

# 협력 무선인지 네트워크에서의 보안 채널 용량 분석

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## On the Secrecy Capacity in Cooperative Cognitive Radio Networks

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### 요 약

본 논문에서는 면허 사용자와 감청 사용자가 존재하는 인지무선 네트워크에서 릴레이 선택 기능을 이용한 물리 계층 보안 시스템을 제안하고 성능을 분석한다. 먼저 감청에 대한 보안성 확보를 위해 수신기 측에서의 채널 정보를 이용하는 기회적 최적 릴레이 선택 방법과 다중 안테나 다이버지시티를 이용하는 시스템을 제안한다. 이러한 시스템에서 인지무선 네트워크의 보안 outage 확률을 정의하고 수학적으로 정확한 확률 식을 유도한다. 아울러 송신전력에 제한이 없는 경우에 대한 접근적 outage 확률을 구한다. 수치 해석 결과를 제시함으로써 유도한 확률식의 정확성을 검증한다.

**Key Words** : Secrecy Capacity, Cognitive Radio (CR), Cooperative Cognitive Radio Networks (CRNs), Relay, Secrecy Outage Probability

### ABSTRACT

In this paper, we investigate physical layer security in a cooperative cognitive radio networks (CRN) with a relay selection in the presence of a primary user and an eavesdropper. To protect the CRN from wiretapping by the eavesdropper, we propose employing an opportunistic relay selection scheme and multiple antennas at the destination that work based on the availability of channel state information at the receivers. Under these configurations, we derive an exact closed-form expression for the secrecy outage probability of the CRN, and also derive an asymptotic probability. Numerical results will be presented to verify the analysis.

### I. Introduction

As the radio spectrum becomes crowded and scarce, efficient utilization of radio spectrum becomes increasingly important. Cognitive radio networks (CNRs), first proposed by Mitola<sup>[1]</sup>, provide a solution for improving spectrum utilization

in wireless networks through optimistic spectrum sharing. Under a CRN, secondary users need to sense the spectrum to detect spectrum holes that are not used by primary (licensed) users. When using the resources that primary users are using, the secondary users and to limit the harmful interference that may be caused to the primary users<sup>[2-4]</sup>.

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Recently, physical layer security has attracted significant interest in the research community as the information security becomes crucial for pervasive and personalized wireless devices<sup>[5-8]</sup>. With the help of relays, the secrecy capacity of a wireless system can be significantly improved. The secrecy capacity of the secondary system in a CRN was investigated in [9-11], where the secondary users exploit multiple antennas to protect the confidential signal. On the other hand, optimal relay selection (ORS) scheme can be adopted to improve the performance of wireless relaying<sup>[12,13]</sup>. In particular, it has been shown that the ORS can achieve optimal performance in terms of the outage probability and capacity for both decode-and-forward (DF) and amplify-and-forward (AF) protocols.

In this paper, we consider a CRN in which there exists an eavesdropper that can overhear the confidential signal transmitted from the secondary user. Passive eavesdropper is considered, where the channel state information (CSI) is not available at the secondary transmitter. We take into account the peak interference constraint at primary receiver and maximal transmit power at secondary transmitter. Particularly, the eavesdropper is equipped with multiple antennas to wiretap channel. To deal with it, we consider the ORS scheme based on the availability of CSI at the secondary receiver and multiple antennas at primary receiver to promote

secure data transmission. With this in mind, we derive new exact and asymptotic expression in closed-form for the secrecy outage probability. Numerical results will be provided to verify the analysis.

The rest of this paper is organized as follows. Section II describes a CRN model and the optimal relay selection scheme. In Section III, the secrecy outage probability of the secondary system is derived for the CRN. In Section IV, numerical results are presented and discussed. Finally, conclusions are drawn in Section V.

## II. System Model

As illustrated in Fig. 1, we consider a CRN with a secondary transmitter (S), a secondary receiver (D), a primary receiver (P), and an eavesdropper (E). We assume that there is no direct link between the secondary transmitter and the secondary receiver. Accordingly, the secondary transmitter sends data to the secondary receiver with the help of  $M$  secondary relays  $R_m$ ,  $m = 1, 2, \dots, M$ . We assume that the channel between any two nodes is assumed to be independent and flat Rayleigh fading channel, and that perfect CSI is available at the receiver. Each node is assumed to operate in half-duplex mode. The secondary receiver and the eavesdropper are equipped with  $N$  and  $K$  antennas, respectively, while each of the secondary transmitter, the primary receiver, and  $M$  relays, is equipped with a single antenna. The eavesdropper attempts to wiretap and decode the data of the secondary system.

Let  $h_{SP}, h_{SR_m}, h_{SE}, h_{R_mD}, h_{R_mP}$  and  $h_{R_mE}$  denote the channel coefficients of the links  $S \rightarrow P$ ,  $S \rightarrow R_m$ ,  $S \rightarrow E$ ,  $R_m \rightarrow D$ ,  $R_m \rightarrow P$ , and  $R_m \rightarrow E$ , respectively. The corresponding channel gains  $|h_{XY}|^2$ ,  $X \in \{S, R_m\}$  and  $Y \in \{R_m, D, E, P\}$ , will follow exponential distribution with a parameter  $\Omega_{XY}$ . Therefore, the probability density function (PDF) of the random variable  $|h_{XY}|^2$  is given as

$$f_{XY}(x) = \Omega_{XY} \exp(-\Omega_{XY}x) \quad (1)$$

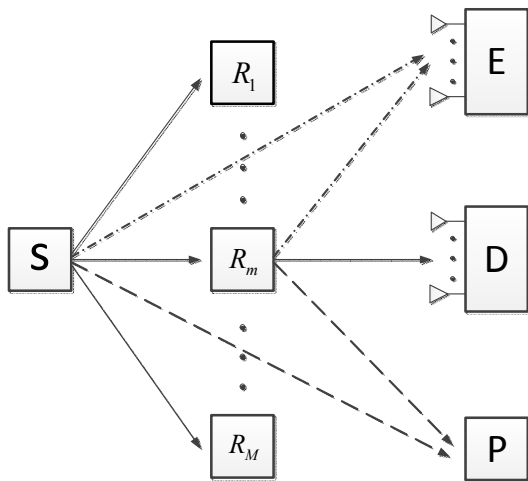


Fig. 1. A CRN with  $M$  relay nodes and an eavesdropper.

where  $\Omega_{XY} = E\{|h_{XY}|^2\} = d_{XY}^\beta$ ,  $d$  is the distance between two nodes  $X$  and  $Y$ , and  $\beta$  denotes the path loss exponent. Moreover,  $n_Y \sim CN(0,1)$  denotes additive white Gaussian noise (AWGN) at the node  $Y$ . In an underlay CRN, the secondary system may simultaneously use the spectrum with the primary system. Therefore, the transmit power at  $S$  and  $R_m$  must satisfy a peak interference power constraint so that the interference at the primary receiver is less than threshold  $Q$ . We assume that antenna selection is employed at  $D$  and  $E$  to achieve full diversity gain<sup>[14]</sup>. During the first phase of relaying,  $S$  transmits to  $M$  relays and the corresponding signal-to-noise ratio (SNR) at  $R_m$  and  $E$  is respectively given as

$$\begin{aligned} \gamma_{1D} &= P_S |h_{SR_m}|^2, \\ \gamma_{1E} &= \max_{k=1, \dots, K} P_S |h_{SE_k}|^2, \end{aligned} \quad (2)$$

where  $P_S$  denote the transmit power of  $S$ . During the second phase, a relay transmits data to  $D$  and the SNR at  $D$  and  $E$  is respectively given as

$$\begin{aligned} \gamma_{2D} &= \max_{n=1, \dots, N} P_{R_m} |h_{R_m D_n}|^2, \\ \gamma_{2E} &= \max_{k=1, \dots, K} P_{R_m} |h_{R_m E_k}|^2, \end{aligned} \quad (3)$$

where  $P_{R_m}$  denotes the transmit power of  $R_m$ . Note that the transmit power  $P_S$  and  $P_{R_m}$  need to satisfy the interference constraint at  $P$ :

$$\begin{aligned} P_S &= \min\left(P_T, \frac{Q}{|h_{SP}|^2}\right), \\ P_{R_m} &= \min\left(P_T, \frac{Q}{|h_{R_m P}|^2}\right). \end{aligned}$$

### III. PERFORMANCE ANALYSIS

For the physical layer security relying on multiple relays, the main objective is to maximize the SNR in the desired link and minimize the SNR in the eavesdropping link at the same time. We consider an optimal relay selection based on the available CSI at

the receiver:

$$m^* = \arg \max_{m=1, \dots, M} \min(C_{1m}^s, C_{2m}^s), \quad (4)$$

where  $C_{1m}$  and  $C_{2m}$  are the secrecy capacity of the first hop and that of the second hop, respectively. We define the secrecy capacity of each hop as<sup>[15]</sup>

$$\begin{aligned} C_{1m}^s &= \left[ \frac{1}{2} \log_2 \left( \frac{1 + \gamma_{1D}}{1 + \gamma_{1E}} \right) \right]^+, \\ C_{2m}^s &= \left[ \frac{1}{2} \log_2 \left( \frac{1 + \gamma_{2D}}{1 + \gamma_{2E}} \right) \right]^+, \end{aligned} \quad (5)$$

where  $[x]^+ \equiv \max(x, 0)$ . From (4) and (5), the secrecy outage probability of the optimal selection scheme is give by

$$P_{out}^s = \Pr(\max_{m=1, \dots, M} \min(C_{1m}^s, C_{2m}^s) < R_{th}), \quad (6)$$

where  $R_{th}$  is the threshold for the secrecy rate.

Let  $T_{1m} = \frac{1 + \gamma_{1D}}{1 + \gamma_{1E}}$  and  $T_{2m} = \frac{1 + \gamma_{2D}}{1 + \gamma_{2E}}$ , then the

following two lemmas can be derived.

**Lemma 1.** The exact cumulative distribution function (CDF) of  $T_{2m}$  is given as

$$\begin{aligned} F_{T_{2m}}(z) &= \sum_{n=0}^N \binom{N}{n} (-1)^n \cdot \\ &\left[ \exp\left(-\frac{n\Omega_{R_m D}(z-1)}{P_T}\right) \left(1 - \exp\left(-\frac{\Omega_{R_m P} Q}{P_T}\right)\right) \right] \\ &+ \frac{\Omega_{R_m P} P_T}{\Omega_{R_m P} P_T + n\Omega_{R_m D}(z-1)} \\ &\times \exp\left(-\frac{n\Omega_{R_m D}(z-1) + \Omega_{R_m P} Q}{P_T}\right) \\ &\times \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{R_m E}}{n\Omega_{R_m D}z + k\Omega_{R_m E}}. \end{aligned} \quad (7)$$

*Proof:*

Let  $x_k \equiv |h_{R_m E_k}|^2$  and  $y \equiv |h_{R_m P}|^2$ , then the CDF of  $T_{2m}$  conditioned on  $x_k$  and  $y$  can be computed as

$$\begin{aligned}
 & F_{T_{2m}}(z|x_k,y) \\
 &= \Pr\left(\frac{1 + \max_{n=1,\dots,N} \min(P_T, Q/y) |h_{R_m, D_n}|^2}{1 + \max_{k=1,\dots,K} \min(P_T, Q/y) x_k} < z\right) \\
 &= F_U\left(\frac{z-1}{\min(P_T, Q/y)} + z \max_{k=1,\dots,K} x_k\right), \tag{8}
 \end{aligned}$$

where  $U \equiv \max_{n=1,\dots,N} |h_{R_m, D_n}|^2$  and the CDF of  $U$  can be written as

$$F_U(u) = \sum_{n=0}^N \binom{M}{n} (-1)^n \exp(-n\Omega_{R_m, D} u). \tag{9}$$

Substituting (9) into (8), we have

$$\begin{aligned}
 F_{T_{2m}}(z|x_k,y) &= \sum_{n=0}^N \binom{M}{n} (-1)^n \\
 &\exp\left(-n\Omega_{R_m, D} \left(\frac{z-1}{\min(P_T, Q/y)} + z \max_{k=1,\dots,K} x_k\right)\right). \tag{10}
 \end{aligned}$$

Next, the CDF of  $T_{2m}$  conditioned only on  $y$  is computed as

$$\begin{aligned}
 F_{T_{2m}}(z|y) &= \int_0^\infty \sum_{n=0}^N \binom{M}{n} (-1)^n \\
 &\exp\left(-n\Omega_{R_m, D} \left(\frac{z-1}{\min(P_T, Q/y)} + zx\right)\right) f_X(x) dx, \tag{11}
 \end{aligned}$$

where  $X \equiv \max_{k=1,\dots,K} x_k$  and the PDF of  $X$  is given as

$$f_X(x) = \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} k \Omega_{R_m, E} \exp(-k\Omega_{R_m, E} x). \tag{12}$$

Substituting (12) into (11) and integrating (11) with respect to  $x$ , we have

$$\begin{aligned}
 F_{T_{2m}}(z|y) &= \\
 &\left(\sum_{n=0}^N \binom{M}{n} (-1)^n \exp\left(-n\Omega_{R_m, D} \frac{z-1}{\min(P_T, Q/y)}\right)\right) \\
 &\times \left(\sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{R_m, E}}{n\Omega_{R_m, D} z + k\Omega_{R_m, E}}\right) \tag{13}
 \end{aligned}$$

Finally, the CDF of  $T_{2m}$  with respect to  $y$  is computed as

$$\begin{aligned}
 & F_{T_{2m}}(z) \\
 &= \sum_{n=0}^N \binom{M}{n} (-1)^n \cdot \\
 &\left[ \exp\left(-\frac{n\Omega_{R_m, D}(z-1)}{P_T}\right) \times \int_0^{Q/P_T} \Omega_{R_m, E} \exp(-\Omega_{R_m, E} y) dy \right. \\
 &\left. + \int_{Q/P_T}^\infty \Omega_{R_m, P} \exp\left(-\frac{n\Omega_{R_m, D}(z-1)y}{Q}\right) \exp(-\Omega_{R_m, E} y) dy \right] \\
 &\times \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{R_m, E}}{n\Omega_{R_m, D} z + k\Omega_{R_m, E}} \tag{14}
 \end{aligned}$$

After some manipulations, the CDF of  $T_{2m}$  is derived as (7).

**Lemma 2.** The exact CDF of  $T_{1m}$  is given as

$$\begin{aligned}
 F_{T_{1m}}(z) &= 1 - \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{SE}}{\Omega_{SR_m} z + k\Omega_{SE}} \\
 &\times \left[ \exp\left(-\frac{\Omega_{SR_m}(z-1)}{P_T}\right) \left(1 - \exp\left(-\frac{\Omega_{SP} Q}{P_T}\right)\right) \right. \\
 &\left. + \frac{\Omega_{SP} P_T}{\Omega_{SP} P_T + \Omega_{SR_m}(z-1)} \exp\left(-\frac{\Omega_{SR_m}(z-1) + \Omega_{SP} Q}{P_T}\right) \right] \tag{15}
 \end{aligned}$$

*Proof:*

The CDF of  $T_{1m}$  follows directly from (7) by exchanging the parameters  $\Omega_{R_m, D}$  to  $\Omega_{SR_m}$ ,  $\Omega_{R_m, E}$  to  $\Omega_{SE}$ ,  $\Omega_{R_m, P}$  to  $\Omega_{SP}$  with single antenna at  $R_m$ .

**Proposition 1.** The exact secrecy outage probability of the proposed secondary system is given as

$$\begin{aligned}
 & P_{out}^s = \\
 & 1 - \sum_{i=1}^M (-1)^{i+1} \sum_{\substack{m_1 = \dots = m_i = 1 \\ m_1 < \dots < m_i}}^M \prod_{t=1}^i \sum_{n=1}^N \binom{M}{n} (-1)^{n+1} \\
 & \left[ \exp\left(-\frac{n\Omega_{R_m, D}(\rho-1)}{P_T}\right) - \frac{n\Omega_{R_m, D}(\rho-1)}{\Omega_{R_m, P} P_T + n\Omega_{R_m, D}(\rho-1)} \right. \\
 & \left. \times \exp\left(-\frac{n\Omega_{R_m, D}(\rho-1) + \Omega_{R_m, P} Q}{P_T}\right) \right] \\
 & \times \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{R_m, E}}{n\Omega_{R_m, D} \rho + k\Omega_{R_m, E}} \\
 & \times \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{SE}}{\Omega_{SR_m} \rho + k\Omega_{SE}}
 \end{aligned}$$

$$\times \left[ \exp\left(-\frac{n\Omega_{R_m D}(\rho-1)}{P_T}\right) - \frac{\Omega_{R_m}(\rho-1)}{\Omega_{SP}P_T + \Omega_{SR_m}(\rho-1)} \right] \times \exp\left(-\frac{\Omega_{SR_m}(\rho-1) + \Omega_{SP}Q}{P_T}\right) \quad (16)$$

where  $\rho \equiv 2^{2R_{th}}$ .

*Proof:*

When  $T_{1m}$  and  $T_{2m}$  are independent, we obtain the outage probability by combining (6), (7) and (15) as

$$P_{out}^s = \prod_{m=1}^M (F_{T_{1m}}(\rho) + F_{T_{2m}}(\rho) - F_{T_{1m}}(\rho)F_{T_{2m}}(\rho)) \quad (17)$$

After some manipulations, we can obtain the result in (16).

**Lemma 3.** An asymptotic expression for  $P_{out}^s$  when  $P_T \rightarrow \infty$  is given as

$$P_{out}^{\infty} = 1 - \sum_{i=1}^M (-1)^{i+1} \sum_{\substack{m_1=\dots=m_i=1 \\ m_1 < \dots < m_i}} \prod_{i=1}^i \sum_{n=1}^N \binom{N}{n} (-1)^{n+1} \times \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{R_m E}}{n\Omega_{R_m D} + k\Omega_{R_m E}} \times \sum_{i=1}^M \binom{K}{k} (-1)^{k+1} \frac{k\Omega_{SE}}{\Omega_{SR_m} \rho + k\Omega_{SE}} \quad (18)$$

*Proof:*

It is not difficult to obtain (18) by letting  $P_T$  to infinity in (16).

#### IV. SIMULATION RESULTS

In this section, we use the closed-form expressions for the secrecy outage probability in (16) and (18) to evaluate the system performance. In particular, we investigate the impact of the number of relay nodes, the number of antennas at the destination D, and number of antennas at the

eavesdropper E. We assume that the source S, the relay  $R_m$ , the destination D, the eavesdropper E, and the primary receiver P are located at (0,0),  $(x_m, 0)$ , (1,0), (1,-0.5), and (1,0.5), respectively. The corresponding distances between certain two nodes are calculated as  $d_{SR_m} = x_m$ ,  $d_{SE} = d_{SP} = \sqrt{1.25}$ ,  $d_{R_m D} = 1 - x_m$ , and  $d_{R_m E} = d_{R_m P} = \sqrt{(1-x_m)^2 + 0.25}$ . The path loss exponent  $\beta$  is assumed to be equal to 4.

In Fig. 2, we investigate the effect of the maximum transmit power  $P_T$  on the secrecy outage probability when the number of antennas at the destination  $N=1$ , the threshold  $R_{th} = 0.3$ , and the peak interference  $Q = 2P_T$ .  $M$  relays are assumed to be deployed in the same location (0.5,0). As expected, when the number of relay nodes  $M$  increases, the secrecy outage probability is found to decrease. In contrast, when the number of antennas at the eavesdropper increases, the secrecy outage probability is found to increase, since the chance of overhearing will increase accordingly. Fig. 2 also verifies that the simulation results and analytical results have an exact agreement.

In Fig. 3, the number of relays are fixed to 3 and they are assumed to be located at (0.6,0). The parameters  $R_{th}$  and  $Q$  are set to 0.3 and 2, respectively. It can be seen that the secrecy outage

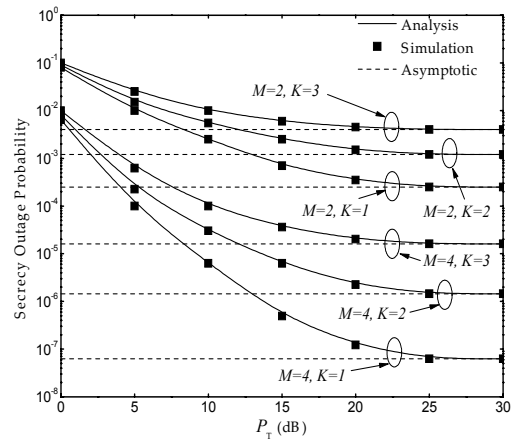


Fig. 2. Secrecy outage probability versus  $P_T$  for  $M=2, 4$  and  $K=1, 2, 3$  ( $R_{th} = 0.3$ ,  $Q/P_T = 2$ ,  $x_m = 0.5$ ,  $N=1$ ).

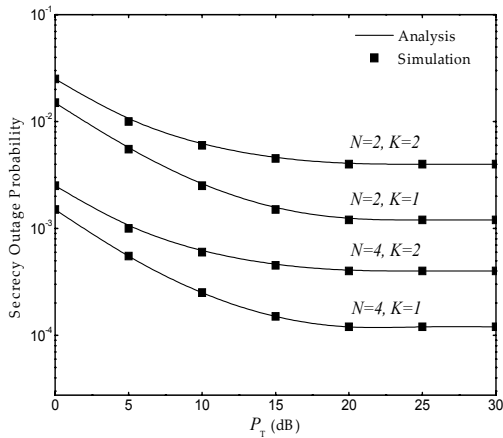


Fig. 3. Secrecy outage probability versus  $P_T$  for  $N=2, 4$  and  $K=1, 2$  ( $R_{th}=0.3$ ,  $Q/P_T=2$ ,  $x_m=0.6$ ,  $M=3$ ).

probability decreases as the number of antennas at the destination increases. Similarly to Fig. 2, the secrecy outage probability is seen to increase as the number of antennas at the eavesdropper increases.

### V. Conclusion

In this paper, we have considered an optimal relay selection scheme with multiple antennas at the destination and eavesdropper in a cognitive radio networks. We have derived exact analytical expressions for the secrecy outage probability in the presence of multiple relay nodes. Numerical results have been provided to validate the analysis. It has been shown that in order to improve the performance of the system, it is necessary to distribute many relay nodes and multiple antennas at the destination rather than to increase the transmit power of the source.

### References

[1] J. Mitola and J. Q. Magire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13-18, Aug. 1999.  
 [2] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas*

*Commun.*, vol. 23, no. 2, pp. 201-220, Feb. 2005.

[3] J. P. Seo, C. S. Yang, and J. H. Chung, "An active interference management scheme for cognitive radio systems," *J. KICS*, vol. 38B, no. 10, pp. 843-850, Oct. 2013.  
 [4] R. M. Choe and Y. S. Byun, "User selection scheme for the performance improvement of the secondary system in cognitive radio systems using underlay mode," *J. KICS*, vol. 38A, no. 3, pp. 249-257, Jan. 2013.  
 [5] L. Lai and H. El Gamal, "The relay-eavesdropper channel: Cooperation for secrecy," *IEEE Trans. Inf. Theory*, vol. 54, no. 9, pp. 4005-4019, Sept. 2008.  
 [6] J. Barros and M. Rodrigues, "Secrecy capacity of wireless channels," in *Proc. IEEE Int. Symp. Inform. Theory 2006 (ISIT 2006)*, pp. 356-360, Seattle, USA, July 2006.  
 [7] L. Dong, Z. Han, A. P. Petropulu, and H. V. Poor, "Secure wireless communications via cooperation," in *Proc. Annual Allerton Conf. Commun., Control, Computing*, UIUC, Illinois, USA, Sept. 2008  
 [8] V. Aggarwal, L. Sankar, A. Calderbank, and H. Poor, "Secrecy capacity of a class of orthogonal relay eavesdropper channels," *EURASIP J. Wirel. Commun. Net.*, pp. 1-14, 2009.  
 [9] Y. Pei, Y. C. Liang, L. Zhang, K. C. Teh, and K. H. Li, "Secure communication over MISO cognitive radio channels," *IEEE Trans. Wirel. Commun.*, vol. 9, no. 4, pp. 1494-1502, Apr. 2010.  
 [10] L. Zhang, R. Zhang, Y.-C. Liang, Y. Xin, and S. Cui, "On the relationship between the multi-antenna secrecy communications and cognitive radio communications," *IEEE Trans. Commun.*, vol. 58, no. 6, pp. 1877-1886, Jun. 2010.  
 [11] Y. Pei, Y. C. Liang, L. Zhang, K. C. Teh, and K. H. Li, "Secure communication in multiantenna cognitive radio networks with imperfect channel state information," *IEEE Trans. Signal Process.*, vol. 59, no. 4, pp.

1683-1693, Apr. 2011.

- [12] A. Bletsas, H. Shin, M. Z. Win, and A. Lippman, "Cooperative diversity with opportunistic relaying," in *Proc. IEEE Wirel. Commun. Net. Conf. (IEEE WCNC 2006)*, pp. 1034-1039, Las Vegas, USA, Apr. 2006.
- [13] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wirel. Commun.*, vol. 6, no. 9, pp. 3450-3460, Sept. 2007.
- [14] J. B. Cho, S. J. Jang, W. S. Jung, and J. M. Kim "Projection of spatial correlation-based antenna selection for cognitive radio systems in correlated channels," *J. KICS*, vol. 37A, no. 1, pp. 8-16, Jan. 2012.
- [15] P. Gopala, L. Lai, and H. Gamal, "On the secrecy capacity of fading channels," *IEEE Trans. Inf. Theory*, vol. 54, no. 10, pp. 4687-4698, Oct. 2008.

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