Asymptotic Capacity Analysis in Multipoint-to-Point Cognitive Radio Networks with an Arbitrary Peak Power

Jianbo Ji, Wen Chen, and Shanlin Sun

Abstract: **In this paper, we investigate the capacity of a multipoint-to-point cognitive radio network. In existing works, the asymptotic capacity is only obtained in the high peak power region at secondary transmitter (ST) or obtained without considering the interference from primary transmitter (PT) for easy analysis. Here, we analyze the asymptotic capacity by considering an arbitrary peak power at the ST and the interference from the PT based on extreme value theory. Simulation results show that our approximated capacity is well-matched to the exact capacity. Furthermore, the scaling law of our capacity is found to be double logarithm of the number of secondary users.**

Index Terms: **Asymptotic capacity, cognitive radio, extreme value theory, interference temperature.**

I. INTRODUCTION

Currently, modern radio spectrum management is faced with the challenge of accommodating a growing number of wireless applications and services on a limited amount of spectrum. Cognitive radio (CR) technology has been proposed as a promising solution to implement efficient reuse of the licensed spectrum by unlicensed/secondary devices [1], [2]. Generally, three categories of CR network paradigms have been proposed: Overlay, interweave and underlay [3]. In the underlay CR, which is the focus of this paper, a secondary user (SU) is allowed to utilize primary user (PU) spectrum only if the interference caused by the SU is regulated below a predetermined level. The maximum allowable interference power is called interference temperature [3]–[6], which guarantees the quality of service (QoS) of the PU regardless of the SU's spectrum utilization. This type of CR is also known as "spectrum-sharing" [3], [4].

Recently, ideas from opportunistic communication were used in spectrum-sharing cognitive radios by selectively activate one or more SUs to maximize the CR throughput while satisfying interference constraints. The average capacity in cognitive networks is studied in [4], [5], [7], and [8], by selecting the SU with the highest signal-to-noise-ratio (SNR) or signal-to-interference-and-noise-ratio (SINR) under the interference constraints.

In [5], [7], and [8], the authors found that the SU capacity can be increased by simultaneously activating as many secondary transmitters (STs) as possible. However, these asymptotic analysis only propose scaling laws for asymptotic SNR, rather than providing exact results. In [4], the closed-form capacity was derived by hypothesis that the transmit peak power of ST is sufficiently larger than interference temperature. The provided concise statistical distribution of the received signal at the SU by the hypothesis is convenient to analyze the capacity. However, this assumption results in less accurateness in limiting statistical distribution, and the asymptotic capacity in [4] has much gap to the exact one. In [5], the authors derives capacity scaling limits for average transmit power constraint at ST which did not consider the maximum transmit power constraint at the ST. These results in [4], [5], and [7] ignore the interference from the primary transmitter (PT) to secondary receivers (SRs). In a practical spectrum-sharing CR, since the SU and PU coexist in the same spectral band, the interference at SR, generated by the nearby PTs is not negligible and must be considered in the capacity analysis.

Motivated by these observations, in this paper, the peak transmit power of SU is considered to be arbitrary and the interference from PU is also taken into consideration. Based on the extreme value theory, the asymptotic capacity is derived and the scaling property of the capacity is presented. Simulations show that our capacity expression is much accurate than the existing result and very closed to the exact one.

The rest of this paper is organized as follows. Section II introduces the system and channel model. In Section III, we analyze the asymptotic capacity of the system. Numerical simulation results are provided to validate the theoretical results in Section IV. Finally, conclusion is drawn in Section V.

II. SYSTEM AND CHANNEL MODEL

A spectrum-sharing homogeneous uplink network in a single cell system is considered in Fig. 1, where a multipoint to point CR networks coexist with an active pair of PUs which includes a PT and a primary receiver (PR). A set of N SUs utilize a spectrum licensed to the PT. All users in the network are assumed to be equipped with a single antenna. In the spectrum sharing systems, any transmission from the SU to the secondary basestation (SBS) is allowed provided that the resulting interference power level at the PR is below the interference temperature constraint. The channel gains from the jth SU to the PR and the SBS are denoted by g_j and β_j, respectively, where $j \in \{1, \cdots, N\}$, which are assumed to be well known at the SU by reliable feedback and the channel gain from the PT to the SBS is denoted by $\alpha_{\rm ps}$.

Depending on the available interference channel gain g_j, the SU then computes the maximum allowable transmit power so as to satisfy the interference temperature constraint at the PR.

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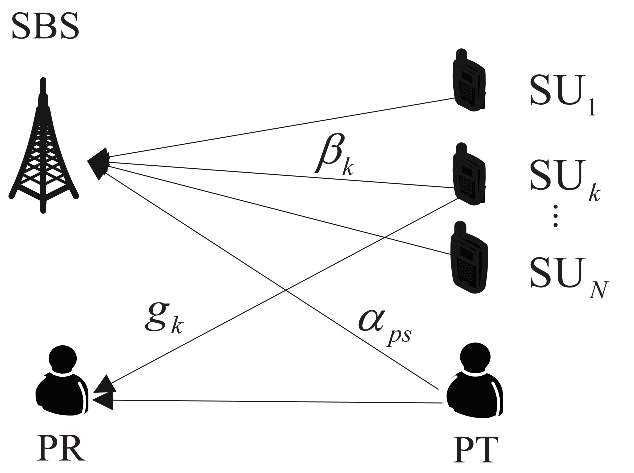

Fig. 1. The system model for a CR network coexisting with a pair of PUs.

The SU allocates its peak power for transmission provided that the interference temperature is satisfied with its peak power. Otherwise, it adaptively adjusts its transmit power to the allowable level so that the interference perceived at the PR is maintained as a given interference temperature level Q. Correspondingly, the transmit power of the jth SU

$$P_j = \min\left(P,\ \frac{Q}{g_j}\right) \tag{1}$$

where P represents peak transmit power of the SU.

III. ASYMPTOTIC CAPACITY ANALYSIS

Considering the interference from the PT, the received SINR at the target secondary receiver is given by

$$\gamma_j = \frac{P_j\beta_j}{P_p\alpha_{\rm ps} + \sigma^2} = \frac{t_j}{I + \sigma^2} \tag{2}$$

where $t_j = P_j\beta_j$, $I = P_p\alpha_{\rm ps}$, and σ^2 denote the variance of white Gaussian noise, respectively. The variable P_p denotes the transmit power of the PT. Similar to [4], to simplify mathematical analysis, $\alpha_{\rm ps}$, β_j, and g_j are assumed to be independent and identically distributed (i.i.d.) exponential random variables with unit mean, and $\sigma^2 = 1$. The cumulative density function (cdf) of the received SNR t_j at the secondary receiver from the jth SU is [4]

$$F_{t_j}(x) = \left(1 - e^{-\frac{Q}{P}}\right)\left(1 - e^{-\frac{x}{P}}\right) + e^{-\frac{Q}{P}}\left(1 - \frac{Q}{Q+x}e^{-\frac{x}{P}}\right). \tag{3}$$

By using a transformation of random variable, the cdf of received SINR γ_j at the secondary receiver with $f_I(y) = e^{-y/P_p}/P_p$ can be expressed as

$$\begin{aligned} F_{\gamma_j}(\gamma) &= \Pr\left(t_j < \gamma(I+1)\right) \\ &= \int_0^\infty F_{t_j}\left(\gamma(y+1)\right) f_I(y)dy \\ &= 1 - \frac{\left(1 - e^{-\frac{Q}{P}}\right)e^{-\frac{\gamma}{P}}}{1 + \frac{\gamma P_p}{P}} - \frac{Q}{\gamma P_p}e^{\frac{Q+\gamma}{\gamma P_p}} \\ &\quad \times\ \Gamma\left(0, \left(1 + \frac{Q}{\gamma}\right)\left(\frac{1}{P_p} + \frac{\gamma}{P}\right)\right) \end{aligned} \tag{4}$$

where the upper incomplete Gamma function is defined as $\Gamma(x,y) = \int_y^\infty h^{x-1}e^{-h}dh$, and the derivation of cdf yields the probability density function (pdf) in (5).

$$\begin{aligned} f_{\gamma_j}(\gamma) = \frac{Q}{\gamma^3 P_p^2}e^{\frac{\gamma+Q}{\gamma P_p}} &\left[(Q + \gamma P_p)\Gamma\left(0, \frac{Q+\gamma}{\gamma}\left(\frac{1}{P_p} + \frac{\gamma}{P}\right)\right)\right. \\ &\left. + \frac{\gamma P_p(\gamma^2 P_p - QP)}{(\gamma+Q)(\gamma P_p + P)}e^{-\left(1+\frac{Q}{\gamma}\right)\left(\frac{1}{P_p}+\frac{\gamma}{P}\right)}\right] \\ &+ \frac{\gamma P_p + P(1+P_p)}{(\gamma P_p + P)^2}\left(e^{\frac{Q}{P}} - 1\right)e^{-\frac{\gamma+Q}{P}}. \end{aligned} \tag{5}$$

Now the SBS chooses the SU that has the maximal received SINR from N SUs at each transmission, therefore, the average capacity of CR network is given by [4]

$$C_{\rm ave} \triangleq E\left[\log\left(1 + \gamma_{\max}\right)\right] = \int_0^\infty \log\left(1+\gamma\right) f_{\gamma_{\max}}(\gamma)\, d\gamma$$

where $\gamma_{\max} \triangleq \max\limits_{1\le i\le N}\gamma_i$, whose pdf is denoted as

$$f_{\gamma_{\max}}(\gamma) = N f_{\gamma_i}(\gamma)\, F_{\gamma_i}(\gamma)^{N-1}.$$

However, this integration is not solvable for large N. Consequently, in this work, we attempt to evaluate $C_{\rm ave}$ in the asymptotic regime of large N. We need the following lemma to identify the asymptotic distribution of received SINR. The distribution function of γ_j, $F_{\gamma_j}(\gamma)$, determines the exact limiting distribution. The following lemma indicates a sufficient condition for a distribution function $F_{\gamma_{\max}}(\gamma)$ belonging to the domain of attraction of the Gumbel distribution.

Lemma 1: As the number of SU $N \to \infty$, for the cdf of γ_j in (4), the variable $(\gamma_{\max} - a_\pi)/b_\pi$ converges to a standard Gumbel random variable with pdf $\exp(-e^{-x})$. The location and scale parameters a_π and b_π are, respectively,

$$a_\pi = F_{\gamma_j}^{-1}\left(1 - 1/N\right), \tag{6}$$

$$b_\pi = F_{\gamma_j}^{-1}\left(1 - 1/(Ne)\right) - a_\pi \tag{7}$$

where $F_{\gamma_j}^{-1}(x) = \inf\{\gamma : F_{\gamma_j}(\gamma) \ge x\}$ represents the quantile function of the distribution of γ_j.

Proof: For i.i.d. positive random variables with continuous and strictly positive pdf $f_{\gamma_j}(\gamma)$ and cdf $F_{\gamma_j}(\gamma)$, the main necessary condition for attraction to the Gumbel distribution is $\lim\limits_{\gamma\to\infty}\left(1 - F_{\gamma_j}(\gamma)\right)/f_{\gamma_j}(\gamma) = c > 0$ [9], [10], where c is constant. Compared with the restriction that the peak transmit power of the SU P is in high region [4], we assume that P is arbitrary. From (4) and (5), by using well-known computational software such as Wolfram Mathematica, it follows

$$\lim_{\gamma\to\infty}\frac{1-F_{\gamma_j}(\gamma)}{f_{\gamma_j}(\gamma)}=P>0.$$

Therefore, $F_{\gamma_{\max}}(\gamma)$ belongs to the domain of attraction of the Gumbel distribution.

Lemma 1 show that as $N\to\infty$, the cdf of $\gamma_{\max}$ becomes $F_{\gamma_{\max}}(\gamma)=\exp\left(-e^{-(\gamma-a_\pi)/b_\pi}\right)$. Based on Lemma 1, the average capacity of the CR network is shown in the following theorem.

Theorem 1: For large N, the average capacity of the CR network can be evaluated by the following expression

$$C_{\text{ave}}\approx a_\phi+\mathsf{E}_0 b_\phi \tag{8}$$

where $\mathsf{E}_0=0.5772\cdots$ is the Euler constant [11], a_ϕ and b_ϕ are in (9) and (10), respectively.

Proof: From Lemma 1, $\gamma_{\max}$ belongs to the Gumbel distribution. According to the limiting throughput distribution theorem in [11], the instant capacity $C_{\text{ins}}=\log(1+\gamma_{\max})$ also falls into the domain of the attraction of the Gumbel distribution. i.e., there must exist normalizing constants a_Φ and b_Φ, the variable $(C_{\text{ins}}-a_\phi)/b_\phi$ also uniformly converges in distribution to a Gumbel random variables as $N\to\infty$. Furthermore, The normalizing constants a_Φ and b_Φ are naturally transformed from (6) and (7) into [11]

$$a_\phi=\log\left(1+a_\pi\right), \tag{9}$$

$$b_\phi=\log\left(1+b_\pi\right)-\log\left(1+a_\pi\right). \tag{10}$$

In general, convergence in distribution does not guarantee the moment convergence. However, according to Lemma 2 in [11], we can obtain that convergence in distribution for the nonnegative maximum random variable results in moment convergence, and the average capacity of the CR network C_{ave}

$$C_{\text{ave}}=E\left[C_{\text{ins}}\right]\approx a_\phi+\mathsf{E}_0 b_\phi. \tag{11}$$

In the following, we need to seek the values of a_π and b_π. Since the exact solutions to the parameters involve with the upper incomplete Gamma function, the closed-form expressions of a_π and b_π can not be obtained. Fortunately, since the function $F_{\gamma_j}(\gamma)$ monotonically increases in γ, a_π, and b_π always have a unique solution. It is in general non-trivial to obtain accurate closed-form expressions for the location and scale parameters, which values can be calculated by $f$solve function in Matlab.

The asymptotic approximation in (8) is much accurate compared to the previous analysis in [4] and closely approximates to the exact simulation capacity. This is because that our analysis is based on exact statistical probability. However, the available results [4] is obtained under the assumption $P\gg Q$ or $P\gg NQ$. This assumption results in a great deviation to exact statistical probability in limiting statistical probability.

Although the closed-form expressions of a_π and b_π is not available, we can obtain their scaling law property. Now, we address the following theorem.

Theorem 2: For fixed P, P_p, and Q, the capacity (8) obeys the asymptotic growth rate as

$$\lim_{N\to\infty}\frac{C_{\text{ave}}}{\log\log N}=1.$$

Proof: From (4) and (6), we have

$$\frac{\left(1-e^{-\frac{Q}{P}}\right)e^{-\frac{\gamma}{P}}}{1+\frac{\gamma P_p}{P}}+\frac{Q}{\gamma P_p}e^{\frac{Q}{\gamma P_p}+\frac{1}{P_p}}\times\Gamma\left(0,\left(1+\frac{Q}{\gamma}\right)\left(\frac{1}{P_p}+\frac{\gamma}{P}\right)\right)=\frac{1}{N}. \tag{12}$$

It is note that the closed-form expression of upper incomplete Gamma function $\Gamma\left(0,\left(1+Q/\gamma\right)\left(1/P_p+\gamma/P\right)\right)$ can not be obtained, we may consider it's bounds. Applying the the following equality [13]

$$\frac{1}{2}\log\left(1+\frac{2}{\gamma}\right)\le e^\gamma\Gamma\left(0,\gamma\right)\le\log\left(1+\frac{1}{\gamma}\right)$$

for $0<\gamma<\infty$, from (12), we can obtain the following inequalities, respectively.

$$\frac{e^{-\frac{\gamma}{P}}}{\gamma P_p(P+\gamma P_p)}\left(Q(P+\gamma P_p)e^{-\frac{Q}{P}}\log\left(1+\frac{\gamma P_pP}{(\gamma+Q)(P+P_p\gamma)}\right)+PP_p\left(1-e^{-\frac{Q}{P}}\right)\gamma\right)\ge\frac{1}{N}, \tag{13}$$

$$\frac{e^{-\frac{\gamma}{P}}}{\gamma P_p(P+\gamma P_p)}\left(\frac{Q}{2}(P+\gamma P_p)e^{-\frac{Q}{P}}\log\left(1+\frac{2\gamma P_pP}{(\gamma+Q)(P+P_p\gamma)}\right)+PP_p\left(1-e^{-\frac{Q}{P}}\right)\gamma\right)\le\frac{1}{N}. \tag{14}$$

Since the fact that the received SINR γ at SU becomes large as $N\to\infty$, the $\gamma P_pP/((\gamma+Q)(P+P_p\gamma))$ term in (13) and (14) become very small. From $\log(1+x)\approx x$ when x is small, and $\gamma+Q\approx\gamma$ when γ is large, the left sides of (13) and (14) are equal. Therefore, we have the following expression after some manipulations

$$\frac{e^{-\frac{\gamma}{P}}}{\gamma P_p(P+\gamma P_p)}\left(PP_p\left(1-e^{-\frac{Q}{P}}\right)\gamma+QP_pPe^{-\frac{Q}{P}}\right)=\frac{1}{N}. \tag{15}$$

From the left side of (15), we can conclude that the term $PP_p\left(1-e^{-Q/P}\right)\gamma$ becomes dominate and the term $QP_pPe^{-Q/P}$ gets nonactive as N increases. Therefore, the solution of (15) without considering the term $QP_pPe^{-Q/P}$ is (16), where $W(\cdot)$ denotes the Lambert W function.

$$\begin{aligned}\gamma\ &=\ P\left(\log N-\log P_p+\log\left(PP_p\left(1-e^{-\frac{Q}{P}}\right)\right)\right)\\&+\ 1/P_pW\left(\frac{e^{\left(\frac{1}{P_p}+\log\left(NPP_p\left(1-e^{-\frac{Q}{P}}\right)\right)\right)}}{P_pP}\right)\\&-\ \log\left(NP\left(1-e^{-\frac{Q}{P}}\right)\right)-1/P_p.\end{aligned} \tag{16}$$

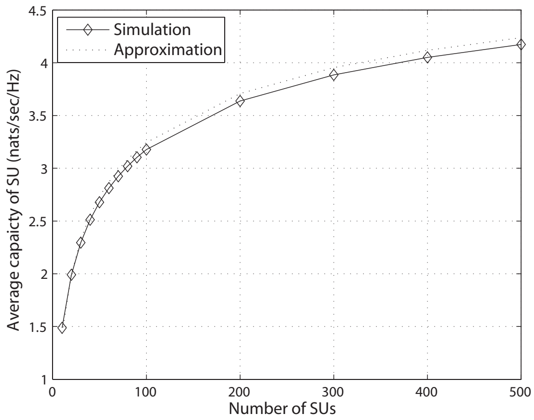

Fig. 2. CR average capacity versus N for $P = 20\ \mathrm{dB}$, $P_p = 10\ \mathrm{dB}$, and $Q = 0\ \mathrm{dB}$.

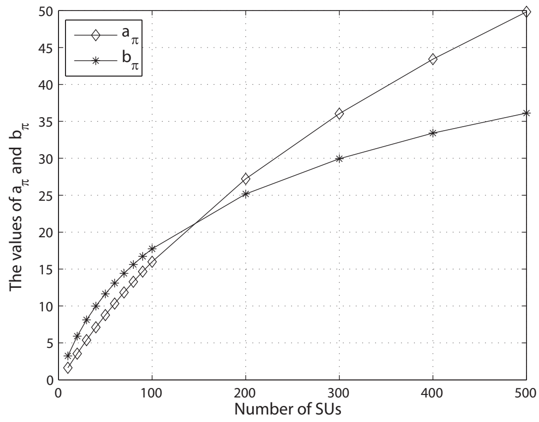

Fig. 3. The location and scale parameters a_π and b_π by $f$solve function for $P = 20\ \mathrm{dB}$, $P_p = 10\ \mathrm{dB}$, and $Q = 0\ \mathrm{dB}$.

That is, $a_\pi = \gamma$. When $N \to \infty$, the second term in (16) can be approximated as $1/P_p W\left(N\left(1 - e^{-Q/P}\right)\right)$. In addition, we have $W(z) \approx \log z$ for large z [12]. Therefore, $a_\pi \approx (P + 1/P_p - 1)\log N$ as $N \to \infty$. By substituting a_π into (9), the limiting value of a_ϕ is given by

$$\lim_{N\to\infty} a_\phi = \lim_{N\to\infty} \log\left(1 + (P + 1/P_p - 1)\log N\right) = \log\log N. \tag{17}$$

Next, the normalizing constant b_ϕ can be shown to vanish

$$\lim_{N\to\infty} b_\phi = \lim_{N\to\infty} \log\left(\frac{1 + (P + 1/P_p - 1)(\log N + 1)}{1 + (P + 1/P_p - 1)\log N}\right) = 0 \tag{18}$$

as $N \to \infty$. By inserting (17) and (18) together into (8), we have Theorem 2. Theorem 2 proves that the average capacity C_{ave} scales as $\Theta^1(\log(\log N))$ over Rayleigh fading channels, which is similar to that in [4] and [5]. From Theorem 1 and Theorem 2, our asymptotic capacity reinforces the results in [4], [5], [7], and [8].

IV. NUMERICAL RESULTS

Here, we present simulation results to validate our analysis. Fig. 2 shows the average capacity versus the number N of SU for $P = 20$ dB, $P_p = 10$ dB, and $Q = 0$ dB.

The a_π and b_π in Fig. 3, which are used to evaluate the capacity in Fig. 2, are obtained by $f$solve function in Matlab2007a. By using the $f$solve function, we can obtain their final values by setting their initial values as a very small constant, e.g. $f\mathrm{solve}\left(@(x)\ \mathrm{myfun}(x), [0.0001], \mathrm{options}\right)$. From Fig. 2, we observe that our approximation result (8) is quite well-matched to the exact capacity simulation, which is more accurate than the results in [4]. From the simulation results in [4], we know that Theorem 1 and Theorem 2 in [4] is about 0.6 nats/s/Hz capacity gap compared with those of exact capacity simulation. And the results in [5] only provides the scaling property of asymptotic capacity. The simulation curves show that the capacity increases with the number of SUs, which scales as $\Theta(\log(\log N))$.

[1]In this paper, $f(n) = \Theta(g(n))$ if and only if there are constants c_1, c_2, and n_0 such that $c_1 g(n) \le f(n) \le c_2 g(n)$ for any $n > n_0$.

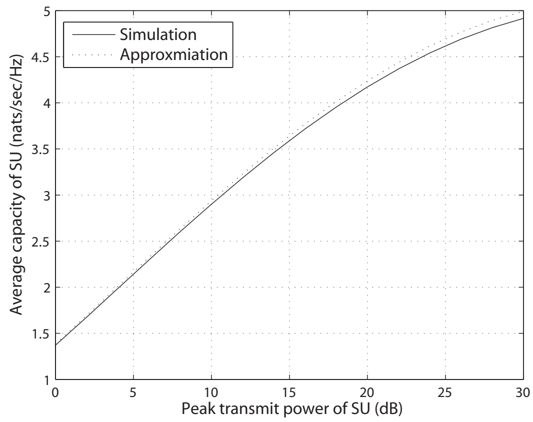

Fig. 4. CR average capacity versus different peak transmit power P for $N = 500$, $P_p = 10\ \mathrm{dB}$, and $Q = 0\ \mathrm{dB}$.

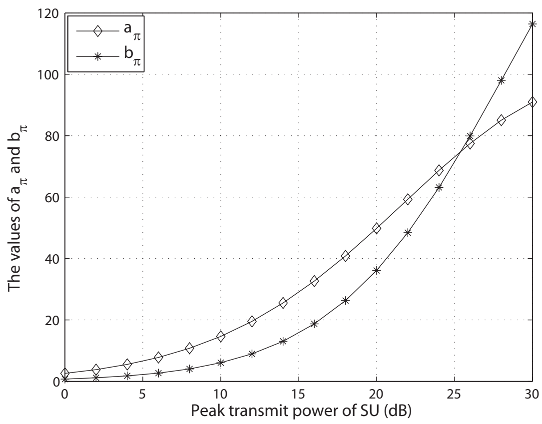

Fig. 5. The location and scale parameters a_π and b_π for different peak power P for $N = 500$, $P_p = 10\ \mathrm{dB}$, and $Q = 0\ \mathrm{dB}$.

The a_π and b_π in Fig. 5, which are used to evaluate the capacity in Fig. 4. Fig. 4 shows the average capacity versus different peak power P for $P_p = 10$ dB, $N = 500$, and $Q = 0$ dB. From Fig. 4, the approximated result well agrees with the exact capacity simulation in all the power region, especially in the low power region. However, the results in [4] only addresses that in high power region.

V. CONCLUSION

In this paper, we have analyzed the asymptotic capacity in a CR uplink system with an arbitrary peak transmit power and considering the interference from the PT. Simulation results show that our capacity approximation is much accurate compared to the existing result, which is quite well-matched to the exact capacity. Furthermore, our analysis reveals the average capacity scaling law $\log \log N$. In the future work, we can investigate the capacity of multiple input single output (MISO) cognitive network with the multiple pairs of primary users, which is worthy to be investigated.

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