Capacity of Spectrum Sharing Cognitive Radio with MRC Diversity under Delay Quality-of-Service Constraints in Nakagami Fading Environments

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Abstract

The paper considers a spectrum sharing cognitive radio (CR) network coexisting with a primary network under the average interference power constraint. In particular, the secondary user (SU) is assumed to carry delay-sensitive services and thus shall satisfy a given delay quality-of-service (QoS) constraint. The secondary receiver is also assumed to be equipped with multiple antennas to perform maximal ratio combining (MRC) to enhance SU performance. We investigate the effective capacity of the SU with MRC diversity under aforementioned constraints in Nakagami fading environments. Particularly, we derive the optimal power allocation to achieve the maximum effective capacity of the SU, and further derive the effective capacity in closed-form. In addition, we further obtain the closed-form expressions for the effective capacities under three widely used power and rate adaptive transmission schemes, namely, optimal simultaneous power and rate adaptation (*opra*), truncated channel inversion with fixed rate (*tifr*) and channel inversion with fixed rate without truncation (*cifr*). Numerical results supported by simulations are presented to consolidate our studies. The impacts on the effective capacity of various system parameters such as the number of antennas, the average interference power constraint and the delay QoS constraint are investigated in detail. It is shown that MRC diversity can significantly improve the effective capacity of the SU especially for *cifr* transmission scheme.

Keywords: Cognitive radio, effective capacity, maximal ratio combining, delay quality-of-service constraint, Nakagami fading

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1. Introduction

In recent years, spectrum scarcity has become a serious problem due to the dramatic growth of wireless multimedia services. To solve this problem, spectrum sharing cognitive radio (CR) has been proposed to improve the spectrum efficiency [1]. Unlicensed user in spectrum sharing CR systems is permitted to concurrently utilize the spectrum with the licensed user provided that the quality-of-service (QoS) degradation of the licensed user due to the interference caused by the unlicensed users is under a tolerable limit. In this respect, the interference temperature, also known as the interference power constraint has been proposed to protect the licensed user transmission [2]. Generally, in spectrum sharing CR systems, the unlicensed user and the licensed user are also referred to as the secondary user (SU) and the primary user (PU), respectively. In such spectrum sharing CR systems, one crucial challenge is how to maximize the capacity of the SU while also maintaining the QoS of the SU as well as the QoS of the PU.

For the SU that carries real-time or delay-sensitive services, the delay QoS requirements of the services shall be satisfied. Note that it is highly impossible for the SU to satisfy a deterministic delay QoS requirement in severe fading environments such as Rayleigh fading [3]. Therefore, it is reasonable for the SU to consider a statistical delay QoS requirement which requires that the delay is lower than a predefined limit for a certain percentage of time. We aim to maximize the constant arrival rate of the SU while also satisfying the statistical delay QoS constraint at the SU as well as the interference power constraint at the PU. In this paper, the concept of effective capacity, which is first introduced by Wu and Negi in [3], is adopted to characterize the maximum constant arrival rate that can be supported by the SU while also meeting the statistical delay QoS constraint.

In this context, there have been some studies that focus on the effective capacity of the SU [4]-[9]. Specifically, Musavian and Aissa derived the optimal power allocation that maximizes the effective capacity of the SU under the minimum-rate constraint and then obtained the closed-form expression for the effective capacity of the SU in [4], and derived the effective capacities of the SU with various power and rate transmission schemes under the average interference power constraint in Nakagami fading channels in [5]. Akin and Gursoy studied the effective capacity of the SU with fixed-power/fixed-rate, fixed-power/variable-rate and variable-power/variable-rate transmission schemes in [6] and found that the effective capacity gain by adapting the power and rate decreases as the delay QoS constraint becomes more stringent. In [7], they investigated the effective capacity of the SU under the minimum-rate constraint and studied the impacts of various system parameters such as delay QoS constraint on the effective capacity. In our precious work [8], we derived the closed-form expression for the effective capacity of the SU under the peak interference power constraint in Nakagami fading channels. In [9], we investigated the effective capacity of the SU under the average interference power constraint with outdated channel information and obtained closed-form expressions for the upper and lower bounds on the effective capacity.

On the other hand, it is well known that maximal ratio combining (MRC) receive diversity can be used to significantly enhance the system performance by equipping multiple antennas at the receiver. In this respect, the ergodic capacity of the SU with MRC diversity has been investigated in [10]-[14]. However, only ergodic capacity, which is a good performance limit indicator for delay-insensitive services, is considered in [10]-[14], whereas, for delay-sensitive services, guaranteeing the delay QoS constraint of the SU is critical and effective capacity is a more suitable performance limit indicator than ergodic capacity. Thus, it is important to investigate the effect of MRC diversity on the effective capacity of the SU. However, to the best of our knowledge, the effective capacity of the SU with MRC diversity has not been studied yet.

Therefore, in this paper, we investigate the effective capacity of the SU with MRC diversity under the delay QoS constraint and the average interference power constraint in Nakagami fading environments. The optimal power allocation is derived to maximize the effective capacity of the SU. Based on the optimal power allocation, the effective capacity of the SU is then derived in closed-form. In addition, we further obtain the closed-form expressions for the effective capacities of the SU under three widely used power and rate adaptive transmission schemes, namely, optimal simultaneous power and rate adaptation (*opra*), truncated channel inversion with fixed rate (*tifr*) and channel inversion with fixed rate without truncation (*cifr*). Numerical results verified by simulations are presented to confirm our studies. The effects of various system parameters such as the number of antennas, the average interference power constraint and the delay QoS constraint on the effective capacity are investigated. It is shown that the effective capacities especially those under *opra*, *tifr and cifr* schemes depend greatly on the number of antennas, the average interference power constraint and the delay QoS constraint. It is also shown that MRC diversity can significantly improve the effective capacities under various transmission schemes especially for *cifr* transmission scheme.

The rest of the paper is organized as follows. Section 2 presents the system and channel models. Section 3 derives the optimal power allocation of the SU under the average interference power constraint and the corresponding closed-form expression for the effective capacity with MRC diversity in Nakagami fading environments. Sections 4 and 5 derive the effective capacities of the SU under optimal simultaneous power and rate adaptation and channel inversion with fixed rate transmission schemes, respectively. In Section 6, numerical results confirmed by simulations are presented and discussed. Finally, Section 7 concludes the paper.

2. System and Channel Models

In this paper, the SU is considered to share the spectrum with the PU under the average interference power constraint, since it is shown that the average interference power constraint is more advantageous than the peak interference power constraint [2][15]. It is assumed that the primary transmitter (PTx), the primary receiver (PRx) and the secondary transmitter (STx) are equipped with a single antenna, while the secondary receiver (SRx) is equipped with L antennas, which are used to perform MRC. The PU and the SU are assumed to share the same narrow-band for transmission with bandwidth B and noise power spectral density N_0. We also assume that for the SU link, the upper layer packets are initially stored in the transmit data buffer before being transmitted in frames of time duration T seconds, at the data-link layer.

All the channels involved are assumed to be block-fading channels. Specifically, the L channels from the STx to the SRx are assumed to follow i.i.d. Nakagami-*m* fading with unit mean and parameter m_s and the corresponding channel gains are denoted as g_s^i, $i = 1,\ldots,L$. The channel from the STx to the PRx is assumed to follow Nakagami-*m* fading with unit mean and parameter m_{sp} and the corresponding channel gain is denoted as g_{sp}. It is noted that smaller m_s or m_{sp} corresponds to more severe multipath channel fading, and vice versa. The probability density function (PDF) of channel gain g (g_s^i or g_{sp}) is thus given by [16]

$$f_g(x) = \frac{m^m x^{m-1}}{\Gamma(m)} e^{-mx}, \tag{1}$$

where $\Gamma(z)$ denotes the gamma function given by $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$ [17]. The channel gain, g_s, of the MRC output at the SRx can be expressed as $g_s = \sum_{i=1}^{L} g_s^i$ and the corresponding PDF is given by [16]

$$f_{g_s}(x) = \frac{m_s^{m_s L} x^{m_s L-1}}{\Gamma(m_s L)} e^{-m_s x}. \tag{2}$$

For delay-sensitive services, the SU transmission shall satisfy a given delay QoS constraint. Define Q as the stationary transmit queue length. Then the probability for the transmit queue length exceeding a certain threshold, q, decays exponentially as a function of q. Define θ as the decay rate of the tail distribution of the queue length Q such that

$$\theta = -\lim_{q\to\infty} \frac{\ln\left(\Pr\left(Q \ge q\right)\right)}{q}, \tag{3}$$

where $\Pr(\cdot)$ denotes the probability. It is noted that larger θ corresponds to a more stringent delay QoS constraint, and vice versa. Therefore, θ can be considered as the delay QoS constraint at the SU, and we obtain the maximum supported constant arrival rate for the SU under the delay QoS constraint, namely, the effective capacity.

3. Effective Capacity

In this section, we derive the optimal power allocation to maximize the effective capacity of the SU under the delay QoS constraint and the average interference power constraint and further derive the closed-form expression for the effective capacity with MRC diversity in Nakagami-*m* fading based on the optimal power allocation. It is noted that the power and rate transmission scheme proposed in this section is referred to as the optimal transmission scheme in the rest of the paper.

For a given QoS constraint θ, The normalized effective capacity in nats/s/Hz can be formulated as [3]

$$\mathrm{C_{eff}} = -\lim_{t\to\infty} \frac{\ln\left(\mathrm{E}\left\{e^{-\theta\sum_{k=1}^{t} r(k)}\right\}\right)}{\theta TBt}, \tag{4}$$

where $\mathrm{E}\{.\}$ denotes the statistical expectation, and $\{r(k), k=1,2,\ldots\}$ is defined as the discrete-time stochastic service process which is assumed to be stationary and ergodic. For independent block fading channels, the sequence $r(k), k=1,2,\ldots$, is independent. Therefore, the effective capacity can be simplified as

$$\mathrm{C_{eff}} = -\frac{\ln\left(\mathrm{E}\left\{e^{-\theta r(k)}\right\}\right)}{\theta TB}. \tag{5}$$

Similar to [4][5][8][9], we ignore the interference from the PTx to the SRx or consider it in the noise, and $r(k)$ can be expressed as

$$r(k) = TB\ln\left(1+\frac{g_s P_s(g_s, g_{sp})}{N_0 B}\right), \tag{6}$$

where $P_s(g_s, g_{sp})$ is the transmit power of the SU. Then, the effective capacity can be further simplified as

$$\mathrm{C}_{\mathrm{eff}} = -\frac{1}{\beta}\ln\left(\mathrm{E}\left\{\left(1+\frac{g_s P_s(g_s, g_{sp})}{N_0 B}\right)^{-\beta}\right\}\right), \tag{7}$$

where $\beta = \theta TB$.

It is shown in [2][15] that the average interference power constraint is more advantageous than the peak interference power constraint. Therefore, to protect the PU transmission from the SU, the average interference power constraint is adopted and expressed as

$$\mathrm{E}\left\{g_{sp} P_s(g_s, g_{sp})\right\} \le Q_{av}, \tag{8}$$

where Q_{av} denotes the average interference power limit. Therefore, the problem of maximizing the effective capacity of the SU under the average interference power constraint is formulated as

$$\mathrm{C}_{\mathrm{eff}}^{\mathrm{opt}} = \max_{P_s(g_s, g_{sp})\ge 0} -\frac{1}{\beta}\ln\left(\mathrm{E}\left\{\left(1+\frac{g_s P_s(g_s, g_{sp})}{N_0 B}\right)^{-\beta}\right\}\right) \tag{9}$$

$$\text{s.t. } \mathrm{E}\left\{g_{sp} P_s(g_s, g_{sp})\right\} \le Q_{av}. \tag{10}$$

Note that $\ln(x)$ is a monotonically increasing function with respect to x. Therefore, the solution of the above problem is the same as that for the following problem

$$\min_{P_s(g_s, g_{sp})\ge 0} \mathrm{E}\left\{\left(1+\frac{g_s P_s(g_s, g_{sp})}{N_0 B}\right)^{-\beta}\right\} \tag{11}$$

$$\text{s.t. } \mathrm{E}\left\{g_{sp} P_s(g_s, g_{sp})\right\} \le Q_{av}. \tag{12}$$

It can be easily verified that the above problem is convex and the solution can be thus found by the Lagrangian optimization method.

The Lagrangian function can be expressed as

$$\mathrm{L} = \mathrm{E}\left\{\left(1+\frac{g_s P_s(g_s, g_{sp})}{N_0 B}\right)^{-\beta}\right\} + \lambda\left(\mathrm{E}\left\{g_{sp} P_s(g_s, g_{sp})\right\} - Q_{av}\right), \tag{13}$$

where λ is the Lagrangian multiplier with respect to the constraint (12) and is obtained such that the constraint (12) is satisfied with equality. Using the fact that the optimal power allocation shall satisfy $\partial \mathrm{L} / \partial P_s(g_s, g_{sp}) = 0$ and $P_s(g_s, g_{sp}) \ge 0$, we have

$$P_s(g_s, g_{sp}) = N_0 B \left(\frac{(\beta\gamma)^{\frac{1}{\beta+1}}}{(g_{sp})^{\frac{1}{\beta+1}} g_s^{\frac{\beta}{\beta+1}}} - \frac{1}{g_s} \right)^+, \tag{14}$$

where $\gamma = 1/\lambda N_0 B$ and $(.)^+$ denotes $\max(.,0)$. The value of γ can be calculated by substituting (14) into the constraint (12) at equality as follows

$$\frac{Q_{av}}{N_0 B} = \mathrm{E}\left\{ \left((\beta\gamma)^{\frac{1}{\beta+1}} \left(\frac{g_{sp}}{g_s} \right)^{\frac{\beta}{\beta+1}} - \frac{g_{sp}}{g_s} \right)^+ \right\}. \tag{15}$$

Let $u = g_{sp} / g_s$. Then, the PDF of u can be expressed as

$$f_u(u) = \frac{\rho^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})} u^{m_{sp}-1} \left(1 + \rho u\right)^{-(m_s L + m_{sp})}. \tag{16}$$

where $\rho = m_{sp} / m_s$ and $\mathrm{B}(a,b)$ denotes the beta function defined as $\mathrm{B}(a,b) = \Gamma(a)\Gamma(b)/\Gamma(a+b)$ [17]. The proof for (16) is given in the Appendix. Then, we can now evaluate the expectation in (15) as

$$\frac{Q_{av}}{N_0 B} = \frac{\rho^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})} \int_0^{\beta\gamma} \left((\beta\gamma)^{\frac{1}{\beta+1}} u^{\frac{\beta}{\beta+1}} - u \right) u^{m_{sp}-1} \left(1 + \rho u\right)^{-(m_s L + m_{sp})} du. \tag{17}$$

With the help of eq. (3.194.1) in [17], we can evaluate the integral in (17) and derive the closed-from expression as follows

$$\begin{aligned} \frac{Q_{av}}{N_0 B} = \frac{\rho^{m_{sp}} (\beta\gamma)^{m_{sp}+1}}{\mathrm{B}(m_s L, m_{sp})} \Bigg(& \left(m_{sp} + \frac{\beta}{\beta+1} \right)^{-1} \\ & \times {}_2F_1\Big(m_s L + m_{sp}, m_{sp} + \frac{\beta}{\beta+1}; m_{sp} + \frac{2\beta+1}{\beta+1}; -\rho\beta\gamma \Big) \\ & - \frac{1}{m_{sp}+1} {}_2F_1(m_s L + m_{sp}, m_{sp}+1; m_{sp}+2; -\rho\beta\gamma) \Bigg), \end{aligned} \tag{18}$$

where ${}_2F_1(a,b;c;z)$ denotes the Gauss's hypergeometric function [17]. The optimal value of γ can be obtained from (18). Now, inserting (14) into (7), we obtain the effective capacity as follows

$$\begin{aligned} \mathrm{C}_{\mathrm{eff}}^{\mathrm{opt}} &= -\frac{1}{\beta} \ln \left(\mathrm{E}\left\{ \left(1 + \left((\beta\gamma)^{\frac{1}{\beta+1}} u^{-\frac{1}{\beta+1}} - 1 \right)^+ \right)^{-\beta} \right\} \right) \\ &= -\frac{1}{\beta} \ln \Big((\beta\gamma)^{-\frac{\beta}{\beta+1}} \int_0^{\beta\gamma} u^{\frac{\beta}{\beta+1}} f_u(u) du + \int_{\beta\gamma}^{\infty} f_u(u) du \Big). \end{aligned} \tag{19}$$

Substituting (16) into (19) and using the fact that $\int_{\beta\gamma}^{\infty} f_u(u) du = 1 - \int_0^{\beta\gamma} f_u(u) du$, we have

$$C_{\text{eff}}^{\text{opt}} = -\frac{1}{\beta}\ln\Bigg(1+\frac{(\rho\beta\gamma)^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})}\Bigg(\left(m_{sp}+\frac{\beta}{\beta+1}\right)^{-1}$$
$$\times {}_2F_1\Big(m_s L + m_{sp}, m_{sp}+\frac{\beta}{\beta+1}; m_{sp}+\frac{2\beta+1}{\beta+1}; -\rho\beta\gamma\Big)$$
$$-\frac{1}{m_{sp}}\, {}_2F_1(m_s L + m_{sp}, m_{sp}; m_{sp}+1; -\rho\beta\gamma)\Bigg)\Bigg), \tag{20}$$

which leads to the closed-form expression for the effective capacity of the SU with MRC diversity under the optimal transmission scheme in Nakagami-*m* fading. It is observed from (20) that the effective capacity is dependent on various system parameters.

In what follows, we derive the upper bound on the effective capacity in (20). According to Jensen's inequality [20], the objective function in (9) satisfies

$$-\frac{1}{\beta}\ln\left(\mathrm{E}\left\{\left(1+\frac{g_s P_s(g_s,g_{sp})}{N_0 B}\right)^{-\beta}\right\}\right) \le \mathrm{E}\left\{\ln\left(1+\frac{g_s P_s(g_s,g_{sp})}{N_0 B}\right)\right\}, \tag{21}$$

from which the upper bound solution can be derived from the following problem

$$C_{\text{eff}}^{\text{opt,ub}} = \max_{P_s(g_s,g_{sp})\ge 0} \mathrm{E}\left\{\ln\left(1+\frac{g_s P_s(g_s,g_{sp})}{N_0 B}\right)\right\} \tag{22}$$

$$\text{s.t. } \mathrm{E}\left\{g_{sp} P_s(g_s,g_{sp})\right\} \le Q_{av}. \tag{23}$$

It is seen that the above problem is to obtain the maximum ergodic capacity under the average interference power constraint which has been addressed in [14]. Note that ergodic capacity does not consider delay QoS constraint, that is, $\theta = 0$. This indicates that the upper bound on the effective capacity, $C_{\text{eff}}^{\text{opt,ub}}$, is equal to the maximum ergodic capacity and when $\theta \to 0$, the effective capacity, $C_{\text{eff}}^{\text{opt}}$, approaches to the upper bound $C_{\text{eff}}^{\text{opt,ub}}$.

4. Effective Capacity under Optimal Simultaneous Power and Rate Adaptation Transmission Scheme

In this case, the optimal simultaneous power and rate adaptation transmission scheme is introduced in [18] and is referred to as *opra*. The power allocation in *opra* transmission scheme can be revised to comply with the average interference power constraint (8) and is given by [19] as follows

$$P_s(g_s,g_{sp}) = N_0 B\left(\frac{\gamma}{g_{sp}} - \frac{1}{g_{ss}}\right)^+, \tag{24}$$

where γ is determined such that the average interference power constraint (8) is satisfied with equality. The optimal value of γ can be thus obtained by inserting (24) into (8) at equality and evaluating the integral as follows

$$\frac{Q_{av}}{N_0 B} = \mathrm{E}\left\{(\gamma - u)^+\right\}$$

$$
\begin{aligned}
&= \frac{\rho^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})} \Big(\gamma \int_0^{\gamma} u^{m_{sp}-1} (1+\rho u)^{-(m_s L + m_{sp})} du - \int_0^{\gamma} u^{m_{sp}} (1+\rho u)^{-(m_s L + m_{sp})} du \Big) \\
&= \frac{\rho^{m_{sp}} \gamma^{m_{sp}+1}}{\mathrm{B}(m_s L, m_{sp})} \Big(\frac{1}{m_{sp}} {}_2F_1(m_s L + m_{sp}, m_{sp}; m_{sp}+1; -\rho\gamma) \\
&\quad - \frac{1}{m_{sp}+1} {}_2F_1(m_s L + m_{sp}, m_{sp}+1; m_{sp}+2; -\rho\gamma) \Big). \qquad (25)
\end{aligned}
$$

The effective capacity of the SU under *opra* transmission scheme can now be derived by inserting (24) into (7) as

$$
\begin{aligned}
C_{\mathrm{eff}}^{\mathrm{opra}} &= -\frac{1}{\beta} \ln \left(\mathrm{E} \left\{ \left(1 + \left(\frac{\gamma}{u} - 1 \right)^{+} \right)^{-\beta} \right\} \right) \\
&= -\frac{1}{\beta} \ln \Big(\gamma^{-\beta} \int_0^{\gamma} u^{\beta} f_u(u) du + \int_{\gamma}^{\infty} f_u(u) du \Big). \qquad (26)
\end{aligned}
$$

According to the fact that $\int_{\gamma}^{\infty} f_u(u)du = 1 - \int_0^{\gamma} f_u(u)du$ and after some mathematical manipulations, we have

$$
\begin{aligned}
C_{\mathrm{eff}}^{\mathrm{opra}} &= -\frac{1}{\beta} \ln \Big(1 + \frac{(\rho\gamma)^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})} \Big(\frac{1}{m_{sp}+\beta} \\
&\quad \times {}_2F_1\big(m_s L + m_{sp}, m_{sp}+\beta; m_{sp}+\beta+1; -\rho\gamma\big) \\
&\quad - \frac{1}{m_{sp}} {}_2F_1(m_s L + m_{sp}, m_{sp}; m_{sp}+1; -\rho\gamma) \Big) \Big), \qquad (27)
\end{aligned}
$$

which leads to the closed-form expression for the effective capacity of the SU with MRC diversity under *opra* transmission scheme in Nakagami-*m* fading. Note that the optimal solution of the problem in (22) is also (24), and using (21), we conclude that the upper bound on the effective capacity in (27) is also $C_{\mathrm{eff}}^{\mathrm{opt,ub}}$ given in (22). This indicates that as $\theta \to 0$, the effective capacity, $C_{\mathrm{eff}}^{\mathrm{opra}}$, approaches to the upper bound $C_{\mathrm{eff}}^{\mathrm{opt,ub}}$, and also approaches to the effective capacity $C_{\mathrm{eff}}^{\mathrm{opt}}$. Therefore, for low θ, the effective capacity under *opra* transmission scheme is closed to that under the optimal transmission scheme.

5. Effective Capacity under Channel Inversion with Fixed Rate Transmission Schemes

In this case, there are two transmission schemes: truncated channel inversion with fixed rate, which is referred to as *tifr*, and channel inversion with fixed rate without truncation, which is referred to as *cifr* [18]. In *tifr* transmission scheme, the STx transmits power to invert the channel fading such that a constant signal-to-noise-ratio (SNR) is maintained at the SRx for a certain percentage of time, while in *cifr* transmission scheme, the constant SNR at the SRx is maintained at all times. Since in *tifr* or *cifr*, constant SNR at the SRx is maintained, thus, the SRx treats the channel as an AWGN channel which simplifies the receiver design.

Define γ as the cutoff value for $u = g_{sp} / g_s$, over which the transmission stops. Then, the power allocation in *tifr* transmission scheme can be expressed as

$$P_s(g_s, g_{sp}) = \begin{cases} \dfrac{\alpha}{g_{ss}}, & \text{if } u \le \gamma, \\ 0, & \text{otherwise.} \end{cases} \tag{28}$$

where α and γ are obtained such that the average interference power constraint (8) is satisfied with equality and the outage probability is constrained to be under a predefined value P_{out}. From (28), the outage probability can be calculated as

$$\begin{aligned} P_{out} &= 1 - \int_0^{\gamma} f_u(u) du \\ &= 1 - \frac{(\rho\gamma)^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp}) m_{sp}} {}_2F_1(m_s L + m_{sp}, m_{sp}; m_{sp}+1; -\rho\gamma), \end{aligned} \tag{29}$$

from which we can obtain the value of γ. Then, inserting (28) into the average interference power constraint (8) at equality, we have the value of α under *tifr* transmission scheme as

$$\begin{aligned} \alpha &= \frac{Q_{av}}{\int_0^{\gamma} u f_u(u) du} \\ &= \frac{(m_{sp}+1)\mathrm{B}(m_s L, m_{sp}) Q_{av}}{\rho^{m_{sp}} \gamma^{m_{sp}+1} {}_2F_1(m_s L + m_{sp}, m_{sp}+1; m_{sp}+2; -\rho\gamma)}. \end{aligned} \tag{30}$$

For *cifr* transmission scheme, the value of γ is chosen to be $\gamma = \infty$ such that the constant SNR at the SRx, $\alpha / N_0 B$, is maintained at all times. Therefore, the value of α under *cifr* transmission scheme can be written as

$$\alpha = \lim_{\gamma \to \infty} \frac{Q_{av}}{\int_0^{\gamma} u f_u(u) du}. \tag{31}$$

For $m_s L > 1$, with the help of eq. (3.194.3) in [17], we can simplify (31) as follows

$$\begin{aligned} \alpha &= \frac{Q_{av}}{\int_0^{\infty} u f_u(u) du} \\ &= \frac{Q_{av} \rho \mathrm{B}(m_s L, m_{sp})}{\mathrm{B}(m_s L - 1, m_{sp} + 1)}, m_s L > 1 \end{aligned} \tag{32}$$

Further using the fact that $\mathrm{B}(a,b) = \Gamma(a)\Gamma(b) / \Gamma(a+b)$ and $\Gamma(x+1) = x\Gamma(x)$, we have obtained the value of α under *cifr* transmission scheme as

$$\alpha = \frac{Q_{av}(m_s L - 1)}{m_s}, m_s L > 1 \tag{33}$$

For $m_s L \le 1$, using eq. (9.131.1) in [17] and (28), we can simplify (31) as

$$\alpha = \lim_{\gamma\to\infty} \frac{(1+\rho\gamma)^{m_s L+m_{sp}} Q_{av}(m_{sp}+1)\mathrm{B}(m_s L, m_{sp})}{\rho^{m_{sp}}\gamma^{m_{sp}+1}{}_2F_1(m_s L+m_{sp},1;m_{sp}+2;\frac{\rho\gamma}{\rho\gamma+1})}$$

$$= \lim_{\gamma\to\infty} \frac{\rho^{m_s L}(\rho^{-1}+\gamma)^{m_s L} Q_{av}(m_{sp}+1)\mathrm{B}(m_s L, m_{sp})}{\gamma {}_2F_1(m_s L+m_{sp},1;m_{sp}+2;1)}, m_s L \le 1 \tag{34}$$

The second equality in (34) is obtained according to $\lim_{\gamma\to\infty}(\rho^{-1}+\gamma)/\gamma = 1$. Thus, for $m_s L < 1$, from (34), it is easily seen that the value of α is $\alpha = 0$. For $m_s L = 1$, we can further simplify (34) as follow

$$\alpha = \frac{\rho Q_{av}(m_{sp}+1)}{m_{sp}{}_2F_1(m_{sp}+1,1;m_{sp}+2;1)}, m_s L = 1 \tag{35}$$

According to the definition of ${}_2F_1(a,b;c;z)$ [17], we have ${}_2F_1(m_{sp}+1,1;m_{sp}+2;1) = (m_{sp}+1)\int_0^1 1/(1-t)dt = \infty$. Thus, for $m_s L = 1$, the value of α is also $\alpha = 0$.

Thus, we have the value of α under *cifr* transmission scheme as

$$\alpha = \begin{cases} \frac{Q_{av}(m_s L-1)}{m_s}, & m_s L > 1 \\ 0, & m_s L \le 1 \end{cases} \tag{36}$$

Therefore, the effective capacity of the SU under *tifr* transmission scheme is derived in closed-form by inserting (28) into (7) as

$$C_{\text{eff}}^{\text{tifr}} = -\frac{1}{\beta}\ln\left(\left(1+\frac{\alpha}{N_0 B}\right)^{-\beta}\int_0^{\gamma} f_u(u)dv + \int_{\gamma}^{\infty} f_u(u)dv\right)$$

$$= -\frac{1}{\beta}\ln\left(\left(1+\frac{\alpha}{N_0 B}\right)^{-\beta}(1-P_{out})+P_{out}\right), \tag{37}$$

where α is given in (30). It can be verified that $C_{\text{eff}}^{\text{tifr}}$ in (37) is a monotonically decreasing function of β. This indicates that the upper bound on $C_{\text{eff}}^{\text{tifr}}$ is achived at $\theta\to 0$ ($\beta\to 0$). Thus, if we set $\theta\to 0$ in (37), we can have the upper bound as $C_{\text{eff}}^{\text{tifr,ub}} = (1-P_{out})\ln(1+\alpha/N_0 B)$. This indicates that $C_{\text{eff}}^{\text{tifr}}$ is almost linear w.r.t. the outage probability under low θ. If we set $\theta\to\infty$, we have $C_{\text{eff}}^{\text{tifr}}\to 0$. This indicates that the effective capacity under *tifr* transmission scheme is zero if the delay QoS constraint becomes infinitely stringent. In addition, if $Q_{av}\to\infty$, from (30), we have $\alpha\to\infty$ and thus $C_{\text{eff}}^{\text{tifr}}\to -\ln(P_{out})/\beta$. This indicates that, under high Q_{av}, $C_{\text{eff}}^{\text{tifr}}$ is upper bounded by $-\ln(P_{out})/\beta$ and is independent of L. In other word, under high Q_{av}, MRC diversity has negligible impact on the effective capacity under *tifr* transmission scheme.

For *cifr* transmission scheme, the effective capacity of the SU can be derived in closed-form as

$$\begin{aligned} C_{\text{eff}}^{\text{cifr}} &= -\frac{1}{\beta}\ln\left(\left(1+\frac{\alpha}{N_0 B}\right)^{-\beta}\right) \\ &= \ln\left(1+\frac{\alpha}{N_0 B}\right), \end{aligned} \tag{38}$$

where α is given in (36). From (36) and (38), it is observed that the effective capacity under *cifr* transmission scheme is independent of the delay QoS constraint θ and the channel characteristic between the STx and the PRx indicated by m_{sp}. This indicates that, compared with *tifr* transmission scheme, *cifr* transmission scheme is more favorable under high θ if $m_s L > 1$. It is also observed from (36) and (38) that the effective capacity under *cifr* transmission scheme without MRC diversity ($L = 1$) is zero for $m_s \le 1$. This indicates that, for severe multipath channel fading $m_s \le 1$ (such as Rayleigh fading $m_s = 1$), *cifr* transmission scheme fails to work for the SU under the delay QoS constraint. However, through equipping mutilple antennas at the SRx to perform MRC, the effective capacity under *cifr* transmission scheme is greatly improved and is non-zero as long as $m_s L > 1$. This indicates that MRC diversity can mitigate severe multipath channel fading and make *cifr* transmission scheme work for the SU under the delay QoS constraint. In addition, for $m_s L \gg 1$, (38) can be approximated as $C_{\text{eff}}^{\text{cifr}} \approx \ln\left(1+Q_{av}L/N_0 B\right)$, which indicates that, for large number of antennas ($L \gg 1/m_s$), the multipath channel fading has negeligible impact on the effective capacity under *cifr* transmission scheme with MRC diversity and the effective capacity is only dependent on the number of antennas and interference power limit and scales as $\ln(Q_{av}L)$.

6. Numerical and Simulation Results

In this section, we provide numerical results supported by simulations to confirm the studies in Sections 3, 4 and 5. In the following, we assume $N_0 B = 1$ and $TB = 1$.

6.1 Effects of the Number of Antennas

Fig. 1 plots the effective capacities of the SU, $C_{\text{eff}}^{\text{opt}}$, $C_{\text{eff}}^{\text{opra}}$ and $C_{\text{eff}}^{\text{cifr}}$, against the number of antennas L for different values of m_s. It is seen that the analytical results perfectly match the simulations, which confirms the correctness of the derived closed-form expressions for the effective capacities. It is observed that the effective capacities increase significantly as L increases. In particular, for $C_{\text{eff}}^{\text{cifr}}$, increasing L can solve the zero-capacity problem caused by severe channel fading (low m_s). It is also observed that $C_{\text{eff}}^{\text{opra}}$ and $C_{\text{eff}}^{\text{cifr}}$ are always lower than $C_{\text{eff}}^{\text{opt}}$, which is intuitive since $C_{\text{eff}}^{\text{opt}}$ is obtained based on the optimal transmission scheme. In addition, it is seen that, $C_{\text{eff}}^{\text{opra}}$ is higher than $C_{\text{eff}}^{\text{cifr}}$ under low L, and is lower than $C_{\text{eff}}^{\text{cifr}}$ under high L. This indicates that, compared with *cifr* scheme, *opra* scheme is preferred only under low L, while under high L, *cifr* transmission scheme is preferred compared with *opra* scheme.

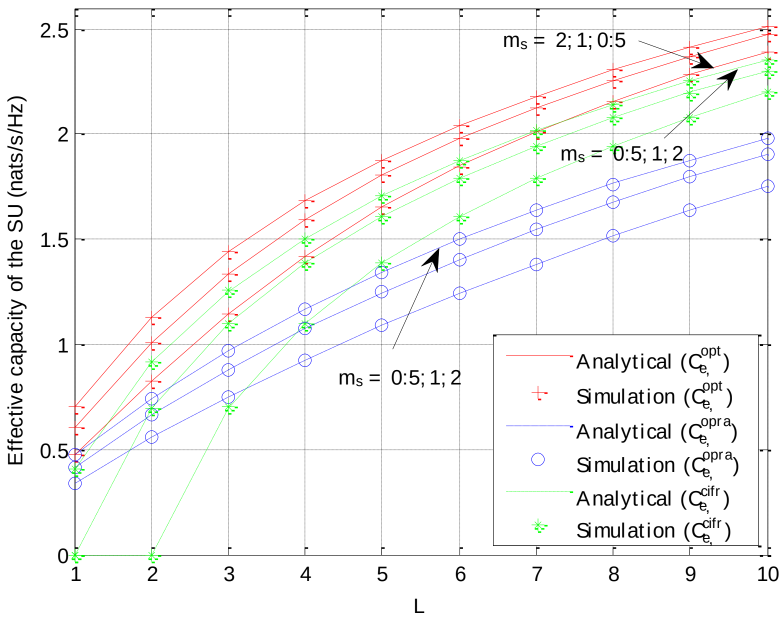

Fig. 1. Effective capacities of the SU, C_{eff}^{opt}, C_{eff}^{opra} and C_{eff}^{cifr}, against the number of antennas L ($Q_{av} = 0$ dB, $\theta = 2$ 1/nat and $m_{sp} = 1$).

Fig. 2 shows the effective capacities of the SU, C_{eff}^{cifr} and C_{eff}^{tifr}, against the number of antennas L for different values of m_s. It is seen that, unlike C_{eff}^{cifr} being zero under severe fading, C_{eff}^{tifr} can be non-zero since a certain outage probability is allowed in *tifr* scheme while it is not allowed in *cifr* scheme. It is interesting to observe that, for low m_s ($m_s = 0.5$ and $m_s = 1$), C_{eff}^{cifr} is lower than C_{eff}^{tifr} under low L and is higher than C_{eff}^{tifr} under high L, whereas, for high m_s ($m_s = 2$), C_{eff}^{cifr} is higher than C_{eff}^{tifr} under low L and is lower than C_{eff}^{tifr} under high L. This indicates that, compared with *cifr* scheme, although *tifr* scheme allows a certain outage probability, the effective capacity achieved by *tifr* scheme, C_{eff}^{tifr}, is not always higher than C_{eff}^{cifr} and is dependent on the number of antennas L. This observation is quite different from the observation in [18], in which it is shown that *tifr* scheme achieves higher ergodic capacity than that of *cifr* scheme. It is also interesting to see that C_{eff}^{tifr} with high P_{out} is higher than that with low P_{out} under low L, and is lower than that with low P_{out} under high L. This indicates that higher outage probability does not always result in higher C_{eff}^{tifr}, which is dependent on the number of antennas L. Therefore, in terms of effective capacity, allowing a certain outage probability in *tifr* scheme is not always good for the SU compared with *cifr* scheme.

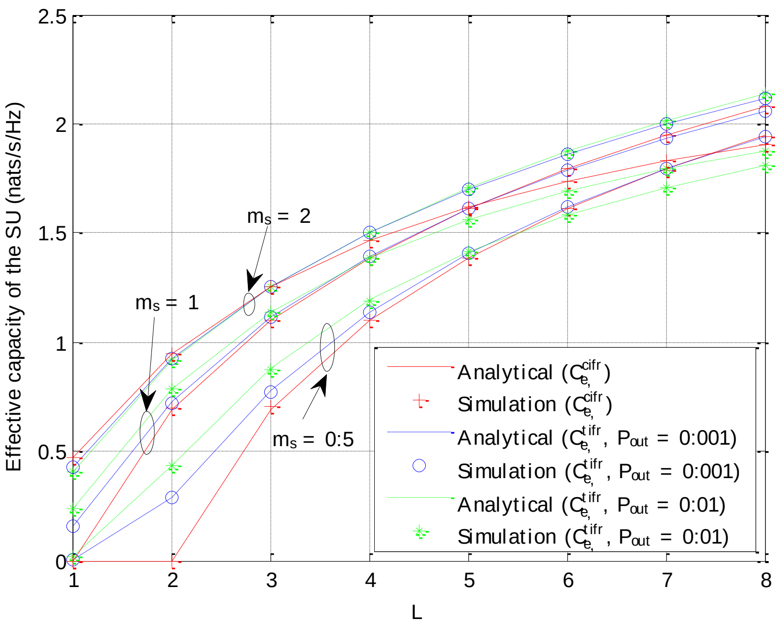

Fig. 2. Effective capacities of the SU, $C_{\text{eff}}^{\text{cifr}}$ and $C_{\text{eff}}^{\text{tifr}}$, against the number of antennas L ($Q_{av} = 0$ dB, $\theta = 2$ 1/nat and $m_{sp} = 1$).

6.2 Effects of the Average Interference Power Constraint

Fig. 3 shows the effective capacities of the SU, $C_{\text{eff}}^{\text{opt}}$, $C_{\text{eff}}^{\text{opra}}$ and $C_{\text{eff}}^{\text{cifr}}$, against the average interference power constraint Q_{av} for different values of L. It is observed that the effective capacities increase with the increase of Q_{av}, except for $C_{\text{eff}}^{\text{cifr}}$ under single antenna ($L = 1$), which is always zero. This indicates that even equipping one more antenna ($L = 2$), the effective capacity gain can be significantly high (see for example $C_{\text{eff}}^{\text{cifr}}$). It is also observed that, for non-zero $C_{\text{eff}}^{\text{cifr}}$, under low Q_{av}, $C_{\text{eff}}^{\text{opra}}$ is higher than $C_{\text{eff}}^{\text{cifr}}$, while under high Q_{av}, $C_{\text{eff}}^{\text{opra}}$ is lower than $C_{\text{eff}}^{\text{cifr}}$. This indicates that, *opra* scheme is favored compared with *cifr* scheme under low Q_{av}, while under high Q_{av}, *cifr* scheme is favored compared with *opra* scheme (under the condition that $C_{\text{eff}}^{\text{cifr}}$ is non-zero, i.e., $m_s L > 1$).

In **Fig. 4**, we plot the effective capacities of the SU, $C_{\text{eff}}^{\text{cifr}}$ and $C_{\text{eff}}^{\text{tifr}}$, against the average interference power constraint Q_{av} for different values of L. It is observed that $C_{\text{eff}}^{\text{tifr}}$'s with different values of L increase as Q_{av} increases and saturate to the same value $-\ln(P_{out})/\beta$ at high Q_{av}, which verifies our theoretical analysis in Section 5 and indicates that the effective capacity under *tifr* scheme cannot be improved by increasing L at high Q_{av}. It is also observed that $C_{\text{eff}}^{\text{cifr}}$ is lower than $C_{\text{eff}}^{\text{tifr}}$ under low Q_{av} and is higher than $C_{\text{eff}}^{\text{tifr}}$ under high Q_{av} (under the condition that $C_{\text{eff}}^{\text{cifr}}$ is non-zero). It is also interesting to observe that $C_{\text{eff}}^{\text{tifr}}$ with high P_{out} is higher than that with low P_{out} under low Q_{av}, and is lower than that with low P_{out}

under high Q_{av}. The above observations indicate that the differences between C_{eff}^{cifr} and C_{eff}^{tifr} as well as between C_{eff}^{tifr}'s with different P_{out}'s are dependent on Q_{av}.

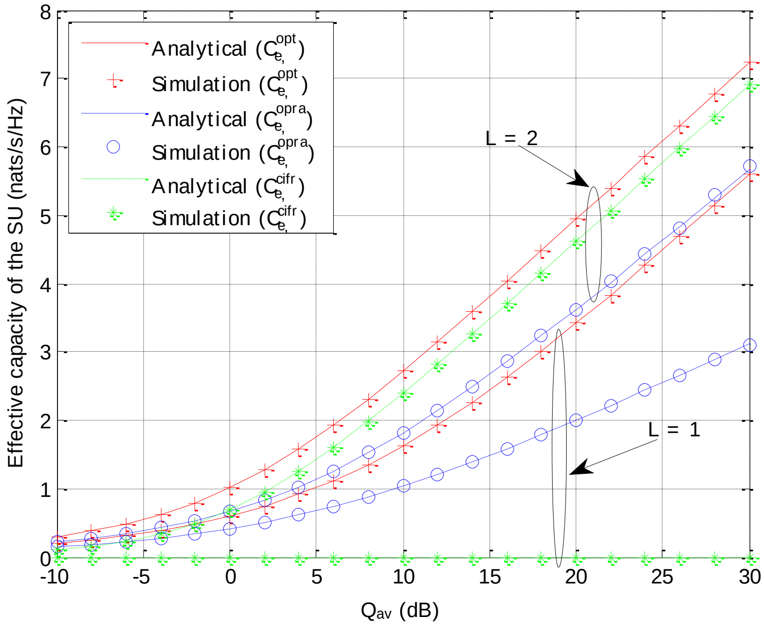

Fig. 3. Effective capacities of the SU, C_{eff}^{opt}, C_{eff}^{opra} and C_{eff}^{cifr}, against the average interference power constraint Q_{av} ($\theta = 2$ 1/nat and $m_s = m_{sp} = 1$).

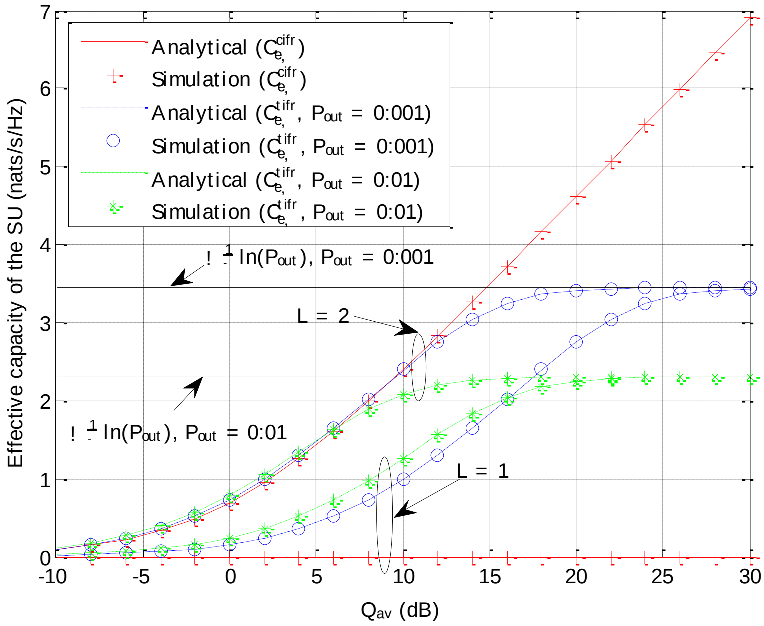

Fig. 4. Effective capacities of the SU, C_{eff}^{cifr} and C_{eff}^{tifr}, against the average interference power constraint Q_{av} ($\theta = 2$ 1/nat and $m_s = m_{sp} = 1$).

6.3 Effects of the Delay QoS Constraint

Fig. 5 illustrates the effective capacities of the SU, C_{eff}^{opt}, C_{eff}^{opra} and C_{eff}^{cifr}, against the delay QoS constraint θ for different values of L. For comparison purpose, we also plot the upper bound effective capacity $C_{eff}^{opt,ub}$ for C_{eff}^{opt} and C_{eff}^{opra}. It is seen that both C_{eff}^{opt} and C_{eff}^{opra} approach to $C_{eff}^{opt,ub}$ as θ decreases and the two curves almost overlap under low θ. This indicates that *opra* scheme achieves almost the same effective capacity as the optimal scheme does under low θ, which verifies our theoritical analysis in Sections 3 and 4. As θ increases, C_{eff}^{opt} and C_{eff}^{opra} decreases and their difference increases. It is also seen that C_{eff}^{cifr} is constant as θ increases and is lower than C_{eff}^{opra} under low θ and is higher than C_{eff}^{opra} under high θ (under the condition that C_{eff}^{cifr} is non-zero). This indicates that *opra* scheme is preferred compared with *cifr* scheme under low θ.

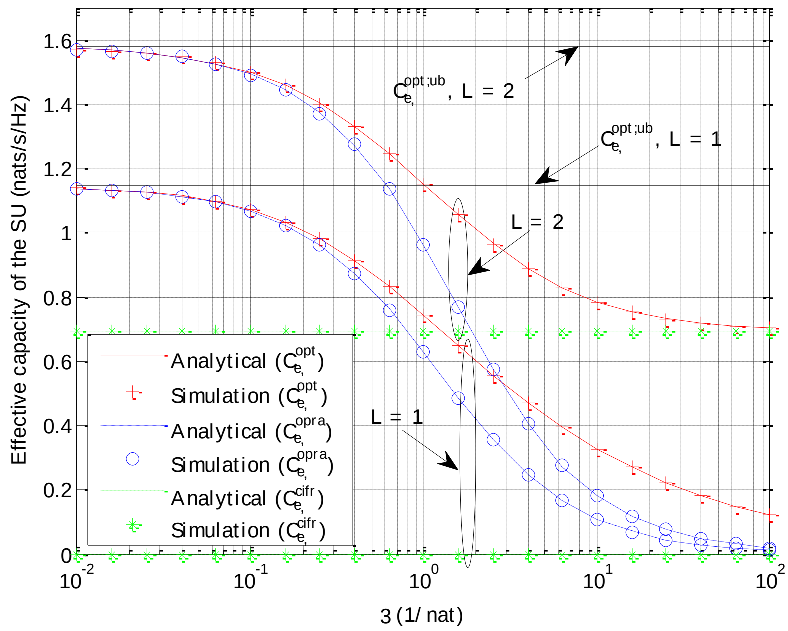

Fig. 5. Effective capacities of the SU, C_{eff}^{opt}, C_{eff}^{opra} and C_{eff}^{cifr}, against the delay QoS constraint θ ($Q_{av}=0$ dB and $m_s = m_{sp} = 1$).

Fig. 6 plots the effective capacities of the SU, C_{eff}^{cifr} and C_{eff}^{tifr}, against the delay QoS constraint θ for different values of L. For comparison purpose, we also plot the upper bound effective capacity $C_{eff}^{tifr,ub}$ for C_{eff}^{tifr}. It is observed that C_{eff}^{tifr} is almost unchanged as θ increases under low θ and is almost equal to $C_{eff}^{tifr,ub}$. This indicates that C_{eff}^{tifr} is insensitive to θ and the upper bound is very tight under low θ. Under high θ, it is observed that C_{eff}^{tifr} decreases as θ increases. It is also observed that C_{eff}^{cifr} is lower than C_{eff}^{tifr} under low θ and is higher than C_{eff}^{tifr} under high θ (under the condition that C_{eff}^{cifr} is non-zero). In addition, it is observed that C_{eff}^{tifr}

with high P_{out} is higher than that with low P_{out} under low θ, and is lower than that with low P_{out} under high θ. The above observations indicate that the differences between C_{eff}^{cifr} and C_{eff}^{tifr} as well as between C_{eff}^{tifr}'s with different P_{out}'s depend on θ.

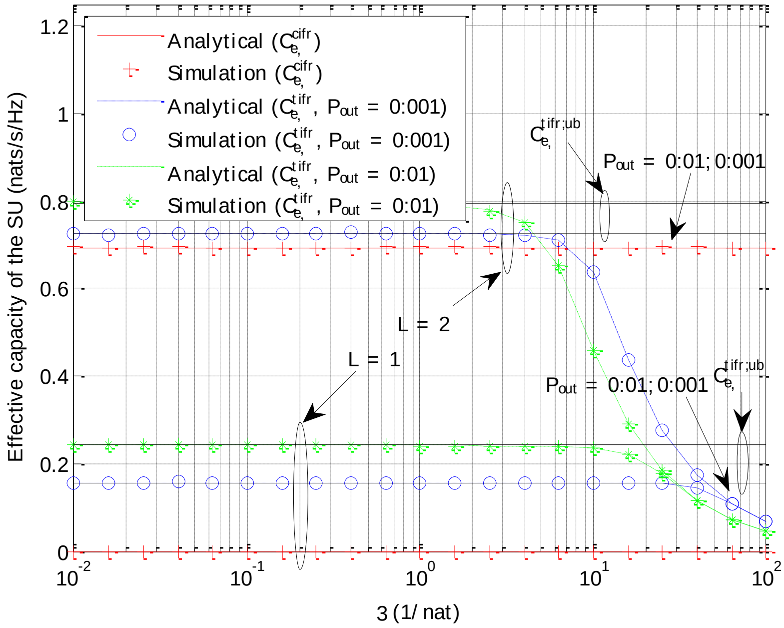

Fig. 6. Effective capacities of the SU, C_{eff}^{cifr} and C_{eff}^{tifr}, against the delay QoS constraint θ ($Q_{av} = 0$ dB and $m_s = m_{sp} = 1$).

7. Conclusion

This paper investigated the effective capacity of the SU with MRC diversity under the delay QoS constraint and the average interference power constraint in Nakagami fading environments. The optimal power allocation as well as the closed-form expression for the effective capacity were derived. Additionally, the closed-form expressions for the effective capacities of the SU under three widely used power and rate adaptive transmission schemes, namely, optimal simultaneous power and rate adaptation (*opra*), truncated channel inversion with fixed rate (*tifr*) and channel inversion with fixed rate without truncation (*cifr*), were also derived. The effects of the number of antennas, the average interference power constraint and the delay QoS constraint on the effective capacities under various transmission schemes were investigated. It was shown that the number of antennas, the average interference power constraint and the delay QoS constraint have great impacts on the effective capacities especially those under *opra*, *tifr* and *cifr* schemes. It was also shown that MRC diversity can significantly improve effective capacity especially for *cifr* transmission scheme.

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Appendix

We derive the distribution of $u = g_{sp} / g_s$ where the PDFs of g_{sp} and g_s are given by (1) and (2), respectively.

For u and g_s, the Jacobian can be calculated as

$$J = \begin{vmatrix} g_s & u \\ 0 & 1 \end{vmatrix} = g_s. \tag{39}$$

Consequently, the joint PDF of u and g_s is obtained as

$$f_{u,g_s}(u, g_s) = g_s f_{g_{sp}}(ug_s) f_{g_s}(g_s). \tag{40}$$

The marginal distribution of u can be obtained by integrating $f_{u,g_s}(u, g_s)$ with respect to g_s as

$$f_u(u) = \int_0^\infty g_s f_{g_{sp}}(ug_s) f_{g_s}(g_s) dg_s, \tag{41}$$

which can be simplified by substituting (1) and (2) into (41) as

$$f_u(u) = \frac{m_s^{m_s L} m_{sp}^{m_{sp}}}{\Gamma(m_s L)\Gamma(m_{sp})} u^{m_{sp}-1} \int_0^\infty g_s^{m_s L + m_{sp} - 1} e^{-(m_{sp} u + m_s) g_s} dg_s. \tag{42}$$

Define $\rho = m_{sp} / m_s$ and with the help of eq. (3.381.4) and eq. (8.384.1) in [17], we can further simplify the above expression as

$$f_u(u) = \frac{\rho^{m_{sp}}}{\mathrm{B}(m_s L, m_{sp})} u^{m_{sp}-1} \left(1 + \rho u\right)^{-(m_s L + m_{sp})}. \tag{43}$$

This completes the proof for (16).

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