Effective Capacity of Statistical Delay QoS Guarantees with Imperfect Channel Information in Spectrum-Sharing Networks

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Abstract**—**This paper considers a spectrum-sharing cognitive network in which a secondary user shares spectrum with an existing primary user as long as the interference caused by the secondary user to the primary user is below permissible levels. We investigate the delay quality-of-service (QoS) guaranteed capacity gains with imperfect channel state information (CSI) between the secondary transmitter and the primary receiver in Rayleigh fading environments. In particular, we quantify the relation between the secondary link effective capacity and the interference inflicted on the primary user. The impacts of channel estimation error on the performance of the secondary link are studied. We further evaluate and compare the capacity gains using proposed power allocation policies and truncated channel inversion with fixed rate (TIFR) transmission policies under different constraint conditions. Our results indicate channel estimation errors, especially in the smaller value range, lead to considerably degradation of capacity gains for the looser delay QoS requirements. Numerical simulations are conducted to corroborate our theoretical analysis.

Index Terms**—**Cognitive radio, effective capacity, imperfect channel information, interference-outage, quality-of-service

I. Introduction

The Spectrum sharing technique in cognitive radio (CR) networks is one kind of promising solutions for improving the spectrum efficiency [1]. There are different spectrum sharing approaches for cognitive radios, e.g., interweave, overlay, and underlay. In the interweave approach, the secondary user (SU) is allowed to transmit only when the primary user (PU) is detected to be off. Hence, the SU should sense the environment and operate in spectrum not in use by PU. In contrast to interweave, the overlay and underlay methods allow the SU to transmit concurrently with PU at the same frequency. The overlay method utilizes an interesting "cognitive relay" idea [2]. For this method, the SU transmitter is assumed to know perfectly all the channels in the coexisting PU and SU links, as well as the PU messages to be sent. Thereby, the SU transmitter is able to forward PU messages to the PU receiver so as to compensate for the interference due to its own messages sent concurrently to the SU receiver. Whereas, in the underlay approach, the SU transmitter requires only the channel state information (CSI) from the SU transmitter to the PU receiver, whereby the SU is permitted to transmit regardless of the on/off status of PU transmission provided that its resulted signal power level at PU receiver is kept below some predefined threshold, also known as the interference-temperature constraint [3]. In this paper, we focus our study on underlay method due to its many advantages from an implementation viewpoint.

There also exist various challenges, such as how to ensure specific delay QoS requirement of the SU for delay-sensitive services, meanwhile, the performance degradation of the PU is tolerable. Effective capacity [4] provides a powerful tool for devising and evaluating the capability of a time-varying wireless channel to support data transmissions with delay statistical QoS guarantees. In recent years, a great deal of research has been devoted to capacity gains of the SU under spectrum-sharing in various channel environments. In [5], [6], the authors derived the ergodic or outage capacity capacities subject to average or peak interference power constraints under the imperfect CSI. In [7], the ergodic capacity under average and peak interference power constraints considering PU's influence to SU was investigated. The authors in [8] gave a unified framework for the ergodic capacity of spectrum sharing systems. It is noted that [5]-[8] only focus on the capacity gains without concerning QoS requirement.

As we know, QoS provisioning plays a critical role in future wireless communication. Differentiated users are expected to tolerate different levels of delay for their service satisfactions. In this respect, there are some studies by introducing the effective capacity for supporting QoS requirements, In [9], the optimal rate and power adaptation policy that maximized the effective capacity was derived in Nakagami-*m* fading channels. It is assumed that perfect CSI is available to the SU. The authors in [10] investigated the effective capacity of delay QoS constraint with outdated channel knowledge under average interference power constraints in Rayleigh fading. However, it is known that average interference power

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constraint is relevant to a long-term power budget over all different fading states, while, peak interference power constraint should be considered when fast fading is considered. Furthermore, [10] used channel correlation model to represent the outdated CSI. This model can not analyze the impact of practical channel estimation errors on the performance of the SU.

In this paper we assume that the SU only obtains imperfect CSI of secondary-to-primary link, we call it cross link. The channel estimation error model based on minimum mean square error (MMSE) is used for describing the imperfect CSI. We consider average or peak interference power constraint at the primary receiver, and investigate the capacity limits of secondary-to-secondary link, we call it secondary link; meanwhile satisfy delay QoS requirement of SU. We first obtain the effective capacity and its power allocation policy under average interference power constraint. Further, for comparison, we investigate the effective capacity with truncated channel inversion with fixed rate (TIFR) transmission policy under the same constraint condition. On the other hand, we also derive the effective capacity lower bound under the peak interference power constraint. In the same way, the effective capacity lower bound based on TIFR transmission policy is obtained. In particular, the effects of channel estimation errors on capacity gains are studied.

The rest of the paper is organized as follows. Section II describes our system and channel models. The effective capacity with the optimal power control policy and TIFR transmission policy under average interference power constraint are developed in Section III. Section IV considers the peak interference power constraint case and presents the channel effective capacity lower bounds of the instantaneous maximum allowed power allocation strategy and TIFR transmission policy. In Section V, the numerical and simulated results are presented. The paper concludes with Section VI.

II. System and Channel Models

A. System Model

We assume a spectrum sharing CR network in which a SU shares a PU's spectrum. The cross link between the secondary transmitter (SUTx) and primary receiver (PURx) and the secondary link between the secondary transmitter (SUTx) and secondary receiver (SURx) are assumed to be a flat-fading channel. We also assume that an infinite buffer is employed at data link layer to store frames in the CR network. The frame time duration is denoted by T_f. Let h_{sp}, h_{ss} denote instantaneous channel values from the SUTx to the PURx and from the SUTx to the SURx, respectively. Both are independent and identically distributed zero mean circularly symmetric complex Gaussian (ZMCSCG) random variables with the unit variance.

The perfect knowledge of h_{ss} is assumed to be available at the transmitter of the SU. However, the SU is only provided with partial information of h_{sp}. We assume that the SU performs a MMSE estimation of the h_{sp}, and we adopt the model $\tilde{h}_{sp} = h_{sp} - \hat{h}_{sp}$, which $\hat{h}_{sp}$ is the cross link channel MMSE estimations, *and* $\tilde{h}_{sp}$ is its estimation error. By the property of MMSE estimation, $\tilde{h}_{sp}$ and $\hat{h}_{sp}$ are uncorrelated, and $\tilde{h}_{sp}$ and $\hat{h}_{sp}$ are zero mean circularly symmetric complex Gaussian (ZMCSCG) random variables with the variances $\sigma^2/2$ and $(1-\sigma^2)/2$, respectively. Furthermore, we refer to the instantaneous channel power gains by $g_{sp}=|h_{sp}|^2$, $g_{ss}=|h_{ss}|^2$, $\hat{g}_{sp}=|\hat{h}_{sp}|^2$ respectively, and the cross link power gain estimation error by $\tilde{g}_{sp} = |\tilde{h}_{sp}|^2$. The probability density function (PDF) of channel power gain g_{ss} and $\hat{g}_{sp}$ are given by

$$f_{g_{ss}}(x) = e^{-x} \tag{1}$$

$$f_{\hat{g}_{sp}}(y) = \frac{1}{1-\sigma^2} \mathrm{e}^{-\frac{y}{1-\sigma^2}} \tag{2}$$

The interference from PUTx to SURx is assumed to be ignored due to the sufficient attenuation or considered in the AWGN. The additive noises at SURx and PURx are assumed to be independent AWGN, which have zero mean and power spectral density by N_0. The system total spectral bandwidth is denoted by B.

B. Statistical Delay QoS Guarantees

The effective capacity, which is associated with the effective bandwidth, describes the maximum arrival rate that can be supported under guaranteed delay QoS requirement. To this end, effective capacity is formulated as follows [4]

$$E_c(\theta) = -\lim_{t\to\infty} \tfrac{1}{\theta t} \log\{\varepsilon[e^{-\theta\sum_{i=1}^{t} R(i)}]\} \tag{3}$$

where the sequence $\{R(i), i=1, 2,\ldots\}$ is a discrete-time stationary and ergodic stochastic service process and denotes the allocated rate to user. The parameter θ, which is a certain positive constant called QoS exponent, signifies the exponential decay rate of the QoS violation probabilities. A more stringent QoS requirement corresponds to a larger QoS exponent θ. On the other hand, a looser QoS requirement corresponds to a smaller QoS exponent θ. $\varepsilon[.]$ stands for the expectation. When the sequence $\{R(i), i = 1, 2,\ldots\}$ is an uncorrelated process. $E_c(\theta)$ satisfies

$$E_c(\theta) = -\tfrac{1}{\theta} \log\{\varepsilon[e^{-\theta R(i)}]\} \tag{4}$$

Therefore, the effective capacity can be regarded as the maximal channel capacity under the constraint of QoS exponent θ. We can formulate an equivalent new problem, which is to maximize the effective capacity for a given θ.

In the following, we will focus attention on this equivalent problem.

III. Effective Capacity Subject to Average Interference Power Constraint

A. Effective Capacity

In this section, we first consider a power control policy which maximizes the secondary user effective capacity with delay QoS guarantees subject to given average interference power constraint. The constraint can be defined as follows.

$$\begin{aligned} Q_{av} &\geq \varepsilon[P(g_{ss},\hat{g}_{sp},\theta)g_{sp}] \\ &= \varepsilon[P(g_{ss},\hat{g}_{sp},\theta)(\hat{g}_{sp}+\tilde{g}_{sp})] \\ &= \varepsilon[P(g_{ss},\hat{g}_{sp},\theta)\hat{g}_{sp}]+\sigma^2\varepsilon[P(g_{ss},\hat{g}_{sp},\theta)] \end{aligned} \tag{5}$$

where Q_{av} presents the average interference power limit at the PURx. In II, we assume the interference from the PUTx to SURx is ignored or considered in AWGN. Hence, the $R(i)$ during each T_f can be expressed as

$$R(i) = T_f B\log[1+g_{ss}P(g_{ss},\hat{g}_{sp},\theta)/N_0B] \tag{6}$$

Now, substituting (6) into (4), we can formally formulate our optimization problem as follows

$$E_c^{opt}(\theta) = \max_{P(g_{ss},\hat{g}_{sp},\theta)>0} -\frac{1}{\theta}\log\{\varepsilon[e^{-\theta T_f B\log(1+g_{ss}P(g_{ss},\hat{g}_{sp},\theta)/N_0B)}]\} \tag{7}$$

where log{ ·} is a monotonically increasing function and QoS exponent θ is always positive, the optimization problem of maximizing $E_c(\theta)$ can be reduced to a minimization problem expressed as

$$\min_{P(g_{ss},\hat{g}_{sp},\theta)\geq 0} \varepsilon[e^{-\theta T_f B\log(1+g_{ss}P(g_{ss},\hat{g}_{sp},\theta)/N_0B)}] \tag{8}$$

$$s.t.\quad \varepsilon[P(g_{ss},\hat{g}_{sp},\theta)\hat{g}_{sp}]+\sigma^2\varepsilon[P(g_{ss},\hat{g}_{sp},\theta)]\leq Q_{av}. \tag{9}$$

To find the optimal power allocation $P(g_{ss}, \hat{g}_{sp}, \theta)$, we form the Lagrangian

$$\begin{aligned} L(P(g_{ss},\hat{g}_{sp},\theta),\lambda) &= \varepsilon\{e^{-\theta T_f B\log(1+g_{ss}P(g_{ss},\hat{g}_{sp},\theta)/N_0B)}\} \\ &+\lambda\{\varepsilon[(g_{ss},\hat{g}_{sp},\theta)\hat{g}_{sp}]+\sigma^2\varepsilon[P(g_{ss},\hat{g}_{sp},\theta)]-Q_{av}\} \end{aligned} \tag{10}$$

Next we differentiate the Lagrangian and set the derivative equal to zero

$$\begin{aligned} &\frac{\partial L(P(g_{ss},\hat{g}_{sp},\theta),\lambda)}{\partial P(g_{ss},\hat{g}_{sp},\theta)} = \lambda(\hat{g}_{sp}+\sigma^2) \\ &-\beta(N_0B)^{\beta} g_{ss}[N_0B+g_{ss}P(g_{ss},\hat{g}_{sp},\theta)]^{-\beta-1} = 0 \end{aligned} \tag{11}$$

Solving (11) with the constraint that $P(g_{ss}, \hat{g}_{sp}, \theta) \geq 0$ yields the optimal power adaptation as

$$P(g_{ss},\hat{g}_{sp},\theta) = [(\frac{(N_0B)^{\beta}\beta}{\lambda(\hat{g}_{sp}+\sigma^2)g_{ss}^{\ \beta}})^{\frac{1}{\beta+1}} - \frac{N_0B}{g_{ss}}]^{+} \tag{12}$$

where $[x]^+$ denotes max{0, x}, $\beta=\theta T_f B$, as the normalized QoS exponent [11], λ as the nonnegative dual variables associated with (9). If (9) is satisfied with strict inequality, λ must be zero correspondingly. Otherwise, λ can be jointly determined by substituting (12) into the constraints $\varepsilon[\hat{g}_{sp}P(g_{ss}, \hat{g}_{sp}, \theta)] + \sigma^2\varepsilon[P(g_{ss}, \hat{g}_{sp}, \theta)] = Q_{av}$. Let $\breve{g}_{sp} = \hat{g}_{sp}+\sigma^2$. Since $\hat{g}_{sp}$ is exponentially distributed, $\breve{g}_{sp}$ has a shifted-exponential distribution with the following probability density function

$$f_{\breve{g}_{sp}}(y) = \frac{1}{1-\sigma^2}e^{\frac{\sigma^2}{1-\sigma^2}}e^{-\frac{y}{1-\sigma^2}} \quad y\geq\sigma^2 \tag{13}$$

Hence, (12) is equivalently given by

$$P(g_{ss},\breve{g}_{sp},\theta) = \begin{cases} \frac{N_0B}{g_{ss}}[(\frac{g_{ss}}{\gamma\breve{g}_{sp}})^{\frac{1}{\beta+1}}-1], & g_{ss}/\breve{g}_{sp}\geq\gamma, \\ 0 & ,otherwise \end{cases} \tag{14}$$

where $\gamma = \lambda N_0B/\beta$. Define random variable $X = g_{ss}/\breve{g}_{sp}$. Due to the independence of $\breve{g}_{sp}$ and g_{ss}, the probability density function of X is derived as

$$f_X(x) = \int_{\sigma^2}^{\infty} t f_{g_{ss}}(xt) f_{\breve{g}_{sp}}(t)dt = \frac{1+\sigma^2(1-\sigma^2)x}{(1+(1-\sigma^2)x)^2}e^{-\sigma^2x}, \quad x\geq 0 \tag{15}$$

Given (14) and (15), we derive the expression for the effective capacity $E_c^{opt}(\theta)$ as follows

$$\begin{aligned} E_c^{opt}(\theta) &= -\frac{1}{\theta}\log\{\int_{\gamma}^{\infty}(\frac{x}{\gamma})^{-\frac{\beta}{1+\beta}}f_X(x)dx+\int_0^{\gamma}f_X(x)dx\} \\ &= -\frac{1}{\theta}\log\{\int_{\gamma}^{\infty}(\frac{x}{\gamma})^{-\frac{\beta}{1+\beta}}\frac{1+\sigma^2(1-\sigma^2)x}{[1+(1-\sigma^2)x]^2}e^{-\sigma^2x}dx \\ &-\frac{1}{1+\gamma-\sigma^2\gamma}e^{-\sigma^2\gamma}+1\} \end{aligned} \tag{16}$$

where, γ is determined as following constraint equation

$$\begin{aligned} \frac{Q_{av}}{N_0B} &= \int_{\gamma}^{\infty}\frac{1}{x}[(\frac{x}{\gamma})^{\frac{1}{\beta+1}}-1]f_X(x)dx \\ &= (\frac{1}{\gamma})^{\frac{1}{\beta+1}}\int_{\gamma}^{\infty}x^{\frac{-\beta}{\beta+1}}\frac{1+\sigma^2(1-\sigma^2)x}{[1+(1-\sigma^2)x]^2}e^{-\sigma^2x}dx+ \\ &(1-\sigma^2)e^{\frac{\sigma^2}{1-\sigma^2}}Ei(1,\frac{\sigma^2(\sigma^2\gamma-\gamma-1)}{\sigma^2-1})- \\ &Ei(1,\sigma^2\gamma)+\frac{1-\sigma^2}{1+\gamma-\sigma^2\gamma}e^{-\sigma^2\gamma} \end{aligned} \tag{17}$$

where $Ei(a,z)=\int_1^\infty t^{-a}e^{-zt}dt \quad \mathrm{Re}(z)>0$ denotes the exponential integral function [12]. To the best of our knowledge, the first integral in (16) and (17) cannot be evaluated in closed-form. Therefore, we analyze one specific case corresponding to $\theta \to 0$. With the help of the tool of Wolfram Mathematica, the closed-form expression is derived as

$$\begin{aligned} & E_c^{opt}(\theta)\big|_{\theta\to 0} \\ &= \lim_{\theta\to 0}\{-\frac{1}{\theta}\log[\int_\gamma^\infty (\frac{x}{\gamma})^{-\frac{\beta}{1+\beta}} \frac{1+\sigma^2(1-\sigma^2)x}{(1+(1-\sigma^2)x)^2} \mathrm{e}^{-\sigma^2 x}dx \\ &\quad -\frac{1}{1+\gamma-\sigma^2\gamma}e^{-\sigma^2\gamma}+1]\} \\ &= Ei(1,\sigma^2\gamma)-Ei(1,\frac{\sigma^2(\sigma^2\gamma-\gamma-1)}{\sigma^2-1})e^{-\frac{\sigma^2}{\sigma^2-1}} \end{aligned} \tag{18}$$

where γ can be derived as

$$\begin{aligned} \frac{Q_{av}}{N_0B} &= (1-\sigma^2)e^{\frac{\sigma^2}{1-\sigma^2}}Ei(1,\frac{\sigma^2(\sigma^2\gamma-\gamma-1)}{\sigma^2-1}) \\ &\quad -Ei(1,\sigma^2\gamma)+\frac{1}{\gamma}e^{-\sigma^2\gamma} \end{aligned} \tag{19}$$

We notice that the effective capacity is affected by σ^2. By the property of the exponential integral function, the effective capacity decreases as the σ^2 increases. Thus, in order to improve the capacity of the secondary link, it is important that the SU obtains accurate CSI of the cross link.

B. Effective Capacity with TIFR Transmission Policy

For delay-sensitive services, TIFR transmission policy has a wide range of applications. In this section, we consider the SUTx employs TIFR by adapting the transmit power to invert the channel fading under the average interference power constraint. Defining γ_0 as cutoff fading depth for $\gamma_0 = g_{ss}/\breve{g}_{sp}$, we can denote the power control policy as

$$P(g_{ss},\breve{g}_{sp})=\begin{cases}\dfrac{\alpha}{g_{ss}}, & g_{ss}\ge\gamma_0\breve{g}_{sp}, \\ 0, & otherwise\end{cases} \tag{20}$$

where α is determined such that the average interference power constraint is satisfied, i.e.

$$\begin{aligned} \frac{Q_{av}}{\alpha} &= \int_{\gamma_0}^\infty \frac{1}{x}\cdot f_{g_{ss}/\breve{g}_{sp}}(x)dx \\ &= Ei(1,\sigma^2\gamma_0)-(1-\sigma^2)e^{\frac{\sigma^2}{1-\sigma^2}}Ei(1,\frac{\sigma^2(\sigma^2\gamma_0-\gamma_0-1)}{\sigma^2-1}) \\ &\quad -\frac{1-\sigma^2}{1+\gamma_0-\sigma^2\gamma_0}e^{-\sigma^2\gamma_0} \end{aligned} \tag{21}$$

We also express the outage probability P_{out} according to

$$\begin{aligned} P_{out} &= p(g_{ss}/\breve{g}_{sp}<\gamma_0)=\int_0^{\gamma_0} f_{g_{ss}/\breve{g}_{sp}}(x)dx \\ &= 1-\frac{1}{1+\gamma_0-\sigma^2\gamma_0}e^{-\sigma^2\gamma_0} \end{aligned} \tag{22}$$

Therefore, the effective capacity associated with a given outage probability P_{out} and corresponding cutoff γ_0 is given by

$$\begin{aligned} E_c^{TIFR}(\theta) &= -\frac{1}{\theta}\log[\int_{\gamma_0}^\infty (1+\frac{\alpha}{N_0B})^{-\beta} f_{g_{ss}/\breve{g}_{sp}}(x)dx+\int_0^{\gamma_0} f_{g_{ss}/\breve{g}_{sp}}(x)dx] \\ &= -\frac{1}{\theta}\log[(1+\frac{\alpha}{N_0B})^{-\beta}(1-P_{out})+P_{out}] \\ &= -\frac{1}{\theta}\log[(1+\frac{\alpha}{N_0B})^{-\beta}\frac{1}{1+\gamma_0-\sigma^2\gamma_0}e^{-\sigma^2\gamma_0} \\ &\quad -\frac{1}{1+\gamma_0-\sigma^2\gamma_0}e^{-\sigma^2\gamma_0}-1] \end{aligned} \tag{23}$$

The maximum of (23) can also be found by searching numerically for the optimal value of γ_0. Whereas, the optimal γ_0 must be selected to find the optimal outage probability P_{out} using (22). Hence, we can find the maximum effective capacity by searching the optimal P_{out} numerically. Furthermore, from (23), it is easy to observe that if $P_{out} << 1$, the effective capacity is not relevant to the QoS exponent θ. This indicates that TIFR policy is not sensitive to delay QoS exponent θ when P_{out} is far smaller than 1.

IV. Effective Capacity Subject to Peak Interference Power Constraint

A. Effective Capacity

In this section, we consider peak interference power constraint at the primary receiver, and investigate the effective capacity of secondary link. The constraint can be formulated as follows

$$P(g_{ss},\hat{g}_{sp})g_{sp}<Q_{pk} \tag{24}$$

We note that it is impossible to satisfy (24) when the secondary user has only imperfect channel information $\hat{g}_{sp}$ for the cross link. Since it does not guarantee that the interference level at the PURx remains below the predetermined threshold at all times. For this reason, it is more reasonable to consider the statistics of the peak interference power constraint instead of the strict peak interference power constraint. So the interference-outage concept is proposed by [5]. This term means the interference to the PURx exceeds a given threshold (such as Q_{pk}) only for a certain probability, P_0. In this case, the peak interference power constraint can be defined as

$$\Pr\{P(g_{ss},\hat{g}_{sp})g_{sp}>Q_{pk}\}\le P_0 \tag{25}$$

where Pr{.} means the probability function. The constraint (25) aims at reducing the instantaneous interference power at the PU for a given secondary link CSI and imperfect cross link CSI. Note that (25) can also be equivalent as

$$\begin{aligned} P_0 &\geq \Pr\{\tilde{g}_{sp} \geq \frac{Q_{pk}}{P(g_{ss},\hat{g}_{sp})} - \hat{g}_{sp}\} \\ &= \varepsilon_{g_{ss},\hat{g}_{sp}}\{\int_{\frac{Q_{pk}}{P(g_{ss},\hat{g}_{sp},\theta)}-\hat{g}_{sp}}^{\infty} \frac{1}{\sigma^2} e^{-\frac{\tilde{g}_{sp}}{\sigma^2}} d\tilde{g}_{sp}\} \\ &= \varepsilon_{g_{ss},\hat{g}_{sp}}\{\frac{\hat{g}_{sp}}{\sigma^2} - \frac{Q_{pk}}{\sigma^2 P(g_{ss},\hat{g}_{sp})}\} \end{aligned} \quad (26)$$

Unfortunately, (26) can not be evaluated in closed-form. Therefore, we find a lower bound by assuming that (26) is satisfied at all times. The lower bound is derived as

$$P(g_{ss},\hat{g}_{sp}) \leq \frac{Q_{pk}}{\hat{g}_{sp} - \sigma^2 \log P_0} \quad (27)$$

Furthermore, we derive a lower bound on the effective capacity by transmitting at the instantaneous maximum allowed power, $P(g_{ss},\hat{g}_{sp}) = Q_{pk}/(\hat{g}_{sp} - \sigma^2 \log P_0)$ in what follows

$$\begin{aligned} E_c(\theta) &= -\frac{1}{\theta}\log\{\iint_{g_{ss},\hat{g}_{sp}} (1+\frac{g_{ss}}{\hat{g}_{sp}-\sigma^2\log P_0}\cdot\frac{Q_{pk}}{N_0 B})^{-\beta}\} \\ &= -\frac{1}{\theta}\log\{\frac{1}{1-\sigma^2}\int_0^{\infty} e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}} \int_0^{\infty} (1+\frac{g_{ss}}{\hat{g}_{sp}-\sigma^2\log P_0}\cdot\frac{Q_{pk}}{N_0 B})^{-\beta} e^{-g_{ss}} dg_{ss} d\hat{g}_{sp}\} \\ &= -\frac{1}{\theta}\log\{\frac{1}{1-\sigma^2}\int_0^{\infty} e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}+\frac{1}{a}} a^{-\beta}\Gamma(1-\beta,\frac{1}{a}) d\hat{g}_{sp}\} \end{aligned} \quad (28)$$

where $a = (\hat{g}_{sp} - \sigma^2 \log P_0)^{-1} Q_{pk} / N_0 B$. $\Gamma(s,z) = \int_z^{\infty} t^{s-1} e^{-t} dt$ denotes the incomplete gamma function. We know from (28) that the effective capacity of the secondary link is closely related to interference-outage P_0 and cross link estimation error σ^2. It is observed that the transmission power trends to zero if interference-outage approaches zero. *i.e.*, the effective capacity trends to zero if no interference-outage at the primary receiver can be tolerated. On the other hand, if σ^2 increases, the transmission power and effective capacity decrease. This is because the SU cannot always satisfy the peak interference power constraint for the imperfect CSI of cross link, and has to decrease its transmission power; hence, the capacity of secondary link degrades.

B. Effective Capacity with TIFR Transmission Policy

In this section, we consider the SUTx employs TIFR under peak interference power constraint with estimation error channel information. Defining γ_0 as cutoff fading depth for $\gamma_0 = g_{ss} / (\hat{g}_{sp} - \sigma^2 \log P_0)$, we denote the power control policy as

$$P(g_{ss},\hat{g}_{sp}) = \begin{cases} \frac{\alpha}{g_{ss}}, & g_{ss} \geq \gamma_0(\hat{g}_{sp} - \sigma^2 \log P_0), \\ 0, & otherwise. \end{cases} \quad (29)$$

Now, inserting (29) into (27), we obtain $\alpha \leq Q_{pk} g_{ss} / (\hat{g}_{sp} - \sigma^2 \log P_0)$, and hence, α can be found as $\alpha = Q_{pk}\gamma_0$. Furthermore, the outage probability can be derived as follows

$$\begin{aligned} P_{out} &= p(g_{ss} < \gamma_0(\hat{g}_{sp} - \sigma^2 \log P_0)) \\ &= 1 - \int_0^{\infty} \frac{e^{-\frac{\hat{g}_{sp}}{1-\sigma^2}}}{1-\sigma^2} \int_{\gamma_0(\hat{g}_{sp}-\sigma^2\log P_0)}^{\infty} e^{-g_{ss}} dg_{ss} d\hat{g}_{sp} \\ &= 1 - \frac{1}{1+\gamma_0(1-\sigma^2)} e^{\gamma_0 \sigma^2 \log P_0} \end{aligned} \quad (30)$$

Therefore, the effective capacity associated with a given outage probability P_{out} and corresponding cutoff γ_0 is given by

$$\begin{aligned} & E_c^{TIFR}(\theta) \\ &= -\frac{1}{\theta}\log[(1+\frac{Q_{pk}\gamma_0}{N_0 B})^{-\beta}(1-P_{out}) + P_{out}] \\ &= -\frac{1}{\theta}\log[(1+\frac{Q_{pk}\gamma_0}{N_0 B})^{-\beta}\frac{1}{1+\gamma_0(1-\sigma^2)} e^{\gamma_0\sigma^2\log P_0} - \\ &\quad \frac{1}{1+\gamma_0(1-\sigma^2)} e^{\gamma_0\sigma^2\log P_0} + 1]. \end{aligned} \quad (31)$$

The maximum outage effective capacity can be found by searching the optimal P_{out} numerically.

V. Numerical and Simulation Results

In this section, we confirm the analytical results derived in sections III and IV via comparisons with Monte Carlo simulations. We assume $N_0 B = 1$. The other parameters are detailed respectively in each of these figures.

A. Average Interference Power Constraints

1) Optimal power adaptation policy

We start by comparing the analytic and simulated results of effective capacity with optimal power adaptation policy under average interference power constraint. Fig.1 shows the normalized effective capacity to Q_{av} for different channel estimation error σ^2. As predicted, the effective capacity of the secondary link increases with Q_{av}. This is quite understandable that Q_{av} constraint limits the SU transmit power. However, it also shows that the effective capacity degrades as σ^2 increases. Fig. 2 shows the effect of σ^2 to the effective capacity when $\theta = 0.01$ (1/*nat*) and $\theta = 1$ (1/*nat*) in more detail. As we see, the more accurate CSI of the cross link, the better performance of the SU. This can be explained that in order to satisfy average interference power constraint, the SU has to degrade transmit power as channel estimation error increases. Furthermore, it is observed that the loss of effective capacity is more sensitive to σ^2 especially to the smaller σ^2 when QoS exponent θ is small. On the other hand, with the increasing of QoS exponent, capacity performance degradation caused by σ^2 gradually declines. This can be explained that for smaller θ values, the transmit power of the SU varies considerably for the σ^2 variation in the smaller value range. This observation is also intuitive. The analytic result is perfectly verified by simulation.

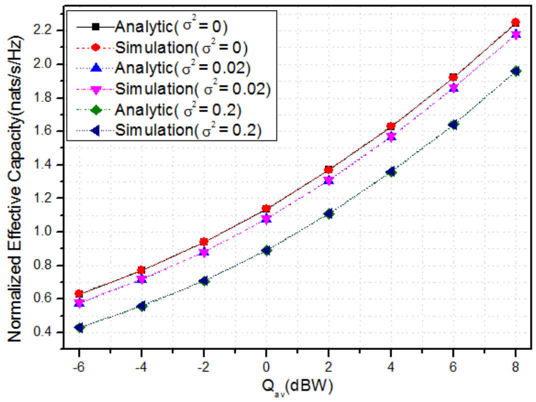

Fig. 1. Normalized effective capacity vs. Q_{av} for various channel estimation error σ^2, $\theta = 0.01$ (1/nat).

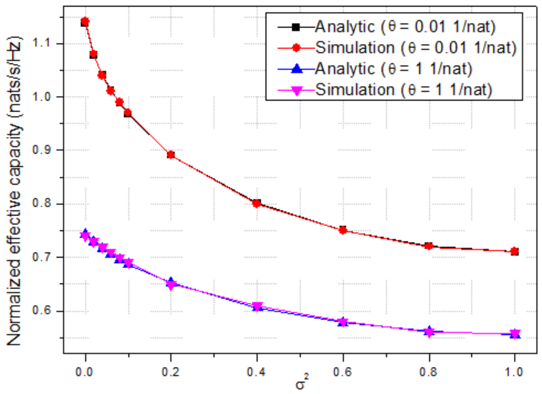

Fig. 2. Normalized effective capacity vs. σ^2 for various QoS exponent θ, $Q_{av} = 0$(dBW).

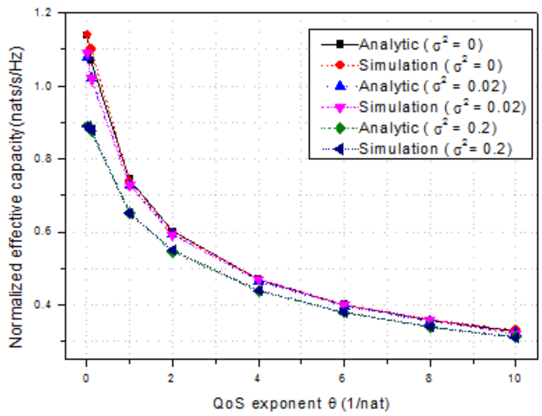

Fig. 3. Normalized effective capacity vs. QoS exponent θ for various channel estimation error σ^2, $Q_{av} = 0$(dBW).

Fig. 3 shows the normalized effective capacity to QoS exponent θ for various σ^2. As predicted, the effective capacity of the secondary link decreases with increasing QoS exponent θ. This indicates that effective capacity degrades as a result of a more stringent delay QoS requirement. This reveals an important fact that there exists a fundamental tradeoff between channel capacity and QoS provisioning. Moreover, it is observed that with the increasing of θ, the effective capacity approaches the same value for various σ^2. This indicates that the variation of σ^2 is less impacting on the effective capacity for the stringent QoS provisioning.

2) TIFR transmission policy

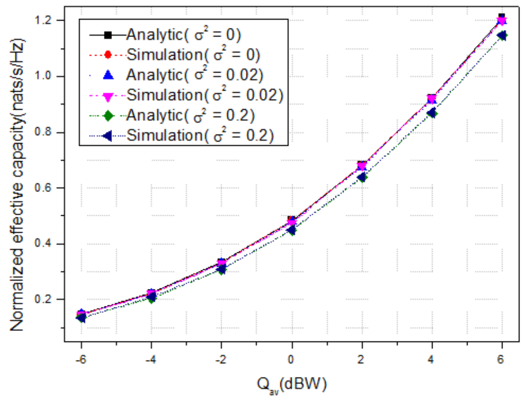

Fig. 4. Normalized effective capacity vs. Q_{av} for various channel estimation error σ^2, $\theta = 0.01$ (1/nat), $P_{out} = 0.1$.

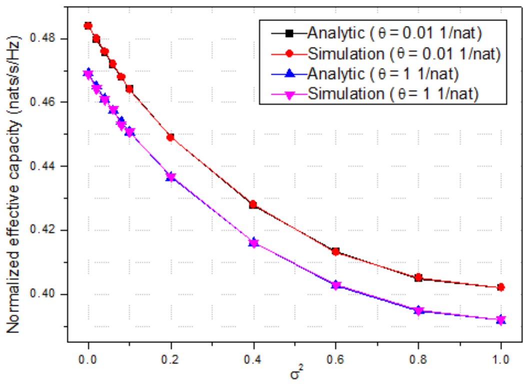

Fig. 5. Normalized effective capacity vs. σ^2 for various QoS exponent θ, $Q_{av} = 0$(dBW), $P_{out} = 0.1$.

Fig. 4 to Fig. 6 show the analytic and simulated results of effective capacity with TIFR transmission policy under average interference power constraint. Fig. 4 shows the effective capacity vs. Q_{av} for different σ^2. As we see, there has the similar result with Fig. 1. Fig. 5 shows the effective capacity vs. σ^2 for $\theta = 0.01$ (1/*nat*) and $\theta = 1$ (1/*nat*) when $P_{out} = 0.1$. It shows that the effective capacity of the secondary link degrades as σ^2 increases. This is because that transmit power has to degrade with the increase of σ^2 to guarantee average interference power constraint. In addition, comparing Fig. 2 and Fig. 5, it is observed that the effective capacity of TIFR policy is less than the effective capacity of the optimal power adaptation policy. This indicates that the capacity performance of proposed optimal power control policy outperforms that of the TIFR policy. This makes sense, as TIFR policy maintains a constant data rate when $g_{ss}/\breve{g}_{sp} \geq \gamma_0$. It can not adapt transmit rate to compensate for fading, so it is a suboptimal transmission strategy. Fig. 6 shows the effective capacity vs. θ for various outage probability P_{out}. Interestingly, it shows that when P_{out} is far less than 1 (such as P_{out} = 0.01), the effective capacity maintain an almost constant, i.e., there is little capacity decrease for all of the QoS exponent θ. This result agrees well with the theoretical analysis (28). When P_{out} increases, Fig. 6 has the similar result with Fig. 3.

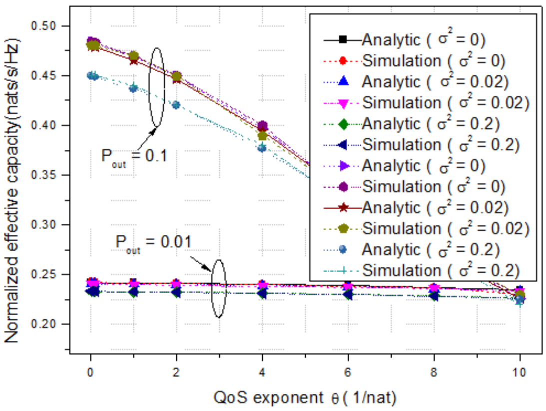

Fig. 6. Normalized effective capacity vs. QoS exponent θ for various channel estimation error σ^2, Q_{av} = 0(dBW).

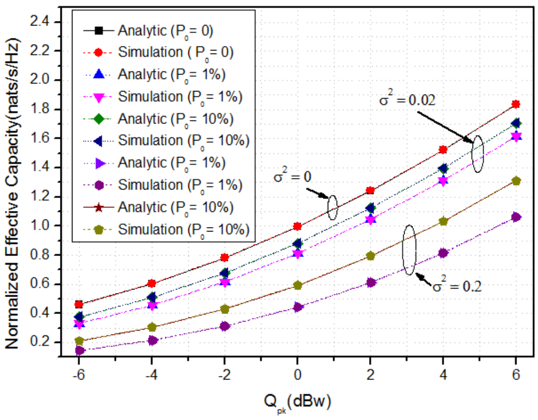

Fig. 7. Normalized effective capacity lower bounds vs. Q_{pk} for various channel estimation error σ^2 under different values of interference-outage, θ = 0.01 (1/nat).

B. *Peak Interference Power Constraints*

1) *Proposed power control policy*

We start by comparing the analytic and simulated results of effective capacity with proposed power control policy under peak interference power constraint. Fig. 7 shows effective capacity lower bounds of the secondary link vs. Q_{pk} for various σ^2. As predicted, the effective capacity of the secondary link increases with Q_{pk}. This can be easily understood since the Q_{pk} also constraint limits the SU transmit power. Furthermore, Fig. 7 reveals that the effective capacity improves with increasing of the interference-outage probability; however, since a high interference-outage probability inevitably causes performance degradation of PU, it is necessary to establish a proper constraint value to guarantee the performance of PU.

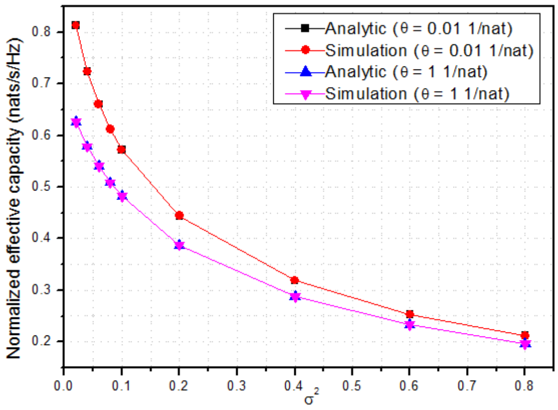

Fig. 8. Normalized effective capacity lower bounds vs. σ^2 for various QoS exponent θ, Q_{pk} = 0(dBW), P_0 =1%.

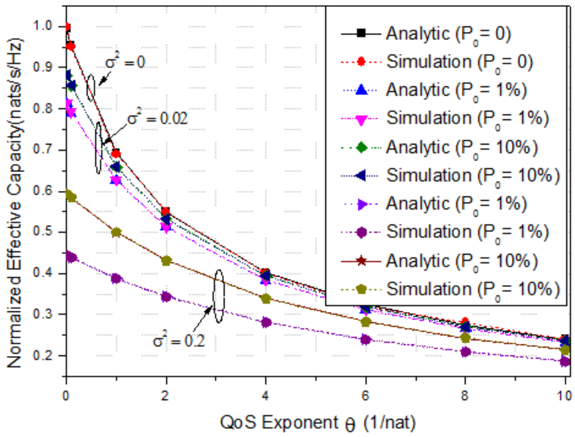

Fig. 9. Normalized effective capacity lower bounds vs. QoS exponent θ for various channel estimation error σ^2 under different values of interference-outage, Q_{pk} = 0 (dBW).

The effect of σ^2 to the effective capacity is shown in Fig. 8. We notices that the effective capacities are reduced by around 45% for P_0 = 1% when σ^2 increases from 0.02 to 0.2. This means the severe channel estimation errors make the capacity performance of the secondary link deteriorative. Furthermore, it is observed that the loss of effective capacity is more sensitive to σ^2 especially to low σ^2. Fig. 9 shows the effective capacity lower bounds of the secondary link versus QoS exponent θ for various σ^2 under different values of interference-outage. It is observed that Fig. 9 has a similar result with Fig. 3. But the capacities in Fig. 3 are normally higher than those in Fig. 9. This can be explained that the peak interference power constraint has the more restrictive nature than the average interference power constraint.

2) *TIFR transmission policy*

Fig. 10 to Fig. 13 show the analytic and simulated results of effective capacity with TIFR transmission policy under peak interference power constraint. Fig. 10 shows the normalized effective capacity lower bounds of the secondary link to Q_{pk} for various σ^2 under different values of interference-outage with respect to the outage probability P_{out} = 0.1. Like the TIFR transmission policy under average interference power constraint, the effective capacity of the secondary link increases with Q_{pk}. The effect of σ^2 on the effective capacity in Fig. 11 has the similar results with TIFR transmission policy under average interference power constraint. Nevertheless, it is observed that the effective capacity in Fig. 11 is far less than the effective capacities in Fig. 5 or Fig. 8. This indicates that the more rigorous interference power constraints or the fixed transmit rate lead to the severe capacity loss of SU.

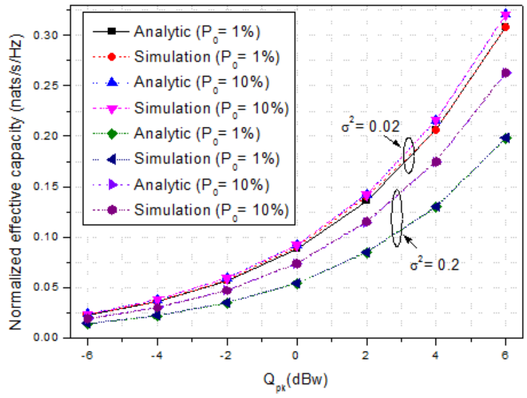

Fig. 10. Normalized effective capacity lower bounds vs. Q_{pk} under different values of interference-outage, θ = 0.01 (1/nat), P_{out} = 0.1.

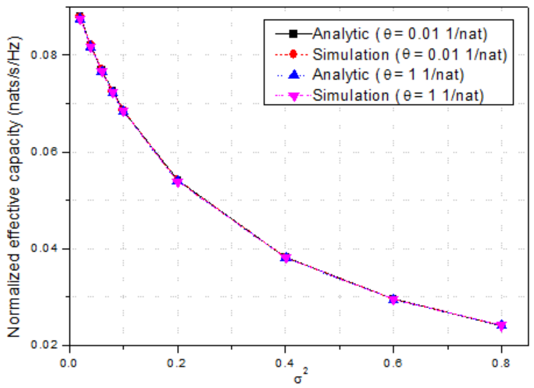

Fig. 11. Normalized effective capacity lower bounds vs. σ^2 for various QoS exponent θ, Q_{pk} = 0(dBW), P_0 =1%, P_{out} = 0.1.

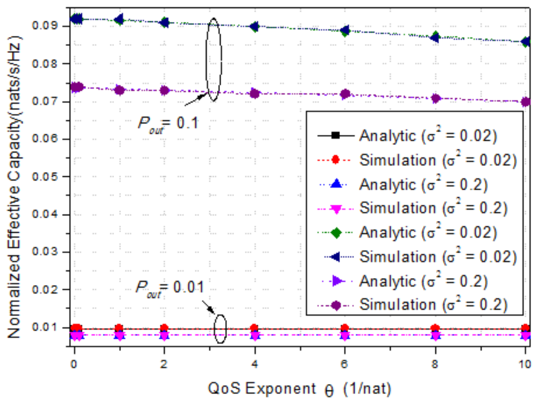

Fig. 12. Normalized effective capacity lower bounds vs. QoS exponent θ under different outage probability, P_0 = 10%, Q_{pk} = 0(dBW).

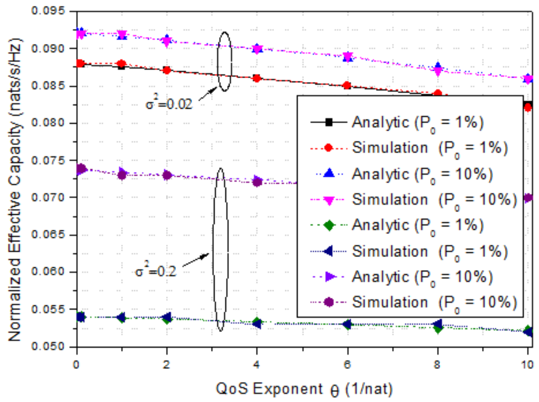

Fig. 13. Normalized effective capacity lower bounds vs. QoS exponent θ under different value of interference-outage, P_{out} = 0.1, Q_{pk} = 0(dBW).

VI. Conclusion

In this paper, we investigated and analyzed the delay QoS guaranteed capacity gains with imperfect CSI of cross link in Rayleigh fading environments. The effective capacities of optimal power allocation policy and TIFR transmission policy under the average interference power constraint were derived, Furthermore, the effective capacity lower bounds of the instantaneous maximum allowed power allocation strategy and TIFR transmission policy under the peak interference power constraint were also derived. Both analytical and simulated results demonstrated that the channel estimation error σ^2, especially the smaller σ^2, has the greater effect on the effective capacity for the looser delay QoS requirements under average or peak interference power constraints. In addition, it has been shown that the proposed power control policy is better than TIFR transmission policy for improving the capacity of the secondary link for the looser QoS provisioning, while, TIFR transmission policy is a better choice corresponding to a more stringent QoS requirement. The simulation results corroborating our theoretical analysis were also provided.

As future work, we intend to extend out results in following directions. Throughout this paper ,we assumed the imperfect CSI of the cross link and perfect CSI of the secondary link. The effect of imperfect CSI of the secondary link on the effective capacity remains to be analyzed. Another extension would be consider the interference from PUTx to SURx and the effect of imperfect CSI of the PUTx to SURx link on the effective capacity of secondary link. These research topics will allow us to develop a completely analytical approach to consider the impact of fully imperfect CSI in spectrum-sharing environments.

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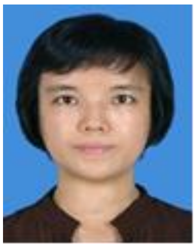

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