# Fuzzy Relay Selection Scheme for a Cognitive Cooperative Network

Samuel Baraldi Mafra, Richard Demo Souza and Glauber Brante

***Abstract*— We propose a relay selection scheme based on fuzzy logic for a cognitive cooperative network. Our goal is to maximize the throughput of the secondary network while minimizing the interference of the selected relay on the primary network. The instantaneous channel state information (CSI) between the relays and the primary destination, and between the relays and the secondary destination are used as inputs to the fuzzy logic-based scheme, whose output is a relay selection degree, which assumes values between zero and one. Then, each relay waits for a time inversely proportional to this degree before transmitting; thus, the relay with the largest degree is the relay selected to transmit. Monte Carlo simulations are carried out to evaluate the throughput and the average interference level of the proposed scheme. Our results show that the proposed scheme has lower interference on the primary destination than other schemes based solely on the CSI between the relay and the secondary destination, with the same performance in terms of throughput.**

***Keywords*— Cognitive radio, Fuzzy logic, Relay selection, Cooperative communications.**

## I. Introduction

In a cognitive radio context under spectrum sharing constraints, an unlicensed (secondary) network may transmit concurrently with the licensed (primary) network as long as the communication of this latter is not compromised. For such an operation, a maximum allowable interference level at the primary receiver is defined, and secondary users (SUs) should take into account this threshold during the transmission in order to adjust their transmit powers to not damage the reception of the primary receiver [1], [2]. This allows a more efficient use of the frequency spectrum.

Cooperative communications [3] have emerged as an alternative technique to boost the performance of communication systems. The idea behind this strategy is to make use of one or more nodes (referred to as relays) in order to emulate a physical antenna array. Thus, the same benefits obtained in multiple-input multiple-output systems can also be achieved with the use of single-antenna nodes through the distributed transmission and processing of the information. In [3], the authors introduce the cooperative decode-and-forward (DF) protocol and its selective (SDF) and incremental (IDF) variants. In the SDF protocol, the message is forwarded only if its decoding at the relay was successful. Whereas in the IDF protocol, similarly to the SDF the message also needs to be correctly decoded by the relay; however, the forwarding occurs only when requested by the destination.

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Coded cooperation [4] is the union of error correction codes with cooperative protocols, and can be classified in repetition coding, in which source and relay use the same encoder, and parallel coding, with source and relay employing different encoders. Although parallel coding is more complex, since the destination must also be able to decode codewords generated by two different encoders, the performance of the DF protocol is considerably improved with the aid of parallel coding [4].

Moreover, in underlay cognitive networks there are usually conflicting objectives: a greater throughput in the secondary network usually causes a greater interference on the primary network. Then, to decrease the interference, it is necessary to reduce the transmit power, which consequently decreases the throughput of the secondary network. With the use of cooperative communications, it is possible to transmit with lower power and to reduce the interference on the primary network at the same time. Furthermore, if multiple relays are available at the secondary network, the probability that at least one relay is in good conditions to cooperate increases, which may lead to throughput improvements at the secondary.

When multiple relays are available, relay selection schemes become attractive solutions to reduce complexity [5]. For instance, [6], [7] deal with centralized relay selection schemes for underlay cognitive networks. A relay selection scheme for an Amplify-and-Forward (AF) cognitive network is proposed in [6]; however, such scheme neglects the interference at the primary network. In [7] a relay selection scheme is proposed for a DF cognitive network, in which the relays have a buffer of finite size. In that work, the direct link is not considered (only a multi-hop DF link is available) and the secondary network operates in an interference-limited scenario.

In [8]–[12], relay selection algorithms based on fuzzy logic are proposed with the goal of minimizing either the energy consumption of the nodes, or the outage probability (or an equivalent error performance metric). For instance, [8] establishes the communication with a set of selected relays using distributed space-time techniques to reduce the symbol error rate. In [9], the outage probability is minimized by taking the signal to noise ratio (SNR) and the delay time (transmission and processing) into account. By using a fuzzy logic scheme the relays are classified into three levels: not selected, considered and selected. Then, in [11], [12] the authors propose a fuzzy multi-objective algorithm that maximizes the lifetime and the throughput of the network. The fuzzy inputs are the instantaneous channel state information (CSI) between the relay and the destination, and the remaining battery energy of each relay while the output is a degree of relevance for each relay. Another example is given by [13], in which the authors adapt the transmit power of the secondary network.

When the SNR of the primary network is below a minimum SNR threshold, the secondary network is able to transmit with the maximum power; however, when the SNR is closer to such threshold, the secondary transmitter uses only a fraction of the maximum power, which is calculated using fuzzy logic.

In this paper we propose a fuzzy logic-based relay selection scheme for an underlay network. Differently from the above works, which aim at optimizing a single variable, we are interested in maximizing the throughput while minimizing the interference on the primary network. Since these two characteristics are usually conflicting, the choice for fuzzy logic comes from the fact that this technique is quite computationally inexpensive [14], [15], and suitable to balance conflicting goals. The proposed scheme classifies the relays according to a relay selection degree, so that each relay waits for a time inversely proportional to this degree before transmitting. Therefore, the relay with the largest degree is the relay selected to transmit in a distributed fashion. Results show that the proposed scheme has lower interference on the primary destination than other schemes based solely on the CSI between the relay and the secondary destination, with similar performance in terms of throughput.

In the sequel, Section II describes the system model and the concepts of outage probability and throughput. Section III describes the relay selection schemes, numerical results are given in Section IV, and Section V concludes the paper.

## II. System Model

The primary network is composed by primary transmitter $T_p$ and a primary destination $D_p$. The secondary network is composed by a secondary transmitter $T_s$, a secondary destination $D_s$ and $N$ potentially cooperating relays denoted as $r(l)$, with $l \in \Lambda = \{1, 2, \ldots, N\}$. We consider that the $N$ relays are in a cluster, so that they are assumed to be at approximately the same position. Fig. 1 illustrates the system model, including $T_p$, $D_p$, $T_s$, $D_s$, and the selected relay $r(l^{\text{sch}})$, with $\text{sch} \in \{\text{Max}, \text{Fuzzy}\}$.

The channel between the transmitter $i$ and the receiver $j$ is denoted by $h_{ij}$, and follows a Rayleigh quasi-static distribution with mean power $\lambda_{ij}$, with $i \in \{p, s, r(l)\}$ and $j \in \{p, s, r(l)\}$, where $p$ denotes one of the primary nodes, $s$ denotes one of the secondary nodes and $r(l)$ is the relay. Moreover, the mean power is defined as $\lambda_{ij} = \frac{1}{(d_{ij})^\alpha}$, where $d_{ij}$ represents the distance between the transmitter $i$ and the receiver $j$, and $\alpha$ is the path loss exponent. We consider that the distances are normalized with respect to the distance between $T_s$ and $D_p$ ($d_{sp}$). In addition, the secondary network operates at the same frequency band and time slot allocated to the primary network. The unilateral noise power spectral density is assumed to be $N_0 = 1$ W/Hz.

Furthermore, we denote by $I_{th}$ the maximum amount of peak interference tolerated by $D_p$, such that the transmit power of transmitter $m \in \{s, r(l)\}$ is limited by

$$P_m \leq \min\left(P_{\max}, \frac{I_{th}}{|h_{mp}|^2}\right), \tag{1}$$

where $P_{\max}$ corresponds to the maximum transmit power (assumed to be the same for all SUs).

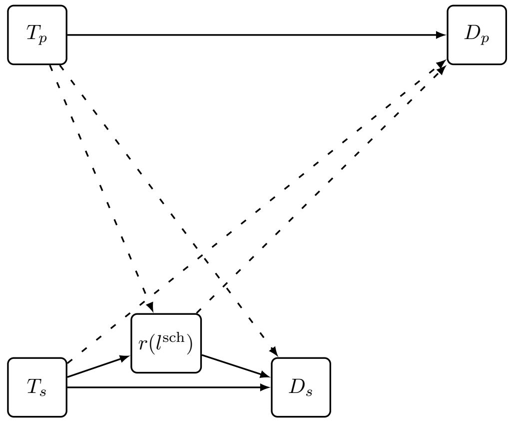


Fig. 1. System model including a pair of primary users ($T_p$ and $D_p$), a pair of secondary users ($T_s$ and $D_s$), aided by the selected relay $r(l^{\text{sch}})$.

The bandwidth normalized mutual information of the links $T_s$-$D_s$ and $T_s$-$r(l)$ are respectively given by

$$I_{ss} = \log_2\left(1 + \frac{|h_{ss}|^2 P_s}{1 + |h_{ps}|^2 P_p}\right), \tag{2}$$

$$I_{sr} = \log_2\left(1 + \frac{|h_{sr(l)}|^2 P_s}{1 + |h_{pr(l)}|^2 P_p}\right), \tag{3}$$

while the bandwidth normalized mutual information between the selected relay and the secondary destination, considering parallel coding, is given by the sum of the mutual information of the links $T_s$-$D_s$ and $r(l^{\text{sch}})$-$D_s$, which can be written as [16]

$$I_s = \log_2\left(1 + \frac{|h_{ss}|^2 P_s}{1 + |h_{ps}|^2 P_p}\right) + \log_2\left(1 + \frac{|h_{r(l^{\text{sch}})s}|^2 P_{r(l)}}{1 + |h_{ps}|^2 P_p}\right). \tag{4}$$

The outage probability is the probability of failure in the communication between nodes $i$ and $j$ [17]. An outage event occurs when the mutual information is less than the attempted information rate $\mathcal{R}_s$. For instance, assuming a unitary bandwidth, complex Gaussian channel inputs, a given link with channel realization $h_{ij}$, transmit power $P_m$, the outage probability is [17]

$$\mathcal{P}_{out} = \Pr\left\{\log_2\left(1 + \frac{|h_{ij}|^2 P_m}{1 + |h_{pj}|^2 P_p}\right) < \mathcal{R}_s\right\}, \tag{5}$$

where $\Pr\{a\}$ represents the probability of the event $a$. While, the throughput is defined as the rate of error-free information transfer and is given by [17]

$$\mathcal{T}_k = \mathcal{R}_s(1 - \mathcal{P}_{out}). \tag{6}$$

The transmission of the message from $T_s$ occurs in two time slots. First, $T_s$ broadcasts its message to the destination and all relays. If at least one of the relays correctly decoded the message from $T_s$, the selected relay forwards the message for the destination. Then, the secondary destination combines the transmissions from $T_s$ and the selected relay using parallel coding.

The outage probability of the links $T_s$-$D_s$, in the first time slot, is given by

$$\mathcal{O}_{ss} = \Pr\{I_{ss} < \mathcal{R}_s\}, \tag{7}$$

while the probability that none relay was able to correctly decode the message from $T_s$ can be written as

$$\mathcal{O}_R = (\Pr\{I_{sr} < \mathcal{R}_s\})^N. \tag{8}$$

The probability that the secondary destination was not able to decode the message from $T_s$, in the second time slot, is [16]

$$\mathcal{O}_{\text{PC}} = \Pr\{I_s < \mathcal{R}_s\}, \tag{9}$$

Finally, the throughput of the secondary network is

$$\begin{aligned}\mathcal{T}_{\text{PC}} &= \left(\frac{\mathcal{R}_s}{2} \cdot (1 - \mathcal{O}_{ss})\right) + \left(\frac{\mathcal{R}_s}{2} \cdot (1 - \mathcal{O}_R) \cdot \Pr\{\overline{\mathcal{O}_{PC}}, O_{ss}\}\right) \\ &= \left(\frac{\mathcal{R}_s}{2} \cdot (1 - \mathcal{O}_{ss})\right) + \left(\frac{\mathcal{R}_s}{2} \cdot (1 - \mathcal{O}_R) \cdot \left(1 - \frac{\mathcal{O}_{PC}}{\mathcal{O}_{ss}}\right) \cdot \mathcal{O}_{ss}\right).\end{aligned} \tag{10}$$

The first fragment in (10) refers to the case where the secondary message is successfully delivered over the secondary direct link between $T_s$ and $D_s$, while the second fragment of (10) considers the case in which the secondary direct link is in outage but at least one relay and the secondary destination correctly decoded the message from $T_s$.

While, the interference caused by $r(l^{\text{sch}})$ at the primary destination is given by

$$I_{\text{sch}} = P_{r(l)} \cdot |h_{r(l^{\text{sch}})p}|^2. \tag{11}$$

## III. Relay Selection Schemes

### A. Benchmarking Relay Selection Scheme

We consider the reactive relay selection scheme proposed in [5], termed as $\text{Max}$ throughout this paper, as a reference for performance comparisons. Such scheme is chosen since the cooperating relay is also selected in a distributed way after a transmission from $T_s$. Let $\Phi \subset \Lambda$ be a set containing the indexes of the relays that correctly decoded the message transmitted by $T_s$. Then, the selected relay, $r(l^{\text{Max}})$, is chosen by doing

$$l^{\text{Max}} = \arg\max_{l \in \Phi} |h_{r(l)s}|^2, \tag{12}$$

*i.e.*, the relay chosen among the subset $\Phi$ is the one with the best channel condition with respect to $D_s$.

### B. Fuzzy Logic-Based Relay Selection

In this section, we propose a fuzzy logic-based algorithm for relay selection in a secondary cooperative network. The algorithm has two input variables: the instantaneous CSI between the relay and the primary destination, $h_{r(l)p}$, and the instantaneous CSI between the relay and the secondary destination, $h_{r(l)s}$. Then, the output of the fuzzy scheme is a relay selection degree, as follows.

First, the CSI of $h_{r(l)p}$ and $h_{r(l)s}$ are classified into three levels: *low*, *medium* and *high*, as illustrated by Figs 2 and 3. When $h_{r(l)p} < 0.5$, the channel is classified as *low*, when $h_{r(l)p} > 1.5$, the channel is classified as *high*, and for other values between 0.5 and 1.5 a combination between the classifications *low*, *medium* and *high* is carried out. Moreover, $h_{r(l)s}$ is classified in a similar manner, according to Fig. 3. Let us remark that the main role of these linguistic terms is to provide a systematic way of characterizing the system.

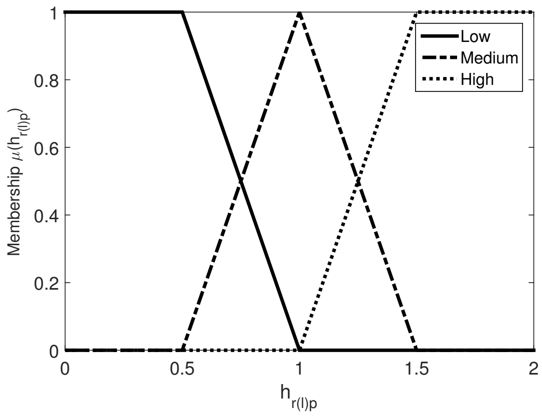


Fig. 2. Membership functions for $h_{r(l)p}$.

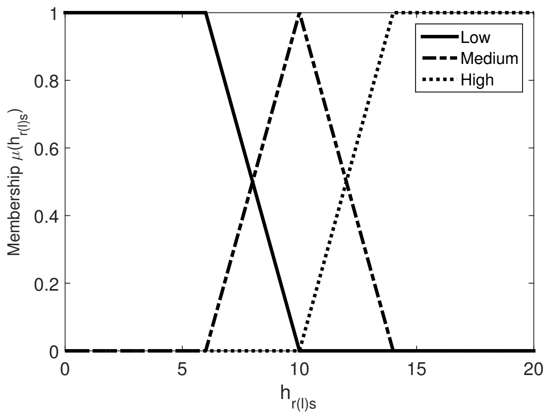


Fig. 3. Membership functions for $h_{r(l)s}$.

TABLE I

Description of the Fuzzy Rules

| Input | | Output |
|---|---|---|
| $h_{r(l)p}$ | $h_{r(l)s}$ | $g_r$ |
| Low | Low | Medium |
| Low | Medium | High |
| Low | High | Very High |
| Medium | Low | Low |
| Medium | Medium | Medium |
| Medium | High | Medium |
| High | Low | Very Low |
| High | Medium | Low |
| High | High | Low |

Moreover, the range for the membership functions of Figs 2 and 3 were obtained based on the histogram of each variable.

The fuzzy relay selection degree ($g_r$) is classified into five levels: *very low*, *low*, *medium*, *high* and *very high*, as shown in the Fig. 4. Then, in order to map $h_{r(l)p}$ and $h_{r(l)s}$ into $g_r$ we define a set of fuzzy rules. Since there are two input variables and each has three levels, there are nine output possibilities specified by the fuzzy rules of Table I. For instance, from Table I, when the channel $h_{r(l)p}$ is classified as *high*, we force the selection degree to be *low* or *very low*, in order to guarantee the minimum interference at the primary destination.

The aggregation of antecedents and the semantic of the

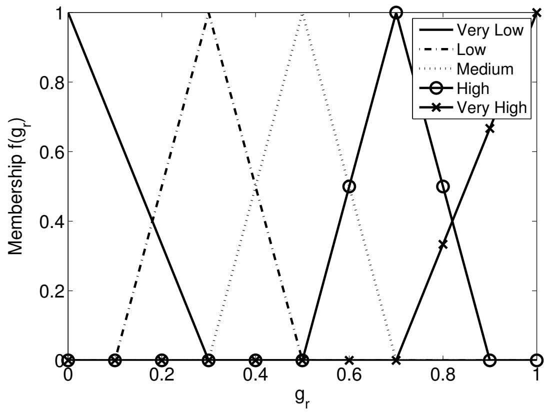


Fig. 4. Membership functions for the relay selection degree, $g_r$.

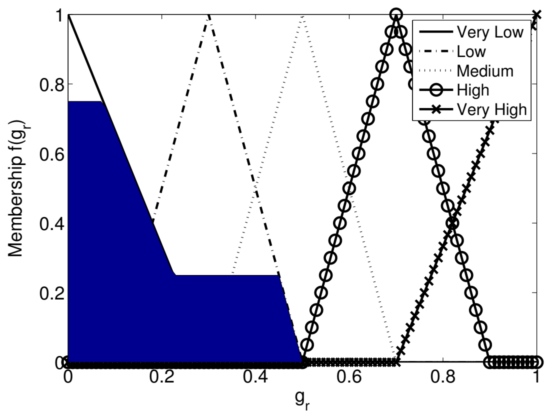


Fig. 5. Example of a relay selection emplying the fuzzy logic-based scheme.

rules employ Mamdani, using as metric the minimum $f(g_r) = \min(\mu(h_{r(l)p}), \mu(h_{r(l)s}))$ [14], according to the rules shown in Table I. Finally, in order to obtain a numerical result from the fuzzy operation, the relay selection degree $G_r$ is obtained through the center of gravity [14]

$$G_r = \frac{\int g_r f(g_r)}{\int f(g_r)}. \tag{13}$$

Note that $g_r$ is a linguistic operator, representing the relay selection degree into the fuzzy domain, while $G_r$ is the defuzzification of $g_r$, which is a numerical value.

As an example, suppose that $h_{r(l)p} = 1.5$ and $h_{r(l)s} = 7$. According to Figs 2 and 3, $h_{r(l)p}$ is classified as *high* with membership $\mu(h_{r(l)p}) = 1.0$, while $h_{r(l)s}$ is simultaneously classified as *low* with membership $\mu(h_{r(l)s}) = 0.75$ and as *medium* with membership $\mu(h_{r(l)s}) = 0.25$. Then, the output is a combination of the rules *high-low* and *high-medium*, yielding *very low* and *low* with the membership function given by the minimum of two entries, $f(g_r) = \min(1, 0.75) = 0.75$ and $f(g_r) = \min(1, 0.25) = 0.25$, respectively. Finally, the relay selection degree $G_r$ is given by the center of gravity of the filled area in Fig. 5. In this example, $G_r = 0.17$.

Then, before transmitting each relay waits for a time $t \propto \frac{1}{G_r} + \xi$, in which $\xi$ is a Gaussian random variable with zero mean and variance $\sigma_\xi^2$, which is very small compared to $G_r$.

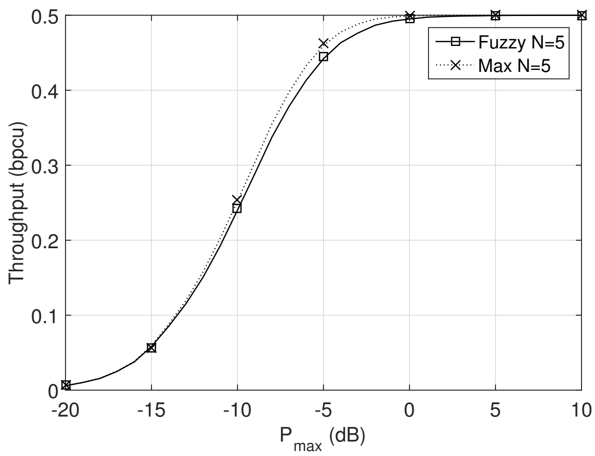


Fig. 6. Throughput of the secondary network for the SDF protocol with $N = 5$ relays.

The introduction of $\xi$ is to avoid collisions if two relays have the same value of $G_r$. Note that the algorithm is fully distributed, so that the selected relay ($r(l^{\text{Fuzzy}})$) will be the first to transmit. Moreover, we assume that the other relays overhear the first retransmission and remain silent to avoid collisions.

## IV. Numerical Results

This section presents the numerical results for the proposed fuzzy logic-based relay selection scheme. The results were obtained through Monte Carlo simulation with $10^4$ transmissions. We consider the path loss model $d_{ij}^{-\alpha}$ with exponent $\alpha = 4$, the attempted rate of the secondary network is $\mathcal{R}_s = 1$ bpcu and $\sigma_\xi^2 = 0.1$. Furthermore, it is assumed that all relays are in a cluster, *i.e.*, have the same distance to the other nodes of the network. Moreover, the nodes are distributed within a square area, with $T_p$ and $D_p$ located at coordinates (0,1) and (1,1), respectively. In the secondary network, $T_s$, the cluster of relays and $D_s$ are located at coordinates (0,0), (0.25,0.25) and (0.5,0), respectively. The distances are normalized with respect to the distance between $T_s$ and $D_p$ ($d_{sp}$), and are equal to $d_{sr} = d_{rs} = 0.25$, $d_{ss} = 0.35$, $d_{sp} = 1$, $d_{rp} = 0.75$, $d_{pr} = 0.56$, and $d_{ps} = 0.79$. Furthermore, we also consider that the transmit powers of $T_s$ and the relays are equal ($P_s = P_{r(l)} = P_{\max}$), while $P_p = 10$ dB and $I_{th} = 15$ dB.

First, Fig. 6 evaluates the throughput as a function of the maximum transmit secondary power $P_{\max}$, with $N = 5$ relays. From the figure we can see that the proposed scheme performs very close in terms of throughput compared to the $\text{Max}$ relay selection scheme proposed in [5]. Note that the $\text{Max}$ scheme performs only slightly better in the range of $P_{\max}$ between $-10$ dB and 0 dB, but with a very small difference.

Fig. 7 shows the interference caused by the selected relay at the primary destination, considering $N = \{5, 10\}$ relays. For instance, with $P_{\max} = 5$ dB, the proposed fuzzy logic-based relay selection scheme decreases the interference in 85% in comparison to the $\text{Max}$ scheme. Moreover, we can also notice that when $P_{\max}$ increases, the interference also increases once the relay is selected more oftenly.

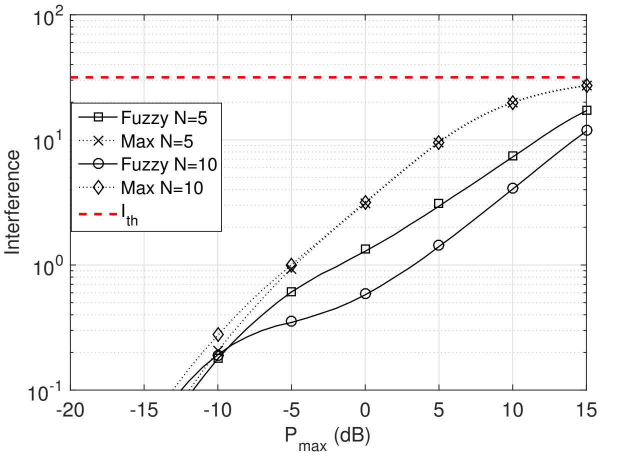


Fig. 7. Interference at the primary destination with $N = \{5, 10\}$ relays.

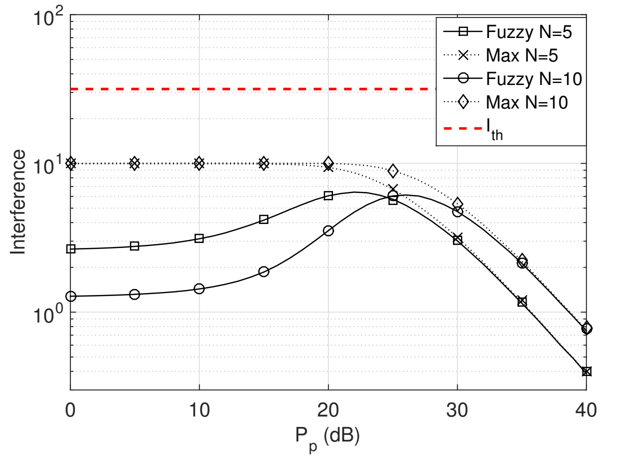


Fig. 8. Interference at the primary destination as a function of $P_p$ with $N = \{5, 10\}$ relays.

Finally, Fig. 8 shows the interference caused by the selected relay at the primary destination, as a function of the primary transmit power $P_p$, with $N = \{5, 10\}$ relays and $P_{max} = 5$ dB. As we can see from the figure, the proposed scheme causes less interference for lower values of $P_p$, while the performances of fuzzy and Max converge to the same value for greater values of $P_p$, which is mainly caused by the high values of outage probability for both schemes. In addition, when the number of relays increases, the probability that none of the relays correctly decodes the message from $T_s$ decreases and, consequently, the interference increases at high $P_p$.

## V. Conclusion

In this paper we proposed a relay selection method based on fuzzy logic, which decreases the interference in comparison with the classical reactive relay selection scheme. Results show that the interference caused by the selected relay decreases with the increment of the number of relays. For instance, with 10 relays it is possible to achieve an interference 85% lower than the interference caused by the benchmark scheme. As future work, we intend to analyze the effect of the line of sight in the secondary network, by means of modeling the channel with Nakagami-$m$ fading.

## Acknowledgements

This work was partially supported by CNPq and Capes.

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