Achievable Outage Rates in Cognitive Radio Networks under Imperfect Spectrum Sensing

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Abstract. *In this paper, we aim at deriving the outage rates achieved by the primary user due to spectrum sensing in a cognitive radio network, that we call sensing-induced primary outage rates. To reach this goal, in the first step, instead of classical spectrum sensing techniques that evaluate sensing performance only based on correct detection of the presence of the primary user's signal, we propose a modified framework that also takes into account the correct detection of the absence of primary user's signal for spectrum sensing performance evaluation. In a second step, we derive the information rates achieved by the coexistence of a primary and a cognitive network. In the last step, assuming slow-fading sensing channels, we derive the sensing-induced primary outage rates, i.e., outage rates achieved by the primary network in the presence of a CR with imperfect spectrum sensing, characterized by a given miss-detection probability. Numerical results show that the proposed spectrum sensing outperforms conventional spectrum sensing techniques in terms of primary signal outage rates and total achievable throughputs, without any increase in the cognitive radio complexity.*

Keywords

Cognitive Radio, outage capacity, imperfect spectrum sensing, achievable throughputs.

1. Introduction

Cognitive radio (CR) technology [1] has been recommended as a key solution to the problem of inefficient use of the allocated spectrum to primary licensed users. This technology allows unlicensed or secondary users (SU) to access spectrum bands allocated to licensed or primary users (PU) while the interference imposed on the PU signal remains below a given threshold [2]. To this end, CR users have to sense the spectrum constantly in order to detect the presence of a primary transmitter signal (PTS). So, spectrum sensing is one of the most important issues in the implementation of each CR network. Due to channel fading conditions and the well-known hidden terminal problem [3], spectrum sensing is usually imperfect and imposes interference on the primary network. Employing multiple cognitive users, specifically by exploiting the available spatial diversity, leads to cooperative spectrum sensing methods which improves the detection reliability.

One of the widely-used techniques for cooperative spectrum sensing is energy detection (ED) [4], [5], [6], [7]. In this technique, each CR user senses the spectrum during a sensing period by measuring the received energy over a particular spectrum band allocated to a PU. In some of these techniques, the measured energy is then compared to a predefined threshold value, and a binary hypothesis is made about the presence or the absence of the primary user at each CR. In some other techniques, instead of the binary hypothesis, the energy measured by each CR user is used for final spectrum sensing decision. Then, at the CR base station (BS), all CR binary hypotheses are collected and a final decision is made about the presence or the absence of the primary user. Furthermore, a study on the interference imposed by ED based cognitive network on primary transmission is provided in [8]. Spectrum sensing performance evaluation is usually based on the so-called receiver operating characteristic (ROC) curves. These ROC curves plot the probability of *miss-detection* (the probability that the CR fails to detect the presence of the PU) versus the probability of *false-alarm* (the probability that the CR decides the PU is in operation whereas it was actually off). It can be easily shown that the probability of false-alarm depends on the threshold value used in ED spectrum sensing. Hence, in conventional spectrum sensing based on ED techniques, the threshold value is set so as to satisfy a maximum acceptable probability of false-alarm [3].

Limits of wireless communication have recently become a wide area of research especially in cognitive networks. One of these limits is the achievable rate region for joint cognitive and primary networks while these networks use the same resources. In [9], the achievable rate region for a genie-aided CR channel is introduced where two cognitive users communicate with two different cognitive receivers. In this scenario, one of the cognitive users has a prior information about the signal that the other user wants to send. In [10], the authors provide a capacity analysis for the cognitive channel by considering distributed and time-varying side information. However, in [10], the interference caused from the cognitive user on the primary signal and vice-versa, and its relation to imperfect spectrum sensing is not taken into account.

Our initial results provided in [11] indicated that there is a great potential to increase the achievable data rates in cognitive networks if we consider the correct detection of the *absence* of the primary signal as an additional information in spectrum sensing. However, [11] considered only the simple AWGN channel model. The main idea of [11] is extended and generalized in this paper by considering the case of Rayleigh multipath fading channel model for both primary and cognitive data transmission. We perform a modified probability metric for ED spectrum sensing which takes into account correct detection of the *absence* of the primary signal as an additional information. Then, we use this metric for setting the threshold value in ED and show that the conventional method can be viewed as a special case of this general framework.[1] Then, we provide the expression of the achievable information rates associated to a cognitive system by assuming an imperfect spectrum sensing. We consider both fast and slow (quasi-static) Rayleigh channel models and we derive the primary achievable outage rates which is appropriate for slow-fading channel models. These rates are related to the accuracy of spectrum sensing characterized by a given *false-alarm* and *miss-detection* probability. We refer to these rates as *sensing-induced* outage rates since the outage event in the primary network is due to an imperfect spectrum sensing in the CR network. The main contributions of this paper compared to [11] are: **i)** the assumption of both fast and slow Rayleigh fading channel models, **ii)** the derivation of the primary instantaneous and outage achievable rates under an imperfect spectrum sensing in the cognitive network by assuming Rayleigh fading channels and **iii)** the derivation of *sensing-induced* outage rates for the case of cooperative spectrum sensing. Our results may serve in the evaluation of the trade-off between the required quality of service (in terms of achieved outage throughputs in the primary network) and the quality/accuracy of spectrum sensing used at the cognitive network.

The rest of this paper is organized as follows. In Section 2 we perform spectrum sensing performance metrics by taking the absence of the PU into account in our theoretical formulation. We also formulate the spectrum sensing system model and the spectrum sensing parameter selection as an optimization problem based on the predefined metric in this Section. In Section 3, we calculate the achievable rates for both the primary and the cognitive network based on the improved and the conventional ED spectrum sensing. The derivation of the achievable outage rates for the primary network over slow-fading sensing channels as well as its interaction with spectrum sensing is provided in Section 4. Section 5 provides simulation results and some discussions about the performance of the proposed technique. Finally, Section 6 draws our conclusions.

2. Spectrum Sensing Probabilistic Framework and System Model

Sensing the presence or the absence of a primary transmitter signal inside a given frequency band is usually viewed as a binary hypothesis testing problem with hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$ defined as:

$$\begin{cases} \mathcal{H}_0: & \text{primary user is not in operation,} \\ \mathcal{H}_1: & \text{primary user is in operation.} \end{cases} \tag{1}$$

Obviously, in this definition, one has to differentiate between the presence (or the absence) of the primary user in reality and from the cognitive radio point of view, i.e., the decision made by the spectrum sensing process. To this end, $\mathcal{H}_i^{PN}$ is defined to denote the absence (for $i=0$) and the presence (for $i=1$) of the primary signal, respectively. Similarly, $\mathcal{H}_i^{CR}$ is also defined to indicate the decision made based on the received signals during spectrum sensing at cognitive terminals about the absence (for $i=0$) and the presence (for $i=1$) of the primary signal. State of the art contributions such as [4] uses the above hypotheses to define the following conditional probabilities:

$$P_m = P\left(\mathcal{H}_0^{CN}|\mathcal{H}_1^{PN}\right) \tag{2}$$

and

$$P_f = P\left(\mathcal{H}_1^{CN}|\mathcal{H}_0^{PN}\right). \tag{3}$$

The conditional probability in (2) (referred to as *miss-detection* probability) is a performance metric for cases where the cognitive radio fails to detect the *presence* of the primary signal whereas equation (3) (referred to as *false-alarm* probability) is another performance metric for cases where the cognitive radio fails to detect the *absence* of the primary signal. Another widely-used key metric for spectrum sensing is the detection probability P_d defined as [12]:

$$P_d = 1 - P_m = P\left(\mathcal{H}_1^{CN}|\mathcal{H}_1^{PN}\right). \tag{4}$$

Note that by using P_d as defined in (4), the conditional event $\left(\mathcal{H}_1^{CN}|\mathcal{H}_1^{PN}\right)$ (i.e., correct detection by the CR of the absence of a primary user) is not taken into account for spectrum sensing metric formulation. The modified detection probability $\widetilde{P}_d$ which is a linear combination of the well-known *miss-detection* and *false-alarm* probabilities (takes into account both the *presence* and the *absence* of the primary signals) is defined as:

$$\begin{aligned} \widetilde{P}_d &= P\left(\mathcal{H}_0^{CN},\mathcal{H}_0^{PN}\right) + P\left(\mathcal{H}_1^{CN},\mathcal{H}_1^{PN}\right) \\ &= P\left(\mathcal{H}_0^{CN}|\mathcal{H}_0^{PN}\right)P\left(\mathcal{H}_0^{PN}\right) + P\left(\mathcal{H}_1^{CN}|\mathcal{H}_1^{PN}\right)P\left(\mathcal{H}_1^{PN}\right). \end{aligned} \tag{5}$$

Noting that we have $P\left(\mathcal{H}_0^{PN}\right) + P\left(\mathcal{H}_1^{PN}\right) = 1$ and $P\left(\mathcal{H}_0^{CN}\right) + P\left(\mathcal{H}_1^{CN}\right) = 1$, we get:

$$\widetilde{P}_d = p_0\left(1-P_f\right) + p_1\left(1-P_m\right) \tag{6}$$

[1]Note that each threshold value corresponds to a different point over the ROC curve that characterizes the spectrum sensing behavior.

where $p_0 \triangleq P\left(\mathcal{H}_0^{PN}\right)$ and $p_1 \triangleq P\left(\mathcal{H}_1^{PN}\right) = 1 - p_0$ are *a priori* probabilities on the absence and the presence of the primary network, respectively. Since initial CR devices are intended to work over licensed TV bands [13] and spectrum sensing performance evaluation is usually performed for the steady state behavior, one can assume that *a priori* probabilities p_0 and p_1 are available in (6). Similarly, modified miss-detection probability can be defined as:

$$\widetilde{P}_m = 1 - \widetilde{P}_d = p_0 P_f + p_1 P_m. \tag{7}$$

Note that the above metrics constitute a more general framework since by setting $p_1 = 1$ (or equivalently $p_0 = 0$), the modified probabilities in (6) become equivalent to the definitions (4) and (2), respectively.

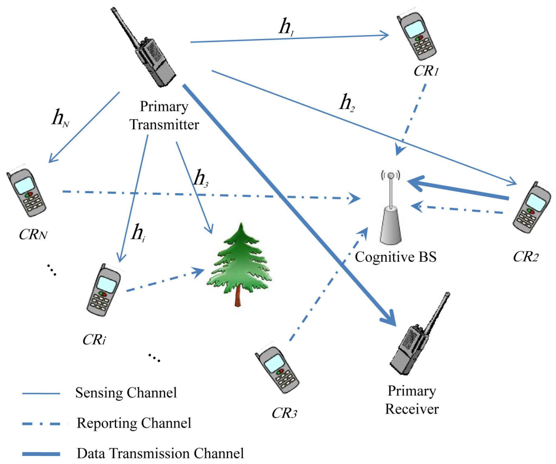

Fig. 1. Architecture of the considered cognitive radio network.

In what follows, the spectrum sensing methodology is explained. The received signal at the j-th cognitive user is:

$$\mathbf{x}_j = \begin{cases} \mathbf{z}_j & \text{under hypothesis } \mathcal{H}_0^{PN}, \\ h_j \mathbf{s} + \mathbf{z}_j & \text{under hypothesis } \mathcal{H}_1^{PN} \end{cases} \tag{8}$$

where the vectors $\mathbf{x}_j = [x_{j,1}, \ldots, x_{j,L}]^T$ and $\mathbf{s} = [s_1, \ldots, s_L]^T$ respectively denote received and transmitted PU symbols during the sensing period; the noise vector $\mathbf{z}_j = [z_{j,1}, \ldots, z_{j,L}]^T$ is assumed to be zero-mean circularly symmetric complex Gaussian (ZMCSCG) with distribution $\mathbf{z}_j \sim \mathcal{CN}(\mathbf{0}, \sigma_{z_j}^2 \mathbf{I}_L)$, and h_j is the channel gain that follows a Rayleigh distribution i.e., $h_j \sim \mathcal{CN}(0, \sigma_{h_j}^2)$. Channel coefficients are assumed to be constant during a frame and change to new independent values from one frame to another, i.e., we assume a quasi-static channel model. In the sequel, ED spectrum sensing is considered at each cognitive user where the test statistic is the observed energy summation within a given sensing period. The energy detection metric for the j-th cognitive user when the primary signal is present, can be obtained as:

$$\mathcal{E}_j = \frac{1}{L} \sum_{i=1}^{L} |h_j s_i + z_{i,j}|^2 \tag{9}$$

where h_j for $j \in \{1, \ldots, N\}$ is the multipath sensing channel coefficient and N is the number of cognitive users (see Fig. 1). Furthermore, we assume that $E(|s_i|^2) = E(|s_i|^4) = 1$. The decision made at the j-th cognitive user is:

$$\hat{\theta}_j = \begin{cases} \mathcal{H}_1 & \text{if } \mathcal{E}_j \geq \zeta_j, \\ \mathcal{H}_0 & \text{if } \mathcal{E}_j < \zeta_j \end{cases} \tag{10}$$

where ζ_j is the energy threshold applied at the j-th cognitive user to differentiate between the two hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$.

To select threshold values ζ_j for $j \in \{1, \ldots, N\}$ over ROC curve at the cognitive BS, we generalize the minimization problem in [11] as:

$$\zeta_{opt} = \arg\min_{\zeta} \ \{\widetilde{P}_m = p_0 P_f + p_1 P_m\} \tag{11}$$

$$\text{subject to :}$$
$$c_1 : P_m \leq P_m^{\max},$$
$$c_2 : P_f \leq P_f^{\max}$$

where the maximum acceptable probability of false-alarm is assumed to be equal to $P_f^{\max}$ and the maximum probability of miss-detection that the primary system can support is assumed to be equal to $P_m^{\max}$. Note that $P_m^{\max}$ corresponds to the maximum interference level that the primary network can support. Moreover, $\widetilde{P}_m$ and $\widetilde{P}_f$ are functions of ζ where $\zeta = (\zeta_1, \ldots, \zeta_N)$ is chosen so as to satisfy a target false-alarm probability. Here, ζ is chosen so as the cost-function $\widetilde{P}_m$ is minimized with respect to the given criteria. To get more insight on (11), let us set $p_0 = 0$ in (11) which leads to minimizing P_m respect to the given criteria. Actually, this is equivalent to set the threshold value ζ associated to the maximum false-alarm probability $P_f^{\max}$.

3. Instantaneous Achievable Information Rates Associated to an Operating Point over the ROC Curve

As shown in Fig. 1, spectrum sensing is affected by various challenges such as shadowing and fading for both sensing and reporting channels. Here, a multipath fading model for the sensing channel (i.e., the channel between the primary transmitter and the cognitive terminals) is considered. In this section, it is assumed that the CR has made a decision by means of spectrum sensing about the presence/absence of the primary network. After that, a cognitive transmitter may establish a connection with a cognitive receiver, in addition to the primary link. If the spectrum sensing process is perfect, the primary and the cognitive transmissions will not interfere with each other. However, in practice, due to imperfect spectrum sensing, interference occurs since the primary and the cognitive network operate over the same frequency band. Here, once the spectrum sensing has decided that the primary user is off, the primary frequency band is allocated to the cognitive user having the best channel gain for an uplink data transmission with the cognitive BS. To achieve transmission opportunities, each cognitive user senses the spectrum during the sensing period and tries to detect the presence of the primary signal in a fraction α of a degrees of freedom (DOF) and the absence of the primary signal in the rest of DOF, i.e., a fraction $(1-\alpha)$. Since the power constraint is on the average across the DOF, there is no difference whether the partitioning is across frequency or across time. So, here without loss of generality, we assume that the partitioning is across time. Here, we generalize the model to achieve the average system throughputs over Rayleigh multipath fading transmission channel. First, the information rates of the primary link by assuming the cognitive transmission as a source of interference is calculated. Second, the achievable information rates of the cognitive network associated to a given operating point (P_f, P_m) over the ROC curve is derived. At the end, the overall information sum-rates achieved by the primary and the cognitive networks are extracted.

In what follows in this section, we assume a number of T frames for the primary network that are sensed by the cognitive network. Then, the cognitive network allocates the free resource to the cognitive user with the best channel condition in each frame. Furthermore, we assume that the number of primary occupied frames is equal to T_p (obviously $T_p \leq T$). So, the *a priori* probabilities (i.e., the fraction of time in which the primary network is in operation) defined in Section 2 can be obtained as:

$$p_1 = P(\mathcal{H}_1^{PN}) = \frac{T_p}{T} = \alpha \tag{12}$$

and

$$p_0 = P(\mathcal{H}_0^{PN}) = \frac{(T-T_p)}{T} = (1-\alpha). \tag{13}$$

As it is stated before, the primary network uses a fraction α of the available DOF, i.e., T frames, for its own transmission and obviously, the rest of the available DOF (i.e., $1-\alpha$) are opportunities for cognitive transmission. Fig. 2 illustrates a DOF and the fraction α used by the primary network.

Based on Fig. 2, dividing the total time-slot allocated to the primary user (T frames) to four different regions, we have the following four regions:

- **region 1**: where only the primary user is in operation (the cognitive network senses the presence of the primary signal correctly),
- **region 2**: where the primary user and the cognitive users interfere with each other (due to imperfect spectrum sensing),
- **region 3**: where only the cognitive user is operation,
- **region 4**: which is not exploited for data transmission (due to false-alarms in the spectrum sensing process).

In what follows, by using the aforementioned regions, the achievable information rates for the primary and the cognitive networks are derived.

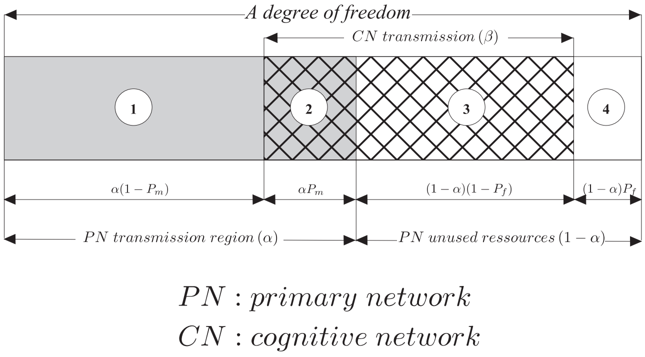

Fig. 2. A degree of freedom in time or frequency domain; **region 1**: only primary transmission, **region 2**: joint primary and cognitive transmission leading to interference, **region 3**: only cognitive transmission, **region 4**: not exploited for transmission due to false-alarm in spectrum sensing.

3.1 Achievable Information Rates of the Primary Network

Fig. 2 illustrates the fraction α of DOF used by the primary network. As shown, in practice, spectrum sensing is imperfect and in a fraction $(1-\delta)$ of a fraction α of the transmission time, the received signal at the primary receiver interferes with the cognitive signal. In this case, the achievable rates for the primary network are written as:

$$R^{PN} \quad = R_1^{PN} + R_2^{PN} \tag{14}$$

where R_1^{PN} is the information rate achieved in a fraction $\alpha\delta$ of the transmission time (depicted in Fig. 2 by region 1) and R_2^{PN} is the information rate achieved in a fraction $\alpha(1-\delta)$ of the transmission time where the cognitive network interfers with the primary transmission (region 2). Let us now relate the parameter δ involved in our analysis to the probabilistic parameters characterizing our spectrum sensing as defined in Section 2. We assume that our spectrum sensing is characterized by the operating point (P_f, P_m) over the ROC curve. Thus, by using the definitions introduced in Section 2, we can state that:

$$\delta = (1-P_m),$$

and so:

$$(1-\delta) = P_m.$$

The instantaneous throughputs achieved by the primary user over Rayleigh fading channel in region 1 is:

$$R_1^{PN} = \frac{1}{T} \sum_{i \in \{region1\}} \log\left\{1 + \frac{f_{p_i}\,\overline{S^{PN}}}{N_0^{PN}}\right\} \quad \text{bits/s/Hz} \tag{15}$$

where f_{p_i} for $i \in \{1,\ldots,T\}$, is the square norm of the i-th channel coefficient for the primary data transmission channel, $\overline{S^{PN}}$ is the primary power transmitted in each frame and N_0^{PN} is the zero-mean Gaussian noise variance. Note that the summation is over the frames that belong to region 1. Considering an AWGN in (15), the achievable rates for the primary network using a fraction $\alpha\delta$ of the transmission time can be written as:

$$\begin{aligned}\widehat{R}_1^{PN} &= \frac{T_p}{T}\,\delta \log\left\{1+\frac{\overline{S^{PN}}}{N_0^{PN}}\right\}\\ &= p_1(1-P_m)\log\left\{1+\frac{S^{PN}}{p_1 N_0^{PN}}\right\} \quad \text{bits/s/Hz} \qquad (16)\end{aligned}$$

where S^{PN} is the received power of the primary user in a fraction α of the transmission time, (equivalent to $\left(\overline{S^{PN}} = \frac{S^{PN}}{\alpha} = \frac{S^{PN}}{p_1}\right)$ joules per DOF).

For region 2, the instantaneous achievable throughput by the primary network is:

$$R_2^{PN} = \frac{1}{T}\sum_{i\in\{region2\}} \log\left\{1+\frac{f_{p_i}\,\overline{S^{PN}}}{I^{CN}+N_0^{PN}}\right\} \quad \text{bits/s/Hz} \quad (17)$$

where I^{CN} is the power of the interference due to imperfect spectrum sensing imposed from the cognitive transmitter on the primary receiver. Note that in (17), we have assumed an AWGN model for the interference I^{CN}. Obviously, per DOF we have:

$$I^{CN} = \frac{S^{CN}}{\beta} \quad (18)$$

where β is the fraction of DOF in which the cognitive network transmits its signal. Again, for an AWGN primary transmission channel, noting that we have an imperfect spectrum sensing and from (12), the achievable rates for the primary network using a fraction $\alpha(1-\delta)$ of the transmission time in region 2 can be written as:

$$\begin{aligned}\widehat{R}_2^{PN} &= \frac{T_p}{T}(1-\delta)\log\left\{1+\frac{\overline{S^{PN}}}{I^{CN}+N_0^{PN}}\right\}\\ &= p_1 P_m \log\left\{1+\frac{S^{PN}}{p_1(I^{CN}+N_0^{PN})}\right\} \quad \text{bits/s/Hz.} \qquad (19)\end{aligned}$$

Thus, the total information rates achieved by the primary network over multipath fading and AWGN channel models can be written respectively as:

$$\begin{aligned}R^{PN} &= \frac{1}{T}\sum_{i\in\{region1\}} \log\left\{1+\frac{f_{p_i}\,\overline{S^{PN}}}{N_0^{PN}}\right\}\\ &+ \frac{1}{T}\sum_{j\in\{region2\}} \log\left\{1+\frac{f_{p_j}\,\overline{S^{PN}}}{I^{CN}+N_0^{PN}}\right\} \quad \text{bits/s/Hz} \qquad (20)\end{aligned}$$

and

$$\begin{aligned}\widehat{R}^{PN} &= p_1(1-P_m)\log\left\{1+\frac{S^{PN}}{p_1 N_0^{PN}}\right\}\\ &+ p_1 P_m \log\left\{1+\frac{S^{PN}}{p_1(I^{CN}+N_0^{PN})}\right\} \quad \text{bits/s/Hz.} \qquad (21)\end{aligned}$$

In addition, the fraction of the transmission time allocated in average to the primary fractions of DOF (α) in Fig. 2 is given by:

- **region 1**: $a_1 = p_1(1-P_m) = p_1 P_d$,
- **region 2**: $a_2 = p_1 P_m$.

Note that under ideal spectrum sensing, a_1 and a_2 are respectively equal to p_1 and 0. In this case, the information rates in (20) and (21) can be rewritten as:

$$R^{PN} = \frac{1}{T}\sum_{i\in\{PNregion(\alpha)\}} \log\left\{1+\frac{f_{p_i}\,\overline{S^{PN}}}{N_0^{PN}}\right\} \quad \text{bits/s/Hz} \quad (22)$$

and

$$\widehat{R}^{PN} = p_1 \log\left\{1+\frac{S^{PN}}{p_1 N_0^{PN}}\right\} \quad \text{bits/s/Hz,} \quad (23)$$

respectively.

3.2 Achievable Information Rates of the Cognitive Network

We now derive the achievable rates for the cognitive network. The fraction of the transmission time allocated on average to the cognitive network in Fig. 2 is given by:

- **region 2**: $a_2 = p_1 P_m$,
- **region 3**: $a_3 = (1-p_1)(1-P_f) = p_0(1-P_f)$.

Note that in region 4 we have $a_4 = (1-p_1)P_f = p_0 P_f$, and consequently the instantaneous achievable throughputs for the primary and the cognitive network are both equal to zero. More precisely, this region gathers the frames which are not exploited for transmission neither by the primary nor by the cognitive network.
We denote by the fraction β of the transmission frame, the resources allocated for cognitive data transmission (depicted in Fig. 2 by the concatenation of regions 2 and 3). We have:

$$\begin{aligned}\beta &= (1-\alpha)(1-P_f)+\alpha P_m\\ &= p_0(1-P_f)+p_1 P_m. \qquad (24)\end{aligned}$$

First, we consider the achievable throughput for the cognitive network under imperfect spectrum sensing. In this case, the throughput in a fraction β of DOF is given by:

$$R^{CN} = R_2^{CN} + R_3^{CN} \quad (25)$$

where R_2^{CN} is the information rate achieved by the CR when the primary user is considered as interference (i.e., region 2 in Fig. 2) and R_3^{CN} is the achieved throughput of the CR in a fraction of DOF without any interference from the primary network (i.e., region 3 in Fig. 2).

In region 2, the instantaneous achievable throughput by the cognitive network over a multipath fading channel is:

$$R_2^{CN} = \frac{1}{T} \sum_{i \in \{region2\}} \log\left\{1 + \frac{f_{c_i}\, \overline{S^{CN}}}{I^{PN} + N_0^{CN}}\right\} \quad \text{bits/s/Hz} \quad (26)$$

where f_{c_i} for $i \in \{1, 2, \ldots, T\}$, is the square norm of the i-th channel coefficient for the cognitive data transmission channel, $\overline{S^{CN}}$ is the cognitive power transmitted in each frame (equivalent to $\overline{S^{CN}} = \frac{S^{CN}}{\beta}$ joules per DOF) and N_0^{CN} is the zero-mean Gaussian noise variance. Moreover, I^{PN} is the power of the interference imposed from the primary signal at the cognitive receiver. Again, we have assumed an AWGN model for the interference I^{PN} in (26). Obviously, per DOF we have:

$$I^{PN} = \frac{S^{PN}}{\alpha} = \frac{S^{PN}}{p_1}. \quad (27)$$

Here, by considering imperfect spectrum sensing, the achievable rates for the cognitive network using a fraction $\alpha(1-\delta)$ of the transmission time in region 2 under AWGN transmission channel can be written as:

$$\begin{aligned} \widehat{R}_2^{CN} &= \frac{T_p}{T}(1-\delta) \log\left\{1 + \frac{\overline{S^{CN}}}{I^{PN} + N_0^{CN}}\right\} \\ &= p_1 P_m \log\left\{1 + \frac{S^{CN}}{\beta\,(I^{PN} + N_0^{CN})}\right\} \quad \text{bits/s/Hz}. \quad (28) \end{aligned}$$

Similarly, considering a multipath fading channel, one can calculate the instantaneous throughputs achieved by a given cognitive user (for instance, the one who has the best channel) in region 3. We have:

$$R_3^{CN} = \frac{1}{T} \sum_{i \in \{region3\}} \log\left\{1 + \frac{f_{c_i}\, \overline{S^{CN}}}{N_0^{CN}}\right\} \quad \text{bits/s/Hz}. \quad (29)$$

Under AWGN, Equation (29) writes:

$$\begin{aligned} \widehat{R}_3^{CN} &= \frac{T - T_p}{T}(1 - P_f) \log\left\{1 + \frac{\overline{S^{CN}}}{N_0^{CN}}\right\} \\ &= p_0 (1 - P_f) \log\left\{1 + \frac{S^{CN}}{\beta N_0^{CN}}\right\} \quad \text{bits/s/Hz}. \quad (30) \end{aligned}$$

Therefore, the total information rate achieved by the cognitive network per DOF over multipath fading and AWGN channel models can be written respectively as:

$$\begin{aligned} R^{CN} &= \frac{1}{T} \sum_{i \in \{region2\}} \log\left\{1 + \frac{f_{c_i}\, \overline{S^{CN}}}{I^{PN} + N_0^{CN}}\right\} \\ &+ \frac{1}{T} \sum_{j \in \{region3\}} \log\left\{1 + \frac{f_{c_j}\, \overline{S^{CN}}}{N_0^{CN}}\right\} \quad \text{bits/s/Hz} \quad (31) \end{aligned}$$

and

$$\begin{aligned} \widehat{R}^{CN} &= p_1 P_m \log\left\{1 + \frac{S^{CN}}{\beta\,(I^{PN} + N_0^{CN})}\right\} \\ &+ p_0 (1 - P_f) \log\left\{1 + \frac{S^{CN}}{\beta N_0^{CN}}\right\} \quad \text{bits/s/Hz}. \quad (32) \end{aligned}$$

Under perfect spectrum sensing, fractions a_2, a_3 and β are equal to 0, p_0 and $(1-\alpha)$, respectively, and hence the achievable rates (31) and (32) can be rewritten as:

$$R^{CN} = \frac{1}{T} \sum_{i \in \{regions\, 2\, and\, 3\}} \log\left\{1 + \frac{f_{c_i}\, \overline{S^{CN}}}{N_0^{CN}}\right\} \quad \text{bits/s/Hz} \quad (33)$$

and

$$\widehat{R}^{CN} = p_0 \log\left\{1 + \frac{S^{CN}}{(1-\alpha) N_0^{CN}}\right\} \quad \text{bits/s/Hz}, \quad (34)$$

respectively.

3.3 Total Achievable Information Rates

The maximum information rates that can be achieved in our considered transmission scenario, is the sum-rates R_{sum}:

$$R_{\text{sum}} = R^{PN} + R^{CN}. \quad (35)$$

Assuming $N_0^{PN} = N_0^{CN} = N_0$, $S^{PN} = S^{CN} = \bar{S}$ and defining $\gamma \triangleq \frac{\bar{S}}{N_0}$, according to (20) and (31), the sum-rates (35) over a multipath channel model can be written as:

$$\begin{aligned} R_{\text{sum}} &= \frac{1}{T} \sum_{i \in \{region1\}} \log\left\{1 + f_{p_i} \frac{\gamma}{p_1}\right\} \\ &+ \frac{1}{T} \sum_{j \in \{region3\}} \log\left\{1 + f_{c_j} \frac{\gamma}{\beta}\right\}\} \\ &+ \frac{1}{T} \sum_{j \in \{region2\}} \log\left\{1 + f_{p_i} \left(\frac{p_1}{\beta} + \gamma^{-1}\right)^{-1}\right\} \\ &+ \frac{1}{T} \sum_{i \in \{region2\}} \log\left\{1 + f_{c_i} \left(\frac{\beta}{p_1} + \gamma^{-1}\right)^{-1}\right\} \\ &\quad \text{bits/s/Hz} \quad (36) \end{aligned}$$

and similarly, according to (21) and (32), the sum-rates (35) for an AWGN channel writes:

$$\begin{aligned} \widehat{R}_{\text{sum}} &= p_1 (1 - P_m) \log\left\{1 + \tfrac{\gamma}{p_1}\right\} \\ &+ p_0 (1 - P_f) \log\left\{1 + \tfrac{\gamma}{\beta}\right\} \\ &+ p_1 P_m \log\left\{1 + \left(\tfrac{p_1}{\beta} + \gamma^{-1}\right)^{-1}\right\} \\ &+ p_1 P_m \log\left\{1 + \left(\tfrac{\beta}{p_1} + \gamma^{-1}\right)^{-1}\right\} \quad \text{bits/s/Hz}. \quad (37) \end{aligned}$$

In (37), the last two terms correspond to the achievable throughputs for the primary and the cognitive network, respectively, in the fraction of DOF (i.e., region 2 in Fig. 2) where the two networks are transmitting simultaneously. Finally, we notice that under an ideal[2] (not practical) spectrum sensing characterized by $P_m = 0$ and $P_f = 0$, from (24) we get $\beta = 1 - \alpha = p_0$ and the sum-rates in (37) reduces to:

$$R_{\text{sum}} = p_1 \log\left\{1 + \frac{\gamma}{p_1}\right\} + p_0 \log\left\{1 + \frac{\gamma}{p_0}\right\} \text{ bits/s/Hz,} \tag{38}$$

which is nothing but the sum of rates obtained respectively in equations (23) and (34), for the primary and cognitive network with an ideal spectrum sensing.

Finally, note that by inserting a given set of parameters (P_f, P_m) (characterizing a given spectrum sensing technique) in (37), one can get the sum-rates associated to the deployed spectrum sensing technique.

4. Sensing-induced Primary Outage Achievable Rates

As mentioned in Section 2, the sensing channel is chosen randomly at the beginning of the transmission frame and is held fixed during the whole transmission session. On the other hand, the primary achievable rates of equation (21) depend on the sensing channel through the miss-detection probability P_m. In this case, the achievable rate is a random entity, as it depends on the instantaneous channel coefficient. More precisely, the capacity in the Shannon sense does not exist since there is a non-zero probability that the realized channel is not capable of supporting even a very small rate. Thus, the concept of *capacity-versus-outage* has to be invoked [15]. However, since the outage (or failure) is due to the sensing channel, we propose here the notion of *sensing-induced outage rates*, which has a different definition than the classical notion of outage capacity, as explained in the sequel.

Let us first define the rates R_1 and R_2 as follows:

$$R_1 \triangleq p_1 \log\left\{1 + \frac{S^{PN}}{p_1 N_0^{PN}}\right\} \tag{39}$$

and

$$R_2 \triangleq p_1 \log\left\{1 + \frac{S^{PN}}{p_1\left(\frac{S^{CN}}{\beta} + N_0^{PN}\right)}\right\} \tag{40}$$

where obviously we have:

$$R_1 \geq R_2. \tag{41}$$

Assuming a predefined value for P_m determined by an operating point over the ROC curve, the primary achievable rates of equation (21) can be rewritten in an equivalent form as:

$$R^{PN}(P_m) = R_1 - P_m(R_1 - R_2). \tag{42}$$

According to (42), since $0 \leq P_m \leq 1$, R^{PN} is bounded as:

$$R_2 \leq R^{PN} \leq R_1. \tag{43}$$

We now define the *sensing-induced outage probability* for an outage rate R and a miss-detection probability P_m as:

$$P_{out}^{PN}(R, P_m) = P(R^{PN} < R) = P\left(\frac{R_1 - R}{R_1 - R_2} < P_m\right). \tag{44}$$

Using this, the outage rate for an outage probability equal to γ is given by:

$$R_{out}^{PN}(\gamma, P_m) = \sup_R\{R \geq 0 : P_{out}^{PN}(R, P_m) \leq \gamma\}. \tag{45}$$

The outage probability of (44) is written in an equivalent form as:

$$P_{out}^{PN} = P(P_{m0} < P_m) \tag{46}$$

where

$$P_{m0} = \frac{R_1 - R}{R_1 - R_2}. \tag{47}$$

To derive the expression of the outage probability (46), we first have to express the miss-detection probability P_m as a function of sensing channel coefficients. This is done in the following for the more general case of cooperative spectrum sensing.

4.1 Cooperative Spectrum Sensing

The observed energy for the the j-th cognitive user when the primary signal is present (the ED metric $\mathcal{E}_j$ in (9)) according to the central limit theorem [16], for large L, has approximately the following Gaussian distribution [17]:

$$\mathcal{E}_j \sim \mathcal{N}(\mu_j, \sigma_j^2) \tag{48}$$

where μ_j and σ_j^2 are given by:

$$\mu_j = |h_j|^2 + \sigma_{z_j}^2 \tag{49}$$

and

$$\sigma_j^2 = |h_j|^4 + 2|h_j|^2\sigma_{z_j}^2 + \sigma_{z_j}^4 = \mu_j^2. \tag{50}$$

Here we use the near optimum energy detector proposed in [6] that compares the summation of the received energies, $M = \sum_{j=1}^{n} \mathcal{E}_j$, to a given threshold value ζ. According to (48), the ED metric M has the following Gaussian distribution:

$$M \sim \mathcal{N}(\mu_M, \sigma_M^2) \tag{51}$$

where μ_M and σ_M^2 are given by:

$$\mu_M = \sum_{j=1}^{N} \mu_j = \sum_{j=1}^{N} |h_j|^2 + N\sigma_z^2 \tag{52}$$

and

[2] It is important to notice that the assumption $P_m = 0$ and $P_f = 0$ is not realistic since the point $(P_f = 0, P_m = 0)$ does not belong to the ROC curve of spectrum sensing. However, we have made this assumption here to get more insights about the sum-rates of (37) when spectrum sensing is assumed *ideal*.

$$\sigma_M^2 = \sum_{j=1}^{N} \sigma_j^2 = \sum_{j=1}^{N} |h_j|^4 + 2\sigma_z^2 \sum_{j=1}^{N} |h_j|^2 + N\sigma_z^4. \quad (53)$$

Note that in (52) and (53) we have assumed $\sigma_{z_j}^2 = \sigma_z^2$ for all $j = 1, \ldots, N$. According to (53), the standard deviation of the ED metric M is:

$$\sigma_M = \sqrt{\sum_{j=1}^{N} \left(|h_j|^2 + \sigma_z^2\right)^2}. \quad (54)$$

The miss-detection probability for the considered near optimum energy detector in cooperative spectrum sensing is obtained as:

$$P_m = Q\left(\frac{\zeta - \mu_M}{\sigma_M}\right) = Q\left(\frac{\zeta - \sum_{j=1}^{N} |h_j|^2 + N\sigma_z^2}{\sqrt{\sum_{j=1}^{N} \left(|h_j|^2 + \sigma_z^2\right)^2}}\right) \quad (55)$$

where $Q(.)$ is the well known Q-function. Equation (55) expresses the probability of miss-detection as a function of sensing channel coefficients. Now we can compute the outage probability for a given outage rate R. Replacing (55) in (46) yields to:

$$P_{out}^{PN} = P\left(P_{m0} < Q\left(\frac{\zeta - \sum_{j=1}^{N} |h_j|^2 + N\sigma_z^2}{\sqrt{\sum_{j=1}^{N} \left(|h_j|^2 + \sigma_z^2\right)^2}}\right)\right). \quad (56)$$

The value of P_{out}^{PN} will be find numerically in Section 5. However, an analytical expression can be derived for non-cooperative spectrum sensing characterized by $N = 1$ in (56). In this case we have:

$$\begin{aligned} P_{out}^{PN} &= P\left(P_{m0} < Q\left(\frac{\zeta}{|h|^2 + \sigma_z^2} - 1\right)\right) \\ &= P\left(hh^* < \left\{\frac{\zeta}{Q^{-1}(P_{m0}) + 1} - \sigma_z^2\right\}\right). \end{aligned} \quad (57)$$

Since the variable hh^* is a χ^2 random variable with 2 degrees of freedom and a mean equal to 1, we can derive the analytical expression of the outage probability for a given information rate R as:

$$P_{out}^{PN} = \gamma\left(1, \left[\frac{\zeta}{Q^{-1}(P_{m0}) + 1} - \sigma_z^2\right]\right) \quad (58)$$

where $\gamma(a, x)$ is the incomplete gamma function.

5. Numerical Results and Discussion

In this section, we provide numerical results to evaluate the performance provided by the proposed spectrum sensing method in comparison with conventional techniques [3], [4], [18]. First, we focus on the achievable information rates (derived in Section 3) associated to improved and classical ED based spectrum sensing. Then, we analyze the achievable outage information rates (derived in Section 4) for our improved ED based spectrum sensing. Throughout the simulations, the transmitted power for both primary and cognitive transmitter is normalized to one and the channel bandwidth

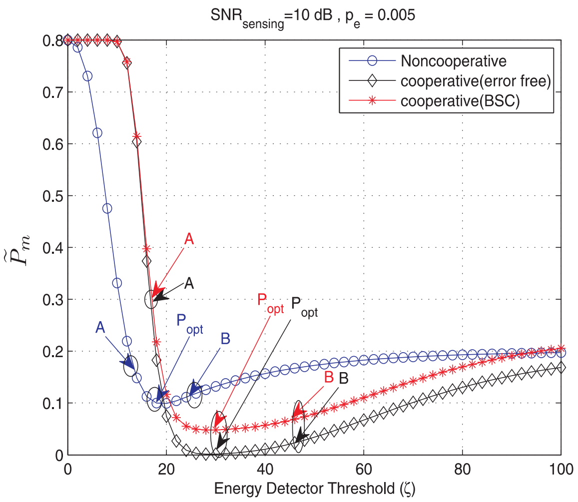

Fig. 3. The modified miss-detection probability $\widetilde{P}_m$ for different spectrum sensing configurations versus ζ. Solutions of the optimization problem (11) are indicated by P_{opt}.

is also normalized to one. The *a priori* probability on the presence of a primary user is $p_1 = P(\mathcal{H}_1^{PN}) = 0.2$. For spectrum sensing, we consider both non-cooperative (i.e., with one CR) and cooperative schemes with 12 cognitive users for the achievable rate results and 24 cognitive users for the achievable outage rate results. However, after the sensing period, once the cognitive network is allowed to communicate with its receiver, we assume only one cognitive device is involved for data transmission. The maximum acceptable values for $P_f^{\max}$ and $P_m^{\max}$ in the optimization problem of (11) are equal to 0.3 and 0.3, respectively. We consider the BSC and the error-free channel models with a transition error probability of 0.005 for the reporting channel involved in spectrum sensing and the AWGN channel model for data transmission channels of either the primary or the cognitive network. The sensing channel used in our spectrum sensing model are assumed as fast fading (in Section 3) and slow fading (in Section 4) with a Rayleigh distribution.

Fig. 3 plots the modified miss-detection probability $\widetilde{P}_m$ versus the threshold value ζ used in the ED for different spectrum sensing configurations. This enables us to find numerically the solutions of the cost function considered in (11). We have denoted by P_{opt} over each curve, the optimal ζ_{opt} value minimizing the cost function (11). We have also indicated by points A and B over each curve the ζ value corresponding to the maximal values $P_m^{\max}$ and $P_f^{\max}$ in (11). Notice that ζ values corresponding to points A over each curve are those used in a conventional ED-based spectrum sensing.

Fig. 4 shows the total (i.e., provided by both the primary and the cognitive network) information rates (in bits/s/Hz) versus the SNR (in dB), obtained by adopting improved and conventional spectrum sensing approaches. For comparison, we also display the upper bound on the information rates provided by an ideal spectrum sensing as well as the information rates achieved by the primary network.

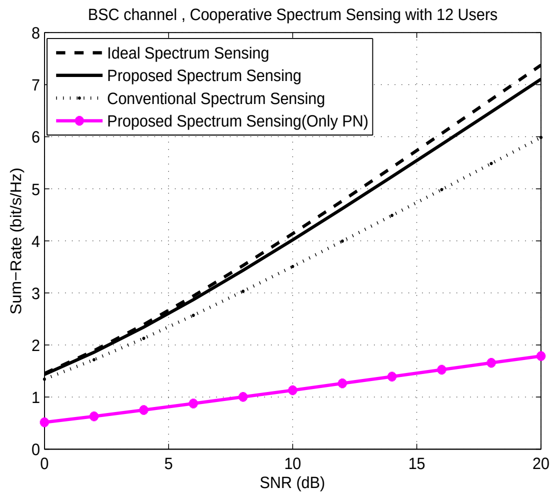

Fig. 4. Total achievable information rates over the BSC reporting channel versus the SNR for different spectrum sensing methods with 12 cognitive user cooperating in the sensing method.

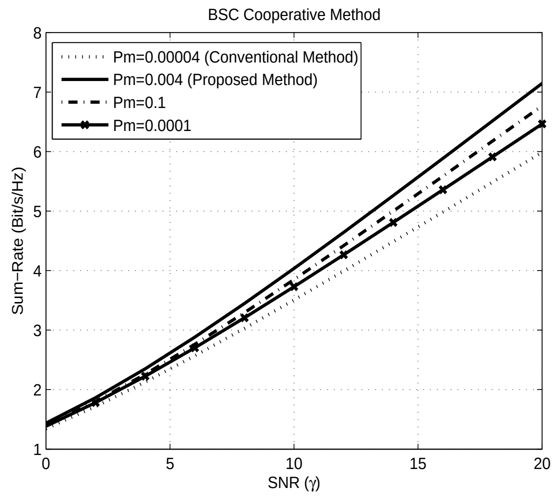

Fig. 5. Total achievable information rates over the BSC reporting channel versus the SNR for different spectrum sensing methods with 12 cognitive user cooperating in the sensing process.

The first observation is the large gain in the achievable information rates provided by using a cognitive network. Furthermore, the figure clearly shows the sub-optimality of conventional spectrum sensing in terms of achievable information rates compared to the rates provided by our proposed improved spectrum sensing. It can be observed that the conventional information rates are about 4.3 dB (at a sum-rate of 6 bits/s/Hz) of SNR far from the rates achieved by the ideal spectrum sensing. We note that by adopting the improved spectrum sensing, the above SNR gap is reduced to about 0.6 dB.

Similar plots are depicted in Fig. 5 for different values of miss-detection probability P_m over the BSC reporting channel. In this figure, the first two P_m values indicate an operating point over the ROC related to the improved and conventional spectrum sensing, respectively. We have shown the performance obtained for two other P_m values for comparison. The figure clearly shows that increasing the value of P_m leads to an increase in the total network achievable information rates toward those provided by our proposed method (i.e., the curve obtained with $P_m = 0.004$). We observe that for miss-detection probabilities greater than 0.004 (i.e., $P_m > 0.004$), the total network achievable information rates are reduced. This confirms that our proposed method provides the highest total network achievable information rates while minimizing the miss-detection probability.

Fig. 6 shows the outage information rates (in bits/s/Hz) achieved by the primary network and its boundaries versus the SNR (in dB), obtained by adopting the improved spectrum sensing approach. The curves are plotted for 24 cognitive users cooperating in spectrum sensing where the sensing channel SNR is equal to 10 dB. The the primary outage information rate for outage probabilities (P^{PN}_{Outage}) 0 (lower bound), 0.2, 0.4, 0.6, 0.8 and 1 (upper bound) are shown in

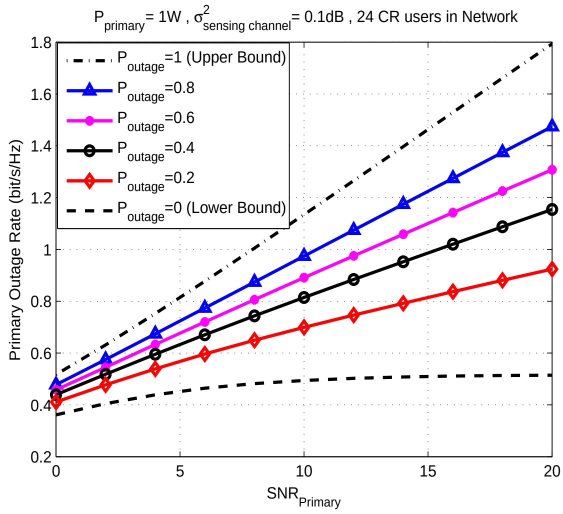

Fig. 6. Achievable outage sum-rates over the error-free reporting channel versus the SNR for proposed spectrum sensing method with 24 cognitive user cooperating in the sensing process.

this figure. Obviously, we observe that smaller outage rates are associated to better quality of services (i.e., smaller outage probabilities).

Fig. 7 depicts the outage sum-rates (in bits/s/Hz) achieved by the both primary and cognitive networks versus the SNR (in dB), obtained by adopting either the improved or the conventional spectrum sensing method. The curves are plotted for 24 cognitive users cooperating in the sensing process where the sensing channel SNR is equal to 10 dB. The figure clearly confirms the superiority of the improved spectrum sensing detector over the conventional method in terms of outage sum-rates.

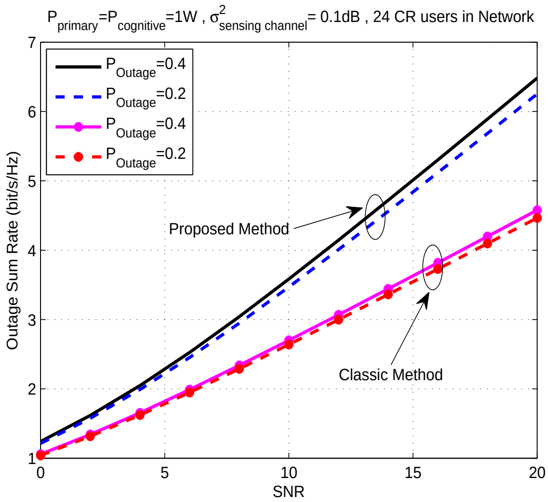

Fig. 7. Primary achievable outage information rates over the BSC reporting channel versus the SNR for the proposed spectrum sensing method with 24 cognitive user cooperating in the sensing process.

6. Conclusion

In this paper, we proposed a new spectrum sensing technique that detects both the *absence* and the *presence* of primary users. First, we derived the expression of the information rates achieved by the primary network. We also derived the expression of the achievable information rates of the CR, based on the proposed and the conventional energy detection spectrum sensing. Our derivations are made for the case of Rayleigh fading channels. For slow varying Rayleigh fading sensing channels, we derived the primary network achievable outage rates induced by an imperfect spectrum sensing. Assuming a cooperative cognitive network, we showed that the rates achieved by the improved detector are very close to those provided by the ideal (interference-free) spectrum sensing. Moreover, our results confirmed the adequacy of the proposed spectrum sensing in terms of outage sum-rates achieved by the improved spectrum sensing compared to those provided by the conventional method. It is worth mentioning that the improvements reported in this paper are obtained only by changing the cost function used for setting the threshold value in energy detection, and thus no additional complexity is required at the cognitive terminal. Results provided in this paper may serve in the evaluation of the trade-off between the required quality of service (in terms of achieved outage rates in the primary network) and the accuracy of spectrum sensing (in terms of miss-detection and false-alarm) used at the cognitive network.

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