFAR-DED over AWGN and rayleigh fading channels for different SNR values

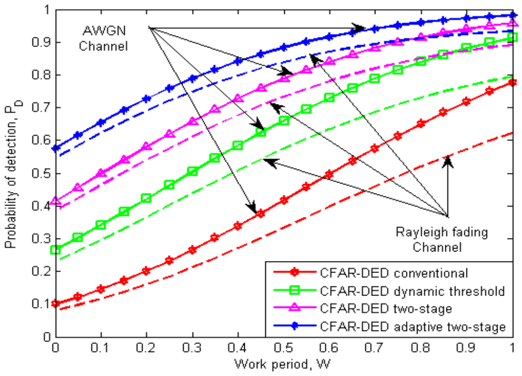


Fig. 4. Comparison detection performance versus work period for different CFAR- DED schemes over AWGN and Rayleigh fading channels

The detection performance is also compared to the *work period* for various CFAR-DED schemes when (*SNR*= -10 dB), as shown in Fig. 4. This investigation displays the performance of detection of the average detection probabilities calculated in Section 4 through the full range of W, and the discussions rely on the different behavior of the proposed CFAR-DED models to the different values of W over AWGN and Rayleigh fading channels. From this figure, it can be seen that the probability of detection is rising significantly when the W increase, irrespective of the method of detection. Moreover, it reveals that the signal strength do not affect the detection performance, but the reduction in the W has a greater effect on lowering the detection performance. Also, for all values of the W, the proposed detection CFAR-DED models, especially based on ATS scenario enhances the detection performance significantly compared with the conventional method.

Fig. 5 shows the effect of different PU signal *work period* on the detection performance versus sensing time of the CFAR-DED model based on TS scenario with PU-W. The results are compared with the *static* conventional ED (i.e. without effect of PU-W) over AWGN channel for SNR (-10dB). From this figure, it can be seen that increase the sensing time will produce a greater positive impact on increasing the probability of detection. In addition, this figure explain that reduce the detection probability when taking the impact of the PU-W (i.e., PU will appear for a portion of the observed signal) in the account on the contrary to not using it, because of the CFAR-DED models is more sensitive to the work period and it has greater accuracy in calculating the detection performance. for example, when PU work period is (W = 0.5), means that the PU signal was present during half of the observed period, while the lower probability of detection get it when (W = 0), which means that there is no PU signal within the observed period. Also, for the highest probability of detection (i.e. W = 1), which indicates that the PU signal is present throughout the observed period, comparison with the *static* conventional ED based on TS which does not take the impact of the PU-*W* into account.

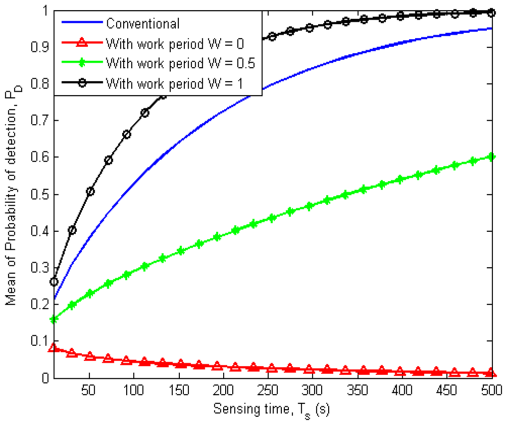


Fig. 5. Comparison detection performance versus sensing time for CFAR-DED model based on TS scenario with different PU work period values

Fig. 6 shows the detection performance for the CFAR-DED model based on TS scenario against the sensing time with and without PU-*W* for different SNR values, as long as the challenge in CR requires low missed detection at low-SNR values, over AWGN and Rayleigh fading channels. In Fig. 6, The continuous lines with and without (triangle, cycle and star) use to show the detection performance for the AWGN channel, while the dotted lines with and without (triangle, cycle and star) use to show the detection performance for Rayleigh fading channel. The detection period varies from (0.01ms) to the maximum duration of (0.5ms), with PU *work period* (W = 0.5). From this figure, it can be seen that increase the sensing time will produce a greater positive impact on increasing the probability of detection. In addition, this figure explains that reduce the detection probability when taking the impact of the PU-*W* in the account on the contrary to not using it, because the CFAR-DED model is more sensitive to the *W* and it has greater accuracy in calculating the detection performance.

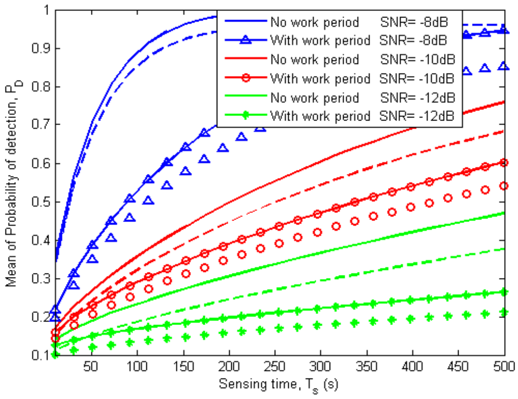


Fig. 6. Comparison detection performance versus sensing time for the CFAR-DED model with and without PU work period over AWGN and Rayleigh fading channels for different SNR values

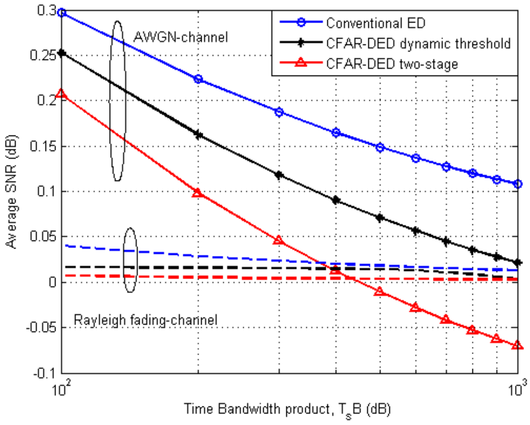


Fig. 7. Average SNR versus time-bandwidth product of the CFAR-DED schemes over AWGN and Rayleigh fading channels

The required average SNR in AWGN and Rayleigh fading channels for the proposed CFAR-DED schemes are compared with the conventional scheme as shown in Fig. 7. It has been observed that the average SNR necessary to attain the desired detection performance in conventional scheme is larger than those required by proposed CFAR-DED schemes. Also, the average SNRs necessary to investigation desired detection performance in Rayleigh fading channel significantly lower than those required by AWGN channel for all schemes.

Fig. 8 shows the detection probability of the CRN versus sensing time for the proposed CFAR-DED models with the effect of PU signal *work period*. In this section, we verify the theoretical detection probability expressions of the CFAR-DED models in section (4) by computer simulations and compared the results with the conventional scheme based detector. To this end, we set the SNR is (-20dB). From this figure, the proposed CFAR-DED-models better performance in both AWGN and Rayleigh fading channels, compared to conventional ED-scheme. It is observed that the detection probability for the proposed ATS scenario is larger than the conventional ED-scheme. This is because the proposed ATS scenario working to improve the detection performance significantly compared with the other detection methods.

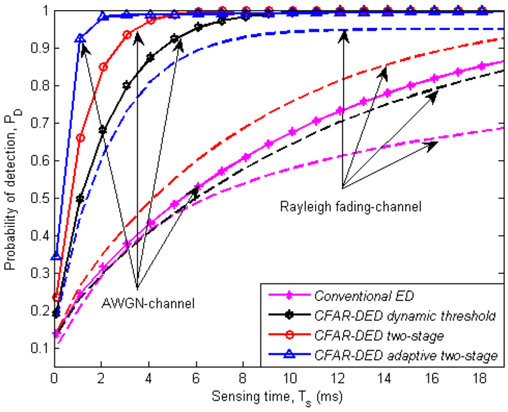


Fig. 8. Comparison detection performance versus sensing time of different CFAR-DED schemes over AWGN and Rayleigh fading channels

VI. CONCLUDING REMARKS

In this paper, a DED model is proposed to study and analyze the effect of *work period* which characterizes the PU activities during a given sensing time duration. The detection performance defined by the detection probability is evaluated for *dynamic* CFAR-DED models with different PU ON to OFF states under three scenarios; which are (i) dynamic threshold, (ii) two-stage, and (iii) adaptive two-stage detections. It was found that the detection performances of the proposed models are affected when the PU changes its state during the observed duration which different from the case when the PU state remains unchanged with no work period introduced. Also, a closed-form expression has been derived for the average detection probability with the effect of PU-*W* for all *dynamic* CFAR-DD models over AWGN and Rayleigh fading channels. The results are compared with conventional ED scheme over AWGN and Rayleigh fading channels with the effect of PU signal *work period*. The simulation results show that a reduced *work period* will negatively affect the detection performance regardless of what type of detection method is used. Finally, the simulation results show that there is a significant impact on the detection performance of the DED schemes by Rayleigh fading especially with low average *SNR*, which leads to poor spectrum usage.

ACKNOWLEDGMENT

The authors would like to thank Malaysia's Ministry of Higher Education for their financial support, under grant scheme number ERGS/1/2013/ICT03/UKM/02/1 and the Ministry of Higher Education & Scientific Research-Foundation of Technical Education in Iraq for providing a doctoral scholarship in Universiti Kebangsaan Malaysia (UKM).

REFERENCES

[1] C. Cordeiro, K. Challapali, D. Birru and N. S. Shankar, "IEEE802.22: The first wordwide wireless standard based on cognitive radios," in *Proc. 1st IEEE International Symposium in New Frontiers in Dynamic Spectrum Access Networks*, 2005, pp. 328-337.

[2] C. Stevenson, C. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 30-138, 2009.

[3] O. Altrad, S. Muhaidat, A. Al-Dweik, A. Shami, and P. D. Yoo, "Opportunistic spectrum access in cognitive radio networks under imperfect spectrum sensing," *IEEE Transaction on Vehicular Technology*, vol. 63, no. 2, pp. 920-925, 2014.

[4] D. Raman and N. P. Singh, "An algorithm for spectrum sensing in cognitive radio under noise uncertainty," *International Journal of Future Generation Communication and Networking*, vol. 7, no. 3, pp. 61-68, 2014.

[5] E. Visotsky, S. Kuffner, and R. Peterson, "On collaborative detection of TV transmissions in support of dynamic spectrum sharing," in *Proc. First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, 2005, pp. 338-345.

[6] S. A. Alvia, M. S. Younisa, M. Imranb, and F. Aminb, "A weighted linear combining scheme for cooperative spectrum sensing," in *Proc. 5th International Conference on Ambient Systems, Networks and Technologies, Procedia Computer Science*, 2014, vol. 32, pp. 149-157.

[7] K. S. Wasan, I. Mahamod, N. Rosdiadee, and A. E. S. Ayman, "Optimality of the HDC rules in cooperative spectrum sensing for cognitive radio network," in *Proc. 1st International Conference on Telematics and Future Generation Networks*, 2015, pp. 22-27.

[8] R. Tandra and A. Sahai, "*SNR* walls for signal detection," *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 4-17, 2008.

[9] K. S. Wasan, I. Mahamod, N. Rosdiadee, and A. E. S. Ayman, "Spectrum sensing schemes for static primary user signal under AWGN and Rayleigh fading channels," *Journal of Theoretical and Applied Information Technology*, vol. 79, no. 2, pp. 291-309, 2015.

[10] L. Chun-Hao, P. Przemyslaw, and C. Danijela, "Primary user traffic classification in dynamic spectrum access networks," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 11, pp. 2237-2251, 2014.

[11] Z. Nan, R. Y. Fei, S. Hongjian, and N. Arumugam, "Energy-Efficient cooperative spectrum sensing schemes for cognitive radio networks," *Eurasip Journal on Wireless Communications and Networking, A Springer Open Journal*, vol. 2013, no. 120, pp. 1-13, 2013.

[12] S. K. Sanket and B. Adrish, "On the effect of primary user traffic on secondary throughput and outage probability under rayleigh flat fading channel," in *Proc. 10th International Conference on Signal Processing and Communications*, 2014, pp. 1-6.

[13] Y. Chen, C. Wang, and B. Zhao, "Performance comparison of feature-based detector for spectrum sensing in the presence of primary user traffic," *IEEE Signal Processing Letters*, vol. 18, no. 5, pp. 291-294, 2011.

[14] W. Yue, C. Feng, C. Guo, and L. Fangfang, "Optimization of parameters for spectrum sensing in cognitive radios," in *Proc. 5th International Conference on Wireless Communications, Networking and Mobile Computing*, 2009, pp. 1-4.

[15] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Communications Surveys & Tutorials*, vol. 11, no. 1, pp. 116-130, 2009.

[16] D. Cabric, A. Tkachenko, and R. W. Brodersen, "Experimental study of spectrum sensing based on energy detection and network cooperation," in *Proc. First International Workshop on Technology and Policy for Accessing Spectrum*, no. 12, 2006.

[17] T. Wang, Y. Chen, E. L. Hines, and B. Zhao, "Analysis of effect of primary user traffic on spectrum sensing performance," in *Proc. Fourth International Conference on Communications and Networking in China*, 2009, pp. 1-5.

[18] K. Chang and B. Senadji, "Spectrum sensing optimisation for dynamic primary user signal," *IEEE Transaction on Communications*, vol. 60, no. 12, pp. 3632-3640, 2012.

[19] L. Xin, Z. Weizhi, Y. Liang, and L. Qingzhong, "Joint optimal sensing time and number of cooperative users in or-rule cooperative spectrum sensing," in *Proc. International Conference on Wireless Communications & Signal Processing*, 2013, pp. 1-5.

[20] G. Yu, C. Long, and M. Xiang, "A Novel spectrum detection scheme based on dynamic threshold in cognitive radio systems," *Research Journal of Applied Science, Engineering and Technology*, vol. 4, no. 21, pp. 4245-4251, 2012.

[21] W. Ejaz, N. U. Hasan, and H. S. Kim, "*SN*R-based Adaptive Spectrum Sensing for Cognitive Radio Networks," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 9, pp. 6095-6105, 2012.

[22] G. Yu, Y. Shao, H. Long, and G. Yue, "Dynamic threshold based spectrum detection in cognitive radio systems," in *Proc. 5th International Conference on Wireless Communications, Networking and Mobile Computing*, 2009, pp. 1-4.

[23] F. F. Digham, M. S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," in *Proc. IEEE International Conference on Communications*, 2003, vol. 5, pp. 3575-3579.

[24] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marichev, *Integrals and Series, vol. 2: Special Functions*, Gordon and Breach science Publishers, 1986.

[25] Y. Zeng and Y. C. Liang, "Eigenvalue-Based spectrum sensing algorithms for cognitive radio," *IEEE Transaction on Communications*, vol. 57, no. 6, pp. 1784–1793, 2009.

Wasan Kadhim Saad received the BSc. Degree in Electrical and Electronic Engineering/ Electronic& Communication from University of Technology, Baghdad, Iraq, 1997. She received the MSc. Degree in Satellite Communication Engineering from University of Technology, Baghdad, Iraq, in 2005. She is currently PhD student in Department of Electronic, Electrical and System Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia (UKM). Her main research interests include cognitive radio networks, cooperative spectrum sensing, and applications of evolutionary algorithms in wireless communications.

Mahamod Ismail Is a full professor in the faculty of engineering at Universiti Kebangsaan Malaysia (Malaysia). He received his B.Sc. (Hons) from University of Strathclyde, UK, M.Sc. from UMIST, Manchester, UK, and His PhD from University of Bradford, UK. His main research interest is in mobile, personal and satellite communication, and wireless networking.

Rosdiadee Nordin received his B. Eng. from Universiti Kebangsaan Malaysia in 2001 and Ph.D. from University of Bristol, United Kingdom in 2011. He is currently a lecturer in Department of Electrical, Electronics and System Engineering in Universiti Kebangsaan Malaysia. His research interests include Multiple-Input Multiple-Output (MIMO), Orthogonal Frequency-Division Multiple Access (OFDMA), resource allocation, green radio, intercell interference, cooperative diversity and indoor wireless localization.