Power Control of Spectrum-Sharing in Fading Environment With Partial Channel State Information

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***Abstract*—This paper addresses the spectrum-sharing for wireless communication where a cognitive or secondary user shares a spectrum with an existing primary user (and interferes with it). We propose two lower bounds, for the primary user mean rate, depending on the channel state information available for the secondary-user power control and the type of constraint for spectrum access. Several power control policies are investigated and the achieved primary-user mean rates are compared with these lower bounds. Specially, assuming all pairs of transmitter–receiver are achieving real-time delay-sensitive applications, we propose a novel secondary-user power control policy to ensure for both users, at a given occurrence, predefined minimum instantaneous rates. This power control uses only the secondary-user direct links gains estimations (secondary-to-secondary link and secondary-to-primary link).**

***Index Terms*—Channel state information, cognitive radio, interference channels, interference constraints, power control, radio spectrum management, Rayleigh channels.**

I. Introduction

WHEN looking at the radio frequency spectrum, all frequencies below 3 GHz have been allocated to specific uses [13]. However, regulatory bodies in various countries found that most of the radio frequency spectrum is inefficiently utilized. The 2002 report of the Federal Communications Commission (FCC)'s Spectrum Policy Task Force made the recommendation that FCC develops a spectrum policy that allows more flexible access to the spectrum [1]. Spectrum-sharing, for unlicensed and licensed bands, and cognitive radio have been proposed as promising solutions for improving the spectrum efficiency. Therefore, these topics have received a lot of attention in the technical literature where it is often a concern of designing spectrum-sharing rules and protocols which allow the systems to share the bandwidth in a way that is efficient and compatible with the incentives of the individual systems [1]–[14].

Power control for spectrum-sharing users has been widely studied. In particular, [3] investigates the maximum ergodic capacity of a secondary user under joint peak and average interference power constraints at the primary receiver. The optimal power control derived in [3] to achieve the secondary maximum ergodic capacity is function of the channel state information (CSI) of the secondary user and of the link between the secondary transmitter and the primary receiver. However, this optimal power allocation does not take into account the interference of the primary user to the secondary user. Moreover, in non-outage states, the secondary's received power could be weak, providing bad quality to the secondary service. [4] presents a criterion to design the secondary transmit power control by introducing a *primary-capacity-loss constraint* (PCLC). This method is shown to be better than the previous ones in terms of achievable ergodic capacities of both the primary and the secondary links. It protects the primary transmission by ensuring that the maximum ergodic capacity loss of the primary link, due to the secondary transmission, is no greater than some predefined value [4]. However, to enable the PCLC-based power control, [4] assumes that not only the CSI of the secondary fading channel and the fading channel from the secondary transmitter to the primary receiver (noted g_{22} and g_{12} in Fig. 1) are known to the secondary transmitter, but also the CSI of the primary direct links (g_{11} and g_{21}). To protect the primary user, [6] requires that the transmission outage probability of the primary user channel due to both its own fading and the additional interference from the secondary user be no greater than a maximum target. Then, by assuming that all the instantaneous channel power gains in the network are available at the secondary user transmitter and/or the secondary user receiver for each fading state, the authors minimize the outage probability of the secondary user subject to the primary user outage constraint and the interference temperature constraint. The derived power allocation strategies achieve substantial outage capacity gains for the secondary user over the conventional power control policies based upon the interference temperature constraint, given the same primary users outage probability constraint. [11] investigates cooperative and noncooperative scenarios of spectrum-sharing for unlicensed bands. The cooperative assumption may be realistic when the different systems are jointly designed with a common goal. They can be complying with some standard or regulation, or they can be as transmitter–receiver pairs of a single global system. Assuming a *selfish behavior* (noncooperative scenario) may be more realistic[1] when systems are competing ones with the others to gain access to the common

[1]The systems are selfish in the sense that they only try to maximize their own utility [11].

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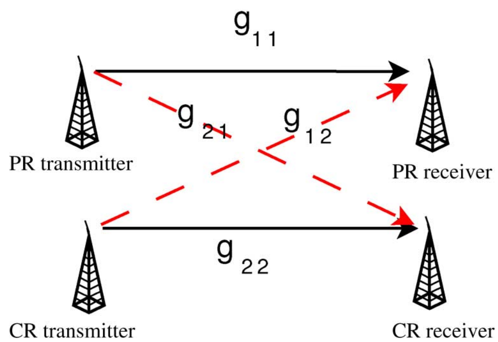

Fig. 1. Spectrum sharing between a PR and a CR communication links.

medium. However, one can imagine spectrum-sharing for systems that carry out real-time delay-sensitive applications, e.g., voice and video. It is then crucial to guarantee, for a given occurrence, predefined minimum instantaneous rates for both users.

In this paper, we consider the spectrum-sharing scheme of Fig. 1 where a secondary or cognitive user (CR) shares a spectrum first licensed to a primary one (PR). We investigate the lower bounds of the primary mean rate according to the channel state information available for the secondary power control and to the type of constraint for spectrum access. Theses lower bounds allow us to evaluate the protection performance of different power control policies at the secondary transmitter by comparing the achieved primary mean rate with its lower bounds. In particular, we propose a novel secondary power control policy to ensure for both users predefined minimum instantaneous rates. Contrary to the optimal power controls, derived in [3] and [4], and the noncooperative games in [11], the goal of the new allocation strategy is neither to achieve the maximum possible rate, nor to maximize selfish utilities. The particularity of the new suboptimal allocation strategy is to achieve, in a same frequency band, applications that require given minimum instantaneous rates. Furthermore, contrary to [6], which assumes the knowledge to the secondary user of all channel gains in the network, our power control uses only the secondary direct links gains estimations (estimations of g_{22} and g_{12}).

The remainder of this paper is organized as follows. In the next section, we describe the system and signals model, our main assumptions and the problem we tackle. We investigate two lower bounds for the primary user mean rate, in Section III. Power control for secondary user is considered in Section IV. Finally, conclusions are discussed in Section V.

II. Problem Formulation

A. System and Channel Model

We consider the network depicted in Fig. 1 with two users transmitting in the same frequency band and interfering with each other. The first user is assumed to be the licensee of the spectrum and is called primary user (PR). The other user is the secondary user (CR). We assume flat fading channels. We define the power gains of direct links by g_{11} and g_{22}. The power gains of transverse links are noted g_{12} and g_{21} as depicted in Fig. 1. The estimations of g_{11}, g_{22}, g_{12}, and g_{21} are respectively noted by $\hat{g}_{11}, \hat{g}_{22}, \hat{g}_{12}$, and $\hat{g}_{21}$. The channels power gains are assumed to be independent and identically distributed according to exponential distribution with parameters $\lambda_{ij}, i, j \in \{1, 2\}$. Moreover they are supposed to be stationary, ergodic and mutually independent from the noise. The noise power spectral density is denoted by σ^2. We assume very simple receivers in which all interfering signals are processed as noise. This assumption is somewhat pessimistic, and our results thus form a conservative lower bound. In practice, some form of multiuser detection allowing for interference suppression or mitigation may be used to enhance the rates achieved. With Gaussian signalling, the instantaneous rates (expressed in nats/s/Hz) of the primary and the secondary users may be expressed as $\mathrm{C}_1 = \log(1 + \frac{p_1 g_{11}}{\sigma^2 + p_2 g_{12}})$ and $\mathrm{C}_2 = \log(1 + \frac{p_2 g_{22}}{\sigma^2 + p_1 g_{21}})$, where p_1 and p_2 denote, respectively, the primary user transmit power and the secondary user transmit power. The mean rates are defined as $\mathbf{C}_1 \triangleq \mathbb{E}[\mathrm{C}_1]$ and $\mathbf{C}_2 \triangleq \mathbb{E}[\mathrm{C}_2]$, where $\mathbb{E}[x]$ denotes the mean of the random variable x.

B. Main Goal

We consider a secondary user trying to access a licensed spectrum. We study the impact of its transmission on the reception quality of the primary user. In contrast, the primary user does not care about its interference to the secondary user. We aim to investigate lower bounds for the primary mean rate according to the CSI available for the secondary power control and to the type of constraint for spectrum access. We then compare these bounds to the primary achievable mean rates when the secondary user is performing different power control policies. In particular, we propose a novel power control policy, for the secondary user, when all pairs of transmitter–receiver are achieving real-time delay-sensitive applications.

For simplicity, in the sequel, we assume the primary user performs a constant power control. Therefore, we have $p_1 = \bar{P}_1$, where $\bar{P}_1$ denotes the mean transmit power of the primary user.

1) Lower Bounds for the Primary User Mean Rate: The lower bound for the primary user mean rate is investigated in two different spectrum-sharing scenarios:

- The first scenario is called in this paper *unconstrained spectrum-sharing*. It consists in a theoretical spectrum-sharing where the secondary user is subject to no constraint from the primary user other than the limited-mean-transmit-power constraint. A lower bound for the primary mean rate is derived when secondary user performs a $\{\hat{g}_{22}\hat{g}_{21}\}$-dependent power control/scheduling.
- The second scenario is called *constrained spectrum-sharing*. The secondary transmission is subject to some interference constraints from the primary user. To meet the interference constraints, we assume that the secondary-to-primary link gain estimation is available at the secondary transmitter. A lower bound for the primary mean rate is derived when the secondary user performs a $\{\hat{g}_{22}, \hat{g}_{21}, \hat{g}_{12}\}$-dependent power control/scheduling.

2) Secondary Power Control: We investigate different power control schemes and compare the primary achievable mean rate to its lower bounds. In particular, we propose an original secondary power control policy with the following requirements:

- the secondary user can only estimate the channel gains g_{22} (secondary-to-secondary link) and g_{12} (secondary-to-primary link);
- each user needs given outage performance to achieve its service.

More precisely, we ensure that the secondary transmission meets the following constraints:

$$\mathbf{Prob}_{g_{11},g_{21}}(\mathrm{C}_1 \le \mathrm{C}_0) \le \epsilon \quad (1)$$

$$\mathbf{Prob}_{g_{11},g_{21}}(\mathrm{C}_2 \le \mathrm{C}_0') \le \epsilon' \quad (2)$$

where $\mathbf{Prob}_{g_{11},g_{21}}(x)$ denotes the probability of event "x", over the distributions of g_{11} and g_{21}. The given rates C_0 and C_0' are the minimum necessary rates for the services of, respectively, the primary and the secondary users. In general, (1) and (2) ensure that primary and secondary instantaneous rates are greater than C_0 and C_0' most of the time, the occurrence is determined by the maximum outage probabilities ϵ and ϵ'.

3) Channel and Parameters Estimation: The channels gains estimations $\hat{g}_{ij}$, the means values $1/\lambda_{ij}$ and the noise power spectral density σ^2 can be brought to the transmitters thanks to the following protocol. First, transmitter $i, i \in \{1,2\}$, sends a pilot signal of normalized power, then, receivers i and j $(j \neq i)$ estimate simultaneously the values of λ_{ii}, λ_{ji}, $\hat{g}_{ii}$, $\hat{g}_{ji}$, and σ^2. We assume the existence of a *low rate control channel* that the receivers can use to feed back λ_{ii}, λ_{ji}, $\hat{g}_{ii}$, $\hat{g}_{ji}$, and σ^2; see [7]. Finally, one can also imagine a coordination channel between transmitters used to communicate between each other. So, to perform the proposed power control, as shown bellow, secondary user needs to know $\bar{P}_1$, λ_{11}, λ_{21}, ϵ, ϵ', C_0, and C_0'. We assume that $\bar{P}_1$, λ_{11}, ϵ, and C_0 are sent to the secondary user via the coordination channel or by a *band manager* which mediates between the two parties.

III. Lower Bounds of the Primary User Mean Rate

In this section, we investigate two lower bounds for the primary user mean rate according to spectrum access constraints and available channel state information at the secondary user transmitter.

A. Unconstrained Spectrum-Sharing

In this part, we are interested in a scenario of spectrum-sharing where there is neither collaboration between the two users, nor interference or capacity loss constraint. We assume that

$$\mathbb{E}[p_2] \le \bar{P}_2 \quad (3)$$

where $\bar{P}_2$ denotes the maximum mean transmit power of the secondary user. Since the secondary user rate C_2 is function of g_{22} and g_{21} only, we assume that to achieve a desired rate, without an interference constraint, the secondary user performs a power scheduling/control scheme such that the transmit power p_2 can be expressed as

$$p_2 = \psi^{(1)}(\hat{g}_{22}, \hat{g}_{21}) \quad (4)$$

due to appropriate techniques to estimate g_{22} and g_{21}. $\psi^{(1)}$ is a $\{\hat{g}_{22}, \hat{g}_{21}\}$-dependent function or operator. It includes all power control schemes which depend either on $\hat{g}_{22}$ only, or on $\hat{g}_{21}$ only, or on both $\hat{g}_{22}$ and $\hat{g}_{21}$, and constant power control scheme. The primary mean rate can be expressed as

$$\mathbf{C}_1 = \mathbb{E}\left[\log\left(1 + \frac{\frac{\bar{P}_1 g_{11}}{g_{12}}}{\frac{\sigma^2}{g_{12}} + p_2}\right)\right].$$

Due to the independence of the channel gains g_{11}, g_{12}, g_{22}, and g_{21},

$$\mathbf{C}_1 = \mathbb{E}_{g_{11},g_{12}}\left[\mathbb{E}_{\{g_{22},g_{21}\}/\{g_{11},g_{12}\}}\left[\log\left(1 + \frac{\frac{\bar{P}_1 g_{11}}{g_{12}}}{\frac{\sigma^2}{g_{12}} + p_2}\right)\right]\right]$$

where $\mathbb{E}_{a,b}[x]$ denotes the expectation of the random variable x over the joint distribution of the random variables a and b, while $\mathbb{E}_{a/b}[x]$ denotes the expectation of the random variable x over the conditional distribution of a given b. Moreover, we have

$$\begin{aligned}\mathbb{E}_{\{g_{22},g_{21}\}/\{g_{11},g_{12}\}}&\left[\log\left(1 + \frac{\frac{\bar{P}_1 g_{11}}{g_{12}}}{\frac{\sigma^2}{g_{12}} + p_2}\right)\right] \\ &\ge \log\left(1 + \frac{\frac{\bar{P}_1 g_{11}}{g_{12}}}{\frac{\sigma^2}{g_{12}} + \mathbb{E}[p_2]}\right) \\ &\ge \log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + \bar{P}_2 g_{12}}\right)\end{aligned}$$

where the first inequality is due to Jensen inequality.[2] The second inequality results from the power constraint (3). Finally, we obtain

$$\mathbf{C}_1 \ge \mathbf{C}_{1,\min}^{(1)} \triangleq \mathbb{E}\left[\log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + \bar{P}_2 g_{12}}\right)\right].$$

The mean rate $\mathbf{C}_{1,\min}^{(1)}$ is achieved for a constant power control from the secondary user, $p_2 = \bar{P}_2$. Therefore, in this unconstrained spectrum-sharing with a constant power control of the secondary user, $p_2 = \bar{P}_2$, achieves the lower bound of the primary mean rate. $\mathbf{C}_{1,\min}^{(1)}$ can be expressed (see Appendix A) as

$$\begin{aligned}\mathbf{C}_{1,\min}^{(1)} = \frac{\bar{P}_1}{\bar{P}_1 - \frac{\lambda_{11}}{\lambda_{12}}\bar{P}_2}&\left[\exp\left(\frac{\sigma^2\lambda_{11}}{\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\sigma^2\lambda_{11}}{\bar{P}_1}\right)\right. \\ &\left. - \exp\left(\frac{\sigma^2\lambda_{12}}{\bar{P}_2}\right)\mathrm{E}_1\left(\frac{\sigma^2\lambda_{12}}{\bar{P}_2}\right)\right] \quad (5)\end{aligned}$$

where the exponential integral function [20] is defined as

$$\mathrm{E}_1(x) \triangleq \int_1^{+\infty} \frac{\exp(-xt)}{t}dt, \quad x \ge 0. \quad (6)$$

B. Constrained Spectrum-Sharing

Next, we investigate a spectrum-sharing scenario where the secondary transmission is subject to some interference

[2]Because of the convexity of the x-dependent function $\log(1+(A/(B+x)))$ with $A \ge 0$, $B \ge 0$ and $x \ge 0$.

constraints in order to protect the primary user. In this case, estimating the secondary-to-primary link gain g_{12} may be crucial because interference constraints involve knowledge, at the secondary user, of its interference level to the primary user. In general, according to the type of constraint, the primary protection should require different CSI at the secondary transmitter.

1) Primary Mean-Rate Loss Constraint: This constraint is useful when it is a question of improving the primary mean rate. It consists of setting a maximum loss of the primary mean rate:

$$\mathbf{C}_{1,\max} - \mathbf{C}_1 \leq \mathbf{C}_{1,\text{loss}}, \tag{7}$$

where $\mathbf{C}_{1,\max} \triangleq \mathbb{E}[\log(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2})]$ is the mean rate of the primary user with no interfering signal. $\mathbf{C}_{1,\text{loss}}$ denotes the maximum mean-rate loss allowed by the primary user. Maximizing the secondary mean rate, subject to (7), may require primary link gain estimation $\hat{g}_{11}$ [4], which might demand sophisticated techniques. Therefore, in the sequel we do not use this constraint.

2) Interference Constraints: The primary transmission can be also protected by using the time and space dimensions of the spectrum to manage the secondary user interference to the primary receiver. The general spatial spectrum-sharing problem considered in [10] concerns the possible coexistence of two different networks (for instance two MAC) such that a network may not create an interference that exceeds a prescribed level Q_I outside of a predefined zone. For the two-user spectrum-sharing problem, we consider the peak and average interference constraints, stated by (8) and (9), commonly used to protect the primary transmission, see [3]–[8],

$$p_2 g_{12} \leq Q_{\text{peak}} \tag{8}$$

$$\mathbb{E}[p_2 g_{12}] \leq Q_{\text{avg}} \tag{9}$$

where Q_{peak} denotes the instantaneous interference threshold and Q_{avg} the average interference threshold. Specially, performing a power control under the instantaneous interference constraint (8) requires the secondary-to-primary link gain estimation $\hat{g}_{12}$.

3) Lower Bound: In order to protect the primary transmission, we assume that the secondary-to-primary link gain estimation $\hat{g}_{12}$ is available for the secondary power control. Therefore, to achieve a desired rate under interference constraints, the secondary user performs a power scheduling/control scheme such that the transmit power p_2 can be expressed as

$$p_2 = \psi^{(2)}(\hat{g}_{22}, \hat{g}_{21}, \hat{g}_{12}) \tag{10}$$

due to appropriate techniques to estimate g_{22}, g_{21}, and g_{12}. $\psi^{(2)}$ is a $\{\hat{g}_{22}, \hat{g}_{21}, \hat{g}_{12}\}$-dependent function or operator. It includes all power control schemes that depend either on $\hat{g}_{22}$ only, or on $\hat{g}_{21}$ only, or on $\hat{g}_{12}$ only, or any combination of $\hat{g}_{22}, \hat{g}_{21}, \hat{g}_{12}$, and the constant power control scheme. The primary mean rate verifies

$$\begin{aligned}\mathbf{C}_1 &= \mathbb{E}_{g_{11}}\left[\mathbb{E}_{\{g_{22},g_{21},g_{12}\}/g_{11}}\left[\log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + p_2 g_{12}}\right)\right]\right]\\ &\geq \mathbb{E}_{g_{11}}\left[\log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + \mathbb{E}[p_2 g_{12}]}\right)\right]\\ &\geq \mathbf{C}_{1,\min}^{(2)} \triangleq \mathbb{E}\left[\log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + Q_{\text{avg}}}\right)\right]\end{aligned}$$

where the first inequality is due to Jensen's inequality, the second inequality results from the mean interference power constraint (9), [5]. The lower bound $\mathbf{C}_{1,\min}^{(2)}$ can be expressed (see Appendix A) as

$$\mathbf{C}_{1,\min}^{(2)} = \exp\left(\frac{\lambda_{11}(\sigma^2 + Q_{\text{avg}})}{\bar{P}_1}\right) \mathrm{E}_1\left(\frac{\lambda_{11}(\sigma^2 + Q_{\text{avg}})}{\bar{P}_1}\right). \tag{11}$$

IV. Power Control for Spectrum Secondary Use

In this section, we investigate the secondary user power control and compare the achieved primary mean rate to its lower bounds found previously.

A. Power Control With Mean-Transmit-Power Constraint Only

We assume that there is only one constraint for the secondary access to the spectrum, the mean transmit power constraint, stated by (3).

1) Optimal Power Control: The optimal power control maximizing the secondary mean rate $\mathbf{C}_2$, under the power constraint (3), is expressed by the well-known *water filling* [19]

$$p_2 = \left(\zeta - \frac{\sigma^2 + \bar{P}_1 g_{21}}{g_{22}}\right)^+ \tag{12}$$

where the constant ζ is such that the mean power constraint is met. $(.)^+$ denotes $\max(.,0)$. Let $w \triangleq \frac{g_{22}}{\sigma^2 + \bar{P}_1 g_{21}}$, the constant ζ verifies

$$\bar{P}_2 = \int_{\frac{1}{\zeta}}^{+\infty} \left(\zeta - \frac{1}{w}\right) f_W(w) dw \tag{13}$$

where f_W is the probability density function of the random variable W with sample w. The probability density function of W is given by (see Appendix A)

$$f_W(w) = \begin{cases} \frac{1+b+\frac{b}{a}w}{a\left(1+\frac{1}{a}w\right)^2} \exp\left(-\frac{b}{a}w\right), & \text{if } w \geq 0 \\ 0, & \text{if } w < 0 \end{cases} \tag{14}$$

with $a = \frac{\lambda_{21}}{\bar{P}_1 \lambda_{22}}$ and $b = \frac{\sigma^2 \lambda_{21}}{\bar{P}_1}$.

2) A Scheduling Approximating the Optimal Power Control: The difficulty of performing the optimal power allocation (12) is due to the uncertain knowledge of the information $w = \frac{g_{22}}{\sigma^2 + \bar{P}_1 g_{21}}$. Using an appropriate estimation technique, $\hat{w}$ provides an estimated value of w. We want to reduce the impact of estimation errors on the power control (12) by using the following scheduling:

$$p_2 = \begin{cases} c, & \text{if } \hat{w} > \frac{1}{\zeta} \\ 0, & \text{if } \hat{w} \leq \frac{1}{\zeta} \end{cases} \tag{15}$$

where the constant c is defined by

$$\mathbb{E}[p_2] = \bar{P}_2 = \int_{\frac{1}{\zeta}}^{+\infty} c f_W(w) dw;$$

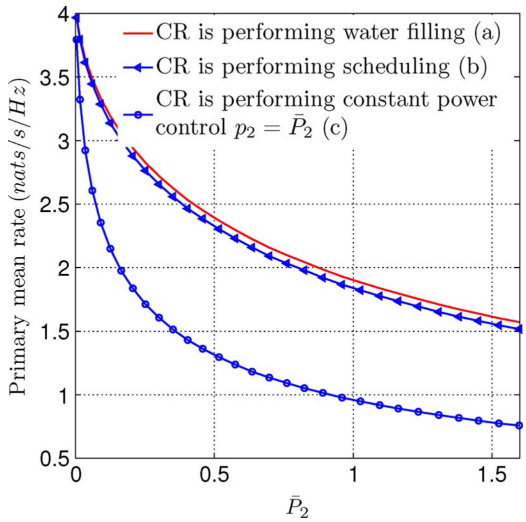

Fig. 2. Primary mean rate versus secondary mean power for different power control schemes from the secondary user: (a) optimal power control *water-filling*; (b) proposed scheduling approximating the optimal power control; and (c) constant power control that provides the lower bound of the primary mean rate. $\bar{P}_1 = 1, \sigma^2 = 0.01$ and $\lambda_{11} = \lambda_{12} = \lambda_{22} = \lambda_{21} = 1$.

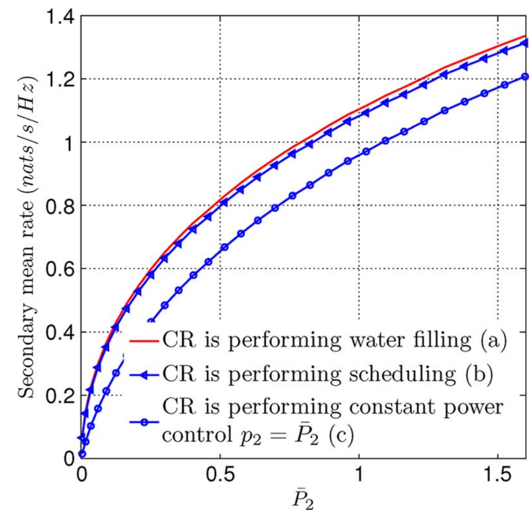

Fig. 3. Secondary mean rate versus mean power for different power control schemes: (a) optimal power control *water-filling*; (b) proposed scheduling approximating the optimal power control; and (c) constant power control that provides the lower bound of the primary mean rate. $\bar{P}_1 = 1, \sigma^2 = 0.01$ and $\lambda_{11} = \lambda_{12} = \lambda_{22} = \lambda_{21} = 1$.

thus, c can be expressed as

$$c = \frac{\bar{P}_2}{\int_{\frac{1}{\zeta}}^{+\infty} f_W(w)dw}.$$

Using expression (14) of f_W, we obtain

$$\int_{\frac{1}{\zeta}}^{+\infty} f_W(w)dw = \frac{\frac{\lambda_{21}}{\lambda_{22}}\bar{P}_1}{\frac{\lambda_{21}}{\lambda_{22}}\bar{P}_1 + \frac{1}{\zeta}} \exp\left(-\frac{\lambda_{22}\sigma^2}{\zeta}\right). \quad (16)$$

Therefore, we deduce the constant c as

$$c = \bar{P}_2 \left(1 + \frac{\lambda_{22}}{\lambda_{21}}\frac{1}{\zeta}\bar{P}_1\right) \exp\left(\frac{\lambda_{22}\sigma^2}{\zeta}\right). \quad (17)$$

In the scheduling (15), the constant c does not depend on the channel realization. By definition, the *binary condition* $\hat{w} \lesseqgtr (1/\zeta)$ is less sensitive to estimation errors than 8. We verify next that this relatively little complex scheduling, for the secondary link, achieves a primary mean rate close to the optimal *water-filling* policy.

3) Numerical Examples: Both the theoretical optimal allocation (12) and the proposed scheduling (15) are functions of the channels gains $\hat{g}_{22}$ and $\hat{g}_{12}$ only. $\mathbf{C}_{1,\min}^{(1)}$ is a lower bound of such kinds of power control/scheduling. Now, we give numerical examples to compare the primary mean rates achieved, using (12) and (15), with the lower bound $\mathbf{C}_{1,\min}^{(1)}$. With the settings $\bar{P}_1 = 1, \sigma^2 = 0.01$ and $\lambda_{11} = \lambda_{12} = \lambda_{22} = \lambda_{21} = 1$, we obtain Figs. 2 and 3.

As it can be noticed in Figs. 2 and 3, the proposed scheduling (15) provides a performance matching almost the optimal *water-filling*. Moreover, we can see the gap level between the lower bound $\mathbf{C}_{1,\min}^{(1)}$ and the considered power controls. The optimal power control at the secondary side does not cause the most harmful interference to the primary transmission, as one would expect. On the contrary, for the same mean powers, $\bar{P}_1 = \bar{P}_2 = 1$ for instance, the optimal *water-filling* provides nearly 1 nat/s/Hz of protection furthermore than the constant power control to the primary user (see Fig. 2). These results do not take into account the primary protection since there is no interference constraint.

B. Power Control With Outage Performance Requirement and Direct Links CSI

In this part, we propose a novel power control under the requirements (1) and (2). We assume that the secondary user can estimate the secondary-to-secondary and the secondary-to-primary links gains only, i.e., only $\hat{g}_{22}$ and $\hat{g}_{12}$ are available for the secondary user power control.

1) Outage Performance Constraints: The primary and secondary outage constraints are modeled by (1) and (2). Replacing C_1 and C_2 by theirs formulas, events "$\mathrm{C}_1 \leq \mathrm{C}_0$" and "$\mathrm{C}_2 \leq \mathrm{C}_0'$" can be expressed, respectively, as

$$\mathrm{C}_1 \leq \mathrm{C}_0 \Rightarrow g_{11} \leq \frac{\alpha_0(\sigma^2 + p_2\hat{g}_{12})}{\bar{P}_1} \quad (18)$$

$$\mathrm{C}_2 \leq \mathrm{C}_0' \Rightarrow g_{21} \geq \frac{1}{\bar{P}_1}\left(\frac{p_2\hat{g}_{22}}{\alpha_0'} - \sigma^2\right) \quad (19)$$

with $\alpha_0 = \exp(\mathrm{C}_0) - 1$ and $\alpha_0' = \exp(\mathrm{C}_0') - 1$. The outage probabilities become

$$\mathbf{Prob}_{g_{11},g_{21}}(\mathrm{C}_1 \leq \mathrm{C}_0) = \int_0^{\gamma} \lambda_{11}\exp(-\lambda_{11}x)dx = 1 - \exp(-\lambda_{11}\gamma) \quad (20)$$

where $\gamma = \frac{\alpha_0(\sigma^2 + p_2\hat{g}_{12})}{\bar{P}_1}$, and

$$\mathbf{Prob}_{g_{11},g_{21}}(\mathrm{C}_2 \leq \mathrm{C}_0') = \int_{\gamma'}^{+\infty} \lambda_{21}\exp(-\lambda_{21}x)dx = \exp(-\lambda_{21}\gamma') \quad (21)$$

with $\gamma' = \frac{1}{\bar{P}_1}(\frac{p_2\hat{g}_{22}}{\alpha'_0}d - \sigma^2)$. Then, outage constraints (1) and (2) can be expressed, respectively, as

$$1 - \exp\left(-\lambda_{11}\frac{\alpha_0(\sigma^2 + p_2\hat{g}_{12})}{\bar{P}_1}\right) \leq \epsilon \quad (22)$$

$$\exp\left(-\frac{\lambda_{21}}{\bar{P}_1}\left(\frac{p_2\hat{g}_{22}}{\alpha'_0} - \sigma^2\right)\right) \leq \epsilon'. \quad (23)$$

After some manipulations, expressions (22) and (23) become

$$p_2\hat{g}_{12} \leq Q_{\text{peak}} \quad (24)$$

$$p_2\hat{g}_{22} \geq K. \quad (25)$$

The peak interference threshold is defined as

$$Q_{\text{peak}} = \frac{\bar{P}_1}{\lambda_{11}\alpha_0}\log\left(\frac{1}{1-\epsilon}\right) - \sigma^2 \quad (26)$$

and the minimum received power K as

$$K = \alpha'_0\left(\sigma^2 - \frac{\bar{P}_1}{\lambda_{21}}\log(\epsilon')\right). \quad (27)$$

Therefore, the primary outage constraint (1) consists in forcing the instantaneous interference $p_2\hat{g}_{12}$, from the secondary user, to be lower than a threshold Q_{peak}, while the secondary outage constraint (2) consists in forcing the secondary instantaneous received power $p_2\hat{g}_{22}$ to be greater than a threshold K. For a given network and system, the peak interference threshold Q_{peak} is determined by the primary minimum required rate C_0, the outage probability ϵ and the mean transmit power $\bar{P}_1$. Specially, Q_{peak} is proportional to $\bar{P}_1$ and log-increasing in ϵ. Otherwise, when the outage probability ϵ' increases, the secondary service quality is low, and thus, the threshold K decreases.

2) Power Control: Previously, we found the constraints (24) and (25) to ensure given outage performance to both the primary and the secondary users. In this respect, the transmit power p_2 of the secondary user must fulfill the set of inequalities

$$\begin{cases} p_2\hat{g}_{12} \leq Q_{\text{peak}} \\ p_2\hat{g}_{22} \geq K. \end{cases} \quad (28)$$

We verify the compatibility of both the equations in (28):

- if $(\frac{\hat{g}_{22}}{\hat{g}_{12}} \geq \frac{K}{Q_{\text{peak}}})$, then[3] power p_2 can be greater than the minimum required $\text{p}_{2,\min} \triangleq K/\hat{g}_{22}$. Yet to meet the interference constraint, p_2 must always fulfill $p_2\hat{g}_{12} \leq Q_{\text{peak}}$. So, the cognitive user can opportunistically communicate with $p_2 = Q_{\text{peak}}/\hat{g}_{12}$;
- if $((\hat{g}_{22}/\hat{g}_{12}) < (K/Q_{\text{peak}}))$, then the minimum power $\text{p}_{2,\min}$ can not meet the interference constraint. Consequently, we set $p_2 = 0$, the CR transmission is off.

However, the maximum transmit power $Q_{\text{peak}}/\hat{g}_{12}$ can be infinitely high (when $\hat{g}_{12}$ is very low), while in real systems instantaneous transmit power is limited. To alleviate this problem, we set the practical constraint $p_2 \leq p_{2,\text{peak}}$. Finally, we propose the following original power control policy:

$$p_2 = \begin{cases} p_{2,\text{peak}}, & \text{if } \frac{\hat{g}_{22}}{\hat{g}_{12}} \geq \frac{K}{Q_{\text{peak}}} \text{ and } p_{2,\text{peak}} \leq \frac{Q_{\text{peak}}}{\hat{g}_{12}} \\ \frac{Q_{\text{peak}}}{\hat{g}_{12}}, & \text{if } \frac{\hat{g}_{22}}{\hat{g}_{12}} \geq \frac{K}{Q_{\text{peak}}} \text{ and } p_{2,\text{peak}} > \frac{Q_{\text{peak}}}{\hat{g}_{12}} \\ 0, & \text{if } \frac{\hat{g}_{22}}{\hat{g}_{12}} < \frac{K}{Q_{\text{peak}}} \end{cases} \quad (29)$$

where $p_{2,\text{peak}}$ is the secondary-user maximum transmit power. Contrary to the optimal power control, derived in [3] and [4], and the noncooperative games in [11], the goal of the allocation strategy (29) is neither to achieve the maximum possible rate, nor to maximize *selfish* utilities. The particularity of our policy (29) is to ensure, at some occurrence predefined by the outage probabilities ϵ and ϵ', at least given minimum instantaneous rates to the two users, using the direct links gains estimations $\hat{g}_{22}$ and $\hat{g}_{12}$ only (that is not considered in the previous works such as [3], [4], and [11]). Our policy is also more appropriate for spectrum-sharing systems that carry out real-time delay-sensitive applications, e.g., voice and video. Next, we will study some typical parameters of this power control.

3) Mean Transmit and Mean Interference Power: We study the evolution of the mean transmit power and the mean received interference power, according to the parameters K, $p_{2,\text{peak}}$ and Q_{peak}, which are imposed by the desired performance of the network, and according to channels fading statistics λ_{11}, λ_{22}, λ_{12} and λ_{21}.

Let $x = \hat{g}_{12}$, and $y = \hat{g}_{22}$. The mean transmit power can be expressed as

$$\mathbb{E}[p_2] = \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}p_{2,\text{peak}} \times \exp(-\lambda_{22}y)\exp(-\lambda_{12}x)dxdy + \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}\frac{Q_{\text{peak}}}{x} \times \exp(-\lambda_{22}y)\exp(-\lambda_{12}x)dxdy.$$

After some manipulations (see Appendix B), we obtain

$$\mathbb{E}[p_2] = \frac{p_{2,\text{peak}}}{1 + \frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\text{peak}}}}\left[1 - \exp\left(-\frac{\lambda_{22}K + \lambda_{12}Q_{\text{peak}}}{p_{2,\text{peak}}}\right)\right] + \lambda_{12}Q_{\text{peak}}\text{E}_1\left(\frac{\lambda_{22}K + \lambda_{12}Q_{\text{peak}}}{p_{2,\text{peak}}}\right). \quad (30)$$

The mean received interference power is obtained similarly as follows:

$$\mathbb{E}[p_2\hat{g}_{12}] = \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}xp_{2,\text{peak}}\exp(-\lambda_{22}y) \times \exp(-\lambda_{12}x)dxdy + \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}Q_{\text{peak}}\exp(-\lambda_{22}y) \times \exp(-\lambda_{12}x)dxdy. \quad (31)$$

[3]When $p_2 = \text{p}_{2,\min} \triangleq \frac{K}{\hat{g}_{22}}$, then $p_2\hat{g}_{12} \leq Q_{\text{peak}} \Leftrightarrow (\hat{g}_{22}/\hat{g}_{12}) \geq (K/Q_{\text{peak}})$

After some manipulations (see Appendix B), it can be expressed as

$$\mathbb{E}[p_2\hat{g}_{12}] = \frac{p_{2,\mathrm{peak}}/\lambda_{12}}{\left(1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}\right)^2} \times \left[1-\exp\left(-\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right)\right]. \quad (32)$$

Therefore, the mean transmit power $\mathbb{E}[p_2]$ and the mean interference power $\mathbb{E}[p_2\hat{g}_{12}]$ are connected via the following equation:

$$\mathbb{E}[p_2] = \lambda_{12}Q_{\mathrm{peak}}\left[\left(1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}\right)\frac{\mathbb{E}[p_2\hat{g}_{12}]}{Q_{\mathrm{peak}}} + \mathrm{E}_1\left(\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right)\right].$$

In practical situations, we assume $\lambda_{12} \geq 1$. Therefore, from (33), the mean interference power could be reduced especially when $\mathrm{E}_1(\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}})$ is high or equivalently when $\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}$ is low. As we can see below with numerical examples, this situation is profitable because the challenge in spectrum-sharing and cognitive networks is to achieve better services to the secondary user while minimizing the interference towards the licensee-primary user.

4) Overall Outage Probability: From the power control (29), an outage occurs if and only if

$$\frac{\hat{g}_{22}}{\hat{g}_{12}} < \frac{K}{Q_{\mathrm{peak}}}.$$

Let $x=\hat{g}_{12}, y=\hat{g}_{22}, z=y/x$ and $z_0=K/Q_{\mathrm{peak}}$. The overall outage probability $\mathrm{P}_{\mathrm{out}}$ is obtained as follows:

$$\mathrm{P}_{\mathrm{out}} = \mathbf{Prob}(z<z_0) = \int_0^{z_0} f_Z(z)dz$$

where f_Z is the probability density function of the ratio $\hat{g}_{22}/\hat{g}_{12}$. The ratio of two independent exponential random variables $\hat{g}_{22}$ and $\hat{g}_{12}$, with parameters λ_{22} and λ_{12}, is a random variable Z with the following probability density function:

$$f_Z(z) = \int_0^{+\infty} x f_Y(zx)f_X(x)dx = \lambda_{22}\lambda_{12}\int_0^{+\infty} x\exp\left(-(\lambda_{22}z+\lambda_{12})x\right)dx = \frac{(\lambda_{12}/\lambda_{22})}{\left(z+\frac{\lambda_{12}}{\lambda_{22}}\right)^2}. \quad (33)$$

The outage probability is then expressed as

$$\mathrm{P}_{\mathrm{out}} = \int_0^{z_0}\frac{(\lambda_{12}/\lambda_{22})}{\left(z+\frac{\lambda_{12}}{\lambda_{22}}\right)^2}dz = 1-\frac{(\lambda_{12}/\lambda_{22})}{\frac{\lambda_{12}}{\lambda_{22}}+z_0}.$$

Finally, we obtain

$$\mathrm{P}_{\mathrm{out}} = \frac{K}{K+\frac{\lambda_{12}}{\lambda_{22}}Q_{\mathrm{peak}}}. \quad (34)$$

The outage occurrence depends on the thresholds K and Q_{peak} that model the quality of service requirements for the two users. The cutoff value z_0 of the ratio $\hat{g}_{22}/\hat{g}_{12}$ is function of the outage probability and of the channel parameters λ_{22} and λ_{12}: $z_0=\frac{\lambda_{12}}{\lambda_{22}}\frac{\mathrm{P}_{\mathrm{out}}}{1-\mathrm{P}_{\mathrm{out}}}$.

5) Connection With TIFR Transmission Policy: Next, we investigate a special case where the primary-to-secondary link is sufficiently attenuated to neglect the primary interference $\bar{P}_1 g_{21}$ to the secondary user. Such a situation occurs for instance when the secondary receiver is located outside an *exclusive region* around the primary transmitter [13], [15], [16]. In this case, we can define a delay-limited capacity (also referred to as zero-outage capacity) which represents the constant-rate that is achievable in all fading states [3]. Assuming the secondary user transmits with the minimum required power $\mathrm{p}_{2,\min}$ in non-outage states, to fulfill the set of constraints (28), we propose

$$p_2 = \begin{cases} \frac{K}{\hat{g}_{22}}, & \text{if } z \geq z_0 \\ 0, & \text{if } z < z_0. \end{cases} \quad (35)$$

The adaptive transmission technique (35) is called *truncated channel inversion with fixed rate* (TIFR), see [3], [17]. Since the secondary user transmits $\mathrm{p}_{2,\min}$ in non-outage events, then, the power transmission policy (35) is a variant of (29) in which the primary user receives always the weakest instantaneous interference. This case is interesting because it protects at best the primary user. We derive the mean transmit power of (35) as follows:

$$\mathbb{E}[p_2] = \int_0^{+\infty}\int_0^{\frac{y}{z_0}} \lambda_{12}\lambda_{22}\frac{K}{y}\exp(-\lambda_{12}x)\exp(-\lambda_{22}y)dxdy = \int_0^{+\infty}\lambda_{22}\frac{K}{y}\exp(-\lambda_{22}y)\left(\int_0^{\frac{y}{z_0}}\lambda_{12}\exp(-\lambda_{12}x)dx\right)dy. \quad (36)$$

Since

$$\int_0^{\frac{y}{z_0}}\lambda_{12}\exp(-\lambda_{12}x)dx = 1-\exp\left(-\lambda_{12}\frac{y}{z_0}\right),$$

we have

$$\mathbb{E}[p_2] = \int_0^{+\infty}\lambda_{22}\frac{K}{y}\exp(-\lambda_{22}y)dy - \int_0^{+\infty}\lambda_{22}\frac{K}{y}\exp\left(-\left(\lambda_{22}+\frac{\lambda_{12}}{z_0}\right)y\right)dy. \quad (37)$$

The first integral can be calculated as

$$\int_0^{+\infty}\lambda_{22}\frac{K}{y}\exp(-\lambda_{22}y)dy = \lambda_{22}K\left[\lim_{y\longrightarrow 0}\mathrm{E}_1(\lambda_{22}y) - \lim_{y\longrightarrow +\infty}\mathrm{E}_1(\lambda_{22}y)\right]. \quad (38)$$

The exponential integral function verifies [20]

$$\lim_{y\longrightarrow+\infty} \mathrm{E}_1(\lambda_{22}y) = 0.$$

So, we obtain the following expression for the first integral in (37):

$$\int_0^{+\infty} \lambda_{22}\frac{K}{y}\exp(-\lambda_{22}y)dy = \lambda_{22}K\lim_{y\longrightarrow 0}\mathrm{E}_1(\lambda_{22}y).$$

The second integral has the same form as the first one. Then,

$$\mathbb{E}[p_2] = \lim_{y\longrightarrow 0}\left[\mathrm{E}_1(\lambda_{22}y) - \mathrm{E}_1\left(y\left(\lambda_{22}+\frac{\lambda_{12}}{z_0}\right)\right)\right]\lambda_{22}K.$$

The exponential integral function $\mathrm{E}_1(.)$ can be approximated around zero [20] as

$$\mathrm{E}_1(y) \approx -\gamma - \log(y) \quad (39)$$

where γ is the Euler–Mascheroni constant $\gamma = 0.57721\ldots$. Using this closed-form approximation, we obtain a closed-form expression of $\mathbb{E}[p_2]$ as follows:

$$\mathbb{E}[p_2] \approx \lambda_{22}K\log\left(1+\frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right). \quad (40)$$

Therefore, for a given mean transmit power $\mathbb{E}[p_2]$, we derive the constant received power K as

$$K = \frac{\mathbb{E}[p_2]}{\lambda_{22}\log\left(1+\frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right)}. \quad (41)$$

The mean interference power for (35) is derived as

$$\begin{aligned}\mathbb{E}[p_2\hat{g}_{12}] &= \int_{z_0}^{+\infty}\frac{K}{z}f_z(z)dz\\ &= \int_{z_0}^{+\infty}\frac{K}{z}\frac{(\lambda_{12}/\lambda_{22})}{\left(z+\frac{\lambda_{12}}{\lambda_{22}}\right)^2}dz\\ &= K\left[\frac{\lambda_{22}}{\lambda_{12}}\log\left(1+\frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right) - \frac{1}{z_0+\frac{\lambda_{12}}{\lambda_{22}}}\right].\end{aligned}$$

We can express $\mathbb{E}[p_2\hat{g}_{12}]$ in terms of $\mathrm{P}_{\mathrm{out}}$ as

$$\mathbb{E}[p_2\hat{g}_{12}] = \frac{\lambda_{22}}{\lambda_{12}}\left(\mathrm{P}_{\mathrm{out}} - 1 - \log(\mathrm{P}_{\mathrm{out}})\right)K. \quad (42)$$

We deduce the zero-outage capacity

$$\mathbf{C}_{2,\mathrm{out}} = (1-\mathrm{P}_{\mathrm{out}})\log\left(1+\frac{K}{\sigma^2}\right). \quad (43)$$

Indeed, this capacity increases with the mean interference power and the speed of increase is function of $\mathrm{P}_{\mathrm{out}}$.

6) Numerical Examples: Next we give some numerical examples in order to evaluate the performances of our policy (29). We set $\bar{P}_1 = 1$ and $\sigma^2 = 0.01$ and $\lambda_{11} = \lambda_{22} = 1$, $\lambda_{21} = 5$, and $\lambda_{12} = 10$. We choose to attenuate the secondary-to-primary link in order to avoid cases of very strong interferences. Some authors, e.g., [13], [15], and [16], advocate to set an *exclusive region* around the primary receiver. No secondary operation is possible inside this range. So we can consider that the choice of $\lambda_{12} = 10$ (the value of the channel gain $\hat{g}_{12}$ is then set to $1/\lambda_{12} = 0.1$) is due to the fact that the secondary transmitter is located outside the primary *exclusive region*.

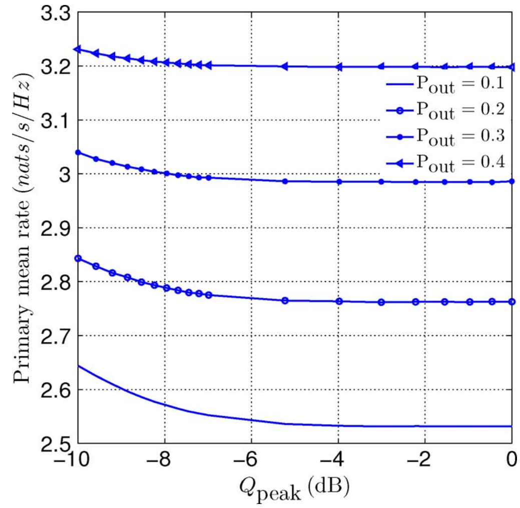

Fig. 4. Primary mean rate, $\mathbf{C}_1$, versus peak interference power, Q_{peak}, for different values of outage probability $\mathrm{P}_{\mathrm{out}}$.

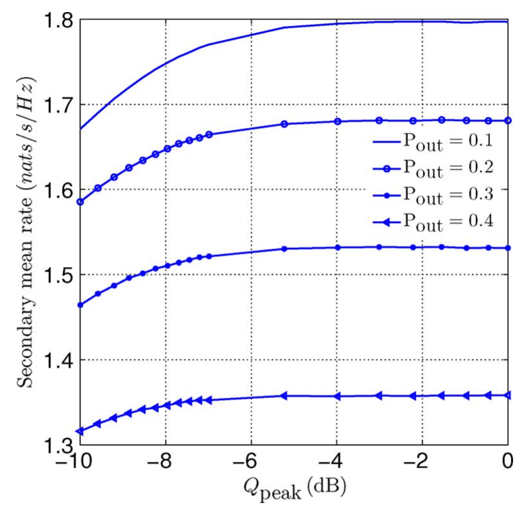

Fig. 5. Secondary mean rate, $\mathbf{C}_2$, versus peak interference power, Q_{peak}, for different values of outage probability $\mathrm{P}_{\mathrm{out}}$.

a) Mean rates: In Figs. 4 and 5, we plot respectively the primary mean rate and the secondary mean rate, versus the peak interference threshold Q_{peak} for different values of the outage probability $\mathrm{P}_{\mathrm{out}}$. We set $p_{2,\mathrm{peak}} = 1$. As the peak interference threshold increases, the secondary mean rate increases too, and consequently the primary mean rate decreases. For higher Q_{peak}, the cutoff value z_0 is weak and $p_{2,\mathrm{peak}}$ is more likely to be lower than $\frac{Q_{\mathrm{peak}}}{g_{12}}$. Consequently, $p_2 = p_{2,\mathrm{peak}}$ in most cases. Therefore, the primary mean rate tends to $\mathbb{E}[\log(1+\frac{\bar{P}_1 g_{11}}{\sigma^2+p_{2,\mathrm{peak}}g_{12}})]$ and the secondary mean rate is tending to $\mathbb{E}[\log(1+\frac{p_{2,\mathrm{peak}}g_{22}}{\sigma^2+\bar{P}_1 g_{21}})]$. For given Q_{peak}, secondary mean rate $\mathbf{C}_2$ decreases with $\mathrm{P}_{\mathrm{out}}$ while primary mean rate $\mathbf{C}_1$ increases.

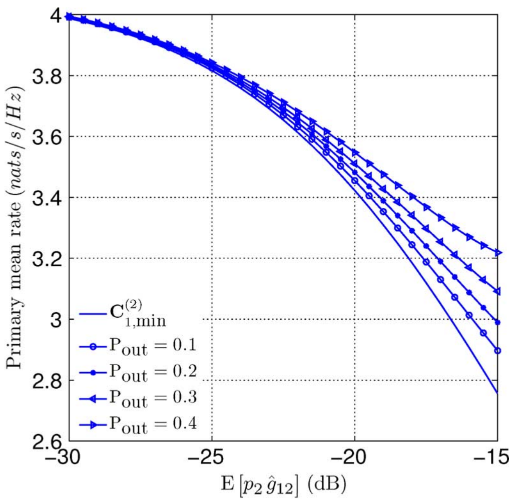

Fig. 6. Primary mean rate, $\mathbf{C}_1$, versus mean interference power, $\mathbb{E}[p_2\hat{g}_{12}]$, for different values of outage probability $\mathrm{P_{out}}$.

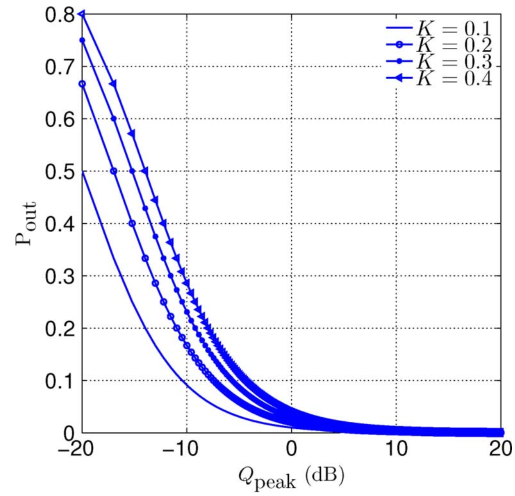

Fig. 8. Outage probability, $\mathrm{P_{out}}$, versus peak interference power, $Q_{\rm peak}$, for different values of minimum received power, K, required for secondary service.

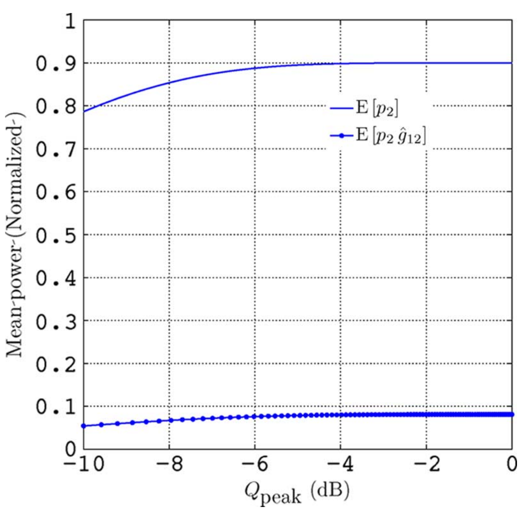

Fig. 7. Mean transmit power, $\mathbb{E}[p_2]$, and mean interference power, $\mathbb{E}[p_2\hat{g}_{12}]$, versus peak interference power $Q_{\rm peak}$. $p_{2,\rm peak} = 1$ and $\mathrm{P_{out}} = 0.1$.

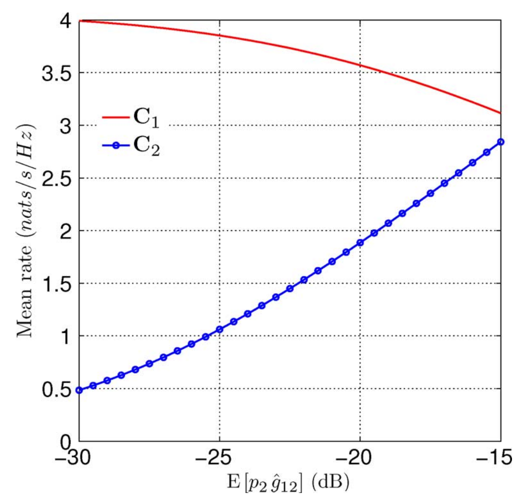

Fig. 9. Primary mean rate, $\mathbf{C}_1$, and secondary zero-outage capacity, $\mathbf{C}_{2,\rm out}$, versus mean interference power, $\mathbb{E}[p_2\hat{g}_{12}]$, for $\mathrm{P_{out}} = 0.1$.

In Fig. 6, we compare the primary mean rate $\mathbf{C}_1$ with the lower bound $\mathbf{C}_{1,\min}^{(2)}$. For given $\mathrm{P_{out}}$, when $Q_{\rm avg}$ increases, $Q_{\rm peak}$ increases as well.[4] Therefore, we have high occurrence of events $p_{2,\rm peak} \le \frac{Q_{\rm peak}}{g_{12}}$ and $p_2 = p_{2,\rm peak}$. As a consequence, the primary mean rate is all the more important than the lower bound $\mathbf{C}_{1,\min}^{(2)}$.

b) Mean transmit and interference powers: In Fig. 7, we compare the mean transmit power $\mathbb{E}[p_2]$ and the mean interference power $\mathbb{E}[p_2\hat{g}_{12}]$ in order to evaluate the ratio between the achievable service for the secondary user and the protection level of the primary user. The mean transmit power $\mathbb{E}[p_2]$ is very high compared to the mean received interference power $\mathbb{E}[p_2\hat{g}_{12}]$, i.e., their ratio >9. Moreover, $\mathbb{E}[p_2]$ increases more speedily than $\mathbb{E}[p_2\hat{g}_{12}]$. Then, we note that the secondary user can achieve important information rate without causing important interference to the primary user.

c) Outage probability: In Fig. 8, we plot the outage probability $\mathrm{P_{out}}$ versus the peak interference power $Q_{\rm peak}$ for different values of the minimum received power K. As predicted, when the primary user is less demanding ($Q_{\rm peak}$ increases), the outage probability decreases. Otherwise, for given $Q_{\rm peak}$, the less the secondary user is demanding (K decreases), the more frequently it can transmit over the common spectrum ($\mathrm{P_{out}}$ decreases). In particular, we note that for greater values of $Q_{\rm peak}$, the outage probability is less sensitive to the variations of K. Therefore, the secondary service quality requirement is less impacting on the outage occurrence.

d) TIFR transmission policy: In this part (Section IV-B6d), we neglect the primary-to-secondary link, so that λ_{21} is not used. In Fig. 9, we plot the evolution of the primary mean rate $\mathbf{C}_1$ and the secondary zero-outage capacity $\mathbf{C}_{2,\rm out}$ versus $\mathbb{E}[p_2\hat{g}_{12}]$ for

[4]From (32), it follows that

$$Q_{\rm peak} = -\frac{p_{2,\rm peak}}{\lambda_{22}z_0 + \lambda_{12}} \log\left(1 - \frac{\mathbb{E}[p_2, \hat{g}_{12}](1 + \frac{\lambda_{22}}{\lambda_{12}}z_0)^2}{p_{2,\rm peak}/\lambda_{12}}\right).$$

In realistic situations, $Q_{\rm peak} \ge \mathbb{E}[p_2\hat{g}_{12}]$ and

$$\mathbb{E}[p_2\hat{g}_{12}] \le \frac{p_{2,\rm peak}/\lambda_{12}}{(1 + \frac{\lambda_{22}}{\lambda_{12}}z_0)^2}.$$

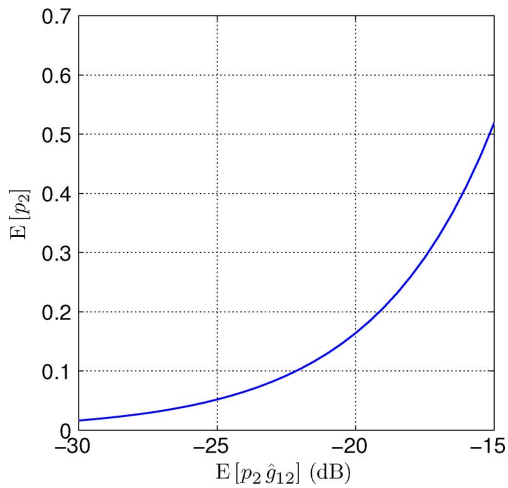

Fig. 10. Mean transmit power, $\mathbb{E}[p_2]$, versus mean interference power, $\mathbb{E}[p_2\hat{g}_{12}]$, for $\mathrm{P_{out}} = 0.1$.

$\mathrm{P_{out}} = 0.1$. Because the secondary user transmits with the minimum required power $\mathrm{p}_{2,\min}$ in non-outage states, the primary mean rate $\mathbf{C}_1$ decreases slowly with the mean interference power $\mathbb{E}[p_2\hat{g}_{12}]$, while $\mathbf{C}_{2,\mathrm{out}}$ increases speedily because the primary interference is neglected. Moreover, Fig. 10 shows that little mean power is required to achieve $\mathbf{C}_{2,\mathrm{out}}$.

V. Conclusion

In future wireless communication systems, there will be a need of smart and flexible spectrum usage due to the increasing demand in user data rates and to the shortage of available spectrum resources. Spectrum sharing and cognitive radio, proposed as promising solutions for improving the spectrum efficiency, will continue to receive a lot of attention. In this paper, we considered the problem of spectrum secondary-user power control in single-antenna flat-fading channels. The secondary user shares the spectrum with an existing spectrum-licensee or primary user. We derived two lower bounds, for the primary mean rate, depending on the secondary user power control scheme. Several power control policies were proposed and the achievable primary mean rates are compared with the lower bounds. In particular, ensuring for each user given outage performance and assuming that only direct links gains estimations (secondary-to-secondary link and secondary-to-primary link) are available at the secondary transmitter, we have proposed an original secondary power control that is useful for real-time delay-sensitive applications.

Appendix A
Lower Bounds of the Primary Mean Rate

In this section we calculate the following integrals:

$$\mathbf{C}_{1,\min}^{(1)} = \mathbb{E}\left[\log\left(1+\frac{X}{\sigma^2+Y}\right)\right] \tag{44}$$

$$\mathbf{C}_{1,\min}^{(2)} = \mathbb{E}\left[\log\left(1+\frac{X}{\sigma^2+\mathrm{Q_{avg}}}\right)\right] \tag{45}$$

where $X = \bar{P}_1 g_{11}$ and $Y = \bar{P}_2 g_{12}$ are exponentially distributed with parameters $\frac{\lambda_{11}}{\bar{P}_1}$ and $\frac{\lambda_{12}}{\bar{P}_2}$.

A. Lower Bounds $\boldsymbol{C}_{1,\min}^{(1)}$

To calculate the integral (44), first, we derive the probability density function of the random variable Ω defined as

$$\Omega = \frac{X}{\sigma^2+Y}. \tag{46}$$

Let $T = \sigma^2 + Y$. Since Y is exponentially distributed, T has a *shifted-exponential distribution* with the following probability density function:

$$f_T(t) = \begin{cases} \frac{\lambda_{12}}{\bar{P}_2}\exp\left(\frac{\lambda_{12}}{\bar{P}_2}\sigma^2\right)\exp\left(-\frac{\lambda_{12}}{\bar{P}_2}t\right), & \text{if } t \ge \sigma^2 \\ 0, & \text{if } \sigma^2 < t \end{cases} \tag{47}$$

The probability density function of the random variable Ω, for $\omega \ge 0$, can be expressed as

$$\begin{aligned} f_\Omega(\omega) &= \int_{\sigma^2}^{+\infty} t f_X(\omega t) f_T(t)\,dt \\ &= \frac{\lambda_{11}}{\bar{P}_1}\frac{\lambda_{12}}{\bar{P}_2}\exp\left(\frac{\lambda_{12}}{\bar{P}_2}\sigma^2\right) \\ &\quad\times \int_{\sigma^2}^{+\infty} t\exp\left(-\left(\frac{\lambda_{11}}{\bar{P}_1}\omega+\frac{\lambda_{12}}{\bar{P}_2}\right)t\right)dt \end{aligned}$$

due to the independence of X and T. After an integration by parts, we obtain

$$f_\Omega(\omega) = \begin{cases} \frac{1+b+\frac{b}{a}\omega}{a\left(1+\frac{1}{a}\omega\right)^2}\exp\left(-\frac{b}{a}\omega\right), & \text{if } \omega \ge 0 \\ 0, & \text{if } \omega < 0 \end{cases} \tag{48}$$

with[5]

$$a = \frac{\bar{P}_1}{\lambda_{11}}\frac{\lambda_{12}}{\bar{P}_2}, \quad b = \sigma^2\frac{\lambda_{12}}{\bar{P}_2}. \tag{49}$$

The following equality holds:

$$\frac{1+b+\frac{b}{a}\omega}{a\left(1+\frac{1}{a}\omega\right)^2}\exp\left(-\frac{b}{a}\omega\right) = \left(\frac{a}{(\omega+a)^2}+\frac{b}{\omega+a}\right) \times\exp\left(-\frac{b}{a}\omega\right); \tag{50}$$

therefore,

$$\begin{aligned} \mathbf{C}_{1,\min}^{(1)} &= \mathbb{E}\left[\log(\Omega+1)\right] \\ &= \int_0^{+\infty}\left(\frac{a}{(\omega+a)^2}+\frac{b}{\omega+a}\right) \\ &\qquad\times\exp\left(-\frac{b}{a}\omega\right)\log(\omega+1)\,d\omega \\ &= a\int_0^{+\infty}\frac{\log(\omega+1)}{(\omega+a)^2}\exp\left(-\frac{b}{a}\omega\right)d\omega \\ &\quad + b\int_0^{+\infty}\frac{\log(\omega+1)}{\omega+a}\exp\left(-\frac{b}{a}\omega\right)d\omega. \end{aligned} \tag{51}$$

[5]In Section IV-A1), we set $w = \frac{g_{22}}{\sigma^2+\bar{P}_1 g_{21}}$. The probability density function f_W has the same expression as f_Ω but with $a = \frac{\lambda_{21}}{\bar{P}_1\lambda_{22}}$ and $b = \frac{\sigma^2\lambda_{21}}{\bar{P}_1}$.

Now, let

$$\mathrm{I}_1 = \int_0^{+\infty} \frac{\log(\omega+1)}{\omega+a} \exp\left(-\frac{b}{a}\omega\right) d\omega \tag{52}$$

$$\mathrm{I}_2 = \int_0^{+\infty} \frac{\log(\omega+1)}{(\omega+a)^2} \exp\left(-\frac{b}{a}\omega\right) d\omega. \tag{53}$$

After an integration of I_1 by parts, we obtain

$$\mathrm{I}_1 = \frac{a}{b} \int_0^{+\infty} \frac{1}{(\omega+1)(\omega+a)} \exp\left(-\frac{b}{a}\omega\right) d\omega - \frac{a}{b}\mathrm{I}_2. \tag{54}$$

Then, we can express $\mathrm{I}_1 + (a/b)\mathrm{I}_2$ as

$$\mathrm{I}_1 + \frac{a}{b}\mathrm{I}_2 = \frac{a}{b}\frac{1}{a-1}\left[\int_0^{+\infty} \frac{1}{\omega+1} \exp\left(-\frac{b}{a}\omega\right) d\omega - \int_0^{+\infty} \frac{1}{\omega+a} \exp\left(-\frac{b}{a}\omega\right) d\omega\right] \tag{55}$$

due to the equality

$$\frac{1}{(\omega+1)(\omega+a)} = \frac{1}{a-1}\left(\frac{1}{\omega+1} - \frac{1}{\omega+a}\right). \tag{56}$$

We can rewrite (55) in terms of integral exponential function E_1 [20]:

$$\mathrm{I}_1 + \frac{a}{b}\mathrm{I}_2 = \frac{a}{b}\frac{1}{a-1}\left[\exp\left(\frac{b}{a}\right)\mathrm{E}_1\left(\frac{b}{a}\right) - \exp(b)\mathrm{E}_1(b)\right] \tag{57}$$

finally, we express the lower bounds $\mathbf{C}_{1,\min}^{(1)}$ as

$$\begin{aligned}\mathbf{C}_{1,\min}^{(1)} &= b\left(\mathrm{I}_1 + \frac{a}{b}\mathrm{I}_2\right)\\ &= \frac{a}{a-1}\left[\exp\left(\frac{b}{a}\right)\mathrm{E}_1\left(\frac{b}{a}\right) - \exp(b)\mathrm{E}_1(b)\right].\end{aligned}$$

Replacing a and b by their expressions in (49) allows us to write

$$\mathbf{C}_{1,\min}^{(1)} = \frac{\bar{P}_1}{\bar{P}_1 - \frac{\lambda_{11}}{\lambda_{12}}\bar{P}_2}\left[\exp\left(\frac{\sigma^2\lambda_{11}}{\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\sigma^2\lambda_{11}}{\bar{P}_1}\right) - \exp\left(\frac{\sigma^2\lambda_{12}}{\bar{P}_2}\right)\mathrm{E}_1\left(\frac{\sigma^2\lambda_{12}}{\bar{P}_2}\right)\right]. \tag{58}$$

B. Lower Bounds $\boldsymbol{C}_{1,\min}^{(2)}$

Now, let $\alpha = 1/(\sigma^2 + Q_{\mathrm{avg}})$. We have

$$\begin{aligned}\mathbf{C}_{1,\min}^{(2)} &= \mathbb{E}\left[\log(1+\alpha X)\right]\\ &= \frac{\lambda_{11}}{\bar{P}_1}\int_0^{+\infty} \log(1+\alpha x)\exp\left(-\frac{\lambda_{11}}{\bar{P}_1}x\right) dx.\end{aligned}$$

After an integration by parts, we can express $\mathbf{C}_{1,\min}^{(2)}$ as

$$\begin{aligned}\mathbf{C}_{1,\min}^{(2)} &= \int_0^{+\infty} \frac{\alpha}{\alpha x+1}\exp\left(-\frac{\lambda_{11}}{\bar{P}_1}x\right) dx\\ &= \exp\left(\frac{\lambda_{11}}{\alpha\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\lambda_{11}}{\alpha\bar{P}_1}\right)\\ &= \exp\left(\frac{\lambda_{11}(\sigma^2+Q_{\mathrm{avg}})}{\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\lambda_{11}(\sigma^2+Q_{\mathrm{avg}})}{\bar{P}_1}\right).\end{aligned} \tag{59}$$

APPENDIX B
MEAN TRANSMIT POWER AND MEAN INTERFERENCE POWER

In this section, we calculate the mean transmit power and the mean interference power of (29). Let $x = g_{12}$ and $y = g_{22}$, the mean transmit power of (29) can be expressed as

$$\begin{aligned}\mathbb{E}[p_2] = &\int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}p_{2,\mathrm{peak}}\exp(-\lambda_{22}y) \times\exp(-\lambda_{12}x)dxdy\\ &+\int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}\frac{Q_{\mathrm{peak}}}{x}\exp(-\lambda_{22}y) \times\exp(-\lambda_{12}x)dxdy.\end{aligned} \tag{60}$$

Now, let

$$\mathrm{I}_1' = \int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}p_{2,\mathrm{peak}}\exp(-\lambda_{22}y) \times\exp(-\lambda_{12}x)dxdy \tag{61}$$

$$\mathrm{I}_2' = \int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty} \lambda_{22}\lambda_{12}\frac{Q_{\mathrm{peak}}}{x}\exp(-\lambda_{22}y) \times\exp(-\lambda_{12}x)dxdy. \tag{62}$$

Integral I_1' is obtained as

$$\begin{aligned}\mathrm{I}_1' &= p_{2,\mathrm{peak}}\int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}} \lambda_{12}\exp(-\lambda_{12}x) \times\left(\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\exp(-\lambda_{22}y)dy\right)dx\\ &= p_{2,\mathrm{peak}}\int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}} \lambda_{12}\exp\left(-\left(\lambda_{12}+\frac{\lambda_{22}K}{Q_{\mathrm{peak}}}\right)x\right)dx\\ &= \frac{p_{2,\mathrm{peak}}}{1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}}\left[1-\exp\left(-\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right)\right].\end{aligned} \tag{63}$$

Integral I_2' is obtained as

$$\begin{aligned}\mathrm{I}_2' &= \int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty} \lambda_{12}\frac{Q_{\mathrm{peak}}}{x}\exp(-\lambda_{12}x) \\ &\quad\times\left(\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\exp(-\lambda_{22}y)dy\right)dx \\ &= \int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty} \lambda_{12}\frac{Q_{\mathrm{peak}}}{x}\exp\left(-\left(\lambda_{12}+\frac{\lambda_{22}K}{Q_{\mathrm{peak}}}\right)x\right)dx \\ &= \lambda_{12}Q_{\mathrm{peak}}\mathrm{E}_1\left(\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right). \end{aligned} \tag{64}$$

Finally, we have

$$\begin{aligned}\mathbb{E}[p_2] &= \frac{p_{2,\mathrm{peak}}}{1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}}\left[1-\exp\left(-\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right)\right] \\ &\quad+\lambda_{12}Q_{\mathrm{peak}}\mathrm{E}_1\left(\frac{\lambda_{22}K+\lambda_{12}Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}\right). \end{aligned} \tag{65}$$

The mean interference power is expressed as $\mathbb{E}[p_2\hat{g}_{12}] = \mathrm{I}_1''+\mathrm{I}_2''$,

$$\begin{aligned}\mathrm{I}_1'' &= \int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\lambda_{12}xp_{2,\mathrm{peak}}\exp(-\lambda_{22}y) \\ &\qquad\times\exp(-\lambda_{12}x)dxdy, \\ \mathrm{I}_2'' &= \int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty}\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\lambda_{12}Q_{\mathrm{peak}}\exp(-\lambda_{22}y) \\ &\qquad\times\exp(-\lambda_{12}x)dxdy. \end{aligned} \tag{66}$$

Integral I_1'' is obtained as follows:

$$\begin{aligned}\mathrm{I}_1'' &= p_{2,\mathrm{peak}}\int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}\lambda_{12}x\exp(-\lambda_{12}x) \\ &\quad\times\left(\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\exp(-\lambda_{22}y)dy\right)dx \\ &= p_{2,\mathrm{peak}}\int_0^{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}\lambda_{12}x\exp\left(-\left(\lambda_{12}+\frac{\lambda_{22}K}{Q_{\mathrm{peak}}}\right)x\right)dx \\ &= \frac{p_{2,\mathrm{peak}}/\lambda_{12}}{\left(1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}\right)^2}\left[1-\left(1+\frac{\lambda_{12}Q_{\mathrm{peak}}+\lambda_{22}K}{p_{2,\mathrm{peak}}}\right)\right. \\ &\qquad\left.\times\exp\left(-\frac{\lambda_{12}Q_{\mathrm{peak}}+\lambda_{22}K}{p_{2,\mathrm{peak}}}\right)\right], \end{aligned}$$

and integral I_2'' as

$$\begin{aligned}\mathrm{I}_2'' &= Q_{\mathrm{peak}}\int_{\frac{Q_{\mathrm{peak}}}{p_{2,\mathrm{peak}}}}^{+\infty}\lambda_{12}\exp(-\lambda_{12}x) \\ &\quad\times\left(\int_{\frac{K}{Q_{\mathrm{peak}}}x}^{+\infty}\lambda_{22}\exp(-\lambda_{22}y)dy\right)dx \\ &= \frac{Q_{\mathrm{peak}}}{1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}}\exp\left(-\frac{\lambda_{12}Q_{\mathrm{peak}}+\lambda_{22}K}{p_{2,\mathrm{peak}}}\right). \end{aligned}$$

Finally, the mean interference power is expressed as

$$\begin{aligned}\mathbb{E}[p_2\hat{g}_{12}] &= \frac{p_{2,\mathrm{peak}}/\lambda_{12}}{\left(1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\mathrm{peak}}}\right)^2} \\ &\qquad\times\left[1-\exp\left(-\frac{\lambda_{12}Q_{\mathrm{peak}}+\lambda_{22}K}{p_{2,\mathrm{peak}}}\right)\right]. \end{aligned} \tag{67}$$

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