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Continuous transmit in cognitive radio systems: outage performance of selection decode-and-forward relay networks over Nakagami-*m* fading channels

Mohammed Ridouani[1*], Aawatif Hayar[2] and Abdelkrim Haqiq[3]

Abstract

Cognitive radio is a promising technology that uses radio spectrum opportunistically and efficiently. In this paper, we present the performance of 'Always transmit' strategy, which consists of allowing the cognitive source to transmit over all time slots and in any time slot. Thus, the cognitive source will be able to operate continuously whenever either the primary user is active or absent. The proposed strategy is projected into dual-hop communication systems with decode-and-forward and relay selection over independent but not necessarily identically distributed Nakagami-*m* fading channels. We derive the closed-form expressions of the outage probability, and we analyze the performance. Simulation results show that the strategy 'Always transmit + Relay' outperforms other conventional cognitive radio strategies and the use of relays enhances the performance in deep fading channel.

Keywords: Continuous transmit in cognitive radio; Decode-and-forward relay; Spectrum sensing; Interference constraints; Interweave approach; Underlay approach; Nakagami-*m* fading; Outage probability

1 Introduction

Recently, significant attention has been given to cognitive radio as a new technology that uses radio spectrum opportunistically and efficiently and which allows new applications to share currently allocated spectrum while the quality of service (QoS) at primary side is guaranteed.

There are three approaches of cognitive radio used to access licensed or unlicensed band [1]: spectrum interweave, spectrum underlay, and spectrum overlay.

a- Spectrum interweave (interference avoiding): the secondary user (SU) uses the first part of time slot (iT) (first phase) for 'spectrum sensing' to detect spectrum hole (spectrum not currently used by primary user) and make a secondary user decision $H_s(i)$ at time slot (iT), and beginning transmission in the second phase, only if the result of sensing in the first phase is $H_s(i) = H_0$ (hole is detected, i.e., primary user is absent). In this approach, the SU does not interfere with primary user.

*Correspondence: mohammed_ridouani@yahoo.fr
[1] Computer Sciences Department, GREENTIC/UH2C/EST, Casablanca, Morocco
Full list of author information is available at the end of the article

b- Spectrum underlay (interference controlling): the SU can transmit simultaneously with primary user over the same spectrum and through all time slots (iT) only if the interference generated by secondary transmitter (cognitive transmitter) at primary receiver is tolerable and controlled by an acceptable level, i.e., below a threshold or an outage probability limit that guarantees certain QoS for primary user's communication.

c- Spectrum overlay (interference mitigating): the SU (cognitive transmitter) can transmit simultaneously with primary user over the same spectrum. In this approach, cognitive transmitter can transmit with any power, part of its power and time slot (iT) used for relaying primary user's transmission, and the remainder of its power and time slot (iT) for own transmission.

Also, cooperative communications with amplify-and-forward (AF) or with decode-and-forward (DF) strategy have gained a great interest in the academic research circles. This is due to benefits over a fading channel, like combating fading and shadowing, and increasing the system capacity. In [2], the authors shown that the best relay selection scheme can achieve the same diversity-multiplexing tradeoff performance as the traditional protocols. As researches go deep and broad, some works introduce cooperative communication techniques into cognitive radio, to enhance the secondary user's data transmission and the reliability of primary user's detection.

One of the QoS parameters for secondary system is the continuity of service. Continuous transmission for secondary users is weakly addressed. Indeed, in [3,4], the SU transmits through underlay method either by controlling interference level [3,4] or outage probability limit. Nevertheless, underlay method underutilizes the spectrum, and SU does not transmit with high power even when primary user is absent. In [5,6], the SU transmits with the interweave method in the second phase only if the result of sensing in the first phase is $H_s(i) = H_0$. In [7], mixed strategies introduced for cognitive transmission in the second phase based on the sensing results in the first phase. Many studies in the literature on such mixed strategies have been conducted [8-13], in their scenarios, the secondary user transmits through interweave method in the second phase if the result of sensing in the first phase is $H_s(i) = H_0$ or transmits with underlay method in the second phase if the result of sensing in the first phase is $H_s(i) = H_1$ (hole is not detected, i.e., primary user is active). However, none of these papers have considered the transmission in two phases, SU does not transmit over all time slots, it transmits only in the second phase, which decreases the spectrum efficiency as some part of the time slot is used for sensing instead of data transmission.

In most of the above presented strategies, sensing is a key functionality that affects the spectral efficiency of SU due to the time dedicated to sensing. However, two different architectures could be adopted to operate spectrum sensing and communication by using single radio or dual radio [14,15]. Nevertheless, in the single radio architecture, no communication is allowed during sensing phase. Our work aims at exploiting sensing phase for transmission also optimizes the SU spectrum efficiency and thus adopts double radios architecture. To be able to do so without creating harmful interference to the primary user, we propose an underlay scheme with limited interference threshold.

In our previous works [16], where we have introduced our new strategy of transmission '*Always Transmit (AT): to enhance the cognitive sources of data transmission and to provide continuous transmit solution by using mixed strategies in cognitive radio context, which it performed via the combination of the underlay and interweave approaches depending on the activity of the primary system*' and have shown that it outperforms other conventional cognitive radio strategies for power transmission and interference management, in [17], where we have derived the closed form and analyzed the performance of outage probability over Rayleigh fading, and in [18], where we have studied the trade-off between spectrum sensing duration and the QoS at cognitive network while guaranteeing certain QoS at primary network controlled by the outage probability limit, over independent but not necessarily identically distributed Nakagami-m channels. In (M Ridouani, A Hayar, A Haqiq, Continuous-transmit in cognitive radio systems: perform sensing and transmission in parallel anytime. submitted to IEEE TWC), we have shown that the use of (average transmit P_{av}, instantaneous interference I) as power constraint is recommended for transmission, because it allows preserving the QoS of primary system at each time while guaranteeing an outage performance limit for the secondary of about $\simeq 20\%$ of maximum degradation, and due to fading and by using average transmit power constraint, the energy efficiency is improved.

Motivated by cooperative communications and our results in [17,18], in this paper, we extend our strategy 'AT' (the cognitive source (CS) will be able to transmit over all time slots and in any time slot, then, it will be able to operate continuously whenever either the primary user is active or absent) into cognitive relay selection. We derive the closed form of outage probability of relay selection in dual-hop transmission over independent but not necessarily identically distributed (i.n.i.d.) Nakagami-m channels, with integer values of fading severity parameter m.

Our main contributions are summarized as follows:

1) The continuity of service: we propose a scenario that enhances secondary user QoS in terms of outage probability by allowing it to transmit over *all time slots and in any time slots*. Therefore, the secondary can continue its transmission whether the primary user is active or absent.

2) We derive the closed-form expressions of the secondary user outage probability for transmission scenario over both phases and over independent but not necessarily identically distributed Nakagami-m fading channels. And we analyze for this considered scenario the impact of spectrum sensing duration and spectrum hole detection, the transmit and the interference power constraints, and the number of relays and fading on the secondary outage probability (QoS).

3) We show that the proposed strategy 'Always transmit + Relay' outperforms other conventional cognitive radio strategies.

This paper is organized as follows. In Section 2, we outline the system model (scenario, spectrum sensing, and the optimal power allocation) of the proposed scheme of cognitive transmission. The closed form of outage probability of cognitive relay selection over a Nakagami-m fading channel is given in Section 3. In Section 4, we present numerical results. Section 5 draws the conclusion.

2 System model

In this section, we describe the cognitive relay network of our scenario. As shown in Figure 1b, the primary destination (PD) coexists with the cognitive nodes (CS, cognitive destination (CD), and N potential cognitive relay (CR_k) $k = 1, .., N$). Each cognitive node has a dual-radio architecture, one radio chain is dedicated for spectrum sensing (see Section 2.1) while the other radio chain operates on a half-duplex mode, and it is dedicated for data transmission and reception.

Notice here that, if we look only at the second radio chain, we can see that it operates on a half-duplex mode. If we look at the cognitive node (which consists of a two radio chains), one radio is dedicated for spectrum sensing (reception), the second chain for communication (for example, transmitting data: transmission), we can see that it operates, globally, on a full-duplex mode.

In this model, we consider a half-duplex mode and a dual-hop communication system with regenerative mode for data transmitting. Also, it is assumed that there is no direct transmission between CS and CD. So the data transmission from CS to CD is subdivided into two steps. In step one, the CS transmits its data (one packet) to (CR_k) which is selected prior to a new transmission. In step two, the CR_k decodes the received data and then re-encodes and forwards it to a CD.

Also, we consider that the transmission of CS and CR_k process can move into two phases through a time slot (iT) as shown in Figure 1a. In the first phase (αT), the CS (resp. CR_k) transmits through underlay approach, in the meantime, each cognitive node senses the spectrum hole existence (activity of primary source (PS)). In the second phase ($(1-\alpha)T$), the CS (resp. CR_k) transmits through interweave or underlay approach whether or not a hole is detected in the first phase, respectively.

The data (frame i) structure of the proposed system is shown in Figure 1a. The time duration of the transmission of each frame is T. Each frame consists of many packet transmission periods, and we assume that each packet transmission period is very small subject to the time slot T, which we allow to suppose that each packet transmitted from CS to the best cognitive relay CR_k and from CR_k to the CD is via the same transmission mode (underlay or interweave), and the best cognitive relay CR_k is selected to transmit all packets of a frame i during the time slot iT.

We assume that the channel changes slowly, so the channel remains constant during a one time slot. Also, we assume that the channels between any of the two nodes are independent but not necessarily identically distributed (i.n.i.d.) Nakagami-m channels, with integer values of fading severity parameter m, so that the probability distribution function (PDF) of the channel gains ($|g_{sp}|^2$, $|h_{SK}|^2$, $|g_{kp}|^2$, and $|h_{KD}|^2$) is statistically characterized by the Nakagami distribution [19], where g_{sp}, h_{SK}, g_{kp}, and h_{KD} are the fading coefficients of the channel from CS to PD, from CS to CR_k, from CR_k to PD, and from CR_k to CD, respectively, as shown in Figure 1. Let $X_k = |h_{SK}|^2$, $Y_k = |h_{KD}|^2$, $Z_0 = |g_{sp}|^2$, and $Z_k = |g_{kp}|^2$.

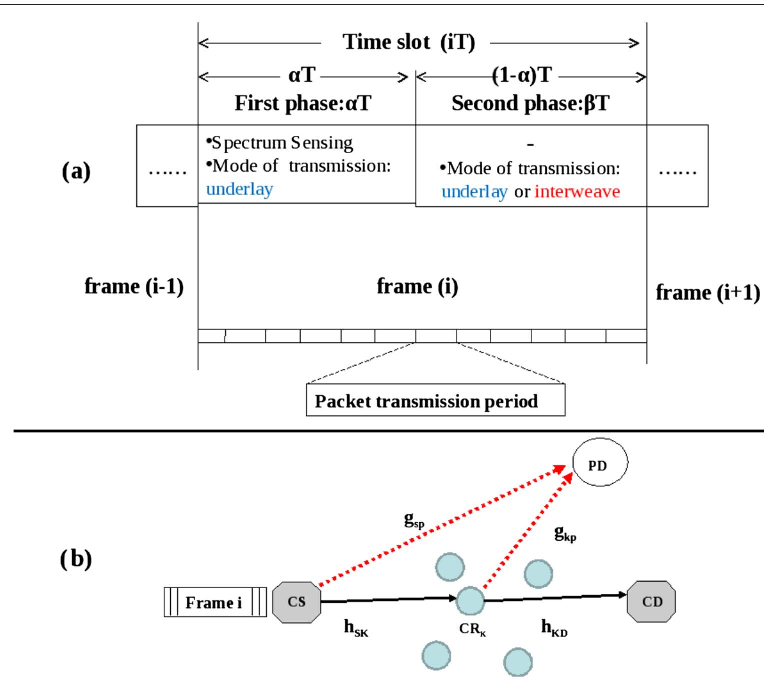

Figure 1 The mode of transmission and the allocation of time durations **(a)** and fading coefficient of the channels **(b)**.

Note that X_k, Y_k, and Z_k ($k = 0, 1, .., N$) follow the probability distribution $p_k(x)$, $p_k(y)$, and $p_k(z)$, respectively, and are independent of each other. Thus, the channel gain, γ ($\gamma = X_k, Y_k, Z_k$), is distributed according to a gamma distribution given by (1) with different fading parameters $\gamma_{xk}, \gamma_{yk}, \gamma_{zk}$ and fading severity parameters m_{xk}, m_{yk}, m_{zk}:

$$p_\gamma(\gamma) = \left(\frac{m}{\overline{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} \exp\left(-m\frac{\gamma}{\overline{\gamma}}\right), \gamma \geq 0, m \geq 1/2 \tag{1}$$

where $\overline{\gamma}$ is the average channel gain ($\overline{\gamma} = E[\gamma]$), m is the Nakagami fading severity parameter, and $\Gamma(.)$ is the gamma function [20].

The Nakagami fading model has proven useful for modeling multipath faded envelope in wireless channels and is widely accepted as best fit to model multipath propagation from severe to light fading. Indeed, it is known to accurately characterize a range of multipath and to model different fading conditions ranging from Rayleigh to strong Rician channels. As the fading parameter m tends to infinity, the Nakagami multipath fading channel converges to an AWGN channel.

For notation convenience, we use the notations as follows:

k: the k-th cognitive node ($k = 0$ refer to CS and $k = 1, \ldots, N$ refer to CR_k).
P_{SK} and P_{KD} are the transmit power of CS and CR_k, respectively.
$H_p(i)$: denote whether or not the licensed band is occupied by PS in the first phase of time slot iT.
H_0: the band is unoccupied by PS (and H_1: otherwise).
CS and CR_k will make a decision $H_s(i)$ to transmit through interweave or underlay method in the second phase
$H_s(i) = H_0$: considers the band is available, then, CS and CR_k transmit through interweave method
$H_s(i) = H_1$: considers the band is unavailable, then, CS and CR_k transmit through underlay method.
$P_a = Pr(H_p(i) = H_0)$: the probability that there is a hole (and $Pr(H_p(i) = H_1) = 1 - P_a$ otherwise).
$P_f^k = Pr(H_s(i) = H_1/H_p(i) = H_0)$: the probability that the k-th cognitive node has a false alarm.
$P_d^k = Pr(H_s(i) = H_1/H_p(i) = H_1)$: the probability that the k-th cognitive node detects the PS presence.
ε: represent the fraction of a time slot utilized for data transmission in the first phase ($\varepsilon = \alpha$) and second phase ($\varepsilon = \beta = 1 - \alpha$)
P_α: the probability to be in the first phase.
$P_\beta = 1 - P_\alpha$: the probability to be in the second phase.

2.1 Spectrum sensing

Cooperative spectrum sensing can improve the performance of spectrum sensing by combating fading and shadowing and decreasing the detection time required. In this technique, each of $N + 1$ cognitive nodes (CS or CR_k) contributes to sense spectrum holes. To protect primary's communication when PS is active ($H_p(i) = H_1$), we use the OR rule [21] (spectrum is not available ($H_s(i) = H_1$) if any of $N + 1$ cognitive nodes sense the presence of PS) which minimizes the probability of interfering at PD.

Each cognitive node periodically senses the channel like in [5,6,22]. We assume that it first estimates the noise floor and distinguishes the rest of the information bearing samples for wireless signals [23]. After, it identifies the CS's signal (the signal transmitted through underlay approach in the first phase (αT)) [23]. And finally, if it detects a collision (i.e., the CS's signal is combined with other signal), then, it decides that the PS is active (a hole is not detected), else, it decides that PS is absent (a hole is detected).

We assume that the $N + 1$ cognitive nodes use the same spectrum sensing detector and sense the spectrum hole existence through the same duration (αT), then, the cooperative probabilities of detection P_d and false alarm P_f are as follows:

$$P_d = 1 - \prod_{k=0}^{N} \left(1 - P_d^k\right) \tag{2}$$

$$P_f = 1 - \prod_{k=0}^{N} \left(1 - P_f^k\right) \tag{3}$$

2.2 Optimal power allocation

In the underlay approach, the CS's (resp. CR_k) transmission power is constrained as $P_{SK}Z_0 \leq I$ (resp. $P_{KD}Z_k \leq I$), where I is the interference threshold that the interference generates by CS (resp. CR_k) on the PD remains below it, and is constrained as $P_{SK} \leq P$ (resp. $P_{KD} \leq P$) , where P is the maximum transmission power.

In the interweave approach, there is just the maximum transmission power constraint, then, $P_{SK} \leq P$ and $P_{KD} \leq P$.

For each time slot iT, in the first phase (first fraction of time αT), the CS's (resp. CR_k) transmits through underlay approach, then, it transmits with a low power P_{US}^k (resp. P_{UR}^k). During the second phase ($(1 - \alpha)T$), the CS's (resp. CR_k) transmits through underlay approach with a low power P_{US}^k (resp. P_{UR}^k) or switch to interweave approach with a high power P_{IS}^k (resp. P_{IR}^k) based on the sensing result.

Subject to $P_{SK} \leq P$ (resp. $P_{KD} \leq P$) and $P_{SK}Z_0 \leq I$ (resp. $P_{KD}Z_k \leq I$), then, the optimal power P_{IS}^k (resp. P_{IR}^k)

and P_{US}^{k} (resp. P_{UR}^{k}) used by CS (resp. CR_k) in interweave and underlay respectively are as follow:

$$P_{IS}^{k} = P_{IR}^{k} = P \tag{4}$$

$$P_{US}^{k} = \min\left(P, \frac{I}{Z_0}\right) = \begin{cases} P, & Z_0 \leq \frac{I}{P} \\ \frac{I}{Z_0}, & Z_0 \geq \frac{I}{P} \end{cases} \tag{5}$$

$$P_{UR}^{k} = \min\left(P, \frac{I}{Z_k}\right) = \begin{cases} P, & Z_k \leq \frac{I}{P} \\ \frac{I}{Z_k}, & Z_k \geq \frac{I}{P} \end{cases} \tag{6}$$

According to the activity of PS and the sensing result, the synthesis of our scenario of transmission and the optimal power allocation in both phases are listed in Table 1.

3 Outage analysis of cognitive relay selection

3.1 Cognitive relay selection

If we select the k-th cognitive relay CR_k for data transmission in dual-hop, the instantaneous capacity in underlay approach C_k^U (resp. interweave approach C_k^I) between cognitive source and cognitive destination is given by [24]:

$$C_k^U = \min\left\{\varepsilon \log_2\left(1 + \frac{X_k P_{US}^k}{N_0}\right), \varepsilon \log_2\left(1 + \frac{Y_k P_{UR}^k}{N_0}\right)\right\} \tag{7}$$

$$C_k^I = \min\left\{\beta \log_2\left(1 + \frac{X_k P_{IS}^k}{N_0}\right), \beta \log_2\left(1 + \frac{Y_k P_{IR}^k}{N_0}\right)\right\} \tag{8}$$

In (7) and (8), we have assumed that any interference from the primary source is neglected (this can be possible if the primary transmitter is located far away from the secondary users, or the interference is represented by the noise term under an assumption that the primary transmitter's signal is generated by random Gaussian codebooks [4]). The coefficient ε (resp. β) is due to the fact that only ε (resp. β) fraction of a time slot is utilized for the CS's and CR_k's data transmission phase. And N_0 is the noise variance.

Substituting (5) and (6) in (7) and (4) in (8), we obtain:

$$C_k^U = \varepsilon \log_2\left(1 + \frac{P}{N_0} \min\left\{X_k \min\left(1, \frac{I}{PZ_0}\right), Y_k \min\left(1, \frac{I}{PZ_k}\right)\right\}\right) \tag{9}$$

$$C_k^I = \beta \log_2\left(1 + \frac{P}{N_0} \min\left\{X_k, Y_k\right\}\right) \tag{10}$$

We introduce two variables $\left(W_k^I, W_k^U\right)$ for briefly. The short-hand notation is as follow:

$$W_k^U = \min\left\{X_k \min\left(1, \frac{I}{PZ_0}\right), Y_k \min\left(1, \frac{I}{PZ_k}\right)\right\} \tag{11}$$

$$W_k^I = \min\left\{X_k, Y_k\right\} \tag{12}$$

For the best relay selection scheme, and by using the max-min criterion [4,25] which maximizes the minimum of signal-to-noise ratios (SNRs) of the source-relay link and relay-destination link, we select the relay for which W_k^U (resp. W_k^I) is maximal in underlay (resp. interweave) approach.

Let:

$$W^U = \max_{1,..,N} W_k^U \tag{13}$$

$$W^I = \max_{1,..,N} W_k^I \tag{14}$$

then, consequently, we obtain for the instantaneous capacity in underlay approach C^U (resp. interweave approach C^I)

$$C^U = \max_{1,..,N} C_k^U = \varepsilon \log_2\left(1 + \frac{P}{N_0} W^U\right) \tag{15}$$

$$C^I = \max_{1,..,N} C_k^I = \beta \log_2\left(1 + \frac{P}{N_0} W^I\right) \tag{16}$$

3.2 Outage probability

Given a predetermined transmission rate of the source C_T, the outage probability mathematically defined as $P_{\text{out}} = Pr(C < C_T)$, where C is the capacity of channel.

The outage probability in underlay approach $P_{\text{out}}^{U,\varepsilon}$ (resp. interweave approach P_{out}^{I}) is given:

$$P_{\text{out}}^{U,\varepsilon} = Pr\left(C^U < C_T\right) \tag{17}$$

$$P_{\text{out}}^{I} = Pr\left(C^I < C_T\right) \tag{18}$$

Table 1 The synthesis of the transmission scenario and the optimal power allocation in both phases

Phase and fraction time	PS's activity	Sensing results	Mode of transmission	Related probability	CS's power	CR_k's power
First phase: αT	Active or absent	-	Underlay	P_α	$\min\left(P, \frac{I}{Z_0}\right)$	$\min\left(P, \frac{I}{Z_k}\right)$
Second phase: βT	Active: $H_p(i) = H_1$	$H_s(i) = H_1$	Underlay	$P_\beta(1-P_a)P_d$	$\min\left(P, \frac{I}{Z_0}\right)$	$\min\left(P, \frac{I}{Z_k}\right)$
	Active: $H_p(i) = H_1$	$H_s(i) = H_0$	Interweave	$P_\beta(1-P_a)(1-P_d)$	P	P
	Absent: $H_p(i) = H_0$	$H_s(i) = H_1$	Underlay	$P_\beta P_a P_f$	$\min\left(P, \frac{I}{Z_0}\right)$	$\min\left(P, \frac{I}{Z_k}\right)$
	Absent: $H_p(i) = H_0$	$H_s(i) = H_0$	Interweave	$P_\beta P_a(1-P_f)$	P	P

Substituting (15) in (17) and (16) in (18), we obtain:

$$P_{\text{out}}^{U,\varepsilon} = Pr\left(W^U < \frac{U_\varepsilon}{P}\right) \tag{19}$$

$$P_{\text{out}}^{I} = Pr\left(W^I < \frac{U_\beta}{P}\right) \tag{20}$$

where $U_\varepsilon = N_0(2^{\frac{C_T}{\varepsilon}} - 1)$
Hence, by using (11) and (12), we get:

$$P_{\text{out}}^{U,\varepsilon} = \prod_{k=1}^{N} Pr\left(W_k^U < \frac{U_\varepsilon}{P}\right) \tag{21}$$

$$P_{\text{out}}^{I} = \prod_{k=1}^{N} Pr\left(W_k^I < \frac{U_\beta}{P}\right) \tag{22}$$

Using Appendix (Equations 32 and 39) and replacing A by $\frac{U_\varepsilon}{P}$ and B by $\frac{I}{P}$, the closed form of (21) yields:

$$P_{\text{out}}^{U,\varepsilon} = \prod_{k=1}^{N} \left(1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\varepsilon}{P}\right) \Phi\left(m_{yk}, \gamma_{yk}, m_{zk}, \gamma_{zk}, \frac{I}{P}, \frac{U_\varepsilon}{P}\right)\right) \tag{23}$$

Replace A by $\frac{U_\beta}{P}$ in Appendix (Equation 33), the closed form of (22) yields:

$$P_{\text{out}}^{I} = \prod_{k=1}^{N} \left(1 - \frac{\Gamma\left(m_{xk}, \frac{m_{xk}}{\gamma_{xk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{xk})} \frac{\Gamma\left(m_{yk}, \frac{m_{yk}}{\gamma_{yk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{yk})}\right) \tag{24}$$

Finally, the outage probability of our system is:

$$P_{\text{out}} = P_\alpha P_{\text{out}}^{\text{first-phase}} + (1 - P_\alpha) P_{\text{out}}^{\text{second-phase}} \tag{25}$$

where:

$$P_{\text{out}}^{\text{first-phase}} = P_{\text{out}}^{U,\alpha}$$

and:

$$\begin{aligned} P_{\text{out}}^{\text{second-phase}} &= \left[Pr(H_s(i) = H_0, H_p(i) = H_0) + Pr(H_s(i) = H_0, H_p(i) = H_1)\right] P_{\text{out}}^{I} \\ &\quad + \left[Pr(H_s(i) = H_1, H_p(i) = H_0) + Pr(H_s(i) = H_1, H_p(i) = H_1)\right] P_{\text{out}}^{U,\beta} \end{aligned} \tag{26}$$

which can also be written as:

$$\begin{aligned} P_{\text{out}}^{\text{second-phase}} &= \left[P_a(1 - P_f) + (1 - P_a)(1 - P_d)\right] P_{\text{out}}^{I} \\ &\quad + \left[P_a P_f + (1 - P_a) P_d\right] P_{\text{out}}^{U,\beta} \end{aligned} \tag{27}$$

Then, the closed form of outage probability of our strategy (Always transmit + Relay) is derived in (28):

$$\begin{aligned} P_{\text{out}-\text{AT}-R} &= P_\alpha \prod_{k=1}^{N} \left(1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\alpha}{P}\right) \times \Phi\left(m_{yk}, \gamma_{yk}, m_{zk}, \gamma_{zk}, \frac{I}{P}, \frac{U_\alpha}{P}\right)\right) \\ &\quad + (1 - P_\alpha) \left(\left[P_a\left(1 - P_f\right) + (1 - P_a)(1 - P_d)\right] \times \prod_{k=1}^{N} \left(1 - \frac{\Gamma\left(m_{xk}, \frac{m_{xk}}{\gamma_{xk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{xk})} \frac{\Gamma\left(m_{yk}, \frac{m_{yk}}{\gamma_{yk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{yk})}\right)\right. \\ &\quad + \left[P_a P_f + (1 - P_a) P_d\right] \times \prod_{k=1}^{N} \left(1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\beta}{P}\right) \left. \times \Phi\left(m_{yk}, \gamma_{yk}, m_{zk}, \gamma_{zk}, \frac{I}{P}, \frac{U_\beta}{P}\right)\right)\right) \end{aligned} \tag{28}$$

If CS and CR_k transmit just through interweave approach, (28) can reduced to (29):

$$\begin{aligned} P_{\text{out}-IN-R} &= P_\alpha + (1 - P_\alpha) \left(\left[P_a\left(1 - P_f\right) + (1 - P_a)(1 - P_d)\right] \times \prod_{k=1}^{N} \left(1 - \frac{\Gamma\left(m_{xk}, \frac{m_{xk}}{\gamma_{xk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{xk})} \frac{\Gamma\left(m_{yk}, \frac{m_{yk}}{\gamma_{yk}} \frac{U_\beta}{P}\right)}{\Gamma(m_{yk})}\right)\right. \\ &\quad \left. + \left[P_a P_f + (1 - P_a) P_d\right]\right) \end{aligned} \tag{29}$$

If CS and CR_k transmit just through underlay approach, (28) can reduced to (30):

$$\begin{aligned} P_{\text{out}-UN-R} &= P_\alpha \prod_{k=1}^{N} \left(1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\alpha}{P}\right) \times \Phi\left(m_{yk}, \gamma_{yk}, m_{zk}, \gamma_{zk}, \frac{I}{P}, \frac{U_\alpha}{P}\right)\right) \\ &\quad + (1 - P_\alpha) \left(\left[P_a P_f + (1 - P_a) P_d\right] \prod_{k=1}^{N} \times \left(1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\beta}{P}\right) \times \Phi\left(m_{yk}, \gamma_{yk}, m_{zk}, \gamma_{zk}, \frac{I}{P}, \frac{U_\beta}{P}\right)\right)\right) \end{aligned} \tag{30}$$

If there is no rely ($k = 0$), CS transmits data directly to PD without help of relays, (28) can reduced to (31):

$$P_{\text{out}-\text{AT}-NR} = P_\alpha \left(1 - \Phi\left(m_{x1}, \gamma_{x1}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\alpha}{P}\right)\right) + (1 - P_\alpha)\left(\left[P_a\left(1 - P_f^1\right) + (1 - P_a)\left(1 - P_d^1\right)\right] \times \left(1 - \frac{\Gamma\left(m_{x1}, \frac{m_{x1}}{\gamma_{x1}}\frac{U_\beta}{P}\right)}{\Gamma(m_{x1})}\right) + \left[P_a P_f^1 + (1 - P_a) P_d^1\right] \times \left(1 - \Phi\left(m_{x1}, \gamma_{x1}, m_{z0}, \gamma_{z0}, \frac{I}{P}, \frac{U_\beta}{P}\right)\right)\right) \quad (31)$$

4 Numerical results

Computer simulations were carried out in order to validate the performance of the proposed scenario ('Always transmit + Relay') based on the outage probability. We analyze the impact of the fraction α of time slot used for spectrum sensing and other parameters (number of relay N, fading severity parameters (m_{xk}, m_{yk}, m_{zk}, m_{z0}), the transmit (resp. interference) power constraint P (resp. I)) over data transmission. Throughout simulations, we have assumed a perfect spectrum hole detection, thus, $P_f^k = 0.1 (k = 1, \ldots, N)$ to use the cognitive channel with a higher chance with the interweave method, and $P_d^k = 0.9 (k = 1, .., N)$ to protect the primary source transmission. We consider that P_α follows a uniform distribution, then, $P_\alpha = \alpha$ and $P_\beta = 1 - \alpha$. Also, in all simulations, we fix: $\gamma_{xk} = \gamma_{yk} = \gamma_{zk} = \gamma_{z0} = 1$ dB ($k = 1, .., N$), $N_0 = 1$, $P_a = 0.8$, $C_T = 0.5$, and we vary α, m, N, I, and P.

From the figures (Figures 2, 3, 4, 5, and 6), it has been observed that outage performances are degraded when α increases; in contrast, we see a higher reduction of outage probability, thus improving the system performance, when α is near 0. Indeed, when α is near 0, which is referred to as perfect sensing, the CS and CR_k transmit with underlay method just in short time αT in the first phase and can have more chance to transmit with the interweave method in a large amount of time $(1 - \alpha)T$ in the second phase. But when α increases, the CS and CR_k transmit in large time with the underlay method, and thus, the system is more probable to have an outage.

These figures also show that the outage probability decreases (which is the indication of performance improvement) as P, I, or N increase. Indeed, a) if the transmit power P at (CS and CR_k) increases, then, the SNRs increase which denote the increase of their capacity and finally the decrease of their outage probability, b) when the interference threshold I is increasing, the constraints are relaxed at the cognitive system side, so the system performance increases as I increases, c) more relays in fading

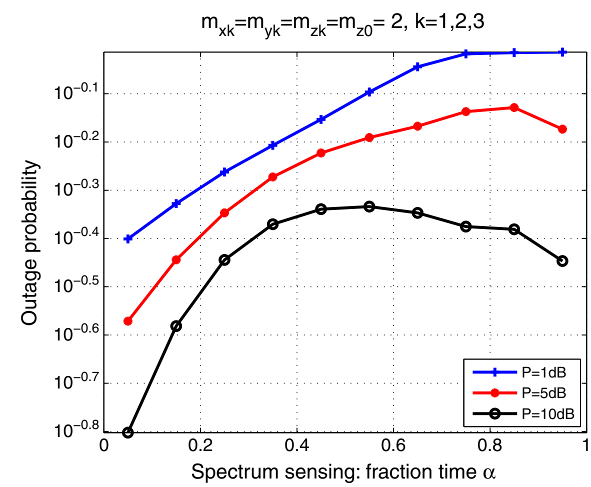

Figure 2 Outage probability versus spectrum sensing overhead $\boldsymbol{\alpha}$ for different values of the transmission power P at (CS and CR_k).

channel network can combat fading and consequently, enhance the performance.

From Figure 5, we show that the outage probability decreases as probability of false alarm P_f decreases. Indeed, when P_f is small, which means that the system of detection is more reliable, which thus leads the CS to transmit with interweave method instead of underlay method when primary system is absent. Also, while looking at Figure 5, we can observe that the outage probability of secondary system converges to the same point when α go to 1, under a different value of P_f and P_d. In fact, when α go to 1, the CS expires the whole of the time slot (iT) for sensing and transmits through the whole of the time slot (iT) via underlay mode in the first phase and can

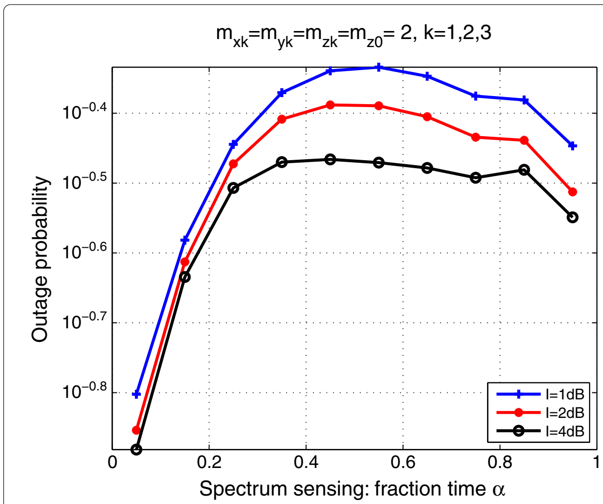

Figure 3 Outage probability versus spectrum sensing overhead $\boldsymbol{\alpha}$ for different values of the interference power constraint I.

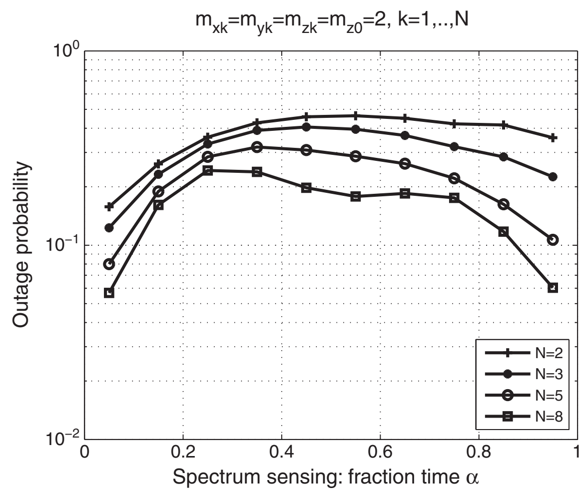

Figure 4 Outage probability versus spectrum sensing overhead $\boldsymbol{\alpha}$ for different values of the number of relay N.

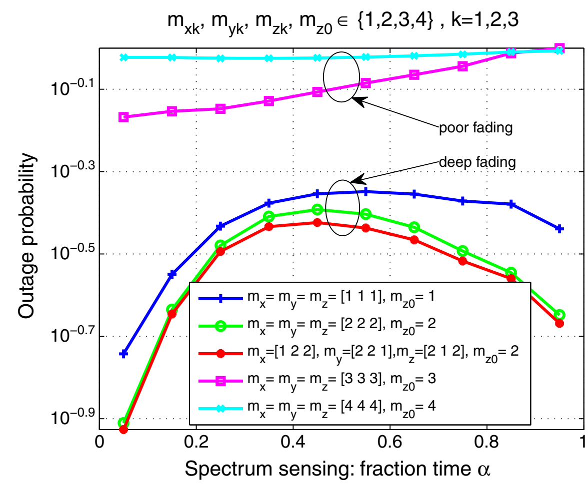

Figure 6 Outage probability versus spectrum sensing overhead $\boldsymbol{\alpha}$ for different values of the fading severity parameters (m_{xk}, m_{yk}, m_{zk}, m_{z0}, k=1,2,3).

have no time in the second phase for transmitting through interweave mode whatever the probability value of detection P_d and/or of a false alarm P_f, and even if primary user is not detected or there is no false alarm.

From Figure 6, we can see the advantage of the use relays in deep fading channel. In contrast, in poor fading channel, the use relays decrease the performance.

An interesting result found from Figure 7 (resp. Figure 8) is that our strategy (Always transmit + Relay) outperforms other conventional cognitive radio strategies like interweave or underlay approach in deep (resp. poor) fading channel.

Also, Figure 7 (resp. Figure 8) presents the comparison of the outage probability between our strategies (Always transmit + Relay) and (Always transmit + No-Relay) in deep (resp. poor) fading channel. As we have shown in [16] that the strategy 'AT' enhances the performance, the performance of a cognitive system can be more improved by using relays in deep fading channel, and it recommended not to use the relays in poor fading channel.

5 Conclusion

We have presented 'Always transmit + Relay' strategy for dual-hop transmission with decode-and-forward and

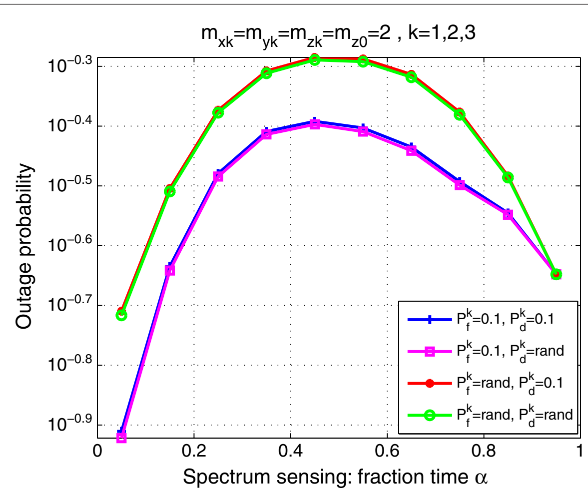

Figure 5 Outage probability versus spectrum sensing overhead $\boldsymbol{\alpha}$ for a fixed/random values of the probabilities of false alarm and of detection.

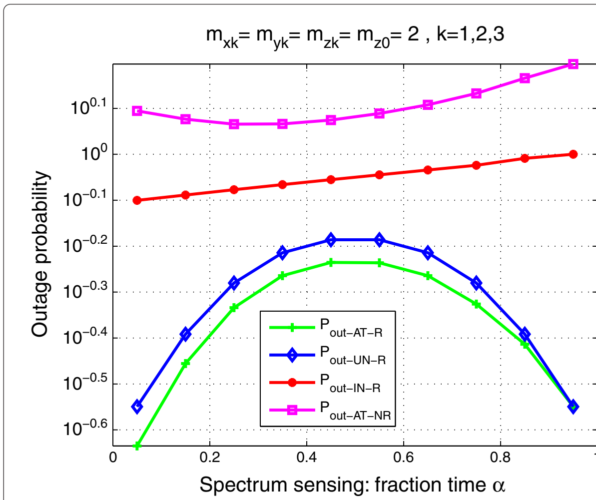

Figure 7 The outage probability of different strategies of transmission under a deep fading and a random average channel gain.

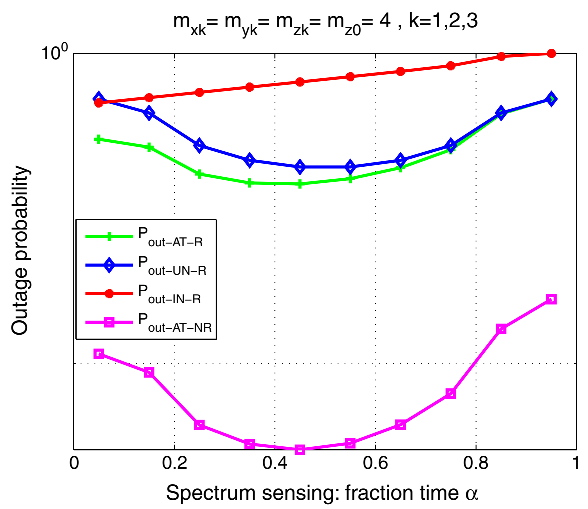

Figure 8 The outage probability of different strategies of transmission under a poor fading and a random average channel gain.

relay selection. The closed-form expressions of the outage probability have been derived over independent but not identically distributed Nakagami-m fading channels on all nodes. Simulation results have shown that the performance increases as either the transmit power P, the interference power constraint I, and the number of relays N increases and when spectrum sensing duration α is small (near to 0). Finally, we have shown that the strategy 'Always transmit + Relay' outperforms other conventional cognitive radio strategies and the use of relays enhances the performance in deep fading channel. A future work is dedicated to explore some new ideas on how to perform sensing and detecting the presence or the absence of the primary system while transmitting with underlay approach.

Appendix

Let X_k, Y_k, and $Z_k(k = 0, 1, .., N)$ follow the probability distribution $p_k(x)$, $p_k(y)$, and $p_k(z)$, respectively, and are independent random variables distributed according to gamma distribution given by the Equation (1) with different fading parameters γ_{xk}, γ_{yk}, γ_{zk} and fading severity parameters m_{xk}, m_{yk}, m_{zk}:

$$Pr\left(\min\left(X_k, Y_k\right) < A\right) = 1 - Pr\left(X_k > A\right) Pr\left(Y_k > A\right) \quad (32)$$

then:

$$Pr\left(\min\left(X_k, Y_k\right) < A\right) = 1 - \frac{\Gamma\left(m_{xk}, \frac{m_{xk}}{\gamma_{xk}}A\right)}{\Gamma\left(m_{xk}\right)} \frac{\Gamma\left(m_{yk}, \frac{m_{yk}}{\gamma_{yk}}A\right)}{\Gamma\left(m_{yk}\right)} \quad (33)$$

Let $t_k = X_k \min\left(1, \frac{B}{Z_k}\right)$, the cumulative distribution function of t_k

$$F_{t_k}(A) = Pr\left(t_k < A\right) = Pr\left(X_k \min\left(1, \frac{B}{Z_k}\right) < A\right) \quad (34)$$

$$F_{t_k}(A) = \int_{x=0}^{A} \int_{z=0}^{B} p_k(x)p_k(z)dxdz + \int_{x=0}^{\frac{AZ}{B}} \int_{z=B}^{\infty} p_k(x)p_k(z)dxdz \quad (35)$$

$$F_{t_k}(A) = \left(1 - \frac{\Gamma\left(m_{xk}, \frac{m_{xk}A}{\gamma_{xk}}\right)}{\Gamma\left(m_{xk}\right)}\right)\left(1 - \frac{\Gamma\left(m_{zk}, \frac{m_{zk}B}{\gamma_{zk}}\right)}{\Gamma\left(m_{zk}\right)}\right) + \frac{\Gamma\left(m_{zk}, \frac{m_{zk}B}{\gamma_{zk}}\right)}{\Gamma\left(m_{zk}\right)} - \int_{z=B}^{\infty} \frac{\Gamma\left(m_{xk}, \frac{m_{xk}AZ}{\gamma_{xk}B}\right)}{\Gamma\left(m_{xk}\right)} p_k(z)dz \quad (36)$$

Assuming m_x is integer and $a \geq 0$. And using the fact that $\Gamma\left(m_x, x\right) = \left(m_x - 1\right)! \, e^{-x} \sum_{i=0}^{m_x-1} \frac{x^i}{i!}$, we have:

$$\frac{\Gamma(m_x, az)}{\Gamma(m_x)} = \frac{\Gamma(m_x, az)}{(m_x - 1)!} = e^{-az} \sum_{i=0}^{m_x-1} \frac{a^i}{i!} z^i \quad (37)$$

With the help of the equation $\int_u^{\infty} x^n e^{-\mu x} dx = \mu^{-n-1} \Gamma(n + 1, \mu u)$ ([19], equation (3.351.2)), we can get:

$$\int_{z=B}^{\infty} \frac{\Gamma(m_x, az)}{\Gamma(m_x)} p_k(z)dz = \left(\frac{\frac{m_z}{\gamma_z}}{\frac{m_z}{\gamma_z} + a}\right)^{m_z} \frac{1}{\Gamma(m_z)} \sum_{i=0}^{m_x-1} \left(\frac{a}{\frac{m_z}{\gamma_z} + a}\right)^i \times \frac{\Gamma\left(m_z + i, \left(\frac{m_z}{\gamma_z} + a\right) B\right)}{i!} \quad (38)$$

Let $a = \frac{m_{xk}A}{\gamma_{xk}B}$ and using (38), we can rewrite (36) as:

$$F_{t_k}(A) = 1 - \Phi\left(m_{xk}, \gamma_{xk}, m_{zk}, \gamma_{zk}, B, A\right) \quad (39)$$

where:

$$\Phi(m_{xk}, \gamma_{xk}, m_{zk}, \gamma_{zk}, B, A) = \frac{\Gamma\left(m_{xk}, \frac{m_{xk}A}{\gamma_{xk}}\right)}{\Gamma(m_{xk})} \left(1 - \frac{\Gamma\left(m_{zk}, \frac{m_{zk}B}{\gamma_{zk}}\right)}{\Gamma(m_{zk})}\right) - \left(\frac{\frac{m_{zk}}{\gamma_z}}{\frac{m_{zk}}{\gamma_{zk}} + \frac{m_{xk}A}{\gamma_{xk}B}}\right)^{m_{zk}} \frac{1}{\Gamma(m_{zk})} \sum_{i=0}^{m_{xk}-1} \left(\frac{\frac{m_{xk}A}{\gamma_{xk}B}}{\frac{m_{zk}}{\gamma_{zk}} + \frac{m_{xk}A}{\gamma_{xk}B}}\right)^i \times \frac{\Gamma\left(m_{zk} + i, \frac{m_{zk}}{\gamma_{zk}}B + \frac{m_{xk}}{\gamma_{xk}}A\right)}{i!} \quad (40)$$

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Computer Sciences Department, GREENTIC/UH2C/EST, Casablanca, Morocco. [2]Computer Sciences Department, GREENTIC/UH2C/ENSEM, Casablanca, Morocco. [3]Department of Mathematics and Computer, GREENTIC/UH1/FST, Settat, Morocco.

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