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Effective Capacity of A Novel Spectrum-Band Selection Scheme in Spectrum-Sharing Networks

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***Abstract*— In this correspondence, a spectrum-band selection scheme is developed for secondary users (SUs) in underlay spectrum-sharing networks, to balance the performance between SUs and primary users (PUs) while guaranteeing PUs' priority. With the developed scheme, among multiple candidate spectrum-bands, a given secondary transmitter (ST) is scheduled to access the spectrum-band with minimum ratio of the ST–PU channel power gain to the SU link channel power gain. To evaluate this scheme, the SU's performance is investigated concerning its service delay. Under the constraint on average interference from the ST to PUs, the ST's optimal power allocation is obtained in a closed form to achieve the maximum effective capacity over SU links. Illustrative numerical results and asymptotic discussions substantiate the validity of our derivations and, moreover, demonstrate that for the case of stringent delay requirements but loose average-interference constraint, the band-selection scheme developed in this correspondence achieves better performance than both the selection of the band with maximum SU link channel power gain and that with minimum ST–PU channel power gain.**

***Index Terms*— Spectrum sharing, band selection, power allocation, effective capacity (EC).**

I. Introduction

As a limited resource, the radio frequency spectrum is experiencing ever-increasing congestion due to more and more wireless services emergence. To provide more flexibility for spectrum allocation, dynamic spectrum access has been widely studied, where secondary users (SUs) are allowed to access a licensed spectrum as long as the quality-of-service (QoS) over primary links is acceptable [1]–[3].

One way to make sure primary users (PUs) in underlay spectrum-sharing networks have acceptable QoS is the service-delay constraint imposed on SUs. That is, SUs are required to operate in a delay-sensitive mode so that PUs may not suffer long-time interference from SUs. Given that SUs' service delay is limited to be less than a predetermined threshold, their performance is investigated in terms of effective capacity (EC). The concept of EC has been introduced as a metric at the link layer [4], [5], and it is defined as the maximum achievable data rate that can be supported by the communicating link while satisfying the delay requirement [6]. For a single band available in spectrum-sharing networks, the SUs' EC behaviors have been considered in [7], [8]. As revealed in [9], if the delay requirement gets more stringent, the EC degrades significantly. This issue can be handled by engaging multiple parallel channels, e.g., non-overlapping spectrum-bands.

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Currently, multi-band sensing has been initiated in spectrum-sharing networks, e.g., [10], [11] and references therein. Motivated by this issue, this work considers the SUs' EC behaviors in the spectrum-sharing networks with multiple bands available. In this context, the most important question is how to exploit these spectrum bands with the highest efficiency. An intuitive solution is to select one out of those available bands for a given SU, so as to avoid severe interference to PUs while lowering the complexity in network design, operating synchronization and hardware realization.

In the band selection, we need to consider the performance balance between SUs and PUs. To achieve efficient operations over secondary links while guaranteeing PUs' priority, two fading channels are involved in the selection criteria, i.e., the channel from the secondary transmitter (ST) to its own receiver, i.e., the secondary receiver (SR), and the channel from the ST to the PU that is the most sensitive to the ST's transmissions. Herein, the ST–SR channel is referred to as *desired channel*, whereas the ST–PU channel is referred to as *interference channel*. In [12], a band-selection criterion is developed to choose the band with the maximum ratio of desired channel power gain to interference channel power gain. Moreover, in our previous work [13], two band-selection criteria were developed — one is to select the band with the maximum desired channel power gain, and the other is to select the band with the minimum interference channel power gain.

In this correspondence, we consider the criterion that selects the spectrum-band with the minimum ratio of interference channel power gain to desired channel power gain. With this criterion, exact EC performance analysis over general Rayleigh fading channels is fulfilled and the maximal EC in the SU link is obtained in closed form. Specifically, the main contributions in this correspondence are three-fold:

- The assumption on finite means of channel power gains is released. In this correspondence, the general Rayleigh fading channel model is considered for arbitrary means of channel power gains in the desired channel and interference channel.
- With the general channel model, closed-form solutions are obtained for the band-selection criterion considered in this correspondence to the convex optimization problem of SUs' achieving maximum EC under the delay requirement.

- Given the generality, it is convenient to exploit the obtained closed-form solutions in the comparisons among different band-selection criteria, thus allowing more band-selection strategies to circulate in our research community.

In detailing the above highlighted contributions, the remainder of this correspondence is organized as follows. Section II describes the spectrum-sharing system model with multiple spectrum-bands available for SUs and proposes the criterion to select a spectrum band out of multiple candidates for a given SU. In Section III, the SU's optimal power allocation and EC behaviors are analyzed for the proposed band-selection scheme. Based on the theoretical analyses, Section IV presents numerical results and asymptotic discussions, as well as compares the SU's performance between the band-selection scheme considered in this correspondence and those developed in [13]. In addition, the assumption of independent and non-identically distributed (i.n.i.d.) channels is discussed in Section V. Finally, Section VI concludes this correspondence.

Notations: For a random variable X, $f_X(X)$ denotes the probability density function (PDF) and $F_X(X)$ denotes the cumulative distribution function (CDF). Subsequently, $\mathcal{E}\{X\}$ represents the expectation operator and $\mathcal{E}_X\{\cdot\}$ represents the expectation over the PDF of X. Moreover, the probability of an event is denoted by $\Pr\{\cdot\}$. Furthermore, the operator $\{x\}^+$ denotes $\max\{0, x\}$ and ${}_2F_1(a, b; c; x)$ is the Gauss hypergeometric function.

II. System Model

In this work, we consider a spectrum-sharing network, where K non-overlapping spectrum bands are available for secondary communications and the width of each band is B.

For the multi-band operating environment under study, a ST trying to access each spectrum-band should consider the impact of its transmissions on the reception quality of the PUs in this band and control its transmit power to guarantee its interference to the PUs below a target threshold. In each band, we focus on the interference to the PU that is the most sensitive to the ST's transmissions [7], [14]. As such, the PU affected most by the ST in the k^{th} band is denoted by $\text{PU}^{(k)}$, where $k = 1, 2, \cdots, K$. If the interference from the ST to $\text{PU}^{(k)}$ is below the predetermined threshold, the interference from the ST to other PUs in this band will be acceptable.

Let h_k and g_k ($k = 1, 2, \cdots, K$) denote the instantaneous channel power gains from ST to SR (i.e., *desired channel* power gain) and from ST to $\text{PU}^{(k)}$ (i.e., *interference channel* power gain), respectively, over the k^{th} band. All these channels are frequency-flat and block-fading. As the distance between SR and $\text{PU}^{(k)}$ is surely larger than half of the carrier wavelength, h_k and g_k must be independent of each other. Without loss of generality, the mean power gain of the interference channel (ST–$\text{PU}^{(k)}$) over each band is assumed to be the same, i.e., $\bar{g}_k = \bar{g}$, $\forall k \in \{1, 2, \cdots, K\}$, and so does the mean power gain of the desired channel (ST–SR) over each band, i.e., $\bar{h}_k = \bar{h}$, $\forall k \in \{1, 2, \cdots, K\}$.

A. Spectrum-Sharing Constraint

Over an arbitrary band, the constraint on the received interference at PUs therein can be characterized by translating it into the constraint on the ST's transmit power. In the k^{th} band, the ST's instantaneous transmit power is denoted by $P_k(h_k, g_k)$, which is determined by the instantaneous channel power gains h_k and g_k. Elaborating slightly further, the spectrum-sharing constraint imposed on the interference from ST to $\text{PU}^{(k)}$ in the k^{th} band can be expressed by [14]

$$\mathcal{E}_{h_k, g_k}\{P_k(h_k, g_k) g_k\} \leqslant Q, \tag{1}$$

where Q is the predetermined threshold that limits average interference from the ST to $\text{PU}^{(k)}$. All PUs active in the k^{th} band do not tolerate average interference higher than the limitation Q.

In collaboration schemes [7], [14], the ST may obtain the information of h_k from the SR's feedback and observe g_k by monitoring the PU's transmission, so as to control its transmit power. In addition, the ST's power allocation can also be carried out by a band manager that intervenes between SUs and PUs [1]–[3], while balancing SUs' performance and the interference to PUs.

B. Band-Selection Criterion

In order to lower hardware cost and avoid severe interference to primary links, the SU selects one among the K available spectrum-bands to fulfill its operation in each transmission period. A superscript "$*$" is used to denote the selected band, e.g., h^* and g^* denote the desired and interference channel power gains, respectively, over the selected spectrum-band.

For the spectrum sharing, SUs are supposed to achieve the best performance while maintaining the PUs' QoS at the required level. Aiming at this issue, we develop a criterion for a given SU to select a band among K available candidates, where the selected band is the one having the minimum ratio of $\rho^* = g^*/h^*$, i.e., $\rho^* = \min\{\rho_1, \rho_2, \cdots, \rho_K\}$ with $\rho_k = g_k/h_k$. The goal is to balance the performance between PUs and SUs, i.e., to guarantee the QoS for PUs while achieving efficient operations for SUs.

As the channels follow independent and identically distributed (i.i.d.) complex Gaussian distributions with Rayleigh distributed amplitudes, their channel power gains follow independent exponential distributions with the PDFs given by

$$f_h(h_k) = \left(1/\bar{h}\right) \exp\left(-h_k/\bar{h}\right), \qquad h_k \geqslant 0, \tag{2}$$

and

$$f_g(g_k) = (1/\bar{g}) \exp(-g_k/\bar{g}), \qquad g_k \geqslant 0, \tag{3}$$

for $k = 1, 2, \cdots, K$.

Therefore, the PDF of $\rho_k = g_k/h_k$, $k = 1, 2, \cdots, K$, can be calculated by

$$\begin{aligned} f_\rho(\rho_k) &= \int_0^\infty h_k f_g(\rho_k h_k) f_h(h_k)\, \mathrm{d}h_k \\ &= \frac{1}{\bar{g}\bar{h}} \int_0^\infty h_k \exp\left(-\frac{\rho_k h_k}{\bar{g}} - \frac{h_k}{\bar{h}}\right) \mathrm{d}h_k \\ &\overset{(a)}{=} \frac{\bar{g}\bar{h}}{\left(\bar{h}\rho_k + \bar{g}\right)^2}, \end{aligned} \tag{4}$$

where the equality (a) makes use of [15, 3.351]. Then, the CDF of ρ_k is obtained by

$$F_\rho(\rho_k) = \int_0^{\rho_k} \frac{\bar{g}\bar{h}}{\left(\bar{h}\rho + \bar{g}\right)^2} \mathrm{d}\rho = 1 - \frac{\bar{g}}{\bar{h}\rho_k + \bar{g}}. \tag{5}$$

Subsequently, the CDF of $\rho^* = \min\{\rho_1, \rho_2, \cdots, \rho_K\}$ is formulated as

$$F_{\rho^*}(\rho^*) = 1 - \prod_{k=1}^{K} \left[1 - F_{\rho_k}(\rho^*)\right] = 1 - \left(\frac{\bar{g}}{\bar{h}\rho^* + \bar{g}}\right)^K, \tag{6}$$

and, accordingly, the PDF of ρ^* is given by

$$f_{\rho^*}(\rho^*) = \frac{\mathrm{d}F_{\rho^*}(\rho^*)}{\mathrm{d}\rho^*} = \frac{K\bar{g}^K\bar{h}}{(\bar{h}\rho^* + \bar{g})^{K+1}}. \tag{7}$$

III. Effective Capacity and Power Allocation with Novel Spectrum-Band Selection

For the ST–SR communications, upper-layer packets are structured into frames with the same time duration, T_f, at the data-link layer. These frames are stored in the transmit buffer and then divided into bit streams that will be transmitted via the physical layer. Herein, the number of available bands for ST–SR communications is assumed to keep constant for a long period, which is consistent with the EC concept.

In practice, the ST's transmission is required to satisfy a constraint on the service delay. As shown in [4] and [5], the probability that the queue length of the transmit buffer exceeds a certain threshold, x, decays exponentially as a function of x. Accordingly, the requirement on service delay can be characterized by a factor in the unit of [1/bit], defined as

$$\theta = -\lim_{x\to\infty} \frac{\log_2\left(\Pr\{q(\infty) > x\}\right)}{x}, \tag{8}$$

where $q(n)$ denotes the length of transmit buffer at time n, $n = 1, 2, \cdots, \infty$. Note that a smaller θ corresponds to a looser necessity, whereas a larger θ implies a stringent one. In particular, $\theta \to 0$ means that the system is able to tolerate infinite packet delay, and $\theta \to \infty$ implies that no delay is allowed in the system.

Based on the dual of effective bandwidth concept, the EC of a wireless link is defined as the maximum achievable data rate that can be supported in the system under the requirement on service delay (with the factor θ) [4], [6]. To maximize the data rate over each channel as channel capacity, the ST's transmitted signals are assumed to be random variable from i.i.d. complex Gaussian ensemble. In addition, the interference from PUs to the SR is assumed to be additive white Gaussian noise and, accordingly, the equivalent power spectral density of the total noise received at the SR is denoted by N_0. As such, in block-fading channels, the SU's EC over the selected band can be formulated as [7], [8]

$$E_c(\theta) = -\frac{1}{\theta}\ln\left(\mathcal{E}_{h^*,g^*}\left\{e^{-\theta T_f B \ln\left(1+\frac{Ph^*}{N_0 B}\right)}\right\}\right), \tag{9}$$

where P is the ST's transmit power. In the following, we will show that the ST's power allocation can be expressed as a function of the delay requirement factor θ, the interference channel power gain g^* and the desired channel power gain h^*.

Since $\ln(\cdot)$ is a monotonically increasing function, to achieve the maximization of the SU's EC in (9), i.e., $\max\{E_c(\theta)\}$, the ST's optimal transmit power P can be determined as the solution to the optimization problem given by

$$\min\left\{\mathcal{E}_{h^*,g^*}\left\{\left(1+\frac{Ph^*}{N_0 B}\right)^{-\theta T_f B}\right\}\right\} \tag{10}$$

$$\text{subject to:} \quad \mathcal{E}_{h^*,g^*}\{Pg^*\} \leqslant Q, \tag{10a}$$

$$P \geqslant 0. \tag{10b}$$

By denoting the function $s(P^*) \triangleq \left(1+\frac{P^*h^*}{N_0B}\right)^{-\xi}$, where $\xi = \theta T_f B > 0$, we have

$$\frac{\mathrm{d}^2 s(P^*)}{\mathrm{d}(P^*)^2} = \left(\frac{h^*}{N_0B}\right)^2 \xi(\xi+1)\left(1+\frac{P^*h^*}{N_0B}\right)^{-\xi-2} > 0. \tag{11}$$

As such, according to the second-order conditions of convex function, $s(P^*)$ is strictly convex for P^*. Further, since the expectation with respect to h^* and g^* is a linear operation for P^*, $\mathcal{E}_{h^*,g^*}\{s(P^*)\}$ is also strictly convex for P^* [16, Ch3]. As a consequence, (10) is a convex optimization problem and the Karush-Kuhn-Tucker (KKT) conditions are necessary and sufficient for its optimality [16, Ch5]. Thereby, the Lagrangian is formed as

$$\mathcal{L}(P,\lambda) = \mathcal{E}_{h^*,g^*}\left\{\left(1+\frac{Ph^*}{N_0B}\right)^{-\xi}\right\} + \lambda\left[\mathcal{E}_{h^*,g^*}\{Pg^*\} - Q\right], \tag{12}$$

and the optimal power allocation should satisfy

$$\left[\left(-\frac{\xi h^*}{N_0B}\right)\left(1+\frac{Ph^*}{N_0B}\right)^{-\xi-1} + \lambda g^*\right] f_{h^*}(h^*)\, f_{g^*}(g^*) = 0. \tag{13}$$

By solving (13), given that $P \geqslant 0$ in (10b), the ST's optimal transmit power in the selected band is achieved at

$$P^* = \left\{\left(\frac{\xi}{\lambda g^*}\right)^{\frac{1}{\xi+1}}\left(\frac{N_0B}{h^*}\right)^{\frac{\xi}{\xi+1}} - \frac{N_0B}{h^*}\right\}^+, \tag{14}$$

where the Lagrange multiplier λ is determined by (10a), i.e., the constraint on the interference from the ST to the considered PU in the selected band.

Further, (14) can be re-written as

$$P^* = \begin{cases} \left(\frac{\xi}{\lambda g^*}\right)^{\frac{1}{\xi+1}}\left(\frac{N_0B}{h^*}\right)^{\frac{\xi}{\xi+1}} - \frac{N_0B}{h^*}, & \rho^* \leqslant \frac{\xi}{\lambda N_0 B}; \\ 0, & \rho^* > \frac{\xi}{\lambda N_0 B}. \end{cases} \tag{15}$$

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As the ST's power allocation is imposed by its interference limitation to PUs, one may observe that (14) behaves similarly to the well-known water-filling power allocation algorithm constrained by the maximum transmit power [17]. The item $\xi/(\lambda N_0 B)$ pertains to the so-called water-level, which prescribes the proportion between the interference and desired channel power gains, subject to the interference threshold Q. If the ratio $\rho^* = g^*/h^*$ is larger than the water-level, i.e., the instantaneous interference channel power gain $g^* > h^*\xi/(\lambda N_0 B)$, the ST has to be silent so as to guarantee primary communications in the spectrum-sharing context.

By substituting (15) into (10a) and setting the latter to equality, the Lagrange multiplier λ can be obtained by solving the following equation:

$$\begin{aligned} Q &= \int_0^{\frac{\xi}{\lambda N_0 B}} \left[\left(\frac{\xi}{\lambda}\right)^{\frac{1}{\xi+1}} (N_0 B\rho^*)^{\frac{\xi}{\xi+1}} - N_0 B\rho^* \right] f_{\rho^*}(\rho^*)\mathrm{d}\rho^* \\ &= \frac{\beta K \xi^2(\xi+1)}{\lambda^2 N_0 B(2\xi+1)}\, {}_2F_1\left(K+1, \frac{2\xi+1}{\xi+1}; \frac{3\xi+2}{\xi+1}; -\frac{\beta\xi}{\lambda N_0 B}\right) \\ &\quad - \frac{\beta K \xi^2}{2\lambda^2 N_0 B}\, {}_2F_1\left(K+1, 2; 3; -\frac{\beta\xi}{\lambda N_0 B}\right), \end{aligned} \tag{16}$$

where the PDF $f_{\rho^*}(\rho^*)$ is given by (7) and the parameter $\beta = \bar{h}/\bar{g}$. Moreover, the second equality follows [15, 3.194].

Subsequently, under the constraint on the interference from the ST to PUs, the SU's EC in the selected band is established as

$$\begin{aligned} E_c^*(\theta) &= -\frac{1}{\theta}\ln\left(\int_0^{\frac{\xi}{\lambda N_0 B}} \left(\frac{\lambda N_0 B\rho^*}{\xi}\right)^{\frac{\xi}{\xi+1}} f_{\rho^*}(\rho^*)\mathrm{d}\rho^* \right) \\ &= -\frac{1}{\theta}\ln\left(\int_0^{\frac{\xi}{\lambda N_0 B}} \left(\frac{\lambda N_0 B\rho^*}{\xi}\right)^{\frac{\xi}{\xi+1}} \frac{K\bar{g}^K\bar{h}}{(\bar{h}\rho^* + \bar{g})^{K+1}}\mathrm{d}\rho^* \right) \\ &= -\frac{1}{\theta}\ln\left(\frac{\beta K\xi(\xi+1)}{\lambda N_0 B(2\xi+1)} \right. \\ &\qquad \left. \times\, {}_2F_1\left(K+1, \frac{2\xi+1}{\xi+1}; \frac{3\xi+2}{\xi+1}; -\frac{\beta\xi}{\lambda N_0 B}\right)\right), \end{aligned} \tag{17}$$

thus leading to a closed-form expression for the SU's EC of the proposed band-selection scheme, concerning the requirement on its service delay.

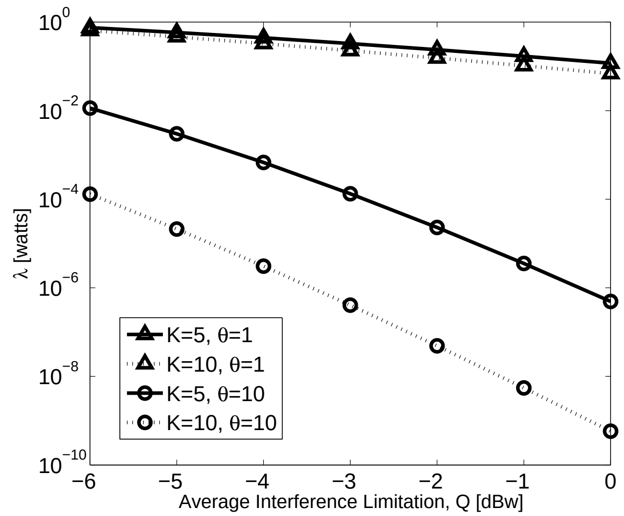

Fig. 1. The Lagrangian multiplier λ vs. the interference threshold, Q, for the number of available spectrum-bands $K = 5, 10$, the delay requirement factor $\theta = 1, 10$, and the ratio of mean channel power gains $\beta = \bar{h}/\bar{g} = 1$.

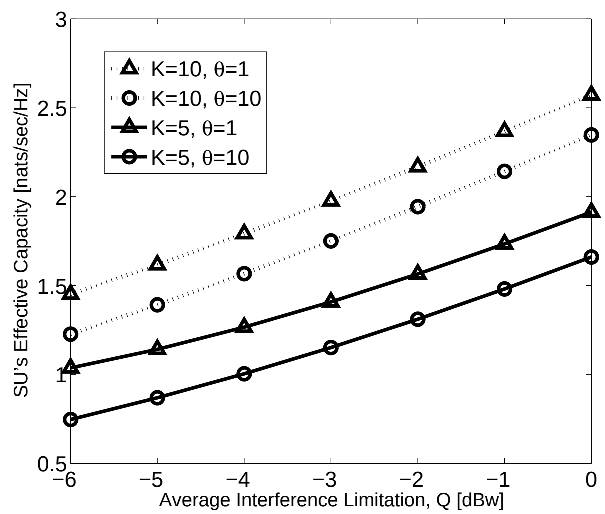

Fig. 2. Secondary user's effective capacity vs. the interference threshold, Q, for the number of available spectrum-bands $K = 5, 10$, the delay requirement factor $\theta = 1, 10$, and the ratio of mean channel power gains $\beta = \bar{h}/\bar{g} = 1$.

IV. Performance Evaluation

Based on the above analysis and mathematical derivations, in this section we numerically and asymptotically illustrate the SU's EC performance with the delay requirement θ for the proposed band-selection criterion, under constraint on the interference from ST to PUs, to get advanced insights. Moreover, to further demonstrate the merit of the band-selection criterion considered in this correspondence, it is compared with those criteria developed in [13].

A. Numerical Results

Herein, we assume $T_f B = 1$, i.e., $\xi = \theta T_f B = \theta$, and $N_0 B = 1$. To begin with, by setting the mean channel power gains $\bar{h} = \bar{g}$, i.e, $\beta = \bar{h}/\bar{g} = 1$, we plot the Lagrangian multiplier λ and the SU's EC in Figs. 1 and 2, respectively, as functions of the interference threshold Q, for $K = 5$ and 10 available spectrum-bands in the spectrum-sharing network, with the delay requirement factor $\theta = 1$ and 10.

As shown in Fig. 1, the value of λ is reduced with the increase in Q, which is in accordance with (16). In detail, for the first equality of (16), if λ decreases, both the integrand and the domain of the integration get larger, which leads to increasing Q.

From Fig. 2, we observe that the SU's EC is improved with the increase in the number of available spectrum-bands, K, as well as with the increase in the interference threshold Q. On the other hand, as θ increases, i.e., the requirement on service

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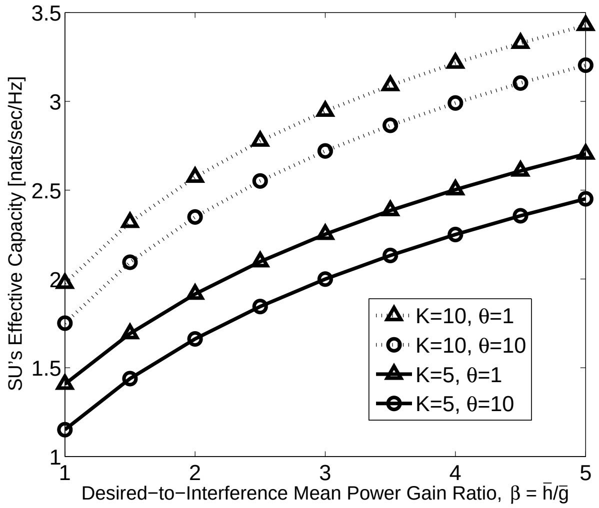

Fig. 3. Secondary user's effective capacity vs. the ratio of desired-to-interference mean channel power gains, $\beta = \bar{h}/\bar{g}$, for the number of available spectrum-bands $K = 5, 10$, the delay requirement factor $\theta = 1, 10$, and the average interference limitation $Q = -3$dB.

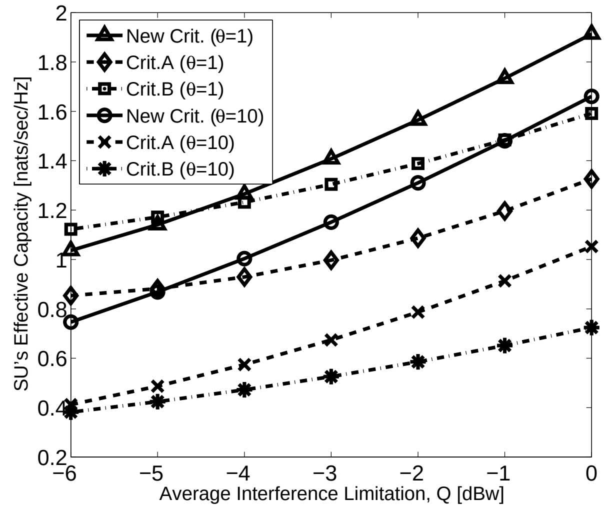

Fig. 4. Comparisons among different band-selection criteria for the number of available spectrum-bands $K = 5$, the delay requirement factor $\theta = 1, 10$, and the ratio of mean channel power gains $\beta = \bar{h}/\bar{g} = 1$. ("New Crit." stands for the band-selection criterion considered in this correspondence, i.e., to select the spectrum-band with minimum ratio of interference-to-desired channel power gains. "Crit. A" stands for Criterion A in [13], i.e., to select the spectrum-band with maximum desired channel power gain. "Crit. B" stands for Criterion B in [13], i.e., to select the spectrum-band with minimum interference channel power gain.)

delay gets more stringent, the SU's EC is reduced.

Furthermore, to demonstrate the effect of the difference between desired and interference channels power gains on the SU's performance, the SU's EC versus the ratio of desired-to-interference mean channel power gains $\beta = \bar{h}/\bar{g}$ is depicted in Fig. 3, where the average interference limitation $Q = -3$dB, the delay requirement factor $\theta = 1, 10$, and the number of available spectrum-bands $K = 5, 10$. This figure reveals that, as β increases, the SU's EC is improved. That is, the higher is the desired channel power gain over the interference channel power gain, the higher is the achievable EC over secondary links.

B. Asymptotic Discussions

1) The Delay Requirement $\theta \to 0$: In this case, the system can tolerate infinite packet delay and, thus, the parameter $\xi = \theta T_f B \to 0$. From the SU's EC expression in (17), we have

$$\lim_{\theta \to 0} E_c^*(\theta) = +\infty, \tag{18}$$

That is, if there is no limitation imposed on the packet delay, i.e., the transmission duration goes to infinity, the SU can achieve infinite EC as the interference threshold Q, the number of available spectrum-bands, K, and the ratio of mean channel power gains, $\beta = \bar{h}/\bar{g}$, are given.

2) The ratio of mean channel power gains $\beta = \bar{h}/\bar{g} \to 0$: In this case, the mean power gain of the interference channel is far more than that of the desired channel, i.e., $\bar{g} \gg \bar{h}$. Therefore, the ST's transmission results in heavy interference to PUs, compared to its poor service to the SR.

By comparing (16) and (17), we have the relation between $E_c^*(\theta)$ and Q as

$$E_c^*(\theta) = -\frac{1}{\theta} \ln \left(\frac{\lambda Q}{\xi} + \frac{\beta K \xi}{2\lambda N_0 B} \times {}_2F_1\left(K+1, 2; 3; -\frac{\beta\xi}{\lambda N_0 B}\right)\right). \tag{19}$$

Then, the SU's EC in the case of $\beta \to 0$ can be obtained by

$$\lim_{\beta \to 0} E_c^*(\theta) = -\frac{1}{\theta} \ln \left(\frac{\lambda Q}{\xi}\right) = -\frac{1}{\theta} \ln \left(\frac{\lambda Q}{\theta T_f B}\right). \tag{20}$$

C. Comparisons with Other Band-Selection Criteria

In our previous work [13], two different band-selection criteria were developed, where *Criterion A* is to select the spectrum-band with maximum desired channel power gain and *Criterion B* is to select the spectrum-band with minimum interference channel power gain. To further demonstrate the advantage of the band-selection criterion considered in this correspondence (referred to as *new criterion* in this subsection), the SU's EC behaviors are compared among Criterion A, Criterion B and the new criterion in Fig. 4 under the constraint on average interference from ST to PUs, where the ratio of mean channel power gains $\beta = \bar{h}/\bar{g} = 1$, the number of available spectrum-bands $K = 5$, and the delay requirement factor $\theta = 1, 10$. As is shown in this figure, the new criterion almost dominates the comparisons, specifically in the case of stringent service-delay requirement (i.e., $\theta = 10$). However, for the case of loose service-delay requirement (i.e., $\theta = 1$), when the average interference limitation Q is lower than

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-5dBw, Criterion B achieves better performance than the new criterion.

V. Discussions on Independent and Non-Identically Distributed Channels

In previous sections, we focused on i.i.d. channels in the spectrum-sharing network under study. As this condition may not hold in some applications, we further consider the scenarios with i.n.i.d. channels in this section. Herein, the desired and interference channel power gains, h_k and g_k, follow independent exponential distributions with the PDFs expressed as $f_h(h_k) = (1/\bar{h}_k)\exp(-h_k/\bar{h}_k)$, $h_k \geqslant 0$, and $f_g(g_k) = (1/\bar{g}_k)\exp(-g_k/\bar{g}_k)$, $g_k \geqslant 0$, respectively, where $\bar{h}_k$ and $\bar{g}_k$ denote mean channel power gains of the corresponding desired and interference channels, with $k = 1, 2, \cdots, K$ standing for the indexes of candidate spectrum-bands.

As such, the PDF and CDF of $\rho_k = g_k/h_k$, $k = 1, 2, \cdots, K$, can be formulated by $f_\rho(\rho_k) = \bar{g}_k\bar{h}_k/(\bar{h}_k\rho_k + \bar{g}_k)^2$ and $F_\rho(\rho_k) = 1 - \bar{g}_k/(\bar{h}_k\rho_k + \bar{g}_k)$, respectively.

With the band-selection criterion considered in this correspondence, the SU operates over the spectrum-band with minimum ratio of interference-to-desired channel power gains in each transmission period. Therein, the CDF of $\rho^* = \min\{\rho_1, \rho_2, \cdots, \rho_K\}$ is formulated as

$$F_{\rho^*}(\rho^*) = 1 - \prod_{k=1}^{K}\left[1 - F_{\rho_k}(\rho^*)\right] = 1 - \prod_{k=1}^{K}\frac{\bar{g}_k}{\bar{h}_k\rho^* + \bar{g}_k}, \quad (21)$$

and, accordingly, the PDF of ρ^* is obtained by

$$\begin{aligned} f_{\rho^*}(\rho^*) &= \frac{\mathrm{d}F_{\rho^*}(\rho^*)}{\mathrm{d}\rho^*} \\ &= \sum_{k=1}^{K}\left(\prod_{l=1, l\neq k}^{K}\frac{\bar{g}_l\bar{g}_k\bar{h}_k}{(\bar{h}_l\rho^* + \bar{g}_l)(\bar{h}_k\rho^* + \bar{g}_k)^2}\right). \end{aligned} \quad (22)$$

Subsequently, by substituting (22) into $E_c^*(\theta) = -(1/\theta)\ln\left(\int_0^{\eta}(\rho^*/\eta)^{\xi/(\xi+1)} f_{\rho^*}(\rho^*)\mathrm{d}\rho^*\right)$, where $\eta = \xi/(\lambda N_0 B)$, the SU's EC of the band-selection scheme considered in this correspondence can be achieved in a numerical way.

VI. Conclusions

For spectrum-sharing networks with multiple spectrum-bands available, we developed a novel scheme for SUs to select the spectrum band. With this scheme, the band with minimum ratio of interference channel power gain to desired channel power gain is scheduled for a given ST to access. Moreover, concerning the service-delay requirement on SU links, we investigated the SU's EC performance of the proposed band-selection scheme under the constraint on average interference from the ST to PUs. Therein, the ST's optimal transmit power allocation was achieved to maximize the SU's EC. Subsequently, illustrative numerical results and asymptotic discussions not only endorsed our theoretical analysis but also provided a useful reference for the exploitation of the developed scheme. Furthermore, as demonstrated in performance comparisons between the band-selection scheme considered in this correspondence and those developed in our previous work [13], the novel scheme almost predominates over the others, especially for the case of stringent delay requirements but loose average-interference constraint.

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