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Full-Duplex Relaying for Opportunistic Spectrum Access Under an Overall Power Constraint

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ABSTRACT To meet the bold requirements of future generation networks, emerging technologies such as opportunistic spectrum access, multi-tier networks, full-duplexing and cooperative networks have to be exploited. In this paper, we propose to blend all the above and globally optimize a relay-aided cognitive radio network composed of a licensed link and an opportunistic link, which is helped by a full-duplex relay node. The opportunistic transmission is allowed provided that a minimum Quality of Service (QoS) constraint is met at the licensed user. First, we derive the achievable rate region under two relaying schemes, namely Decode-and-Forward (DF) and Compress-and-Forward (CF). Then we investigate the optimal power allocation policies for the opportunistic user and the relay under an overall power constraint. The resulting optimization problems are non-convex programs because of the non-trivial operations at the relay (for both CF and DF) and, for DF relaying, the non-convex QoS constraint. Remarkably, the optimal solution is stated in closed-form for CF, whereas it is obtained numerically for DF. Finally, we evaluate numerically the network performance under the two relaying schemes. It turns out that DF outperforms CF only when the relay is close to the opportunistic transmitter and that CF relaying is always useful.

INDEX TERMS Full-duplex relaying, opportunistic spectrum access, optimal power allocation.

I. INTRODUCTION

Future communication networks must now take into account the explosion of communicating devices and target very ambitious objectives: an unprecedented increase in the user, network capacity and throughput, energy efficiency, ultra-low latency, etc. To reach such objectives, a variety of proposed technologies – ranging from cooperative communications, full-duplexing, massive multi-antennas, mmWave to cognitive radio and device-to-device (D2D) communications – have to be skillfully exploited and combined together [1].

Traditionally, mobile networks rely either on frequency or time division duplexing, requiring thus two separate modes in order to achieve an orthogonal reception and transmission. This leads to a waste of half of the available resources. To counter this waste, *full-duplexing* is an emerging technology that enables full-duplex nodes to transmit and receive data simultaneously in the same frequency band and to double the spectral efficiency [2].

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Cognitive radio is another candidate technology to tackle the spectrum scarcity by allowing an opportunistic access to underutilized licensed bands, provided that the impact on the licensed communications is kept below acceptable levels [2], [3]. For instance, device-to-device (D2D) enabled cellular networks [4], where devices are allowed to directly communicate with each other without going through the cellular infrastructure, exploit this underlay technology.

At last, *cooperative communications* aim at increasing the network capacity and throughput by taking advantage of the wireless medium, which allows any node within range to access and potentially relay the transmitted message, enhancing thus the communication between the source and its destination. Three main relaying schemes have been proposed in the literature: Amplify-and-Forward (AF), where the relay amplifies its observed signal [5]; Decode-and-Forward (DF), where the relay decodes the sent message; and Compress-and-Forward (CF), where the relay quantizes the received signal [6]. None of the above is optimal in all settings; nevertheless, they have been shown to perform well over various extensions of the basic relay channel [7], such as the two-way relay channel [8], the diamond relay channel [9], the multiway relay channel [10], [11], and the interference relay channel [12], [13].

In this paper, we combine the three promising technologies above and consider a relay-aided cognitive radio network, in which the opportunistic transmission is assisted by a full-duplex operating relay node. In the underlay mode, the opportunistic communication is allowed provided that the impact on the licensed network is kept below a tolerated threshold. Our main objective is to derive an optimal power splitting policy among the opportunistic user and its helping relay under an overall power budget [14], [15]. Two different relaying schemes will be analyzed: DF and CF.

We do not consider AF relaying in this study for two main reasons. First, AF is expected to perform poorly in most multi-user interference settings since the relay also amplifies the interference plus noise terms, which enhances the noise variance at the opportunistic destination compared to DF and CF. Indeed, even in the standard Gaussian relay channel, which is not impaired by multi-user interference, both DF and CF schemes achieve large rates than AF [16]. Second, AF relaying in multi-user networks has been investigated mostly in the multi-hop special case, in which the direct link between the user and its destination is negligible [17]–[25]. When the direct link is taken into account, as in our work, AF turns the channel into a channel with memory [16], under which the achievable rate regions have very complex expressions [26], [27] leading to highly non trivial optimization problems.

Coming back to the present study, we further propose a minimum Quality of Service (QoS) constraint in order to protect the licensed user [28] allowing the opportunistic user to transmit as long as the licensed user achieves its desired target Shannon rate, which differs from the more common maximum interference constraints [3]. For instance, such a network could model a D2D-enabled cellular network where the licensed network consists of a cellular user and a base station whereas the opportunistic network consists of a relay-aided D2D transmission. The opportunistic relay could be either an idle cellular user or some other device.

Regarding the state of the art on relay-aided cognitive radio networks, several works have investigated power allocation problems from an outage probability minimization perspective [15], [29], [30], whereas this paper focuses on maximizing the opportunistic users' transmission rate. The authors of [17], [31] investigate rate maximization problems under AF, either in half-duplex mode or by neglecting the direct link, whereas we aim to study DF and CF in a general full-duplex mode. Also, [17], [31] considered maximum peak interference constraints, while we focus on a different rate-driven QoS constraint. In [18], [32]–[34], the interference from the licensed network does not impact the opportunistic network, as opposed to our model.

To the best of our knowledge, the closest works to ours are [28], [35], [36]. In [35], the authors investigate the energy-efficiency and rate maximization problems in a cognitive radio network assisted by a full-duplex DF-operating relay composed by a single licensed and opportunistic user/destination pair. The main differences with the present work are two-fold: a) we aim to study and compare DF and CF instead of only DF; b) we consider a rate-based constraint imposed by the licensed user as opposed to peak interference constraints. In our previous paper [28], we considered a similar problem but assumed that the interfering links between the licensed and opportunistic users are negligible. Moreover, in [28], the transmit powers of the opportunistic user and relay were constrained separately, while here an overall and more general power constraint is assumed. Finally, in [36], we considered a special case where the opportunistic users are not able to directly communicate with each other, but only through the helping relay node. This assumption greatly simplified the problem under investigation as opposed to the general case considered in this paper.

Our main contributions can be summarized as follows.

- First, we derive the achievable rate regions for the cooperative cognitive network when the relay performs either DF or CF. For DF, superposition coding is employed in order to coherently combine the messages from the opportunistic user and the relay. Regarding CF, lattice codes are used at both the opportunistic user and the relay, as well as for the quantization operation.
- Then, we formulate the opportunistic power allocation problems that maximize the achievable rate under both DF and CF relaying. A primary QoS constraint, which is expressed as a tolerated loss in its achievable Shannon rate caused by the opportunistic user, jointly with and an overall power constraint at the relay and opportunistic transmitter are considered.
- Remarkably, we provide the optimal power allocation policy in closed-form for CF relaying by exploiting the monotone properties of the objective. For DF relaying, the optimization problem is a more difficult non-convex program. We nevertheless prove that finding the 3-dimensional optimal solution can be reduced to a 2-dimensional search.
- Our numerical simulations demonstrate that the best relaying scheme between CF and DF depends on the position of the relay. More precisely, DF outperforms CF when the relay is close to the opportunistic transmitter, and CF outperforms DF when the relay is close to the opportunistic destination.
- Moreover, exploiting the relay cannot decrease the opportunistic performance when CF is used, which we also prove analytically. At the opposite, DF relaying can actually be harmful in terms of achievable rates for some channel setups.

The rest of the paper is organized as follows: Section II presents the considered system model in details. In Section III and Section IV, we analyze the achievable rate regions and derive the optimal power allocation policies under CF and DF, respectively. Numerical evaluations and comparisons

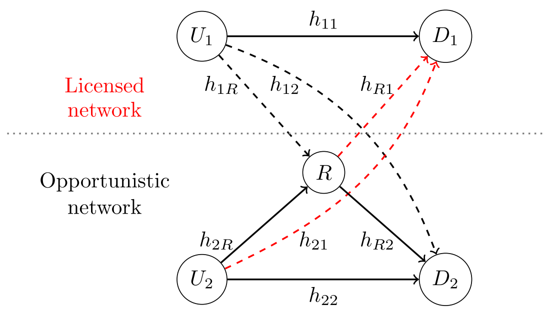

FIGURE 1. Cognitive relay-aided network.

between CF and DF relaying are performed in Section V. Finally, Section VI concludes the paper.

II. SYSTEM AND PROBLEM FORMULATION

The cooperative cognitive radio network under study is illustrated in FIGURE 1 and consists of one licensed user U_1, also called primary user, and it's associated destination D_1, whereas the cooperative opportunistic network is composed by a source node U_2, its associated destination D_2 and a relay R. The opportunistic user has an underlay access mode to the spectrum and cannot perturb the licensed transmission above a tolerated level. This model has been widely studied from an outage point of view, either with a single relay and power allocation [30], or with multiple relay selection and without power allocation [37]–[39], or with a single relay and no power allocation [15], [40], [41].

A showcase example could be a cooperative D2D-enabled cellular network. In such networks, two cases can arise regarding the opportunistic transmission: either the source and destination devices are close enough from one another to ensure an efficient direct link, or the communication is performed in a multi-hop fashion via a relay node, which can be either an idle cellular user or another device [42]–[44]. Here, we exploit both transmission modes at the same time in order to increase the opportunistic rate.

We assume that the relay operates in a full-duplex manner, allowing the transmission and the reception phase to occur simultaneously at the relay. Moreover, we assume that the relay can perfectly cancel out any self-interference and that the nodes' inputs depend only of their current message and not of previously decoded symbols. Even if the assumption of perfect self-interference cancellation may not be realistic in practical settings, it allows us to simplify the expressions of the achievable rates, and hence the considered optimization problems, leading to low-complexity optimal power allocation policies. In order to provide insights or closed-form expressions of the outage probabilities when the relay cannot perfectly cancel the self-interference, other assumptions such as: a high SNR regime, an interference-limited environment, or neglecting some links in the network, etc. are necessary [15], [37]–[40]. In this work, besides the ideal self-interference cancellation, we do not make any further simplifying assumptions regarding the network model.

Block Markov coding is used at the transmitters such that during each block k, the nodes receive and can process the messages sent during the previous block $k-1$. The received signal at the relay and at the two destinations are given as

$$Y_R = h_{1R}X_1 + h_{2R}X_2 + Z_R, \tag{1}$$
$$Y_i = h_{Ri}X_R + h_{ii}X_i + h_{ji}X_j + Z_i, \tag{2}$$

where $i \in \{1, 2\}$, $j = \{1, 2\} \setminus i$. The signals X_R, X_2 and X_1 denote the transmitted signal of the relay, the opportunistic transmitter and the licensed user respectively, which are of average power P_R, P_2 and P_1, respectively. Z_R and Z_i are the additive white Gaussian noise (AWGN) at the relay and at the destination D_i of variance N_R and N_i respectively.

A. OVERALL OPPORTUNISTIC POWER CONSTRAINT

Regarding the opportunistic link, we consider here a more general and overall power constraint between the transmitter and the relay node [14], [15], [19], [21], [31], [34]:

$$P_2 + P_R \leq \overline{P},$$

as opposed to the individual constraints in [28]. This constraint implicitly assumes that the two nodes are able to exchange energy or power via the wireless medium. Indeed, if the opportunistic users can harvest energy and split their transmission between power exchange and data transmission, the achievable opportunistic rate should increase compared to the case where nodes cannot exchange energy and are thus constrained by a maximum power per device. Nevertheless, the energy harvesting model and the splitting protocol between data and energy transfer is left for future work and is not considered here.

B. PRIMARY QoS CONSTRAINT

Let $\mathcal{R}_i$, $i \in \{1, 2\}$ denote the achievable rate of the licensed and opportunistic user respectively. Moreover, let $\overline{\mathcal{R}_1}$ denote the primary achievable rate in the absence of the opportunistic network, which can be easily computed as

$$\overline{\mathcal{R}_1} = \frac{1}{2}\log\left(1 + \frac{h_{11}^2 P_1}{N_1}\right).$$

In this paper, we aim at maximizing the opportunistic achievable rate $\mathcal{R}_2$ under a minimum QoS constraint protecting the licensed user's rate [28]

$$\mathcal{R}_1 \geq (1-\tau)\overline{\mathcal{R}_1}, \tag{3}$$

which differs from the more common maximum interference constraints. In other words, the licensed user can tolerate at most a fractional decrease of $\tau \in [0, 1]$ in its achievable rate compared to its maximum rate achieved in the absence of the opportunistic network.

We further consider the message sent by the licensed user as additional noise at both the relay and the opportunistic destination. Thus, one can consider an equivalent additive Gaussian noise at the relay and at the opportunistic destination respectively, of variance $\widetilde{N}_R = h_{1R}^2 P_1 + N_R$ and

$\widetilde{N}_2 = h_{12}^2 P_1 + N_2$ respectively. Note that these two equivalent noises are correlated: one can thus define the correlation coefficient as $\rho_Z = \frac{h_{12}h_{1R}P_1}{\sqrt{\widetilde{N}_R\widetilde{N}_2}} \geq 0$.

C. PROBLEM FORMULATION

To sum up, the optimization problem under study in its general form writes as

$$\begin{aligned} \max_{P_2,P_R} \quad & \mathcal{R}_2(P_2, P_R) \\ \text{s.t.} \quad & P_2 \geq 0, P_R \geq 0 \\ & \mathcal{R}_1 \geq (1-\tau)\overline{\mathcal{R}_1} \\ & P_2 + P_R \leq \overline{P} \end{aligned} \tag{4}$$

where the objective, i.e., the achievable rate of the opportunistic user $\mathcal{R}_2(P_2, P_R)$ depends on the specific relaying scheme performed. In the following, we will investigate two relaying schemes, namely CF and DF, for which the resulting allocation problems are not convex ones and standard convex solvers cannot be exploited.

Under both CF and DF, the optimal power allocation policy can either be computed at a centralized node that has to be provided perfect channel state information (CSI) and then forwarded to the secondary user and the relay; or directly computed at each node individually, provided that each node has access to perfect CSI. Perfect CSI is a common assumption in the relevant literature [6], [8]–[10], [13], [16], [21], [28], [31], [36], [39], [42], [45], which can be obtained by pilot-based channel estimation prior to any data transmission.

D. NOTATIONS

We will use the well-known capacity function $\mathcal{C}(x) = \frac{1}{2}\log_2(1+x)$. Also, to simplify the mathematical expressions and derivations, the following notations, which are fixed constants depending on the system parameters will be used: $g_{ij} = h_{ij}^2,\ i,j \in \{1, 2, R\}$ and

$$A = \frac{g_{11}P_1}{\left(1 + \frac{g_{11}P_1}{N_1}\right)^{(1-\tau)} - 1} - N_1.$$

III. COMPRESS-AND-FORWARD

We start our analysis by investigating the optimal power splitting scheme between the opportunistic user and the relay when CF relaying is employed. Under CF relaying, the relay sends a compressed version of its received signal.

To simplify the presentation, the following notations will be used in this section:

$$\begin{aligned} K_1 &= g_{2R}\widetilde{N}_2 + g_{22}\widetilde{N}_R - 2h_{2R}h_{22}\rho_Z\sqrt{\widetilde{N}_2\widetilde{N}_R}, \\ K_2 &= (1-\rho_Z^2)\widetilde{N}_R\widetilde{N}_2, \\ B_1 &= g_{R2}\frac{A}{g_{R1}}\left(K_1 - \frac{g_{22}}{\widetilde{N}_2}K_2\right), \\ B_2 &= \frac{A}{g_{R1}}\left(K_2 g_{R2} - K_1\widetilde{N}_2\frac{g_{R1}}{g_{21}}\right), \\ B_3 &= \widetilde{N}_2\left(K_1\frac{A}{g_{21}} + K_2\right), \\ B_4 &= \frac{g_{22}}{\widetilde{N}_2}, \\ C_1 &= g_{R2}\overline{P}^2\left(K_1 - \frac{g_{22}}{\widetilde{N}_2}K_2\right), \\ C_2 &= \overline{P}(K_2 g_{R2} - K_1\widetilde{N}_2), \\ C_3 &= \widetilde{N}_2(K_1\overline{P} + K_2), \\ C_4 &= \frac{g_{22}\overline{P}}{\widetilde{N}_2}. \end{aligned}$$

Below, we provide the achievable rate region, which can be derived by exploiting the results for the Gaussian relay channel with correlated noises [45].

Proposition 1: Assuming CF at the relay and that all non-intended messages are treated as additional noise, the following rate region is achievable over the cooperative opportunistic network:

$$\begin{aligned} \mathcal{R}_1 &\leq \mathcal{C}\left(\frac{g_{11}P_1}{g_{R1}P_R + g_{21}P_2 + N_1}\right) \\ \mathcal{R}_2 &\leq \mathcal{C}\left(\frac{P_2(K_1 + g_{22}D)}{K_2 + \widetilde{N}_2\, D}\right) \ \textit{with}\ D = \frac{K_1P_2 + K_2}{g_{R2}P_R}. \end{aligned}$$

Proof: At the licensed destination, the message from both the relay and the opportunistic user are considered as additional noise when recovering the licensed message, leading to $\mathcal{R}_1$ given above.

Regarding the opportunistic network, the situation corresponds to the use of CF over a Gaussian relay channel with correlated additive noise at the relay and destination. The achievable opportunistic rate can thus be obtained from Proposition 1 of [45]. ■

The optimization problem (4) under CF relaying becomes

$$\begin{aligned} \max_{P_2,P_R} \quad & \frac{K_1 g_{R2}P_2P_R + g_{22}P_2(K_1P_2 + K_2)}{K_2 g_{R2}P_R + \widetilde{N}_2(K_1P_2 + K_2)} \\ \text{s.t.} \quad & P_2 \geq 0,\ P_R \geq 0 \\ & g_{21}P_2 + g_{R1}P_R \leq A \\ & P_2 + P_R \leq \overline{P} \end{aligned} \tag{5}$$

To analyze the problem above, let us first focus one the two linear constraints in (5), which can be written in a parametric manner:

$$\begin{aligned} P_R &= \delta\overline{P}, P_2 = (1-\delta)\overline{P}, \quad \delta \in [0, 1] \\ P_R &= \gamma\frac{A}{g_{R1}}, P_2 = (1-\gamma)\frac{A}{g_{21}}, \quad \gamma \in [0, 1]. \end{aligned}$$

The two constraints lead to four different cases that are depicted in FIGURE 2, which will be discussed in details below: either the two constraints intersect or one of the constraints always dominates the other. In the latter case, the nonrestrictive constraint can be thus removed from the analysis.

If either ($A < g_{R1}\overline{P}$ and $A > g_{21}\overline{P}$), which we will refer to as assumption **[H1]**, or ($A > g_{R1}\overline{P}$ and $A < g_{21}\overline{P}$), which we will refer to as **[H2]**, the two constraints intersect in the

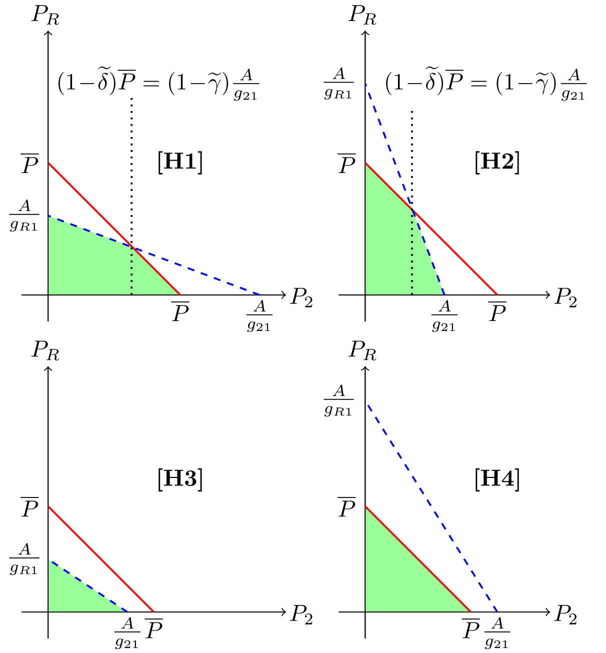

FIGURE 2. When considering the primary QoS constraint and the total power constraint, four cases can arise for CF relaying: either the two constraints intersect in a unique point or not at all. In all cases, the optimal power allocation policy lies on the boundary of the feasible set depicted by the green-filled area.

unique point:

$$\widetilde{P}_2 = (1-\widetilde{\delta})\overline{P} = (1-\widetilde{\gamma})\frac{A}{g_{21}},$$
$$\widetilde{P}_R = \widetilde{\delta}\,\overline{P} = \widetilde{\gamma}\frac{A}{g_{R1}},$$

where $0 \leq \widetilde{\delta} \leq 1$ and $0 \leq \widetilde{\gamma} \leq 1$ are given as

$$\widetilde{\delta} = \frac{A - g_{21}\overline{P}}{(g_{R1} - g_{21})\overline{P}},$$
$$\widetilde{\gamma} = \frac{g_{R1}(g_{21}\overline{P} - A)}{A(g_{21} - g_{R1})}.$$

The difference between the two hypotheses is that, under **[H1]**, the most restrictive constraint is first the QoS one and then the overall power one; whereas the order is reversed under **[H2]**.

If on the other hand ($A \leq g_{R1}\overline{P}$ and $A \leq g_{21}\overline{P}$), i.e., **[H3]**, the primary QoS constraint is the most restricting one and the overall power constraint can be ignored when searching for the optimal solution. Otherwise, if either ($A > g_{R1}\overline{P}$ and $A \geq g_{21}\overline{P}$) or ($A = g_{R1}\overline{P}$ and $A > g_{21}\overline{P}$), i.e., **[H4]**, the overall power constraint is the most restricting one and the QoS constraint can be ignored.

Regarding the objective function, we can prove that it is increasing in P_R for a fixed P_2 and is also increasing in P_2 for a fixed P_R. This directly implies that the optimal power allocation policy lies on the Pareto-boundary of the feasible set depicted in green in FIGURE 2. We can thus first restrict the search for the optimal power allocation policy on one of the two linear constraints and then take into account the overall feasible set to derive the global solution.

In order to do so, we replace P_R and P_2 with their parametric description based on δ and γ and define two functions $f_{\text{CF,QoS}}(\gamma)$ and $f_{\text{CF,pow}}(\delta)$ corresponding to the objective function restricted only by the primary QoS constraint and by the overall power constraint respectively. The two functions write as

$$f_{\text{CF,QoS}}(\gamma) = \frac{B_1\gamma(1-\gamma)}{B_2\gamma + B_3} + B_4(1-\gamma),$$
$$f_{\text{CF,pow}}(\delta) = \frac{C_1\delta(1-\delta)}{C_2\delta + C_3} + C_4(1-\delta).$$

Depending on the system parameters, the two functions above can either be: i) strictly decreasing (when $B_1 + B_2B_4 < 0$ or ($B_1 + B_2B_4 \geq 0$; and $B_1 - B_3B_4 < 0$) and $C_1 + C_2C_4 < 0$ or ($C_1 + C_2C_4 \geq 0$ and $C_1 - C_3C_4 < 0$), respectively); or ii) quasi-concave (first increasing and then decreasing) with the following maximum points:

$$\widehat{\gamma} = \frac{B_3(B_1 + B_2B_4) - \sqrt{B_1B_3(B_1 + B_2B_4)(B_2 + B_3)}}{-B_2(B_1 + B_2B_4)},$$
$$\widehat{\delta} = \frac{C_3(C_1 + C_2C_4) - \sqrt{C_1C_3(C_1 + C_2C_4)(C_2 + C_3)}}{-C_2(C_1 + C_2C_4)}.$$

To sum up, the optimal solution can be found in closed and analytical form by taking into account the above considerations regarding the objective functions and the critical points (when they exist) and the Pareto-boundary of the feasible set. The next Theorem, although tedious, details the optimal power allocation in all the possible cases depending on the system parameters when the relay performs CF. The complete proof is provided in the Appendix.

Theorem 1: The optimal power allocation policy (P_R^*, P_2^*) *when the relay performs CF depends on the system parameters and is given in closed-form as follows.*

*If **[H1]** is met, i.e. the two constraints are restrictive and intersect in a unique point: The optimal solution depends on two parameters* γ^* *and* δ^* *given below.*

i) If ($B_1 + B_2B_4 \geq 0$ *and* $B_1 - B_3B_4 \geq 0$)*, then* $\gamma^* = \max\{\widehat{\gamma}, \widetilde{\gamma}\}$*, otherwise* $\gamma^* = \widetilde{\gamma}$.

ii) If ($C_1 + C_2C_4 \geq 0$ *and* $C_1 - C_3C_4 \geq 0$)*, then* $\delta^* = \min\{\widehat{\delta}, \widetilde{\delta}\}$*, otherwise* $\delta^* = 0$.

Now, if $f_{\text{CF,pow}}(\delta^*) \geq f_{\text{CF,QoS}}(\gamma^*)$*, then the optimal solution is* $P_R^* = \delta^*\overline{P}$*,* $P_2^* = (1-\delta^*)\overline{P}$*, otherwise* $P_R^* = \gamma^*\frac{A}{g_{R1}}$*,* $P_2^* = (1-\gamma^*)\frac{A}{g_{21}}$.

*If **[H2]** is met, the two constraints are restrictive and intersect in a unique point similarly to **[H1]**.*

i) If ($B_1 + B_2B_4 \geq 0$ *and* $B_1 - B_3B_4 \geq 0$)*, then* $\gamma^* = \min\{\widehat{\gamma}, \widetilde{\gamma}\}$*, otherwise* $\gamma^* = 0$.

ii) If ($C_1 + C_2C_4 \geq 0$ *and* $C_1 - C_3C_4 \geq 0$)*, then* $\delta^* = \max\{\widehat{\delta}, \widetilde{\delta}\}$*, otherwise* $\delta^* = \widetilde{\delta}$.

Now, if $f_{\text{CF,pow}}(\delta^*) \geq f_{\text{CF,QoS}}(\gamma^*)$*, then the optimal solution is* $P_R^* = \delta^*\overline{P}$*,* $P_2^* = (1-\delta^*)\overline{P}$*, otherwise* $P_R^* = \gamma^*\frac{A}{g_{R1}}$*,* $P_2^* = (1-\gamma^*)\frac{A}{g_{21}}$.

*If **[H3]** is met, only the QoS constraint is impacting the power allocation policy. If* ($B_1 + B_2B_4 \geq 0$ *and* $B_1 - B_3B_4 \geq$

0), *then* $\gamma^* = \widehat{\gamma}$, *otherwise* $\gamma^* = 0$. *The optimal solution is* $P_R^* = \gamma^* \frac{A}{g_{R1}}, P_2^* = (1-\gamma^*)\frac{A}{g_{21}}$.

Otherwise, if **[H4]** *is met, only the overall power constraint is impacting the power allocation policy. If* $(C_1 + C_2C_4 \geq 0$ *and* $C_1 - C_3C_4 \geq 0)$, *then* $\delta^* = \widehat{\delta}$, *otherwise* $\delta^* = 0$. *The optimal solution is* $P_R^* = \delta^*\overline{P}, P_2^* = (1-\delta^*)\overline{P}$.

IV. DECODE-AND-FORWARD ANALYSIS

In this section, we investigate the performance of DF relaying. Under this relaying scheme, the relay first decodes the message sent by the opportunistic user and then sends a re-encoded version of this message towards the destinations.

The following notations will be used in this section:

$$E_1 = g_{R1} - g_{21},$$
$$E_2 = g_{21}\overline{P} - A,$$
$$E_3 = 2\alpha\sqrt{g_{R1}g_{21}},$$

where $\alpha \in [0, 1]$ follows from the use of superposition coding and allows to trade off between sending a new message and repeating the message from the previous block.

The achievable rates in this case are given in the next proposition, which can be obtained using standard information theoretic arguments.

Proposition 2: Assuming DF scheme at the relay and that all non-intended messages are treated as additional noise, the following rate region is achievable over the cooperative opportunistic network:

$$\mathcal{R}_1 \leq \mathcal{C}\left(\frac{g_{11}P_1}{g_{R1}P_R + g_{21}P_2 + 2h_{21}h_{R1}\alpha\sqrt{P_2P_R} + N_1}\right)$$
$$\mathcal{R}_2 \leq \min\left\{\mathcal{C}(f_{\text{DF},R}(\alpha, P_2, P_R)), \mathcal{C}(f_{\text{DF},2}(\alpha, P_2, P_R))\right\},$$

where $\alpha \in [0, 1]$ *and*

$$f_{\text{DF},R}(\alpha, P_2, P_R) = \frac{g_{2R}(1-\alpha^2)P_2}{\widetilde{N}_R},$$
$$f_{\text{DF},2}(\alpha, P_2, P_R) = \frac{g_{22}P_2 + g_{R2}P_R + 2h_{R2}h_{22}\alpha\sqrt{P_2P_R}}{\widetilde{N}_2}.$$

Proof: Superposition coding is used at the opportunistic user in order to coherently combine the message sent by the relay and by the opportunistic user at the opportunistic destination. α allows to trade off between sending a new message and repeating the one from the previous block at the opportunistic user. At the primary destination, the message from the relay and from the opportunistic user also coherently combine leading to an increase of the additional noise of $2h_{21}h_{R1}\alpha\sqrt{P_2P_R}$. The opportunistic achievable rate follows from perfect decoding at both the relay and the opportunistic destination. ∎

Hence, the optimization problem (4) under DF relaying writes as

$$\max_{P_2,P_R,\alpha} \quad \min\left\{f_{\text{DF},R}(\alpha, P_2, P_R), f_{\text{DF},2}(\alpha, P_2, P_R)\right\}$$
$$\text{s.t.} \quad P_2 \geq 0, P_R \geq 0$$
$$0 \leq \alpha \leq 1$$
$$g_{21}P_2 + g_{R1}P_R + 2h_{21}h_{R1}\alpha\sqrt{P_2P_R} \leq A$$

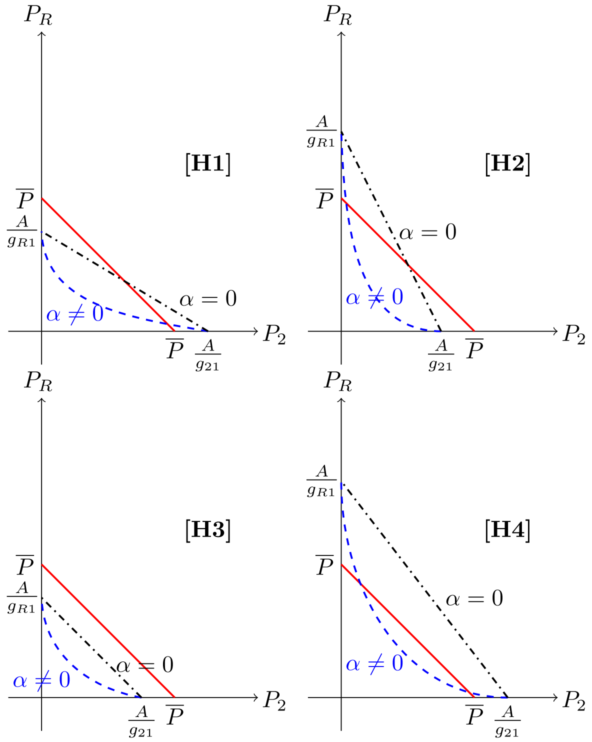

FIGURE 3. Relative position of the constraints under DF for a fixed value of α. The solid line corresponds to the overall power constraint, whereas the dashed one corresponds to the primary QoS one for a given $\alpha \neq 0$ and the dashed-dotted one to the primary QoS constraint with $\alpha = 0$.

$$P_2 + P_R \leq \overline{P} \tag{6}$$

Unfortunately, because of the terms containing $\sqrt{P_2\,P_R}$ in the objective function and the constraints, the optimization problem is much more complex than in the previous section and cannot be solved in a closed-form manner in this case. Nevertheless, we show below that the problem can still be solved numerically in a more efficient way than brute force (e.g., exhaustive search).

For simplicity, let us first assume that the power splitting at the opportunistic transmitter, $\alpha \in [0, 1]$, is fixed. Then, one needs only to optimize over P_R and P_2. Similarly to CF relaying, we study first the feasible set. Four cases arise depending on the system parameters, which are depicted in FIGURE 3. When $\alpha = 0$ (no superposition coding), the constraints are linear and a similar analysis can be done as with CF. In the non-trivial case when $\alpha > 0$, the QoS constraint is no longer linear and the analysis of the feasible set is more involving.

Indeed, unlike CF relaying, under hypothesis **[H4]**, the two constraints can either have two, one or no intersection points depending on the system parameters. The cases **[H1]**, **[H2]** and **[H3]** are similar to CF relaying in term of number of intersection points between the two constraints.

Regarding the objective function, it is increasing in P_R for a fixed P_2 and in P_2 for a fixed P_R. Hence, for a fixed α, the optimal power allocation is again on the Pareto boundary; and although the optimal solution on the boundary can only be found numerically, an exhaustive search on the entire feasible set is not necessary. At last, maximizing numerically over $\alpha \in [0, 1]$ provides the overall optimal power allocation policy.

The following proposition summarizes the feasible set analysis as well as the description of the exact boundary to be considered in the numerical search for the optimal solution, depending on the system parameters. The complete proof is provided in the Appendix.

Proposition 3: When the relay performs DF, the optimal solution lies on the boundary of the feasible set. This search can be restricted further as follows.

*If **[H1]** is met, the two constraints are restrictive and intersect in a unique point given as*

$$\widetilde{P}_{R1} = \frac{-(2E_1E_2 - E_3^2\overline{P}) - \sqrt{\Delta}}{2(E_1^2 + E_3^2)},$$

with $\Delta = E_3^2\left(E_3^2\overline{P}^2 - 4E_2(E_1\overline{P} + E_2)\right) \geq 0$ *and* $\widetilde{P}_2 = \overline{P} - \widetilde{P}_{R1}$. *The optimal solution* (P_R^*, P_2^*) *lies on the boundary such that either* $0 \leq P_R^* \leq \widetilde{P}_{R1}$ *and* $P_2^* = \overline{P} - P_R^*$ *(the solution lies on the total power constraint) or* $\widetilde{P}_{R1} < P_R^* \leq \frac{A}{g_{R1}}$ *and the solution lies on the QoS constraint, whichever of the two possibilities maximizes the objective function.*

*If **[H2]** is met, the two constraints are restrictive and intersect in a unique point given as*

$$\widetilde{P}_{R2} = \frac{-(2E_1E_2 - E_3^2\overline{P}) + \sqrt{\Delta}}{2(E_1^2 + E_3^2)}.$$

with the same $\Delta \geq 0$ *as above and* $\widetilde{P}_2 = \overline{P} - \widetilde{P}_{R2}$. *The optimal solution* (P_R^*, P_2^*) *lies on the boundary such that either* $0 \leq P_R^* \leq \widetilde{P}_{R2}$ *and the solution lies on the QoS constraint or* $P_{R1} < P_R^* \leq \overline{P}$ *and* $P_2^* = \overline{P} - P_R^*$.

*If **[H3]** is met, only the QoS constraint impacts the solution.*

*If **[H4]** is met, two cases can arise depending on the sign of* Δ *and other parameters.*
i) If $\Delta \geq 0$, $E_1\widetilde{P}_{R1} + E_2 \leq 0$ *and* $E_1\widetilde{P}_{R2} + E_2 \leq 0$, *the constraints intersect in two points* $\widetilde{P}_{R1}$ *and* $\widetilde{P}_{R2}$ *(which coincide when* $\Delta = 0$*). The optimal solution is such that either* $0 \leq P_R^* \leq \widetilde{P}_{R1}$ *and* $P_2^* = \overline{P} - P_R^*$ *or* $\widetilde{P}_{R1} < P_R^* \leq \widetilde{P}_{R2}$ *and the optimal solution lies on the QoS constraint or* $\widetilde{P}_{R2} < P_R^* \leq \overline{P}$ *and* $P_2^* = \overline{P} - P_R^*$.
ii) Otherwise, the two constraints do not intersect at all and only the total power constraint impacts the power allocation policy.

V. COMPARISON OF THE RELAYING SCHEMES

Throughout this section, we consider the following setup to numerically compare the opportunistic rate achieved by CF, DF relaying and without the relay. The muti-tier network is located in a square cell of normalized size of 1×1 as in [16]. Nevertheless, all our conclusions are generic and carry over many practical settings. We further assume that the licensed and opportunistic user/destination pairs are fixed and that the relay's position ranges over the cell. The channel gains are assumed to follow a common path-loss model as $\frac{1}{d^{3/2}}$, where d is the distance between any two nodes of the network. Note that when the relay is absent, the optimal power allocation policy is $P_2^* = \min\left\{\overline{P}, \frac{A}{g_{21}}\right\}$ and the achievable opportunistic rate is given as $R_D^* = \mathcal{C}\left(\frac{g_{22}P_2^*}{N_2}\right)$.

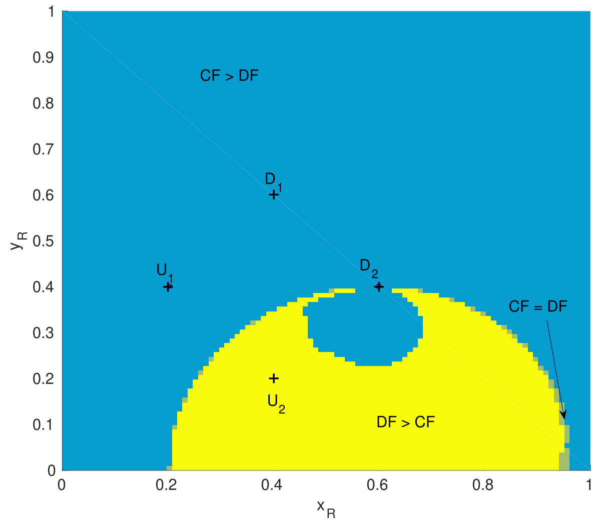

FIGURE 4. Comparison between CF and DF, $N_1 = 10$, $N_2 = N_R = 1$, $P_1 = 10$, $\overline{P} = 1$, $\tau = 0.3$.

Notice that all our optimal power allocation policies under CF relaying or without the help of the relay are given in closed-form expressions; hence, the resulting computational complexity (i.e., $\mathcal{O}(1)$) and latency are optimal. For DF, we reduce the search over the 3-dimensional space to a 2-dimensional one composed of a scalar line search over α and a simplified search on the Pareto bound described in Proposition 3.

A. WHICH RELAYING SCHEME TO USE?

In [28], we showed via numerical simulations that when the two networks are too far apart such that $g_{21} = g_{12} = 0$, DF outperforms CF when the relay is close to the opportunistic user. Also, CF outperforms DF when the relay is close to the opportunistic destination. These sets of positions where one scheme outperforms the other one under individual power constraints are the same as for the standard Gaussian relay channel. A natural question here is whether this observation still holds under an overall power constraint and for a network in which the interference between the licensed and opportunistic networks is taken into account.

FIGURE 4 compares the achievable opportunistic rates when $N_1 = 10$, $N_2 = N_R = 1$, $P_1 = 10$, $\overline{P} = 1$, $\tau = 0.3$. The position of the users and destinations are fixed and depicted on the cell. Similarly to [28], we can note that DF outperforms CF when the relay is close to the opportunistic user. The larger region corresponds to the case where CF outperforms DF.

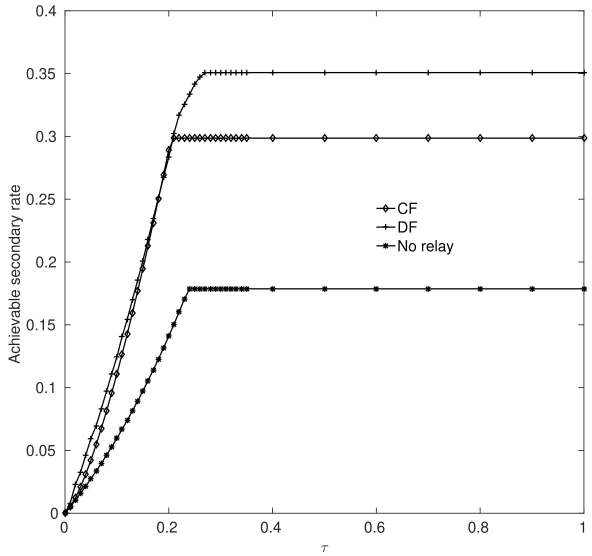

FIGURE 5. Achievable rates with CF, DF and only over the direct opportunistic link as a function of τ, the percentage of rate loss the licensed user can tolerate. The positions of all nodes are fixed and given as $U_1(0.2, 0.4)$, $D_1(0.4, 0.6)$, $U_2(0.4, 0.2)$, $D_2(0.6, 0.4)$, $R(0.6, 0.2)$; and $N_1 = 10$, $N_2 = N_R = 1$, $P_1 = 10$, $\overline{P} = 1$.

FIGURE 5 shows the influence of $\tau \in [0, 1]$, the percentage of rate loss the licensed user can tolerate, on the two relaying schemes DF and CF as well as solely over the opportunistic direct link. First, one can observe that DF outperforms CF because of the position of the relay, which is fixed and chosen to be closer to the opportunistic user. Moreover, one can observe a saturation for all transmissions schemes: for DF and CF, the saturation comes from the fact that the case **[H4]** is reached, and thus, the optimal solution lies on overall power constraint, which does not depend on τ. Similarly, for the transmission over the direct link, the saturation is reached because $\min\left\{\overline{P}, \frac{A}{g_{21}}\right\} = \overline{P}$ and the solution lies on the overall power constraint.

B. IS THE RELAY ALWAYS HELPFUL?

In [28], we proved that under individual power constraints, performing CF at the relay cannot decrease the performance compared to the case without the relay. Moreover, we proved that depending on the system parameters, DF can decrease the performance compared to the transmission only over the direct link. The question is whether this still holds under the total power constraint and when the interfering links between the two networks are taken into consideration.

Proposition 4: Using the CF relaying scheme can either increase the achievable opportunistic rate or achieve the same rate as the one obtained only over the opportunistic direct link and without the relay.

This result follows from the fact that the achievable opportunistic rate under CF when the relay is allocated no power reduces to the capacity of the point-to-point transmission over the opportunistic direct link. Since the objective function is increasing with P_R, CF cannot decrease the performance compared to a direct transmission with no relay.

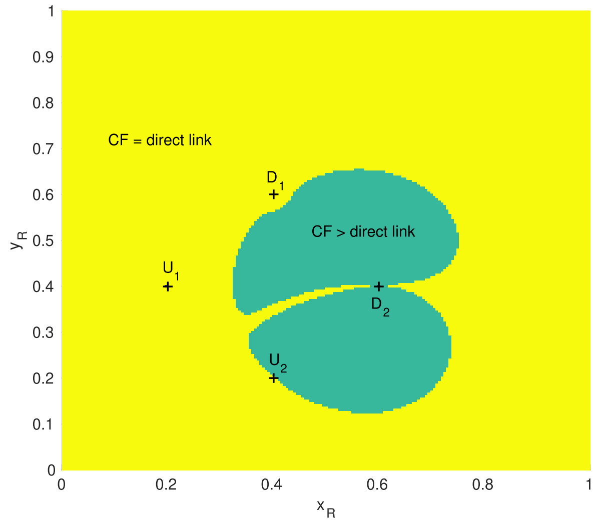

FIGURE 6. Comparison between rate regions obtained with CF and only over the opportunistic direct link, $N_1 = 10$, $N_R = N_2 = 1$, $P_1 = 10$, $\overline{P} = 1$, $\tau = 0.3$.

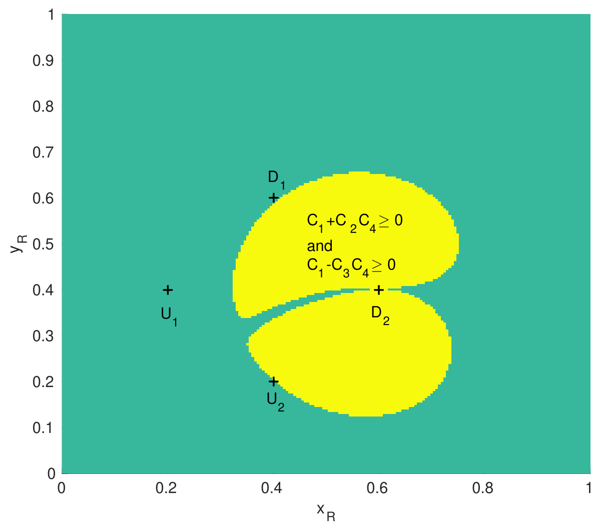

FIGURE 7. Study of the constraint ($C_1 + C_2C_4 \geq 0$ and $C_1 - C_3C_4 \geq 0$), $N_1 = 10$, $N_R = N_2 = 1$, $P_1 = 10$, $\overline{P} = 1$, $\tau = 0.3$.

FIGURE 6 compares the opportunistic rate achieved using either CF or only the opportunistic direct link. First, one can note that indeed CF does not decrease the performance compared to direct transmission. Similarly to the Gaussian relay channel, CF performs well when the relay is close to the opportunistic destination. One can observe in FIGURE 6 the presence of an area close to the opportunistic destination where CF performs as the direct transmission. This area is within the set of relay's position falling into **[H1]**. Under **[H1]**, if $C_1 + C_2C_4 \leq 0$ and/or $C_1 - C_3C_4 \leq 0$, no power is allocated to the relay, leading to the same rate as the direct transmission as shown in FIGURE 7.

Regarding DF, the set of relay positions such that the opportunistic achievable rate is increased compared to the direct transmission cannot be obtained in a closed-form manner but only characterized numerically. FIGURE 8 compares

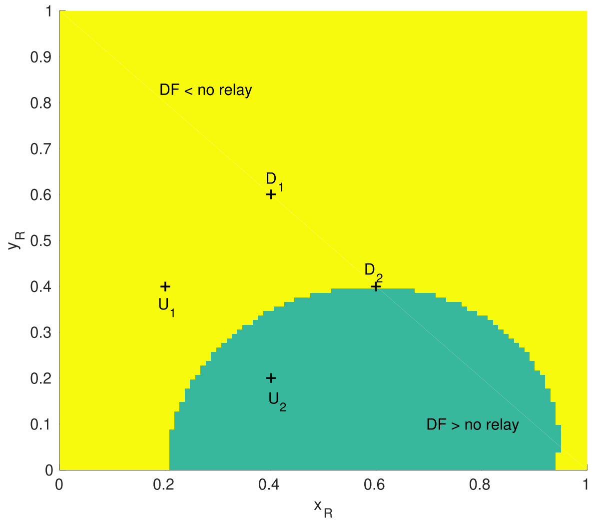

FIGURE 8. Comparison between DF and transmission only over the opportunistic direct link, $N_1 = 10$, $N_2 = N_R = 1$, $P_1 = 10$, $\bar{P} = 1$, $\tau = 0.3$.

the opportunistic rates achieved under DF relaying and the direct transmission (no relay). In some cases, when the relay is far apart from the secondary network, DF decreases the achievable opportunistic rate compared to the direct transmission. In order to increase the opportunistic rate under DF, the relay has to be close to the opportunistic transmitter.

VI. CONCLUSIONS AND PERSPECTIVES

In this paper, we studied a full-duplex relay-aided cognitive network under two relaying schemes, namely Decode-and-Forward and Compress-and-Forward, assuming the relay can perfectly cancel out all self-interference. We derived the achievable rate regions as well as the optimal power allocation policy when an overall power constraint on the opportunistic transmitter and its relay. The primary QoS constraint is expressed as a maximum allowed penalty on the rate of the licensed link. We performed extensive simulations showing that none of the two aforementioned relaying schemes performs best under all transmission setups: DF is shown to outperform CF when the relay is close to the opportunistic user, and CF outperforms DF when the relay is close to the opportunistic destination. Moreover, CF relaying cannot harm the opportunistic communication, whereas DF relaying is only helpful if the relay is close to the opportunistic transmitter.

The ideal full-duplex relaying scheme, where the relay can perfectly cancel any self-interference, allowed us to provide optimal power allocation policies maximizing the opportunistic achievable rate either in closed-form or via a reduced dimensional space search. Due to hardware impairments, this assumption may prove to be too stringent in practice. Future work taking into account the self-interference residual at the relay will lead to a non-trivial characterization of the network's achievable rate region. Moreover, finding the optimal power allocation policies will involve solving quite complex optimization problems. In such practical cases, a non-trivial tradeoff between optimality and complexity will have to be made: it is not at all clear whether the solution taking into account the self-interference is better suited in practice than our derived simple solution ignoring the self-interference.

Finally, extensions of this work taking into account multiple-antenna devices, security aspects in jamming impaired networks, or latency constraints are interesting research axes for future work.

APPENDIX

A. PROOF OF THEOREM 1

In the following, we will consider the four cases separately. Since the feasible sets under **[H1]** and **[H2]** are given as the intersection between the feasible sets under **[H3]** and **[H4]**, we will start by studying the two latter ones.

If **[H3]** is met, the optimization problem (5) reduces to

$$\max_{0 \le \gamma \le 1} f_{\text{CF,QoS}}(\gamma).$$

When solving for $\frac{df_{\text{CF,QoS}}}{d\gamma} = 0$, the discriminant of the obtained polynomial is given as

$$\Delta = 4B_1B_3(B_1 + B_2B_4)(B_2 + B_3).$$

First note that B_3 is positive since both K_1 and K_2 are positive. Indeed,

$$\begin{aligned} K_1 &= 2h_{2R}h_{22}\left(\sqrt{(g_{12}P_1+N_2)(g_{1R}P_1+N_R)} - h_{12}h_{1R}P_1\right) \\ &\quad + \left(h_{2R}\sqrt{\widetilde{N}_2} - h_{22}\sqrt{\widetilde{N}_R}\right)^2 \ge 0 \\ K_2 &= \widetilde{N}_R\widetilde{N}_2 - g_{12}g_{1R}P_1^2 \ge 0 \end{aligned}$$

Furthermore, B_1 and $B_2 + B_3$ are positive since $B_1 = \left(h_{2R}\sqrt{\widetilde{N}_2} - \rho_Z h_{22}\sqrt{\widetilde{N}_R}\right)^2$ and $B_2 + B_3 = K_2\left(\widetilde{N}_2 + \frac{g_{R2}A}{g_{R1}}\right)$. Thus, Δ is of the sign of $B_1 + B_2B_4$ and two cases can arise:

1) If $B_1 + B_2B_4 \ge 0$, i.e. the discriminant is positive, the equation $\frac{df_{\text{CF,QoS}}}{d\gamma} = 0$ admits two roots,

$$\gamma_1 = \frac{2B_3(B_1 + B_2B_4) + \sqrt{\Delta}}{-2B_2(B_1 + B_2B_4)} \text{ and}$$
$$\gamma_2 = \widehat{\gamma} = \frac{2B_3(B_1 + B_2B_4) - \sqrt{\Delta}}{-2B_2(B_1 + B_2B_4)}.$$

One can furthermore prove that:
a) If $B_1 - B_3B_4 \ge 0$, the objective function is increasing over the interval $[0, \widehat{\gamma}]$ and decreasing over the interval $]\widehat{\gamma}, 1]$.
b) If $B_1 - B_3B_4 < 0$, the objective function is decreasing over the interval $[0, 1]$.

2) If $B_1 + B_2B_4 < 0$, i.e. the discriminant is negative, the objective function is decreasing over the interval $[0, 1]$.

If **[H4]** is met, the optimization problem (5) reduces to

$$\max_{0 \le \delta \le 1} f_{\text{CF,pow}}(\delta).$$

Since the objective function is of the same form as the one under **[H3]**, One can follow the same procedure and start by proving that C_1, C_3 and $C_2 + C_3$ are positive so that the obtained discriminant is of the sign of $C_1 + C_2C_4$. The remaining study is the same as under **[H3]**.

If **[H1]** or **[H2]** is met, one needs to combine the previously obtained allocation policies as well as some domain constraints for δ and γ given as $(0 \leq \delta \leq \widetilde{\delta}; \widetilde{\gamma} \leq \gamma \leq 1)$ under **[H1]** and as $(\widetilde{\delta} \leq \delta \leq 1; 0 \leq \gamma \leq \widetilde{\gamma})$ under **[H2]**. In both cases, the objective function states as

$$\max \left\{ \max_{\delta} f_{\mathrm{CF,pow}}(\delta), \max_{\gamma} f_{\mathrm{CF,QoS}}(\gamma) \right\}.$$

B. PROOF OF PROPOSITION 3

The intersection point between the two constraints must satisfy the following equality

$$E_1 P_R + E_2 = -E_3 \sqrt{P_R(\overline{P} - P_R)} \tag{7}$$

One can first solve for the square of (7), yielding

$$P_R^2(E_1^2 + E_3^2) + P_R(2E_1E_2 - E_3^2\overline{P}) + E_2^2 = 0,$$

whose discriminant equals $\Delta = E_3^2\left(E_3^2\overline{P}^2 - 4E_2(E_1\overline{P} + E_2)\right)$.

Two cases can thus arise: either $\Delta < 0$, leading to zero roots and the most restricting constraint being the total power one; or $\Delta \geq 0$, leading to the two roots $\widetilde{P}_{R1}$ and $\widetilde{P}_{R2}$ given in section IV, which are eventually collocated if $\Delta = 0$.

In order for the roots $\widetilde{P}_{R1}$ and $\widetilde{P}_{R2}$ to be valid solutions of (7), they need to be such that

$$E_1 \widetilde{P}_{Ri} + E_2 < 0 \tag{8}$$

Under **[H1]**, there can be only one intersection point, i.e. only one of the two roots $\widetilde{P}_{Ri}$ verifies (8). Since $E_1 > 0$ and $E_2 < 0$, $E_1\widetilde{P}_{R2} + E_2 \geq E_1\widetilde{P}_{R1} + E_2$, i.e. the valid intersection point is $\widetilde{P}_{R1}$.

Under **[H2]**, there can be only one intersection point, i.e. only one of the two roots $\widetilde{P}_{Ri}$ verifies (8). Since $E_1 < 0$ and $E_2 > 0$, $E_1\widetilde{P}_{R2} + E_2 \leq E_1\widetilde{P}_{R1} + E_2$, i.e. the valid intersection point is $\widetilde{P}_{R2}$.

Under **[H4]**, two cases can arise: either two, one or no intersection point.

a) If $\Delta < 0$ or ($\Delta \geq 0$ and none of the roots $\widetilde{P}_{Ri}$ satisfies the condition given in (8)), there is no intersection point between the QoS and the overall power constraints.

b) Otherwise, there are two intersection points, eventually collocated, between the QoS and the overall power constraints.

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