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# 언더레이 인지기술에서 양방향 릴레이 증분 협력 전송에 관한 연구

# Incremental Cooperative Transmission of Bidirectional Relaying Schemes in Underlay Cognitive Radio

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**요 약** 본 논문에서는, 양 방향 언더레이 인지 네트워크의 점진적 협력 전송을 제안한다. 제안된 프로토콜은 두 2차 소스가 간섭 조건에 따라 보조 릴레이의 도움으로 서로의 패킷을 전송하려 시도하는 것이다. 성능 평가를 위해, 레일리히 페이딩 채널의 평균 정전 확률에 대한 폐구간의 정확한 식을 유도한다. 또한, 유도된 식을 확인하기 위해 몬테 카를로 시뮬레이션을 수행한다. 그 결과, 시뮬레이션과 이론적 결과가 일치하며, 제안된 프로토콜의 정전 확률은 양방향 직접 통신 프로토콜보다 더욱 우수하다.

**Abstract** In this paper, we propose an incremental cooperative transmission protocol in two-way underlay cognitive radio networks. In the proposed protocol, two secondary sources attempt to transmit their packet to each other with help of a secondary relay under interference constraint. For performance evaluation, we derive exact closed-form expressions of average outage probability over Rayleigh fading channel. Then, we perform Monte Carlo simulations to verify the derivations. Results present that the simulation and theoretical results are in good agreement and the outage performance of the proposed protocol is better than that of two-way direct transmission protocol.

**Key Words :** Underlay networks, Incremental cooperative relaying, Two-way relay networks, Outage probability.

## Ⅰ. Introduction

Traditionally, in cognitive radio networks, secondary users can only use licensed bands if they are not used by primary users. Hence, secondary users must sense the presence and absence of primary users′ operations. In[1]-[3], the authors introduced a cognitive radio scheme in which the primary users and secondary users cooperate to enhance performance of both networks. In an alternative model called underlay cognitive radio network[4]-[6], secondary transmitters must adapt their transmit power so that the interference caused at the primary user is lower than an allowed interference level. So

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far, almost published works on underlay networks have mainly focused on one-way relaying schemes. In[7], the authors proposed a two-way underlay protocol with relay selection in cognitive radio networks. However, this protocol did not consider the direct link between the secondary source and the secondary destination. Furthermore, the authors in[7] did not also considered the maximum transmit power at the secondary transmitters.

In this paper, we consider a cooperative protocol using network coding in two-way underlay networks. In the proposed protocol, two secondary sources use incremental cooperative transmission[8] to exchange their packet with help of a secondary relay. To evaluate and compare performance of the proposed protocol with two-way direct transmission protocol (DT), we derive exact closed-form expressions of average outage probability over Rayleigh fading channel. Then, all of the mathematical derivations will be verified by Monte Carlo simulations. Results show that the theoretical results match very well with the simulation results.

The rest of the paper is organized as follows. The system model is described in Section Ⅱ and performance analysis is discussed in Section Ⅲ. In Section Ⅳ, we will show the simulation results and Section Ⅴ concludes the paper.

## Ⅱ. System Model

In the proposed scheme which is named CC, the secondary source S1 (S2) attempts to transmit packet $p_1(p_2)$ to the secondary source S2 (S1) with the help of the secondary relay R. Assume that each node is equipped with a single antenna and the transmissions are realized by using time division multiple access (TDMA) technique. In underlay network, all of the transmitters must adjust their transmit power so that their transmit power is lower than a pre-determined maximum transmit power $P_{\max}^{CC}$ and the interference caused at the primary user (PU) is lower than an allowed interference level $I_{PU}^{CC}$ [5].

Let $h_{A,B}^{(i)}$ denote block and flat Rayleigh fading channel coefficient between the transmitter A and the receiver B in time slot $i$, where $A \in \{S1, S2, R\}$, $B \in \{S1, S2, R, PU\}$ and $i \in \{1,2,3\}$. Hence, $|h_{A,B}^{(i)}|^2$ is an exponential random variable (RV) with parameter $\lambda_{A,B} = d_{A,B}^{\beta}$, where $d_{A,B}$ is the distance between A and B, and $\beta$ is path-loss exponent.

Now, we describe the operation of the proposed protocol as follows. In the first time slot, the source S1 broadcasts the packet $p_1$ to the source S2 and the relay R. Before transmitting the packet $p_1$, the source S1 adjusts its transmit power follows the strategy as[5]: $P_{S1}^{(1)} = \min\left(P_{\max}^{CC}, I_{PU}^{CC}/|h_{S1,PU}^{(1)}|^2\right)$. Hence, we can respectively express the instantaneous signal-to-noise ratio (SNR) received at the source S2 and relay R as

$$\Psi_{S1,S2}^{(1)} = \frac{P_{S1}^{(1)}|h_{S1,S2}^{(1)}|^2}{N_0} = \min\left(\gamma_{S1,S2}^{(1)}, Q\frac{\gamma_{S1,S2}^{(1)}}{\gamma_{S1,PU}^{(1)}}\right) \tag{1}$$

$$\Psi_{S1,R}^{(1)} = \frac{P_{S1}^{(1)}|h_{S1,R}^{(1)}|^2}{N_0} = \min\left(\gamma_{S1,R}^{(1)}, Q\frac{\gamma_{S1,R}^{(1)}}{\gamma_{S1,PU}^{(1)}}\right) \tag{2}$$

where $Q = I_{PU}^{CC}/N_0$, $\gamma_{S1,S2}^{(1)} = P_{\max}^{CC}|h_{S1,S2}^{(1)}|^2/N_0$, $\gamma_{S1,R}^{(1)} = P_{\max}^{CC}|h_{S1,R}^{(1)}|^2/N_0$ and $\gamma_{S1,PU}^{(1)} = P_{\max}^{CC}|h_{S1,PU}^{(1)}|^2/N_0$ with $N_0$ is variance of Gaussian noise.

If the source S2 can receive the packet $p_1$ successfully, it sends an ACK message to the source S1 and the relay R to inform. Otherwise, it feedbacks a NACK message to request a re-transmission from the relay R. At the second time slot, the source S2 transmits the packet $p_2$ to the source S1, which is also received by the relay R. Also, before transmitting this packet, the source S2 uses a transmit power which is determined by $P_{S2}^{(2)} = \min\left(P_{\max}^{CC}, I_{PU}^{CC}/|h_{S2,PU}^{(1)}|^2\right)$. Hence, the instantaneous signal-to-noise ratio (SNR) received at the source S1 and relay R at the second time slot is respectively expressed as

$$\Psi_{S2,S1}^{(1)} = \frac{P_{S2}^{(2)}|h_{S2,S1}^{(2)}|^2}{N_0} = \min\left(\gamma_{S2,S1}^{(2)}, Q\frac{\gamma_{S2,S1}^{(2)}}{\gamma_{S2,PU}^{(2)}}\right) \tag{3}$$

$$\Psi_{S2,R}^{(1)} = \frac{P_{S2}^{(2)}|h_{S2,R}^{(2)}|^2}{N_0} = \min\left(\gamma_{S2,R}^{(2)}, Q\frac{\gamma_{S2,R}^{(2)}}{\gamma_{S2,PU}^{(2)}}\right) \tag{4}$$

where $\gamma_{S2,S1}^{(2)} = P_{\max}^{CC}|h_{S2,S1}^{(2)}|^2/N_0$, $\gamma_{S2,R}^{(2)} = P_{\max}^{CC}|h_{S2,R}^{(2)}|^2/N_0$ and $\gamma_{S2,PU}^{(2)} = P_{\max}^{CC}|h_{S2,PU}^{(2)}|^2/N_0$.

Also, if the source S1 can receive the packet $p_2$ successfully, it sends an ACK message to inform the decoding status. Otherwise, a NACK message is generated by the source S1 to request a re-transmission from the relay R. Relying on the decoding status at two sources and the relay R, we have three cases as follows:

**Case 1**: Two sources correctly decode the received packet.

In this case, the relay R does nothing because the successful reception at the sources.

**Case 2**: One of two sources successfully decodes the received packet.

Without loss generality, we assume that the source S1 correctly decodes and the source S2 does not. In this case, the source S2 needs a re-transmission from the relay R. If the relay R cannot receive the packet $p_1$ correctly, this packet is dropped. Otherwise, the relay R forwards the packet $p_1$ to the source S2 in the third time slot. Also, the relay R adapts its transmit power before transmitting the packet $p_1$ as $P_R^{(3)} = \min\left(P_{\max}^{CC}, I_{PU}^{CC}/|h_{R,PU}^{(3)}|^2\right)$. Hence, the SNR received at the source S2 in third time slot is

$$\Psi_{S2,R}^{(1)} = \frac{P_{S2}^{(2)}|h_{S2,R}^{(2)}|^2}{N_0} = \min\left(\gamma_{S2,R}^{(2)}, Q\frac{\gamma_{S2,R}^{(2)}}{\gamma_{S2,PU}^{(2)}}\right) \tag{5}$$

where $\gamma_{R,S2}^{(3)} = P_{\max}^{CC}|h_{R,S2}^{(3)}|^2/N_0$ and $\gamma_{R,PU}^{(3)} = P_{\max}^{CC}|h_{R,PU}^{(3)}|^2/N_0$.

**Case 3**: Both sources unsuccessfully decode the received packets

If the relay R only receives one packet successfully, e.g., $p_1$, it forwards this packet to the intended source, e.g., S2, at the third time slot. In this case, the operation of data transmission is similar to that in Case 2. If the relay R can successfully decode both packets, it first combines two packets by using XOR operation, i.e., $p_\oplus = p_1 \oplus p_2$. Then, it broadcasts the combined packet $p_\oplus$ to two sources at the third time slot. The SNR received at the source S1 and S2 is respectively expressed as

$$\Psi_{R,S1}^{(3)} = \frac{P_R^{(3)}|h_{R,S1}^{(3)}|^2}{N_0} = \min\left(\gamma_{R,S1}^{(3)}, Q\frac{\gamma_{R,S1}^{(3)}}{\gamma_{R,PU}^{(3)}}\right) \tag{6}$$

$$\Psi_{R,S2}^{(3)} = \frac{P_R^{(3)}|h_{R,S2}^{(3)}|^2}{N_0} = \min\left(\gamma_{R,S2}^{(3)}, Q\frac{\gamma_{R,S2}^{(3)}}{\gamma_{R,PU}^{(3)}}\right) \tag{7}$$

where $\gamma_{R,S1}^{(3)} = P_{\max}^{CC}|h_{R,S1}^{(3)}|^2/N_0$.

In this case, if the source S2 (S1) can receive the packet $p_\oplus$ successfully, it obtains the packet $p_1(p_2)$ by using the XOR operation as $p_1 = p_\oplus \oplus p_2$ $(p_2 = p_\oplus \oplus p_1)$.

For base-line comparison, we present the two-way direct transmission protocol (DT). In the DT protocol, without the help of the relay R, the source S1 and S2 directly transmits its packet to the source S2 and S1 at the first and second time slot, respectively. For a fair comparison, we assume that the maximum transmit power and the maximum interference level in the DT protocol is respectively given as $P_{\max}^{DT}=3/2P_{\max}^{CC}$ and $I_{\max}^{DT}=3/2I_{\max}^{CC}$. Hence, the SNR received at the source S2 and S1 in the DT protocol is given as

$$\Psi_{S1,S2}^{(1)}=\frac{3}{2}min\left(\gamma_{S1,S2}^{(1)},Q\frac{\gamma_{S1,S2}^{(1)}}{\gamma_{S1,PU}^{(1)}}\right) \qquad (8)$$

$$\Psi_{S2,S1}^{(2)}=\frac{3}{2}min\left(\gamma_{S2,S1}^{(2)},Q\frac{\gamma_{S2,S1}^{(2)}}{\gamma_{S2,PU}^{(2)}}\right) \qquad (9)$$

## Ⅲ. Performance Analysis

Assume that a receiver can decode a received packet successfully if the instantaneous SNR received at that receiver is larger than a threshold $\phi_{th}$. If the SNR received is lower than $\phi_{th}$, the transmission is assumed to be in outage.

Considering the RV $\gamma_{A,B}^{(i)}$ which is given as $\gamma_{A,B}^{(i)}=P_{\max}^{CC}|h_{A,B}^{(i)}|^2/N_0$, from (8), the outage probability at the source S2 in the DT protocol is formulated as

$$P_{S2}^{DT,out}=\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th}\right] \qquad (10)$$

Using (8) and [5, Eq. (8)] for (10), we obtain

$$P_{S2}^{DT,out}=1-\exp\left(-\frac{2\lambda_{S1,S2}\phi_{th}}{3}\right)+\frac{2\lambda_{S1,S2}\phi_{th}\exp\left(-\left(\frac{2\lambda_{S1,S2}\phi_{th}}{3}+\lambda_{S1,PU}Q\right)\right)}{2\lambda_{S1,S2}\phi_{th}+3\lambda_{S1,PU}Q} \qquad (11)$$

From (11), $P_{S2}^{DT,out}$ at high $Q$ and $P$ values can be given as

$$\lim_{Q\to+\infty}P_{S2}^{DT,out}=1-\exp\left(-\frac{2\lambda_{S1,S2}\phi_{th}}{3}\right) \qquad (12)$$

$$\lim_{P\to+\infty}P_{S2}^{DT,out}=\frac{2\lambda_{S1,S2}\phi_{th}}{\lambda_{S1,S2}\phi_{th}+3\lambda_{S1,PU}Q} \qquad (13)$$

In the CC protocol, the average outage probability at the source S2 can be formulated as

$$\begin{aligned}P_{S2}^{CC,out}&=\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}<\phi_{th}\right]\\&+\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}\geq\phi_{th},\Psi_{R,PU}^{(3)}<\phi_{th}\right]\end{aligned} \qquad (14)$$

In (14), similar the methods presented in[7], the term $\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}<\phi_{th}\right]$ can be exactly calculated as

$$\begin{aligned}&\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}<\phi_{th}\right]\\&=\left(1-\exp(-\lambda_{S1,PU}Q)\right)\left(1-\exp(-\lambda_{S1,S2}Q)\right)\\&\times\left(1-\exp(-\lambda_{S1,R}Q)\right)+\exp(-\lambda_{S1,PU}Q)\\&-\frac{\lambda_{S1,PU}Q\exp(-\lambda_{S1,PU}Q-\lambda_{S1,S2}\phi_{th})}{\lambda_{S1,PU}Q+\lambda_{S1,S2}\phi_{th}}\\&-\frac{\lambda_{S1,PU}Q\exp(-\lambda_{S1,PU}Q-\lambda_{S1,R}\phi_{th})}{\lambda_{S1,PU}Q+\lambda_{S1,R}\phi_{th}}\\&+\frac{\lambda_{S1,PU}Q\exp(-\lambda_{S1,PU}Q-\lambda_{S1,S2}\phi_{th}-\lambda_{S1,R}\phi_{th})}{\lambda_{S1,PU}Q+\lambda_{S1,S2}\phi_{th}+\lambda_{S1,R}\phi_{th}}\end{aligned} \qquad (15)$$

Also, we can obtain an exact closed-form expression for $\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}\geq\phi_{th},\Psi_{R,PU}^{(3)}<\phi_{th}\right]$ as

$$\begin{aligned}&\Pr\left[\Psi_{S1,S2}^{(1)}<\phi_{th},\Psi_{S1,R}^{(1)}\geq\phi_{th},\Psi_{R,PU}^{(3)}<\phi_{th}\right]=\\&\left[\begin{array}{l}\left(1-\exp(-\lambda_{S1,PU}\phi_{th})\right)\left(1-\exp(-\lambda_{S1,S2}\phi_{th})\right)\\\times\exp(-\lambda_{S1,R}\phi_{th})\\+\dfrac{\lambda_{S1,PU}Q\exp(-\lambda_{S1,PU}Q-\lambda_{S1,R}\phi_{th})}{\lambda_{S1,PU}Q+\lambda_{S1,R}\phi_{th}}\\+\dfrac{\lambda_{S1,PU}Q\exp(-\lambda_{S1,PU}Q-\lambda_{S1,S2}\phi_{th}-\lambda_{S1,R}\phi_{th})}{\lambda_{S1,PU}Q+\lambda_{S1,S2}\phi_{th}+\lambda_{S1,R}\phi_{th}}\end{array}\right]\\&\times\left[\begin{array}{l}1-\exp(-\lambda_{R,S2}\phi_{th})+\\\dfrac{\lambda_{R,S2}\phi_{th}\exp(-\lambda_{R,PU}Q-\lambda_{R,S2}\phi_{th})}{\lambda_{R,PU}Q+\lambda_{R,S2}\phi_{th}}\end{array}\right]\end{aligned} \qquad (16)$$

From (14)-(16), the outage probability at the source S2 is given by an exact closed-form expression. Now, we express $P_{S2}^{CC,out}$ at high values of $Q$ and $P$ as

$$\lim_{Q \to +\infty} P_{S2}^{CC,out} = \left(1 - \exp\left(-\lambda_{S1,S2}\phi_{th}\right)\right) \times \left(1 - \exp\left(-\lambda_{S1,R}\phi_{th} - \lambda_{S2,R}\phi_{th}\right)\right) \tag{17}$$

$$\begin{aligned}\lim_{P \to +\infty} P_{S2}^{CC,out} = {} & 1 - \frac{\lambda_{S1,PU}Q}{\lambda_{S1,PU}Q + \lambda_{S1,S2}\phi_{th}} \\ & - \frac{\lambda_{S1,PU}Q}{\lambda_{S1,PU}Q + \lambda_{S1,R}\phi_{th}} \\ & + \frac{\lambda_{S1,PU}Q}{\lambda_{S1,PU}Q + \lambda_{S1,S2}\phi_{th} + \lambda_{S1,R}\phi_{th}} \\ & + \left(\frac{\lambda_{S1,PU}Q}{\lambda_{S1,PU}Q + \lambda_{S1,R}\phi_{th}} - \frac{\lambda_{S1,PU}Q}{\lambda_{S1,PU}Q + \lambda_{S1,S2}\phi_{th} + \lambda_{S1,R}\phi_{th}}\right) \\ & \times \frac{\lambda_{R,S2}\phi_{th}}{\lambda_{R,S2}\phi_{th} + \lambda_{R,PU}Q}\end{aligned} \tag{18}$$

It is noted that we only present the outage probability at the source S2 because that of the source S1 can be given similarly.

## Ⅳ. Simulation Results

In this section, we present Monte Carlo simulations to verify the derived expressions. In a two-dimensional network in which the coordinate of the source S1, the source S2, the relay R and the primary user PU are (0,0), (1,0), $(x_R, 0)$ and $(x_{PU}, y_{PU})$, respectively. In all simulations, we assume the threshold $\phi_{th}$ equals to 1, the path-loss exponent equals to 3 and the co-ordinate $y_{PU}$ equals to 0.5.

In Fig. 1, we present the outage probability as a function of $Q$ in dB. In this figure, we place the relay R at (0.5, 0) and primary user PU at (0.5, 0.5). Note that the values of $P$ and $Q$ in this figure is used for the CC protocol. For the DT protocol, because $P_{\max}^{DT} = 3/2 P_{\max}^{CC}$ and $I_{\max}^{DT} = 3/2 I_{\max}^{CC}$, so $P_{DT} = P + \log_{10}(1.5)(dB)$ and $Q_{DT} = Q + \log_{10}(1.5)(dB)$, respectively. As we can see, for almost values of $Q$, the CC protocol outperforms the DT protocol. It is due to the fact that the proposed protocol uses cooperative transmission which enhances the reliability of the packet transmission. In addition, at high value of $Q$, the average outage probability does not depend on $Q$, as presented in (12) and (17).

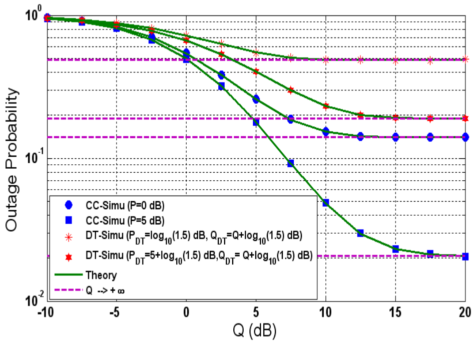

그림 1. $x_R = x_{PU} = 0.5$ 일 때, Q–함(dB) 평균 정전 확률

Fig. 1. Average outage probability as a function of Q when $x_R = x_{PU} = 0.5$.

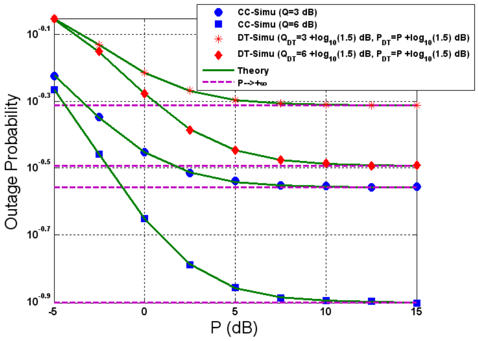

그림 2. $x_R = x_{PU} = 0.5$ 일 때, P–함수 (dB) 평균 정전 확률.

Fig. 2. Average outage probability as a function of P when $x_R = x_{PU} = 0.5$.

In Fig. 2, the outage performances of the DT and CC protocols are presented as a function of $P$ in dB. Similar to Fig. 1, the performance of the CC protocol increased significantly when compared with that of the DT protocol. Also, as given in (13) and (18), when the value of P is high, the outage performance of both protocols does not depend on $P$.

In Fig. 3, we investigate the impact of the relay R's position on the sum outage probability at the sources S1 and S2. In this figure, we fix the position of the PU at (0.2, 0.5) and (0.8, 0.5) while changing the co-ordinate $x_R$ from 0.1 to 0.9. As presented in Fig. 3, the sum outage probability is higher if the relay R is near to one of two sources. Moreover, it can be observed that the sum outage probability gets a minimum value when $x_R$ is about 0.5. This means that the optimal position of the relay R in this simulation is at the middle of two sources.

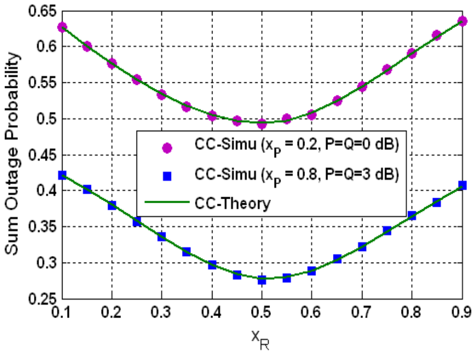

그림 3. $x_R$ 함수의 정전 확률의 합.
Fig. 3. Average sum outage probability as a function of $x_R$.

## V. Conclusion

In this paper, a joint scheme of two-way network coding and incremental cooperative relaying was proposed and analyzed. The proposed protocol obtains better performance than the two-way direct transmission protocol due to usage of cooperative communication. We derived the exact closed-form expression of the outage probability over Rayleigh fading channel. Finally, Monte Carlo simulations were presented to verify our derivations.

## Reference

[1] Y. Han and S. H. Ting, "Cooperative Decode-and-Forward Relaying for Secondary Spectrum Access," IEEE Transactions on Wireless Communications, vol. 8, no. 10, pp. 4945-4950, 2009.

[2] T. T. Duy and H.Y. Kong, "Cooperative Multi-relay Scheme for Secondary Spectrum Access," KSII Transactions on Internet and Information Systems, vol. 4, no. 3, pp. 273-288, 2010.

[3] T. T. Duy and H.Y. Kong, "Performance Analysis of Two-Way Hybrid Decode-and-Amplify Relaying Scheme with Relay Selection for Secondary Spectrum Access", Wireless Personal Communications (WPC), vol. 69, no. 2, pp. 857-878, March 2013.

[4] Y. Guo, G. Kang, N. Zhang, W. Zhou and P. Zhang, "Outage Performance of Relay assisted cognitive-radio system under spectrum sharing constraints" Electronics Letters, vol. 46, no. 2, pp. 182 - 184, 2010.

[5] J. Lee, H. Wang, J.G. Andrews, D. Hong, "Outage Probability of Cognitive Relay Networks with Interference Constraints", IEEE Trans. on Wire. Commun., 10, pp. 390-395, Feb. 2011.

[6] T. T. Duy and H.Y. Kong, "Performance Analysis of Incremental Amplify-and-Forward Relaying Protocols with Nth Best Partial Relay Selection under Interference Constraint", Wireless Personal Communications (WPC), pp. 1-17, Online First, Dec. 2012.

[7] T. T. Duy and H.Y. Kong, "Exact Outage Probability of Cognitive Two-Way Relaying Scheme with Opportunistic Relay Selection under Interference Constraint", IET Communications, vol. 6, no. 16, pp. 2750-2759, Nov. 2012.

[8] S. Ikki, M. H. Ahmed and M. Uysal "Performance Analysis of Incremental Relay Selection Decode-and-Forward Technique", in Proc. of IEEE Global Telecommunications Conference, pp. 1-6, 2009.

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