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# Outage analysis in cooperative cognitive networks with opportunistic relay selection under imperfect channel information

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ABSTRACT

This paper proposes exact and limit outage probability expressions for thoroughly evaluating the performance of cooperative cognitive networks with opportunistic relay selection under imperfect channel information, independent and non-identical (i.n.i.) Rayleigh fading channels, maximum transmit power constraint, and interference power constraint. The proposed derivations can be straightforwardly extended to corresponding analysis in dual-hop cognitive networks with opportunistic relay selection to investigate how much performance gain can be achieved from using the direct channel between the source and the destination in relaying communications. Numerous results illustrate significant outage performance degradation and performance saturation due to channel information imperfection but the degradation and saturation level can be remedied by increasing the number of relays. Also, the channel direct brings a considerable performance improvement without any additional expense of system resources such as power and bandwidth. Moreover, channel information imperfection can cause interference power at primary users to exceed a pre-defined level, deteriorating the quality of service of primary users.



## 1. Introduction

Traditional static spectrum allocation is not flexible and induces low spectrum utilization efficiency [1]. This issue turned with high radio spectrum demand of emerging wireless services requires appropriate solutions to mitigate current spectrum under-utilization. Cognitive radio technology, which allows secondary/unlicensed users (SUs) to opportunistically access the spectrum inherently allotted to primary/licensed users (PUs), is a right solution to these critical issues [2]. Nevertheless, in order to assure transparent communication of PUs, SUs must limit their transmit power for acceptable interference at PUs, and thus, reducing the communication coverage of secondary transmitters. With the advantage of wide radio coverage, relaying techniques have recently been incorporated into SUs to complement the drawback of the short radio range of SUs [3]. The relaying process can be assisted by multiple relays for high performance but low bandwidth efficiency due to the requirement of orthogonal channels for different relays in order to prevent mutual interference. As such, selecting a single relay among all possible candidates according to a certain criterion is preferred to optimize system resource utilization (e.g., power and bandwidth), in comparison with multi-relay assisted transmission while remaining the same diversity order [4]. Furthermore, channel state information is very important in the process of system design optimization (e.g., optimal signal detection). However, it is inevitable that this information cannot be collected without any error. Therefore, the impact of imperfect channel information (ICI) on the outage performance of relay selection criteria in cognitive relaying networks should be thoroughly investigated before practical implementation.

The impact of ICI[1] on the opportunistic relay selection in dual-hop cognitive networks (i.e., without considering the direct channel), which selects the relay with the maximum end-to-end

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[1] The impact of ICI on cognitive radio networks was studied in different aspects; for example, dual-hop relaying with relay selection (e.g., [7,6,5]), direct transmission (i.e., no relay) [8], the amplify-and-forward relay selection (e.g., [10,9]), relay non-selection (e.g., [11,13,15,12,14]). Moreover, several relay selection criteria in cognitive radio networks are suggested without investigating the impact of ICI in [16–18,27,28,26,29,23,30,24,31,38,32,35,36,34,25,33,37,39,44,43,42,40,41]. The current paper concentrates on the opportunistic relay selection in decode-and-forward cooperative cognitive networks, and thus, the literature related to the aspects studied in [11,16–18,27,28,26,29,23,30,24,31,38,32,35,36,34,25,33,37,44,43,42,40,7,6,8,10,9,13,15,12,14,39,41,5] should not be further surveyed.

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signal-to-noise ratio (SNR), is investigated in [45]. Nevertheless, this work does not investigate ICI on all fading channels simultaneously, that is, ICI on interference channels (i.e., channels from SUs to PUs) while perfect channel information (PCI) on transmission channels (i.e., between SUs); or ICI on transmission channels but PCI on interference channels. Also, [45] only considers independent partially-identical (i.p.i.) fading distributions (i.e., relays are assumed to be closely located). The effect of ICI on the reactive relay selection, which selects the relay among all possible candidates (i.e., all relays are assumed to correctly decode source information) with the largest SNR to the destination, and the $L$th-worst relay selection, which selects the $L$th-worst relay, is investigated in [46,47]. However, both [46,47] are limited to the case of ICI on interference channels while PCI on transmission channels, and the i.p.i. fading distribution assumption. The effect of ICI on the partial relay selection, which simply selects the relay with the largest SNR from the source, is studied in [42,48–50]. Nevertheless, for analysis simplicity, the works in [42,48–50] impose several assumptions such as only ICI on interference channels while PCI on transmission channels, i.p.i. fading distributions, and dual-hop relaying.

The opportunistic relay selection is proved to be capacity-optimal [16], and hence, it is interesting to predict its information-theoretic performance limit (i.e., outage probability). Motivated by the above, this paper thoroughly analyzes its outage performance. The contributions of this paper are summarized below:

- Propose an exact closed-form outage probability expression for cooperative cognitive networks with opportunistic relay selection, neglecting all assumptions of [45]. More specifically, this expression is applicable to a general scenario: ICI on all channels concurrently, i.n.i. fading distributions, maximum transmit power constraint, interference power constraint, the usage of the direct channel.
- Derive the performance limit of cooperative cognitive networks with opportunistic relay selection, which proves no diversity gain achievable in the presence of ICI.
- Perform numerous comparisons between dual-hop and cooperative cognitive networks with opportunistic relay selection, which demonstrate a significant gain of utilizing the direct channel in relaying communications at almost no expense of system resources (e.g., power and bandwidth).
- Provide numerous results to have useful insights into system performance such as performance saturation phenomenon and considerable performance deterioration due to ICI, significant performance improvement with respect to the increase in the number of relays.
- Outline an interference probability[2] expression to reflect the effect of channel information imperfection on the quality of service of primary users. Illustrative results are also provided to show that the interference probability is proportional to the number of relays, which conflicts with outage performance improvement of secondary users when the number of relays increases, establishing the performance trade-off between the primary network and the secondary network with respect to the number of relays.

The rest of the current paper is structured as follows. The system model under consideration is presented in Section 2. Exact and limit outage analysis framework for the opportunistic relay selection in cooperative cognitive networks as well as in dual-hop cognitive networks is elaborately described in Section 3. The interference probability expression is outlined in Section 4. Results and discussions on the outage performance of these networks as well as the interference probability are provided in Section 5. Finally, the paper is closed with useful conclusions in Section 6.

## 2. System model

A cooperative cognitive network with opportunistic relay selection is demonstrated in Fig. 1. Cooperative relaying is implemented in the secondary network in which information transmission from the source $S_s$ to the destination $S_d$ is helped by the selected relay $S_b$ in the group of $K$ relays, $\mathcal{S} = \{S_1, S_2, \ldots, S_K\}$. We assume cognitive radios to operate in the underlay mechanism (e.g., [16,19–22]), and hence, $S_s$ and $S_b$ interfere the PU, namely $P_p$, but the interference level at $P_p$ must be lower than the maximum interference power, $\bar{\mathcal{I}}$, that can be tolerated by $P_p$.

We investigate frequency-flat and i.n.i. Rayleigh fading channels. Therefore, the channel coefficient, $h_{tr}$, between a transmitter and a receiver, where $t$ and $r$ denote the indices of the transmitter and the receiver, respectively (the specific values of $t$ and $r$ will be specified later), can be modelled as a circular symmetric complex Gaussian random variable with zero mean and $1/\lambda_{tr}$-variance, i.e. $h_{tr} \sim \mathcal{CN}(0, 1/\lambda_{tr})$. Since our work investigates i.n.i. fading distributions, all $\lambda_{tr}$'s, $\forall\{t, r\}$, are not necessarily equal. Therefore, it is more general and practical than most existing works on relay selection where i.p.i. (i.e., $\lambda_{tr}$'s are partitioned into groups of identical value. For example, $\lambda_{sr}$'s, $\lambda_{rd}$'s, $\lambda_{rp}$'s with $r \in \{1, \ldots, K\}$ are assumed to be identical in [7,16,23,24,26,29,42,45–48]) or independent and identical (i.e., $\lambda_{tr}$'s, $\forall\{t, r\}$, are equal in [25,27,28,31]) fading distributions are assumed for simplicity of performance analysis.

It is inevitable that PCI is impossibly available owing to the limitations of channel estimation algorithms. As such, in order to support performance analysis, we should model channel information imperfection appropriately. In this work, we apply the well-known channel information imperfection model used in [8,10,13,39,42,45,46,48,49,51]. According to this model, the real channel coefficient, $h_{tr}$, is related to the estimated one, $\hat{h}_{tr}$ as

$$\hat{h}_{tr} = \rho_{tr} h_{tr} + \sqrt{1 - \rho_{tr}^2}\varepsilon_{tr}, \tag{1}$$

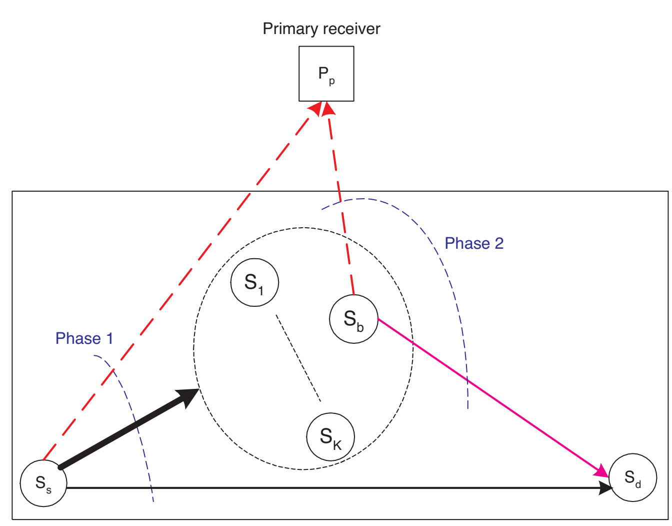


**Fig. 1.** System model.

[2] Interference probability is defined as the probability that the interference power constraint is invalidated. Some works proposed the interference probability expression for the partial relay selection (e.g., [42,48,50]) and the reactive relay selection (e.g., [46]). To the best of the author's knowledge, the interference probability expression for the opportunistic relay selection have not been presented in open literature.