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 on the type of constraint for spectrum access. Several power control policies are investigated and the achieved primary-user mean rates are compared with the 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). We take into account all links in the network.

I. Introduction

When looking at the radio frequency spectrum, all frequencies below 3GHz have been allocated to specific uses [12]. 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 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 papers 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] to [13].

Power control for spectrum-sharing users has been widely studied. In particular, [3] investigated 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 superior over 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}). [10] investigates cooperative and non-cooperative 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* (non-cooperative scenario) may be more realistic[1] when systems are competing with one another to gain access to the common 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 the 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

[1] *The systems are selfish in the sense that they only try to maximize their own utility [10].*

performance of different types of power control 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, at a given occurrence, predefined minimum instantaneous rates. Contrary to the optimal power controls, derived in [3] and [4], and the non-cooperative games in [10], the goal of the new allocation strategy is neither to achieve, in any case, 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 a given minimum instantaneous rates. Furthermore, this 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.

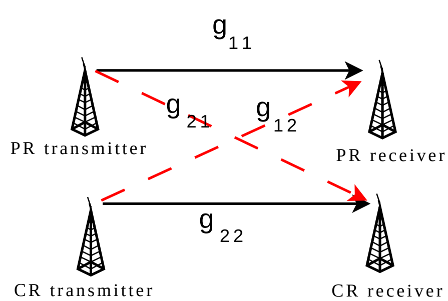

Figure 1. Spectrum sharing between a PR and a CR communication links

II. Problem formulation

A. System and channel model

We consider the network depicted in figure 1 with two users transmitting in the same frequency band and interfering with each other. The first user (PR) is assumed to be the licensee of the spectrum and is called primary user. The second user (CR) is the secondary user. We assume the fading channels are flat and time-discrete. 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 λ_{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. Thus, with Gaussian signalling, the instantaneous rates (expressed in nats/s/Hz) of the primary and the secondary users may be expressed as $\mathrm{C}_1 = \log\left(1 + \frac{p_1\, g_{11}}{\sigma^2 + p_2\, g_{12}}\right)$ and $\mathrm{C}_2 = \log\left(1 + \frac{p_2\, g_{22}}{\sigma^2 + p_1\, g_{21}}\right)$, where p_1 and p_2 denote, respectively, the primary user transmit power and the secondary user transmit power. This assumption is somewhat pessimistic, and our results thus form a conservative lower bound. In practice, some form of multi-user detection allowing for interference suppression or mitigation may be used to enhance the rates achieved. The mean rates are defined as $\mathbf{C}_1 \triangleq \mathbb{E}\left[\mathrm{C}_1\right]$ and $\mathbf{C}_2 \triangleq \mathbb{E}\left[\mathrm{C}_2\right]$, where $\mathbb{E}\left[x\right]$ 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 other scenario is called *constrained spectrum-sharing*. 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 in a more general case when 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 spectrum user needs given outage performance to achieve its service.

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

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

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

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: For more real channels, one can include path-loss to the means, $1/\lambda_{ij}$, of the channels power gains g_{ij}. The channels gains estimations $\hat{g}_{ij}$ and the means values $1/\lambda_{ij}$ can be brought to the transmitters thanks to the following protocol. First, transmitter i, for $i \in \{1,2\}$, sends a pilot signal of normalized power, then, receivers i and j ($j \neq i$) estimate simultaneously the values of λ_{ii}, λ_{ji}, $\hat{g}_{ii}$ and $\hat{g}_{ji}$. Moreover, one can imagine the existence of a *low rate control channel* that the receivers can use to feed back λ_{ii}, λ_{ji}, $\hat{g}_{ii}$ and $\hat{g}_{ji}$, [6]. Finally, one can also imagine a coordination channel between transmitters that they can use to communicate to each other. So, to perform the proposed power control, as shown farther, 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. The result will be that, contrary to what we could imagine, the optimal power control for the secondary link, does not cause the most harmful interference to the primary transmission. We assume that

$$\mathbb{E}\left[p_2\right] \leq \bar{P}_2, \tag{3}$$

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:

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

thanks 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 both $\hat{g}_{22}$ and $\hat{g}_{21}$, and constant power control scheme. The primary mean rate can be expressed as:

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

Thanks to the independence of g_{11}, g_{12}, g_{22} and g_{21}, it follows that

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

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

Moreover, we have:

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

where the first inequality is due to Jensen inequality[2]. The second inequality is due to the power constraint

[2]Because of the convexity of the x-dependent function $\log\left(1 + \dfrac{A}{B + x}\right)$ with $A \geq 0$, $B \geq 0$ and $x \geq 0$.

(3). Finally, we obtain:

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

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, 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 (appendix A) as:

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

where the exponential integral function is defined as, [19],

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

B. Constrained spectrum-sharing

Now we investigate a spectrum-sharing scenario where the secondary transmission is subject to some interference constraints in order to protect the primary user. In this case, estimating the secondary-to-primary link gain, g_{12}, may be crucial. In general, depending on the type of constraint, primary protection should require different CSI to the secondary transmitter.

1) Primary mean-rate loss constraint: This constraint is useful when improving the primary mean rate is in concern. It consists in setting a maximum loss of the primary mean rate:

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

where $\mathbf{C}_{1,\max} \triangleq \mathbb{E}\left[\log\left(1+\frac{\bar{P}_1\, g_{11}}{\sigma^2}\right)\right]$ is the mean rate of the primary user without 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], that might demand sophisticated techniques. In the sequel, we do not use this constraint.

2) Interference constraints: The primary transmission can be also protected by using the dimensions time and space of the spectrum to manage the secondary user interference to the primary receiver. More general spatial spectrum-sharing problem is considered in [9]: given two different networks (for instance two MAC), to enable coexistence, we can regulate their transmission power, 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, peak and average interference constraints, stated by (8) and (9), are commonly used to protect the primary transmission, [3] to [7], :

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

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

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 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:

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

thanks 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 constant power control scheme. The primary mean rate verifies:

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

where the first inequality is due to Jensen. The second inequality is due to the mean interference power constraint (9). The lower bound $\mathbf{C}^{(2)}_{1,\text{min}}$ can be expressed (appendix A) as[3]:

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

IV. Power control for spectrum secondary use

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

[3]This case includes obviously the unconstrained spectrum-sharing case, consequently $\mathbf{C}^{(1)}_{1,\text{min}} \geq \mathbf{C}^{(2)}_{1,\text{min}}$.

A. Power control with mean-transmit-power constraint only

We assume that there is only one constraint for 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* [18]:

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

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

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

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 (appendix A):

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

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

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 adequate estimation technique, assume $\hat{w}$ is the estimated value of w. We can reduce the impact of estimation errors on the power control (12) by using the following scheduling:

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

where the constant c is obtained such that

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

thus, it 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:

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

Therefore, constant c is expressed as:

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

In the scheduling (15), constant c does not depend on the channel realizations. Moreover, the *binary condition* $\hat{w} \lesseqgtr \frac{1}{\zeta}$ is less sensitive to the estimation errors. This relatively easy-done scheduling, for the secondary link, should achieve a primary mean rate close to the one achieved using the optimal *water-filling*.

3) Numerical examples: both the theoretical optimal allocation (12) and the scheduling (15) are functions of the channels gains $\hat{g}_{22}$ and $\hat{g}_{12}$. So they have the form of (4). $\mathbf{C}^{(1)}_{1,\min}$ 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 $\mathbf{C}^{(1)}_{1,\min}$. With the settings $\bar{P}_1 = 1$, $\sigma^2 = 0.01$ and $\lambda_{11} = \lambda_{12} = \lambda_{22} = \lambda_{21} = 1$, we obtain the figures 2 and 3.

As it can be noticed in Fig. 2 and 3, the proposed scheduling (15) provides a performance that is very close to the optimal *water-filling*. Moreover, we can see the gap level between the lower bound $\mathbf{C}^{(1)}_{1,\min}$ 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 we should imagine. On the contrary, for same mean power, $\bar{P}_1 = \bar{P}_2 = 1$ for instance, the optimal *water-filling* provides nearly 1 nat/s/Hz protection, to the primary user, more than the constant power control (Cf. 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. That is, only $\hat{g}_{22}$ and $\hat{g}_{12}$ are available for the secondary user power control.

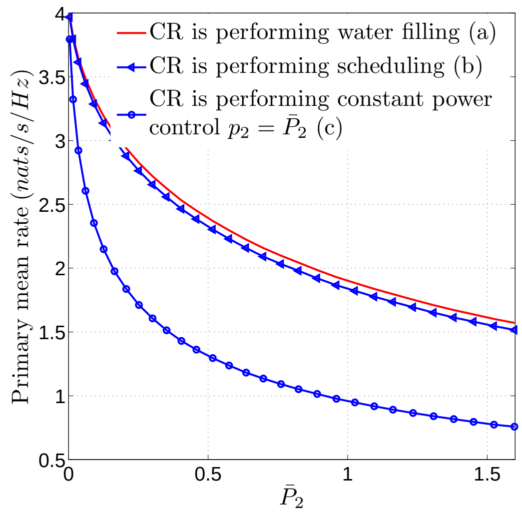

Figure 2. Primary mean rate versus secondary mean power for different power control schemes from the secondary user: (a) optimal power control *water-filling*; (b) proposed scheduling approximating the optimal power control; (c) constant power control that provides the lower bound of the primary mean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

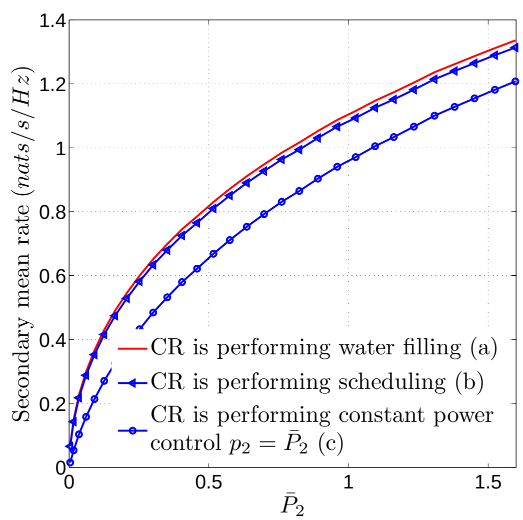

Figure 3. Secondary mean rate versus mean power for different power control schemes: (a) optimal power control *water-filling*; (b) proposed scheduling approximating the optimal power control; (c) constant power control that provides the lower bound of the primary mean rate. $\bar{P}_1 = 1$, $\sigma^2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

1) Outage performance constraints: the primary and secondary outage constraints are modeled by (1) and (2). By replacing C_1 and C_2 by theirs formulas, events "$C_1 \leq C_0$" and "$C_2 \leq C_0'$" can be expressed, respectively, as:

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

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

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

$$\begin{aligned} \mathbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_1 \leq \mathrm{C}_0\right) &= \int_0^{\gamma} \lambda_{11}\ \exp\left(-\lambda_{11}\,x\right)\ dx \\ &= 1 - \exp\left(-\lambda_{11}\,\gamma\right), \end{aligned} \tag{20}$$

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

$$\begin{aligned} \mathbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_2 \leq \mathrm{C}_0'\right) &= \int_{\gamma'}^{+\infty} \lambda_{21}\ \exp\left(-\lambda_{21}\,x\right)\ dx \\ &= \exp\left(-\lambda_{21}\,\gamma'\right), \end{aligned} \tag{21}$$

with $\gamma' = \frac{1}{\bar{P}_1}\left(\frac{p_2\,\hat{g}_{22}}{\alpha_0'} - \sigma^2\right)$. Then, outage constraints (1) and (2) can be expressed, respectively, as:

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

$$\exp\left(-\frac{\lambda_{21}}{\bar{P}_1}\left(\frac{p_2\,\hat{g}_{22}}{\alpha_0'} - \sigma^2\right)\right) \leq \epsilon'. \tag{23}$$

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

$$p_2\,\hat{g}_{12} \leq Q_{\text{peak}}, \tag{24}$$

$$p_2\,\hat{g}_{22} \geq K. \tag{25}$$

Where the peak interference threshold is defined as:

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

and the minimum received power K as:

$$K = \alpha_0'\left(\sigma^2 - \frac{\bar{P}_1}{\lambda_{21}}\log\left(\epsilon'\right)\right). \tag{27}$$

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 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, transmit power p_2 of the secondary user must fulfill the set of inequalities

$$\begin{cases} p_2\,\hat{g}_{12} & \leq & Q_{\text{peak}} \\ p_2\,\hat{g}_{22} & \geq & K \end{cases} \tag{28}$$

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

- if $\left(\frac{\hat{g}_{22}}{\hat{g}_{12}} \geq \frac{K}{Q_{\text{peak}}}\right)$, then[4] power p_2 can be greater than the minimum required $\mathrm{p}_{2,\min} \triangleq \frac{K}{\hat{g}_{22}}$. But to meet the interference constraint, power p_2 must always fulfill $p_2\,\hat{g}_{12} \leq Q_{\text{peak}}$. So, the cognitive user can opportunistically communicate with $p_2 = \frac{Q_{\text{peak}}}{\hat{g}_{12}}$;
- if $\left(\frac{\hat{g}_{22}}{\hat{g}_{12}} < \frac{K}{Q_{\text{peak}}}\right)$, then the minimum power $\mathrm{p}_{2,\min}$ can not meet the interference constraint. Consequently, we set $p_2 = 0$ (CR transmission is off).

However, the maximum transmit power $\frac{Q_{\text{peak}}}{\hat{g}_{12}}$ can be infinitely high (when $\hat{g}_{12}$ is very low), while in real system 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:

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

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 non-cooperative games in [10], the goal of the allocation strategy (29) is neither to achieve, in any case, maximum possible rate, nor to maximize *selfish* utilities. But the particularity of (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, while using only the direct links gains

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

estimations $\hat{g}_{22}$ and $\hat{g}_{12}$ (that is not considered in the previous works such as [3], [4] and [10]). It is then more appropriate for spectrum-sharing systems that carry out real-time delay-sensitive applications, e.g. voice and video.

Now, we will study some typical parameters of this power control.

3) Mean transmit and mean interference power: now, 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 the parameters λ_{11}, λ_{22}, λ_{12} and λ_{21}, which are imposed by the channel fades.

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

$$\begin{aligned}\mathbb{E}\left[p_2\right] &= \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,p_{2,\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy \\ &+ \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,\frac{Q_{\text{peak}}}{x}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy.\end{aligned}$$

After some manipulations (Cf. appendix B), we obtain:

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

The mean received interference power is obtained similarly as follows:

$$\begin{aligned}\mathbb{E}\left[p_2\,\hat{g}_{12}\right] &= \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,x\,p_{2,\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy \\ &+ \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,Q_{\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy.\end{aligned} \tag{31}$$

After some manipulations (Cf. appendix B), it can be expressed as:

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

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

$$\mathbb{E}\left[p_2\right] = \lambda_{12}\,Q_{\text{peak}}\left[\left(1+\frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\text{peak}}}\right)\frac{\mathbb{E}\left[p_2\,\hat{g}_{12}\right]}{Q_{\text{peak}}}+\mathrm{E}_1\left(\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right)\right]. \tag{33}$$

In practical situations, we assume $\lambda_{12} \geq 1$. Therefore, from (33), the mean transmit power is greater than the mean interference power, especially when $\mathrm{E}_1\left(\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right)$ is high or equivalently when

$\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}$ 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: previously, the strategy for the power control (29) is stated by firstly setting $\textbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_2 \leq \mathrm{C}_0'\right) = \epsilon'$ or equivalently $p_2 = \mathrm{p}_{2,\min}$. Then, to transmit if $\textbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_1 \leq \mathrm{C}_0\right) \leq \epsilon$. The overall outage probability of (29) can be expressed as:

$$\mathrm{P}_{\text{out}} = \textbf{Prob}\left(\textbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_1 \leq \mathrm{C}_0\right) > \epsilon \,/\, \textbf{Prob}_{g_{11},\,g_{21}}\left(\mathrm{C}_2 \leq \mathrm{C}_0'\right) = \epsilon'\right). \tag{34}$$

Let $x = \hat{g}_{12}$, $y = \hat{g}_{22}$, $z = y/x$ and $z_0 = K/Q_{\text{peak}}$. From (29), the outage probability P_{out} is obtained as follows:

$$\mathrm{P}_{\text{out}} \;=\; \textbf{Prob}\left(z \,<\, z_0\right) = \int_0^{z_0} f_Z(z)\,dz,$$

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:

$$\begin{aligned} f_Z(z) &= \int_0^{+\infty} x\, f_Y(z\,x)\, f_X(x)\,dx \\ &= \lambda_{22}\,\lambda_{12}\int_0^{+\infty} x\,\exp\left(-\left(\lambda_{22}\,z+\lambda_{12}\right)\,x\right)\,dx \\ &= \frac{\left(\lambda_{12}/\lambda_{22}\right)}{\left(z+\dfrac{\lambda_{12}}{\lambda_{22}}\right)^2} \end{aligned} \tag{35}$$

The outage probability is then expressed as:

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

Finally, we obtain:

$$\mathrm{P}_{\text{out}} = \frac{K}{K+\frac{\lambda_{12}}{\lambda_{22}}Q_{\text{peak}}}. \tag{36}$$

The outage occurrence depends on the thresholds K and Q_{peak} that model the quality requirements of the services for the two users. The cut-off 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}: $z_0 = \dfrac{\lambda_{12}}{\lambda_{22}}\dfrac{\mathrm{P}_{\text{out}}}{1-\mathrm{P}_{\text{out}}}$.

5) Connection with TIFR transmission policy: now, 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, [12], [14], [15]. 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:

$$p_2 = \begin{cases} \dfrac{K}{\hat{g}_{22}} & \text{if} \quad z \geq z_0 \\ 0 & \text{if} \quad z < z_0. \end{cases} \tag{37}$$

The adaptive transmission technique (37) is called *truncated channel inversion with fixed rate* (TIFR), [3], [16]. Since the secondary user transmits $\mathrm{p}_{2,\min}$ in non-outage events, then, power transmission policy (37) is a variant of (29) in which primary user receives always the weakest instantaneous interference. This case is interesting because it protects, the best, primary user. We derive the mean transmit power of (37) as follows:

$$\begin{aligned} \mathbb{E}\left[p_2\right] &= \int_0^{+\infty} \int_0^{\frac{y}{z_0}} \lambda_{12}\, \lambda_{22}\, \frac{K}{y} \exp\left(-\lambda_{12}\, x\right) \exp\left(-\lambda_{22}\, y\right)\, dx\, dy \\ &= \int_0^{+\infty} \lambda_{22}\, \frac{K}{y} \exp\left(-\lambda_{22}\, y\right) \left(\int_0^{\frac{y}{z_0}} \lambda_{12} \exp\left(-\lambda_{12}\, x\right)\, dx \right) dy. \end{aligned} \tag{38}$$

Since

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

we have

$$\mathbb{E}\left[p_2\right] = \int_0^{+\infty} \lambda_{22}\, \frac{K}{y} \exp\left(-\lambda_{22}\, y\right)\, dy - \int_0^{+\infty} \lambda_{22}\, \frac{K}{y} \exp\left(-\left(\lambda_{22} + \frac{\lambda_{12}}{z_0}\right) y\right)\, dy. \tag{39}$$

The first integral can be calculated as:

$$\int_0^{+\infty} \lambda_{22}\, \frac{K}{y} \exp\left(-\lambda_{22}\, y\right)\, dy = \lambda_{22}\, K \left[\lim_{y \longrightarrow 0} \mathrm{E}_1\left(\lambda_{22}\, y\right) - \lim_{y \longrightarrow +\infty} \mathrm{E}_1\left(\lambda_{22}\, y\right) \right]. \tag{40}$$

The exponential integral function verifies, [19]:

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

So, we obtain the following expression for the first integral in (39):

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

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

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

The exponential integral function $\mathrm{E}_1(.)$ can be approximated around zero, [19], as

$$\mathrm{E}_1\left(y\right) \approx -\gamma - \log(y), \tag{41}$$

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

$$\mathbb{E}\left[p_2\right] \approx \lambda_{22}\,K\,\log\left(1 + \frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right). \tag{42}$$

Therefore, for given mean transmit power $\mathbb{E}\left[p_2\right]$, we can determine the constant received power K as follows:

$$K \quad = \quad \frac{\mathbb{E}\left[p_2\right]}{\lambda_{22}\,\log\left(1 + \frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right)}. \tag{43}$$

The mean interference power for (37) is derived as:

$$\begin{aligned}
\mathbb{E}\left[p_2\,\hat{g}_{12}\right] \quad &= \quad \int_{z_0}^{+\infty}\frac{K}{z}\,f_z(z)\,dz \\
&= \quad \int_{z_0}^{+\infty}\frac{K}{z}\,\frac{\left(\lambda_{12}/\lambda_{22}\right)}{\left(z + \frac{\lambda_{12}}{\lambda_{22}}\right)^2}\,dz \\
&= \quad K\left[\frac{\lambda_{22}}{\lambda_{12}}\log\left(1 + \frac{\lambda_{12}}{\lambda_{22}}\frac{1}{z_0}\right) - \frac{1}{z_0 + \frac{\lambda_{12}}{\lambda_{22}}}\right].
\end{aligned} \tag{44}$$

We can express $\mathbb{E}\left[p_2\,\hat{g}_{12}\right]$ in terms of P_{out} as:

$$\mathbb{E}\left[p_2\,\hat{g}_{12}\right] = \frac{\lambda_{22}}{\lambda_{12}}\left(\mathrm{P}_{\text{out}} - 1 - \log\left(\mathrm{P}_{\text{out}}\right)\right)\,K. \tag{45}$$

The zero-outage capacity $\mathbf{C}_{2,\text{out}}$ is expressed as:

$$\mathbf{C}_{2,\text{out}} = (1 - \mathrm{P}_{\text{out}}) \log \left(1 + \frac{K}{\sigma^2}\right). \tag{46}$$

This capacity is obviously increasing with the mean interference power and the increasing speed is function of P_{out}.

6) Numerical examples: now we give some numerical examples in order to evaluate some achievable performances of (29). We set $\bar{P}_1 = 1$ and $\sigma^2 = 0.01$. The channel is set as: $\lambda_{11} = \lambda_{22} = 1$, $\lambda_{21} = 5$ (in the part IV-B6d, we will neglect the primary-to-secondary link, so λ_{21} is not used there) and $\lambda_{12} = 10$. That is, we choose to attenuate the secondary-to-primary link in order to avoid very strong interference. Some authors, e.g. [12], [14], [15], 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 $\frac{1}{\lambda_{12}} = 0.1$) is due to the fact that the secondary transmitter is located outside the primary *exclusive region*.

a) Mean rates: in figures 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 P_{out}. We set $p_{2,\text{peak}} = 1$. As the peak interference threshold increases, the secondary mean rate increases too, and consequently the primary mean rate decreases. For higher Q_{peak}, the cut-off value z_0 is weak and $p_{2,\text{peak}}$ is more likely to be lower than $\frac{Q_{\text{peak}}}{g_{12}}$. Consequently, $p_2 = p_{2,\text{peak}}$ in most of the channel fades. Therefore, primary mean rate is tending to $\mathbb{E}\left[\log\left(1 + \frac{\bar{P}_1 g_{11}}{\sigma^2 + p_{2,\text{peak}}\, g_{12}}\right)\right]$ and secondary mean rate is tending to $\mathbb{E}\left[\log\left(1 + \frac{p_{2,\text{peak}}\, g_{22}}{\sigma^2 + \bar{P}_1\, g_{21}}\right)\right]$. For given Q_{peak}, secondary mean rate $\mathbf{C}_2$ decreases with P_{out} while primary mean rate $\mathbf{C}_1$ increases.

In figure 6, we compare the primary mean rate $\mathbf{C}_1$ with the lower bound $\mathbf{C}_{1,\min}^{(2)}$. For given P_{out}, when Q_{avg} increases, Q_{peak} increases to[5]. Therefore, we have high occurrence of events $p_{2,\text{peak}} \leq \frac{Q_{\text{peak}}}{g_{12}}$ and $p_2 = p_{2,\text{peak}}$. As a consequence, primary mean rate is more and more greater than the lower bound $\mathbf{C}_{1,\min}^{(2)}$.

b) Mean transmit and interference powers: in figure 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 (ratio>9) compared to the mean received interference power $\mathbb{E}[p_2\, \hat{g}_{12}]$. Moreover, $\mathbb{E}[p_2]$

[5]From (32), it follows that $Q_{\text{peak}} = -\frac{p_{2,\text{peak}}}{\lambda_{22}\, z_0 + \lambda_{12}} \log\left(1 - \frac{\mathbb{E}[p_2\, \hat{g}_{12}]\left(1 + \frac{\lambda_{22}}{\lambda_{12}} z_0\right)^2}{p_{2,\text{peak}}/\lambda_{12}}\right)$. In realistic situations, we have $Q_{\text{peak}} \geq \mathbb{E}[p_2\, \hat{g}_{12}]$ and $\mathbb{E}[p_2\, \hat{g}_{12}] \leq \frac{p_{2,\text{peak}}/\lambda_{12}}{\left(1 + \frac{\lambda_{22}}{\lambda_{12}} z_0\right)^2}$.

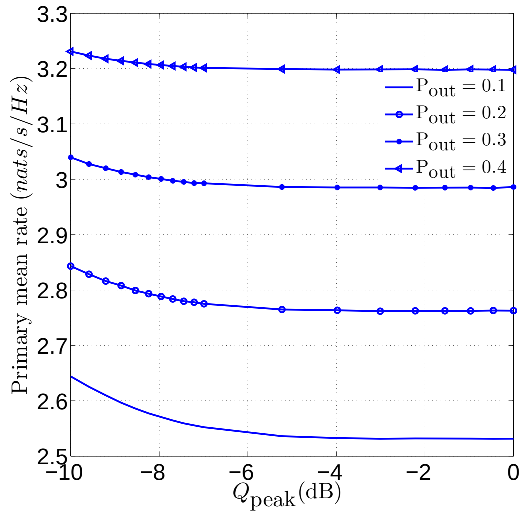

Figure 4. Primary mean rate, $\mathbf{C}_1$, versus peak interference power, Q_{peak}, for different values of outage probability P_{out}.

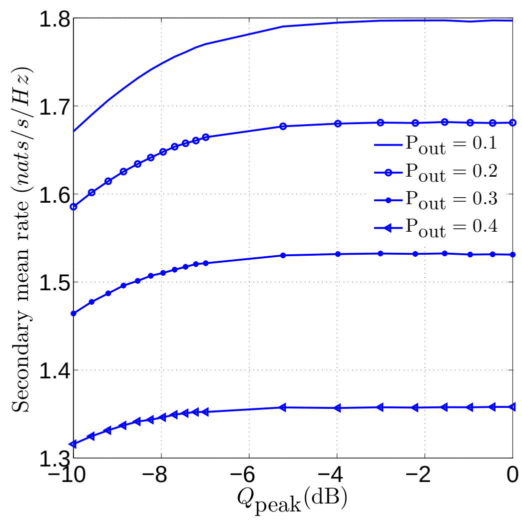

Figure 5. Secondary mean rate, $\mathbf{C}_2$, versus peak interference power, Q_{peak}, for different values of outage probability P_{out}.

increases more speedily than $\mathbb{E}\left[p_2\,\hat{g}_{12}\right]$. Then, we note that the secondary user can achieve important information without causing important interference to the primary user.

c) Outage probability: in figure 8, we plot the outage probability, P_{out}, versus the peak interference power Q_{peak} for different values of the minimum received power K. As predicted, when the primary user is less demanding (Q_{peak} is increasing), the outage probability is decreasing. Otherwise, for given Q_{peak}, the more the secondary user is less demanding (K is decreasing), the more it can transmit frequently over the common spectrum (P_{out} is decreasing). In particular, we note that for greater values of Q_{peak},

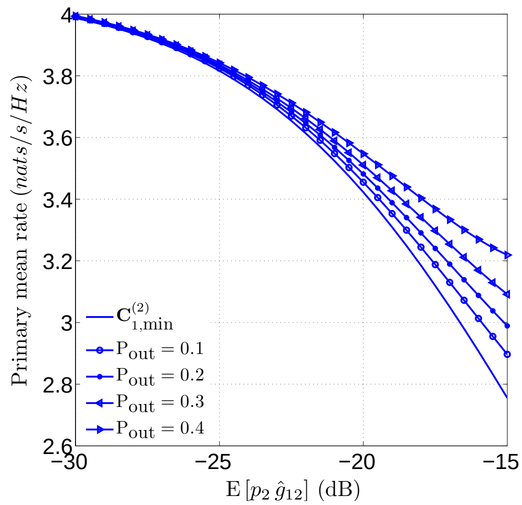

Figure 6. Primary mean rate, $\mathbf{C}_1$, versus mean interference power, $\mathbb{E}\left[p_2\, \hat{g}_{12}\right]$, for different values of outage probability P_{out}.

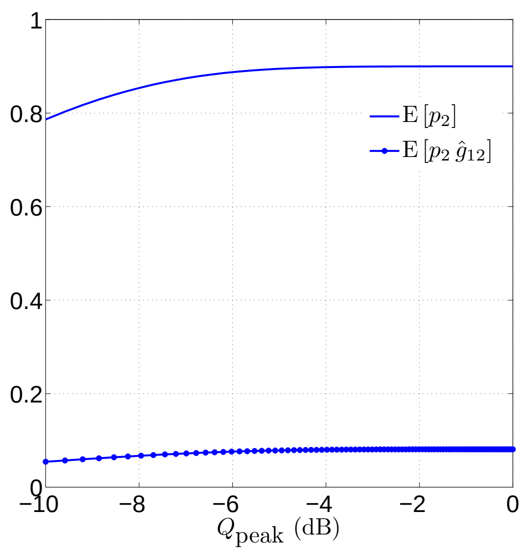

Figure 7. Mean transmit power, $\mathbb{E}\left[p_2\right]$, and mean interference power, $\mathbb{E}\left[p_2\, \hat{g}_{12}\right]$, versus peak interference power Q_{peak}. $p_{2,\text{peak}} = 1$ and $\mathrm{P}_{\text{out}} = 0.1$.

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 figure 9, we plot the evolution of the primary mean rate $\mathbf{C}_1$ and the secondary zero-outage capacity $\mathbf{C}_{2,\text{out}}$ versus $\mathbb{E}\left[p_2\, \hat{g}_{12}\right]$ for $\mathrm{P}_{\text{out}} = 0.1$. Because secondary user transmits with the minimum required power $\mathrm{p}_{2,\text{min}}$ in non-outage states, primary mean rate $\mathbf{C}_1$ decreases slowly with the mean interference power $\mathbb{E}\left[p_2\, \hat{g}_{12}\right]$, while $\mathbf{C}_{2,\text{out}}$ increases speedily because the primary interference

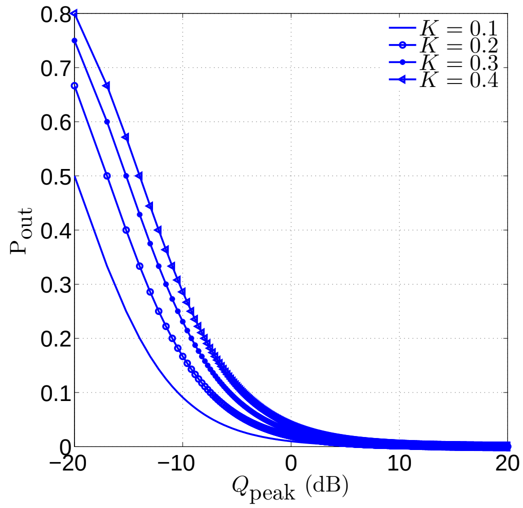

Figure 8. Outage probability, $\mathrm{P}_{\mathrm{out}}$, versus peak interference power, Q_{peak}, for different values of minimum received power, K, required for secondary service.

is neglected. Moreover, figure 10 shows that little mean power is required to achieve $\mathbf{C}_{2,\mathrm{out}}$.

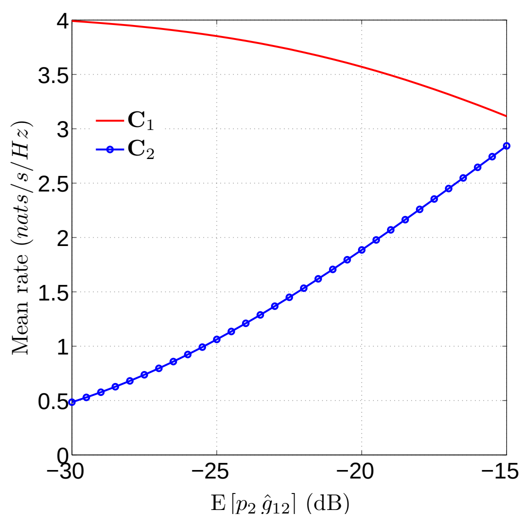

Figure 9. Primary mean rate, $\mathbf{C}_1$, and secondary zero-outage capacity, $\mathbf{C}_{2,\mathrm{out}}$, versus mean interference power, $\mathbb{E}\left[p_2\,\hat{g}_{12}\right]$, for $\mathrm{P}_{\mathrm{out}} = 0.1$.

V. Conclusions

In future wireless communication systems, there will be a need of smart and adequate spectral usage due to the increasing demand in user data rates and to the penury of available spectrum resources. Spectrum

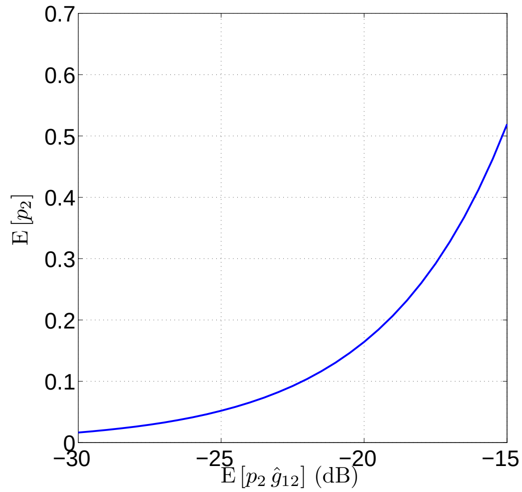

Figure 10. Mean transmit power, $\mathbb{E}\left[p_2\right]$, versus mean interference power, $\mathbb{E}\left[p_2\,\hat{g}_{12}\right]$, for $\mathrm{P}_{\text{out}} = 0.1$.

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 found two lower bounds, for the primary mean rate, depending on the secondary user power control scheme. Several power control policies are investigated 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:

$$\mathbf{C}_{1,\text{min}}^{(1)} = \mathbb{E}\left[\log\left(1 + \frac{X}{\sigma^2 + Y}\right)\right] \tag{47}$$

$$\mathbf{C}_{1,\text{min}}^{(2)} = \mathbb{E}\left[\log\left(1 + \frac{X}{\sigma^2 + \mathrm{Q}_{\text{avg}}}\right)\right], \tag{48}$$

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 (47), first, we derive the probability density function of the random variable Ω defined as

$$\Omega = \frac{X}{\sigma^2 + Y}. \tag{49}$$

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

$$f_T(t) = \begin{cases} \dfrac{\lambda_{12}}{\bar{P}_2} \exp\left(\dfrac{\lambda_{12}}{\bar{P}_2}\sigma^2\right) \exp\left(-\dfrac{\lambda_{12}}{\bar{P}_2} t\right) & \text{if} \quad t \geq \sigma^2 \\ 0 & \text{if} \quad \sigma^2 < t \end{cases} \tag{50}$$

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

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

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

$$f_\Omega(\omega) = \begin{cases} \dfrac{1 + b + \dfrac{b}{a}\omega}{a\left(1 + \dfrac{1}{a}\omega\right)^2} \exp\left(-\dfrac{b}{a}\omega\right) & \text{if} \quad \omega \geq 0 \\ 0 & \text{if} \quad \omega < 0 \end{cases} \tag{51}$$

with [6]

$$a = \frac{\bar{P}_1}{\lambda_{11}} \frac{\lambda_{12}}{\bar{P}_2} \tag{52}$$

$$b = \sigma^2 \frac{\lambda_{12}}{\bar{P}_2}. \tag{53}$$

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

The following equality holds:

$$\frac{1+b+\frac{b}{a}\omega}{a\left(1+\frac{1}{a}\omega\right)^2}\exp\left(-\frac{b}{a}\omega\right)=\left(\frac{a}{(\omega+a)^2}+\frac{b}{\omega+a}\right)\exp\left(-\frac{b}{a}\omega\right), \tag{54}$$

therefore,

$$\begin{aligned}\mathbf{C}_{1,\text{min}}^{(1)} &= \mathbb{E}\left[\log\left(\Omega+1\right)\right]\\ &= \int_0^{+\infty}\left(\frac{a}{(\omega+a)^2}+\frac{b}{\omega+a}\right)\exp\left(-\frac{b}{a}\omega\right)\log\left(\omega+1\right)\,d\omega\\ &= a\int_0^{+\infty}\frac{\log\left(\omega+1\right)}{(\omega+a)^2}\exp\left(-\frac{b}{a}\omega\right)d\omega+b\int_0^{+\infty}\frac{\log\left(\omega+1\right)}{\omega+a}\exp\left(-\frac{b}{a}\omega\right)d\omega. \end{aligned}\tag{55}$$

Now, let

$$\mathrm{I}_1 = \int_0^{+\infty}\frac{\log\left(\omega+1\right)}{\omega+a}\exp\left(-\frac{b}{a}\omega\right)d\omega \tag{56}$$

$$\mathrm{I}_2 = \int_0^{+\infty}\frac{\log\left(\omega+1\right)}{(\omega+a)^2}\exp\left(-\frac{b}{a}\omega\right)d\omega. \tag{57}$$

After an integration of I_1 by parts, we obtain:

$$\mathrm{I}_1=\frac{a}{b}\int_0^{+\infty}\frac{1}{(\omega+1)\,(\omega+a)}\exp\left(-\frac{b}{a}\omega\right)d\omega-\frac{a}{b}\mathrm{I}_2. \tag{58}$$

Then, we can express $\mathrm{I}_1+\frac{a}{b}\mathrm{I}_2$ as:

$$\mathrm{I}_1+\frac{a}{b}\mathrm{I}_2 = \frac{a}{b}\frac{1}{a-1}\left[\int_0^{+\infty}\frac{1}{\omega+1}\exp\left(-\frac{b}{a}\omega\right)d\omega-\int_0^{+\infty}\frac{1}{\omega+a}\exp\left(-\frac{b}{a}\omega\right)d\omega\right], \tag{59}$$

thanks to the equality

$$\frac{1}{(\omega+1)\,(\omega+a)}=\frac{1}{a-1}\left(\frac{1}{\omega+1}-\frac{1}{\omega+a}\right). \tag{60}$$

We can rewrite (59) in terms of integral exponential function E_1, [19]:

$$\mathrm{I}_1+\frac{a}{b}\mathrm{I}_2=\frac{a}{b}\frac{1}{a-1}\left[\exp\left(\frac{b}{a}\right)\mathrm{E}_1\left(\frac{b}{a}\right)-\exp\left(b\right)\mathrm{E}_1\left(b\right)\right], \tag{61}$$

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

$$\begin{aligned}\mathbf{C}_{1,\text{min}}^{(1)} &= b\left(\mathrm{I}_1 + \frac{a}{b}\mathrm{I}_2\right) \\ &= \frac{a}{a-1}\left[\exp\left(\frac{b}{a}\right)\,\mathrm{E}_1\left(\frac{b}{a}\right) - \exp\left(b\right)\,\mathrm{E}_1\left(b\right)\right]. \end{aligned} \tag{62}$$

Replacing a and b by theirs expressions in (52) allows us to write:

$$\mathbf{C}_{1,\text{min}}^{(1)} = \frac{\bar{P}_1}{\bar{P}_1 - \frac{\lambda_{11}}{\lambda_{12}}\bar{P}_2}\left[\exp\left(\frac{\sigma^2\,\lambda_{11}}{\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\sigma^2\,\lambda_{11}}{\bar{P}_1}\right) - \exp\left(\frac{\sigma^2\,\lambda_{12}}{\bar{P}_2}\right)\mathrm{E}_1\left(\frac{\sigma^2\,\lambda_{12}}{\bar{P}_2}\right)\right] \tag{63}$$

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

Now, let $\alpha = \dfrac{1}{\sigma^2 + Q_{\text{avg}}}$. We have:

$$\begin{aligned}\mathbf{C}_{1,\text{min}}^{(2)} &= \mathbb{E}\left[\log\left(1+\alpha\,X\right)\right] \\ &= \frac{\lambda_{11}}{\bar{P}_1}\int_0^{+\infty}\log\left(1+\alpha\,x\right)\,\exp\left(-\frac{\lambda_{11}}{\bar{P}_1}x\right)\,dx. \end{aligned} \tag{64}$$

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

$$\begin{aligned}\mathbf{C}_{1,\text{min}}^{(2)} &= \int_0^{+\infty}\frac{\alpha}{\alpha\,x+1}\,\exp\left(-\frac{\lambda_{11}}{\bar{P}_1}x\right)\,dx \\ &= \exp\left(\frac{\lambda_{11}}{\alpha\,\bar{P}_1}\right)\,\mathrm{E}_1\left(\frac{\lambda_{11}}{\alpha\,\bar{P}_1}\right) \\ &= \exp\left(\frac{\lambda_{11}\left(\sigma^2+Q_{\text{avg}}\right)}{\bar{P}_1}\right)\mathrm{E}_1\left(\frac{\lambda_{11}\left(\sigma^2+Q_{\text{avg}}\right)}{\bar{P}_1}\right). \end{aligned} \tag{65}$$

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:

$$\begin{aligned}\mathbb{E}\left[p_2\right] &= \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,p_{2,\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy \\ &+ \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\frac{Q_{\text{peak}}}{x}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy. \qquad (66)\end{aligned}$$

Now, let

$$\mathrm{I}_1' = \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,p_{2,\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy, \qquad (67)$$

$$\mathrm{I}_2' = \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,\frac{Q_{\text{peak}}}{x}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy. \qquad (68)$$

Integral I_1' is obtained as:

$$\begin{aligned}\mathrm{I}_1' &= p_{2,\text{peak}} \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \lambda_{12}\,\exp\left(-\lambda_{12}\,x\right)\,\left(\int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\exp\left(-\lambda_{22}\,y\right)\,dy\right)\,dx \\ &= p_{2,\text{peak}} \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \lambda_{12}\,\exp\left(-\left(\lambda_{12}+\frac{\lambda_{22}\,K}{Q_{\text{peak}}}\right)\,x\right)\,dx \\ &= \frac{p_{2,\text{peak}}}{1+\frac{\lambda_{22}}{\lambda_{12}}\,\frac{K}{Q_{\text{peak}}}}\left[1-\exp\left(-\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right)\right]. \qquad (69)\end{aligned}$$

Integral I_2' is obtained as:

$$\begin{aligned}\mathrm{I}_2' &= \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \lambda_{12}\,\frac{Q_{\text{peak}}}{x}\,\exp\left(-\lambda_{12}\,x\right)\,\left(\int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\exp\left(-\lambda_{22}\,y\right)\,dy\right)\,dx \\ &= \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \lambda_{12}\,\frac{Q_{\text{peak}}}{x}\,\exp\left(-\left(\lambda_{12}+\frac{\lambda_{22}\,K}{Q_{\text{peak}}}\right)\,x\right)\,dx \\ &= \lambda_{12}\,Q_{\text{peak}}\,\mathrm{E}_1\left(\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right). \qquad (70)\end{aligned}$$

Finally, we have:

$$\mathbb{E}\left[p_2\right] = \frac{p_{2,\text{peak}}}{1+\frac{\lambda_{22}}{\lambda_{12}}\,\frac{K}{Q_{\text{peak}}}}\left[1-\exp\left(-\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right)\right]+\lambda_{12}\,Q_{\text{peak}}\,\mathrm{E}_1\left(\frac{\lambda_{22}\,K+\lambda_{12}\,Q_{\text{peak}}}{p_{2,\text{peak}}}\right) \qquad (71)$$

The mean interference power is expressed as:

$$\mathbb{E}\left[p_2\,\hat{g}_{12}\right] = \mathrm{I}_1'' + \mathrm{I}_2'', \tag{72}$$

with:

$$\begin{aligned} \mathrm{I}_1'' &= \int_0^{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,x\,p_{2,\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy, \\ \mathrm{I}_2'' &= \int_{\frac{Q_{\text{peak}}}{p_{2,\text{peak}}}}^{+\infty} \int_{\frac{K}{Q_{\text{peak}}}x}^{+\infty} \lambda_{22}\,\lambda_{12}\,Q_{\text{peak}}\,\exp\left(-\lambda_{22}\,y\right)\,\exp\left(-\lambda_{12}\,x\right)\,dx\,dy. \end{aligned} \tag{73}$$

Integral I_1'' is obtained as follows:

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

and integral I_2'' as:

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

Finally, the mean interference power is expressed as:

$$\mathbb{E}\left[p_2\,\hat{g}_{12}\right] = \frac{p_{2,\text{peak}}/\lambda_{12}}{\left(1 + \frac{\lambda_{22}}{\lambda_{12}}\frac{K}{Q_{\text{peak}}}\right)^2}\left[1 - \exp\left(-\frac{\lambda_{12}\,Q_{\text{peak}} + \lambda_{22}\,K}{p_{2,\text{peak}}}\right)\right]. \tag{74}$$

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