

Asymptotic Capacity Analysis in Point-to-Multipoint Cognitive Radio Networks

Jianbo Ji*†, and Wen Chen*

*Wireless Network Transmission Laboratory, Shanghai Jiao Tong University, Shanghai, China 200240

†Department of Electronic Engineering, Guilin University of Aerospace Technology, Guilin, China 541004

Email: {jijianbo, wenchen}@sjtu.edu.cn

Abstract—In this paper, we analyze the asymptotic capacity in a spectrum sharing system where a secondary access point (SAP) restrictively utilizes the licensed spectrum of an active primary user (PU) to broadcast information to multiple secondary users (SUs) simultaneously, as long as the interference power inflicted on the PU is less than a predefined threshold. At the SAP, interference channel state information (CSI) between the SAP and the PU is used to calculate the maximum allowable SAP transmit power to limit the interference. We first derive the average capacity when perfect CSIs are known at the SAP based on extreme value theory. When the CSIs are imperfect, specifically, the interference CSI is imperfect, or the CSI of the SU transmission channel is imperfect, which is an important scenario for the secondary system. Then we characterize the capacity loss where perfect CSIs are not always available at the SAP.

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 devices [1], [2]. In general, CR may be implemented by means of opportunistic spectrum access or spectrum sharing. In an opportunistic spectrum access system, the secondary users (SUs) can only transmit in “white spaces”, i.e., the frequency bands or time intervals where the primary users (PUs) are silent [1]; In a spectrum sharing system, SUs may be allowed to transmit simultaneously with active primary users (PUs), as long as the interference power from the SUs to the PUs is less than an acceptable threshold. The maximum allowable interference power is called interference temperature Q [3], [4], which guarantees the quality of service (QoS) of the PU regardless of the SU’s spectrum utilization. Such approaches also have great potential to manage interference in future heterogeneous networks [5] or hierarchical network, e.g., femtocell. Clearly, the latter can achieve higher spectral efficiency at the expense of additional side-information at the SUs and the increased signaling overhead. Spectrum sharing approach has been actively researched [4]–[7].

Over the last few years, opportunistic transmission has drawn much attention as an effective means of exploiting multiuser diversity (MUD) gain in wireless networks. The MUD gain resulting from the statistically independent channels seen by the only one user with the best channel condition. Recently, ideas from opportunistic communication were used

in spectrum-sharing cognitive radios by selectively activate one or more SUs to maximize the SU throughput while satisfying interference constraints [4], [6]. Some of the related works are summarized as follows. The MUD gain in cognitive networks is studied in [4], [8]–[11], by selecting the SU with the highest signal to interference and noise ratio under the PU interference constraints. In [8], the authors have investigated the multiuser diversity gain in an opportunistic CR system, which has been shown to grow like $\log \log(N)$, where N is the number of SU. Jamal et al. [11] and Shen et al. [12] found that the SU throughput can be increased by simultaneously activating as many secondary transmitters as possible. However, these asymptotic analysis only propose scaling laws for asymptotic SNR, rather than providing exact results. In this paper, we first give a closed form of the asymptotic capacity under full CSI knowledge at the SAP. Then we discuss the effects on the capacity under imperfect interference CSI and SUs’ transmission CSI.

II. SYSTEM AND CHANNEL MODEL

As shown in Fig. 1, a spectrum sharing homogeneous network in a single cell system is considered, where an SAP utilizes the licensed spectrum of a PU to broadcast information to a set of N SUs. All users in the network are assumed to be equipped with a single antenna. In the system, any transmission from the SAP to the SUs is allowed provided that the resulting interference power level at the PU is below the predefined threshold, which is called the interference-temperature constraint [2], [7], [13]. The interference-temperature Q represents the maximum allowable interference power level at the PU. The channel gains from the SAP to the PU and the j -th SU are denoted by α_{sp} and β_j , respectively, where $j \in \{1, \dots, N\}$. The channel gains α_{sp} and β_j are assumed to be independent and identically distributed (i.i.d.) exponential random variables.

Utilizing the feedback scheme, the SAP can obtain the interference CSI through periodic sensing of pilot signal from the PU by the hypothesis of channel reciprocity [14], the SAP then computes the maximum allowable transmit power depending on α_{sp} so as to satisfy the interference temperature constraint at the PU. The SAP 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

Secondary Access Point

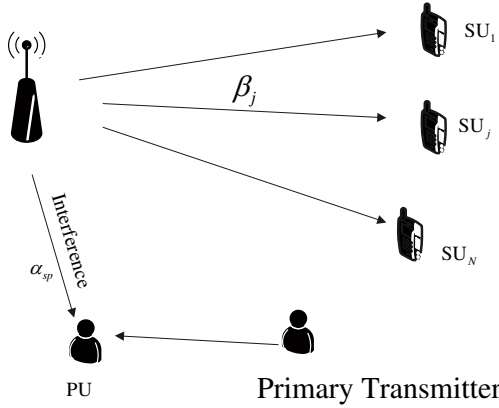


Fig. 1. The system model for the SU network coexisting with a PU

perceived at the PU is maintained as a given interference temperature level Q . Correspondingly, the transmit power of the SAP P_t is [15]

$$P_t = \min \left(P, \frac{Q}{\alpha_{sp}} \right), \quad (1)$$

where P represents the peak power of the SAP transmission.

It is worthwhile to mention that, similar to that in [4], [16], the detailed protocol between the primary transmitter and the primary receiver is ignored, and the interference from primary transmitters can be translated into the noise term of the secondary system.

III. ASYMPTOTIC CAPACITY WITH PERFECT CSIS

We assumed that the SAP can obtain the perfect estimation of interference channel gains α_{sp} by direct feedback from the PU [5] and the SUs' transmission CSI. Accordingly, the received signal-to-noise power ratio (SNR) γ_j at the j -th SU is

$$\gamma_j = \frac{P_t \beta_j}{\sigma^2} = \begin{cases} P \beta_j, & \alpha_{sp} \leq \frac{Q}{P}, \\ \frac{Q \beta_j}{\alpha_{sp}}, & \alpha_{sp} > \frac{Q}{P}, \end{cases} \quad (2)$$

where the variance of white Gaussian noise is normalized to be 1. To simplify mathematical analysis, α_{sp} and β_j are both assumed to be i.i.d. exponential random variables with unit mean. The cumulative density function (cdf) of the received SNR γ_j at the j -th SU is

$$F_{\gamma_j}(\gamma) = \Pr \left[\alpha_{sp} \leq \frac{Q}{P} \right] \left(1 - e^{-\frac{\gamma}{P}} \right) + \Pr \left[\frac{Q \beta_j}{\alpha_{sp}} \leq \gamma \mid \alpha_{sp} > \frac{Q}{P} \right]. \quad (3)$$

After some calculation, we have

$$F_{\gamma_j}(\gamma) = \left(1 - e^{-\frac{Q}{P}} \right) \left(1 - e^{-\frac{\gamma}{P}} \right) + e^{-\frac{Q}{P}} \left(1 - \frac{Q}{Q + \gamma} e^{-\frac{\gamma}{P}} \right). \quad (4)$$

Furthermore, we can obtain the probability density function (pdf) $f_{\gamma_j}(\gamma)$ by differentiating (4) with respect to γ , which

gives

$$f_{\gamma_j}(\gamma) = \frac{1}{P} \left(1 - e^{-\frac{Q}{P}} \right) e^{-\frac{\gamma}{P}} + \frac{Q(P + Q + \gamma)}{P(Q + \gamma)^2} e^{-\frac{\gamma + Q}{P}}. \quad (5)$$

Now the SAP chooses the SU that has maximal received SNR from N SUs at each transmission. The SU average capacity is given by [17], $C_U \triangleq E[\log(1 + \gamma_{\max})] = \int_0^\infty \log(1 + \gamma) f_{\gamma_{\max}}(\gamma) d\gamma$, where $\gamma_{\max} \triangleq \max_{1 \leq i \leq N} \gamma_i$, whose pdf is denoted as $f_{\gamma_{\max}}(\gamma) = N f_{\gamma_i}(\gamma) F_{\gamma_i}(\gamma)^{N-1}$, which is shown in the following Theorem.

Theorem 1: For $P \gg Q$, the SU asymptotic capacity in the spectrum sharing system approximates as

$$C_U \approx (1 - E_0) \log \left(1 + PW \left(\frac{NQ}{P} \right) - Q \right) + E_0 \log \left(1 + PW \left(\frac{NeQ}{P} \right) - Q \right) \quad (6)$$

for the large number N of SU, where $E_0 = 0.5772 \dots$ is the Euler constant [18] and $\mathcal{W}(\cdot)$ denotes a Lambert W function [19].

Proof: Omitted due to limited space. \square

The closed form of the capacity is obtained. From [20], $\mathcal{W}(z) \approx \log z$ for large z . Therefore, (6) can be approximated as $(1 - E_0) \log(1 + P(\log NQ - \log P) - Q) + E_0 \log(1 + P(\log NeQ - \log P) - Q)$ for large N . We can see that the average capacity in the spectrum sharing system grows like $\Theta(\log(\log N))$ ¹. Our result complements and reinforces the result in [8]–[10].

IV. IMPACT OF IMPERFECT CSIS ON THE SU CAPACITY

In practice, however, the SAP may not know the interference CSI on the link between the SAP and the PU, because the PU would not purposely provide its CSI to the SAP. In addition, due to feedback delay, the SAP only obtain the SUs' imperfect CSI. In this section, we mainly address the impacts of imperfect CSI of the interference channel and the SU transmission channels on the capacity.

A. Asymptotic Capacity with Imperfect Interference CSI

Due to limited cooperation between the SAP and the PU, the SAP is only provided with partial channel knowledge of h_{sp} . With partial CSI of the interference channel at the SAP, we have an estimate of the interference channel \hat{h}_{sp} of the form

$$\hat{h}_{sp} = \rho h_{sp} + \sqrt{1 - \rho^2} \epsilon, \quad (7)$$

where \hat{h}_{sp} is the interference channel estimate available at the SAP, and ϵ follows circularly symmetric complex Gaussian distribution with zero mean and variance (i.e., $\mathcal{CN}(0, 1)$) and is uncorrelated with h_{sp} . The correlation coefficient $0 \leq \rho \leq 1$ is a constant that determines the average quality of the channel estimate over all channel states of h_{sp} . This model is well

¹In this paper, $f(n) = O(g(n))$ if and only if there are constant c and n_0 such that $f(n) \leq cg(n)$ for any $n > n_0$. $f(n) = \Theta(g(n))$ if and only if there are constants c_1, c_2 and n_0 such that $c_1 g(n) \leq f(n) \leq c_2 g(n)$ for any $n > n_0$. We use $E(\cdot)$ to denote the expectation. We also use \log to denote nature logarithm, $\Pr(\cdot)$ denotes probability.

estimated in the literature, which investigates the effects of imperfect CSI [21], [22].

Since $\hat{\alpha}_{sp} \neq \alpha_{sp}$, noting that in the presence of partial interference channel information, the second constraint in (1) is no longer well defined, and the interference at times may not be limited to Q . Therefore, a revision is necessary. The interference inflicted at the PU under the imperfect interference CSI can be found from the following [23]

$$P_t = \min \left(P, \frac{Q'}{\hat{\alpha}_{sp}} \right). \quad (8)$$

In this scenario, we may allow the interference to exceed a certain threshold Q with a small probability δ . In this case, the second term in (1) can be replaced by

$$\Pr \left(\frac{Q' \alpha_{sp}}{\hat{\alpha}_{sp}} \leq Q \right) = 1 - \delta. \quad (9)$$

Let $Z = \frac{\alpha_{sp}}{\hat{\alpha}_{sp}}$. In order to find Q' , we have to obtain the cdf of Z . The cdf of Z is given by

$$\Pr(Z < z) = \Pr(\alpha_{sp} < \hat{\alpha}_{sp} z) = \int_0^\infty \int_0^{yz} f_{\alpha_{sp}, \hat{\alpha}_{sp}}(x, y) dx dy, \quad (10)$$

where $f_{\alpha_{sp}, \hat{\alpha}_{sp}}(x, y)$ is the joint pdf of the variables α_{sp} and $\hat{\alpha}_{sp}$. Their joint pdf can be expressed as in [24]

$$f_{\alpha_{sp}, \hat{\alpha}_{sp}}(x, y) = \frac{1}{1 - \rho^2} e^{-\frac{x+y}{1-\rho^2}} I_0 \left(\frac{2\rho\sqrt{xy}}{1-\rho^2} \right), \quad (11)$$

where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind Eq. (8.431.1) in [19]. Substituting the joint pdf $f_{\alpha_{sp}, \hat{\alpha}_{sp}}(x, y)$ in (10) results in the following

$$\Pr(Z < z) = \frac{1}{1 - \rho^2} \int_0^\infty e^{-\frac{y}{1-\rho^2}} \int_0^{yz} e^{-\frac{x}{1-\rho^2}} I_0 \left(\frac{2\rho\sqrt{xy}}{1-\rho^2} \right) dx dy. \quad (12)$$

Using Eq. (10) in [25], the inner integral in (12) can be solved to give

$$\begin{aligned} \Pr(Z < z) &= \frac{1}{1 - \rho^2} \int_0^\infty e^{-\frac{y}{1-\rho^2}} \int_0^{yz} e^{-\frac{x}{1-\rho^2}} I_0 \left(\frac{2\rho\sqrt{xy}}{1-\rho^2} \right) dx dy \\ &= 1 - \int_0^\infty e^{-y} Q_1 \left(\sqrt{\frac{2\rho^2 y}{1-\rho^2}}, \sqrt{\frac{2yz}{1-\rho^2}} \right) dy \end{aligned}$$

where

$$Q_1(a, b) = \int_b^\infty x e^{-\frac{x^2+a^2}{2}} I_0(ax) dx \quad (13)$$

is the first-order Marcum Q-function [25]. Using Eq. (55) in [25], we can obtain the cdf of Z in closed form as

$$\Pr(Z < z) = 1 - \frac{1}{2} \left(1 + \frac{t}{r} \right), \quad (14)$$

where $t = 2 \left(1 + \frac{\rho^2}{1-\rho^2} - \frac{z}{1-\rho^2} \right)$, $r = \sqrt{s^2 - \frac{16\rho^2 z}{(1-\rho^2)^2}}$ and $s = 2 \left(1 + \frac{\rho^2}{1-\rho^2} + \frac{z}{1-\rho^2} \right)$. Let $z = \frac{Q}{Q'}$. Noting that $\Pr(Z \leq z) = 1 - \delta$, we have $1 + \frac{t}{r} = 2\delta$. After some algebraic manipulations, we can obtain the following expression

$$z = 1 + (1 - \rho^2 - 2\delta + 2\rho^2\delta + \hbar) \frac{2\delta - 1}{2\delta(\delta - 1)}, \quad (15)$$

where $\hbar = \sqrt{1 + 4\rho^2\delta - 2\rho^2 + 4\rho^4\delta^2 - 4\rho^4\delta - 4\rho^2\delta^2 + \rho^4}$. Note that the fact $z = \frac{Q}{Q'}$, closed form of Q' is available, i.e., $Q' = \frac{Q}{z}$. It should be noted that when $\rho = 1$ (perfect interference CSI), $z=1$, i.e., $Q' = Q$. Since the pdf of $\hat{\alpha}_{sp}$ is the same as that of α_{sp} [26], similar to the same derivation in section III, we have the following theorem.

Theorem 2: When $P \gg Q$, the SU average capacity with the imperfect interference CSI at the SAP is

$$\begin{aligned} C_{UE} &\approx (1 - E_0) \log \left(1 + PW \left(\frac{NQ'}{P} \right) - Q' \right) \\ &\quad + E_0 \log \left(1 + PW \left(\frac{NeQ'}{P} \right) - Q' \right) \end{aligned}$$

for the large number N of SU.

B. SU Asymptotic Capacity with Imperfect SU Transmit CSI

The imperfect CSI may arise due to a variety of reasons, such as channel estimation error, mobility, and feedback delay. In this subsection, for mathematical tractability, we assume that the imperfectness comes from feedback delay.

The SAP transmission channel estimate \hat{h}_k is obtained by the transmitter from a feedback path with time delay. Letting \hat{h}_k denote the k -th channel coefficient at the SAP and h_k indicate the counterpart at the instant of transmission, then the relation between \hat{h}_k and h_k can be formulated as

$$\hat{h}_k = \delta h_k + \sqrt{1 - \delta^2} \epsilon_k, \quad k = 1, 2, \dots, N \quad (16)$$

where $\delta \equiv J_0(2\pi f_d T)$ is the correlation coefficient of \hat{h}_k and h_k between t and $t + T$ with Doppler frequency f_d , and ϵ_k confirms to $\mathcal{CN}(0, 1)$ and is uncorrelated with h_k . Note that $J_0(\cdot)$ denotes zeroth-order Bessel function of the first kind. Their joint pdf of channel gains $|\hat{h}_k|^2$ and $|h_k|^2$ is given by

$$f_{|h_k|^2, |\hat{h}_k|^2}(x, y) = \frac{1}{1 - \delta^2} e^{-\frac{x+y}{1-\delta^2}} I_0 \left(\frac{2\delta\sqrt{xy}}{1-\delta^2} \right). \quad (17)$$

We account for the uncertainty caused by feedback delay, due to processing delay at the receiver and propagation delay in the feedback. After capturing the SU with the best channel condition, the SAP should determine the transmission rate for this SU. When the SAP allocates the transmission rate matched to the SNR at a measured instant of the SU, a downlink transmission packet error may occur due to a channel quality change prior to the instant of downlink transmission. This mismatch is caused by a feedback delay. One solution to reduce the downlink error probability is to set the actual transmission rate to a lower value than that of the estimated one. To determine a suitable rate, we will first consider the conditional pdf of the current fading for a particular SU based on its outdated channel SNR. We now asymptotically analyze the capacity in order to understand the effects of channel estimation errors.

Theorem 3: When $P \gg Q$, for the large N , the SU average capacity C_{UE} with imperfect SU transmission CSI is lower-bounded as (18)

Proof: Omitted due to limited space. \square

From (18), it is clear that when $\delta = 1$ (perfect CSI), the terms including $\exp \left(-\frac{\delta^2}{1-\delta^2} \right)$ in the right side of (18) is equal

to zero, in the case $C_{UE} = C_U$. It is note that [27], the number of the symbols in the feedback packet grows like $O(\log N)$ as N increases. This implies that the feedback delay also grows like $O(\log N)$ because the SAP can transmit after receiving the feedback packets. This reduces the value of δ and the performance would be degraded.

V. NUMERICAL RESULTS

Here we present simulation results that validate our theoretical claims. These results are obtained through Monte-Carlo simulations. Fig. 2 shows the average capacity versus the number N of SU for two different transmission peak power $P = 20, 30$ dB and $Q = 0$ dB. It is verified that the asymptotic approximation results exactly characterize the performance of the capacity. The simulation curves show that the capacity increases with the number of SUs, which grow like $\log(\mathcal{W}(N))$.

Fig. 3 shows the new interference threshold measurement Q' versus channel correlation coefficient with the probability of interference power exceeding Q . For a certain probability, the new interference threshold Q' will increase with the channel correlation coefficient ρ , likewise, Q' will increase with probability for a certain channel correlation coefficient. This agrees with reality. We further see that when channel correlation coefficient is equal to 1, Q' is always equal to Q in probability 1.

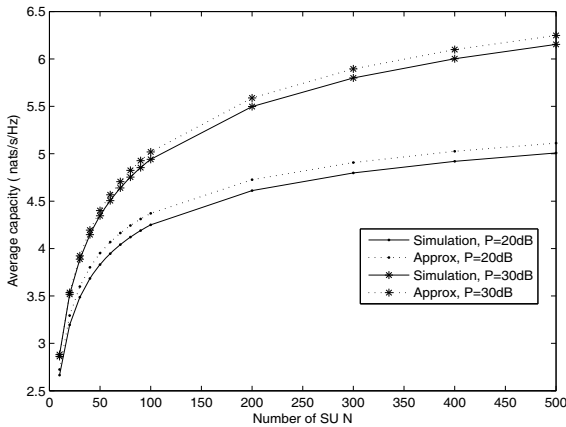


Fig. 2. Average capacity versus the number of SU with perfect CSIs for two different transmission peak power P

Fig. 4 shows the average capacity performance simulation including the effect of the feedback delay. The SAP transmission peak power $P = 30$ dB, and $Q = 0$ dB. To include the effect of the number of feedback bits increase, in the simulation, it is also assumed that the normalized Doppler frequency $f_d T$ is given as $c \log_2 N$. It is assumed that the transmission rate is set to $\log(1 + \lambda \delta^2 \gamma_{\max})$ and the transmission errors occurs when the channel gain at the downlink transmission instant is smaller than $\lambda \delta^2 \gamma_{\max}$. As the Doppler frequency increases, the performance is degraded while the capacity growth rate is maintained as $O(\log \log N)$. This simulation also shows that increasing the value of δ the performance would be degraded.

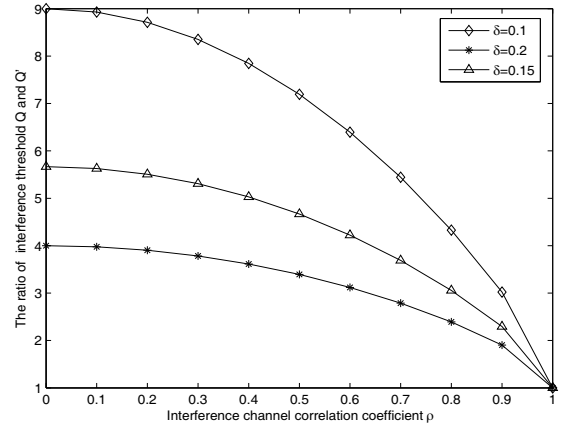


Fig. 3. The ratio of interference threshold versus channel correlation coefficient under three different probability

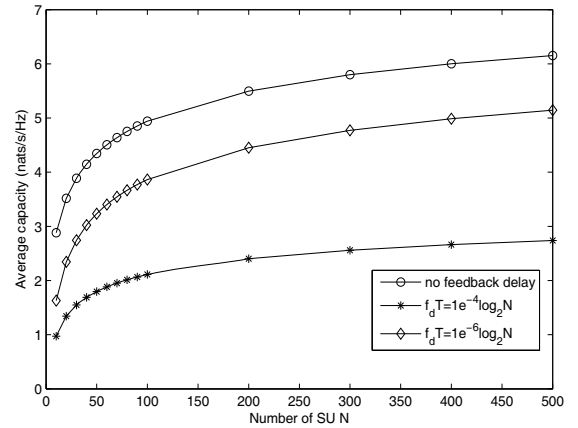


Fig. 4. Average capacity scheme considering feedback delay ($\lambda = 0.8$).

VI. CONCLUSION

The SU average capacity in spectrum sharing has been investigated, based on the asymptotic theory of extreme order statistics. Specially, we have derived the SU average capacity with perfect CSIs available in closed form. In contrast to the previous results in the paper, we also first have investigated the impact of imperfect interference CSI on the SU average capacities. For the case, when the interference channel gain is incorrectly measured, the interference power at the PU may exceed the maximum allowable limit. One measure of addressing this issue is to exploit a modified lower interference limit so that the original limit is only exceeded with a small probability, and a new maximum allowable limit in closed form is obtained. Then we have addressed the impacts on the capacity with the SU transmission feedback delay. For the situation, after capturing the SU with the best channel condition, the SU feeds channel gain to the SAP, and the SAP should determine the transmission rate for this SU. When the SAP assigns the transmission rate matched to the SNR at a measured instant of the SU, due to feedback, transmission

$$C_{UE} \geq C_U \left(1 - O\left(\frac{1}{\log N}\right)\right) \times \left(1 - \frac{1}{2} \exp\left(-\frac{\delta^2(1 - \sqrt{\lambda})^2(\log N - \log \log N)}{1 - \delta^2}\right)\right) + \frac{1}{2} \exp\left(-\frac{\delta^2(1 + \sqrt{\lambda})^2(\log N - \log \log N)}{1 - \delta^2}\right) \quad (18)$$

packet error may occur due to a channel quality change prior to the instant of transmission.

ACKNOWLEDGMENT

This work is supported by NSFC #60972031, by national 973 project #2012CB316106 and #2009CB824900, by NSFC #61161130529, by Guijiao-keyan #200103YB149 and #X10Z003, by national huge special project #2012ZX03004004, by national key laboratory project #ISN11-01, by Huawei Funding #YBWL2010KJ013.

REFERENCES

- [1] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," Ph. D. dissertation, KTH, Stockholm, Sweden, Dec. 2000.
- [2] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Select Areas Commun.*, vol. 23, no. 2, pp. 201-220, Feb. 2005.
- [3] Federal Communications Commission, "Spectrum policy task force report," ET Docket No.02-135, Nov. 2002.
- [4] T. W. Ban, W. Choi, B. C. Jung, and D. K. Sung, "Multi-user diversity in a spectrum sharing system," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 102-106, Jan. 2009.
- [5] A. Ghasemi, and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments," *IEEE Trans. Wireless. Commun.*, vol. 6, no. 2, pp. 649-658, Feb. 2007.
- [6] P. Viswanath, D. N. C. Tse, and R. L. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inform. Theory.*, vol. 48, no. 6, pp. 1277-1294, Jun. 2002.
- [7] Website of FCC, <http://www.fcc.gov/sptf/resports.html>.
- [8] J. -P. Hong and W. Choi, "Capacity scaling law by multiuser diversity in cognitive radio systems," in *Proc. ISIT*, pp. 2088-2092, Jun. 2010.
- [9] R. Zhang and Y. -C. Liang, "Investigation on multiuser diversity in spectrum sharing based cognitive radio networks," *IEEE Commun. Lett.*, Vol. 14, no 2, pp. 133-135, Feb. 2010.
- [10] A. Tajer and X. Wang, "Multiuser diversity gain in cognitive network with distributed spectrum access," in *Proc. Information Sciences and Systems (CISS)*, Mar. 2009, pp. 135-140.
- [11] N. Jamal, H. E. Saffar, and P. Mitran, "Throughput enhancements in point-to-multipoint cognitive systems," in *Proc. ISIT*, July 2009, pp. 2742-2746.
- [12] C. Shen and M. Fitz, "Opportunistic spatial orthogonalization and its application in fading cognitive radio networks," *IEEE J. Select. Topics Signal Processing*, to appear.
- [13] M. Gastpar, "On capacity under receive and spatial spectrum-sharing constraints," *IEEE Trans. Inform. Theory.*, vol. 53, no. 2, pp. 471-487, Feb. 2007.
- [14] Q. Zhao, S. Geirhofer, L. Tong and B. M. Sadler, "Opportunistic spectrum access via periodic channel sensing," *IEEE Trans. Signal Processing*, vol. 56, no. 2, pp. 785-796, Feb. 2008.
- [15] Y. Li and A. Nosratinia, "Capacity limits of multiuser multiantenna cognitive networks," *IEEE Trans. Inform. Theory*, submitted, available online: <http://arxiv.org/pdf/1008.3641>.
- [16] H. Ding, J. Ge, D. B. da Costa and Z. Jiang, "Asymptotic analysis of cooperative diversity systems with relay selection in a spectrum-sharing scenario," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 457-472, Feb. 2011.
- [17] P. Kumar, and H. E. Gamal, "Feedback in wireless networks: cross-layer design, secrecy and reliability," Ph. D. dissertation, The Ohio State University, Columbus, Ohio, Aug. 2007.
- [18] G. Song, Y. Li, "Asymptotic throughput analysis for channel-aware scheduling," *IEEE Trans. Commun.*, Vol. 54, no 10, pp. 1827-1834, Oct. 2006.
- [19] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed. San Diego, CA: Academic, 2007.
- [20] R. M. Corless et al., "On the Lambert W function," *Adv. Computational Maths.* no. 5, pp. 329-359, 1996 [Online]. Available: <http://www.apmaths.uwo.ca/~djeffery/Ofprints/W-adv-cm.ps>
- [21] K. S. Ahn and R. W. Heath, Jr, "Performance analysis of maximum ratio combining with imperfect channel estimation in the presence of cochannel interferences," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1080-1085, Mar. 2009.
- [22] L. Musavian and S. Aissa, "Effective capacity of delay-constrained cognitive radio in Nakagami fading channels," *IEEE Trans. Wireless Commun.*, vol. 9, no. 3, pp. 1054-1062, Mar. 2010.
- [23] Y. J. Zhang, and A. M. So, "Optimal spectrum sharing in mimo cognitive radio networks via semidefinite programming," *IEEE J. Select Areas Commun.*, vol. 29, no. 2, pp. 362-373, Feb. 2011.
- [24] C. Tellambura and A. D. S. Jayalathe, "Generation of bivariate Rayleigh and Nakagami-m fading envelopes," *IEEE Commun. Lett.*, vol. 4, no. 5, pp. 170-172, Oct. 2000.
- [25] A. H. Nuttall, "Some intergrals involving the Q-function," Naval Underwater Syst. Cent., New London, CT, Tech. Rep. 4297, Apr. 1972.
- [26] H. A. Suraweera, P. J. Smith and M. Shafi, "Capacity limits and performance analysis of cognitive radio with imperfect channel knowledge," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1811-1822, May. 2010.
- [27] S. Y. Park, D. Park, and D. J. Love, "On scheduling for multiple-antenna wireless networks using contention-based feedback," *IEEE Trans. Commun.*, Vol. 55, no 6, pp. 1174-1190, Jun. 2007.