Opportunistic Relaying Based Spectrum Leasing for Cognitive Radio Networks

Asaduzzaman, Hyung Yun Kong, and Insoo Koo

Abstract: **Spectrum leasing for cognitive radio (CR) networks is an effective way to improve the spectrum utilization. This paper presents an opportunistic relaying based spectrum leasing for CR networks where the primary users lease their frequency band to the cognitive users. The cognitive users act as relays for the primary users to improve the channel capacity, and this improved capacity is used for the transmission of secondary users' data. We show that the cognitive users can use a significant portion of the communication resource of primary networks while maintaining a fixed target data rate for the primary users. Moreover, the primary network is also benefited by the cooperating cognitive users in terms of outage probability. Information theoretic analysis and simulation results are presented to evaluate the performances of both primary and cognitive networks.**

Index Terms: **Cognitive radio (CR), cooperative diversity, fading channel, opportunistic relaying, spectrum leasing.**

I. INTRODUCTION

Cognitive radio has attracted a great deal of attention in recent years to enhance the utilization of limited communication resources [1]. The basic idea of cognitive radio (CR) networks is coexistence of the unlicensed (secondary) users along with the licensed (primary) users in the same frequency band. The primary users have exclusive access to the designated spectral band while the secondary users only utilize the unused portion of the spectrum. In commonly used CR networks, primary users are expected to be oblivious to the presence of secondary terminals, thus behaving as if they had exclusive access to the spectrum. In this commons model [2], [3] the secondary users sense the spectrum to search the spectral holes and utilize this spectrum holes for transmission of their own data. Alternatively, a property-rights or spectrum leasing model has been proposed in [2], [3] where the primary users lease a part of the spectrum resources to the secondary users in exchange of appropriate remuneration.

The remuneration to lease the spectrum may be financial or in terms of improved quality of service (QoS) of the primary users. Note that even though licensed users have the right to lease or share the spectrum for profit, such sharing is not mandated by the regulation policy [4]. Therefore, leasing spectrum for better QoS may be a suitable option for the licensees. The well known QoS of a system that operates on a fixed transmission rate is the outage probability. In multipath fading environments, the outage probability of a system can be improved by exploiting diversity. The coexisting secondary users that are seeking some communication resource from a primary network can offer transmit-diversity to the primary users in the form of cooperative diversity.

It is well known that cooperative diversity protocols can provide the powerful benefits of spatial diversity and improve the channel capacity under Rayleigh fading environment [5]. The cooperative strategies with parallel relays and the effectiveness of such parallel relay network have been investigation in [6]. In conventional cooperative transmission protocols, relay nodes are devoted to improve the performance of a source node. In this proposal, the CR users are considered as relay nodes and along with improving the performance of primary users, CR users also find their own transmission opportunity. Hence, the primary nodes lease a fraction of its communication resource in exchange of enhanced quality of service (outage probability). The secondary users can improve the channel capacity through user cooperation and then utilize a portion of the improved capacity for transmitting their own data. The primary users are also benefited by the cooperation because of the diversity gain achieved and the primary users also operate with a lower outage probability.

In [7], a cognitive relaying approach has been presented to increase the transmission opportunities of the secondary nodes. In [8] a distributed cooperation based spectrum leasing scheme has been proposed. In this proposal a group of secondary nodes cooperate with primary nodes using distributed space time code (DSTC). The focus of [8] is to maximize the primary rate while leasing the spectrum to the secondary. In the DSTC based scheme of [8], a set of relay nodes cooperate with the primary. In such scenario, the system needs to solve an optimization problem over the subsets of secondary relays, total transmission power and time. A game theoretic approach to find a suboptimal solution of the problem is proposed in [8].

In this paper, we investigate the spectrum leasing model of CR networks where the secondary users are used as relay for the primary users. We consider that the primary network is operating on a fixed target rate. Hence, the focus of this proposal is to minimize the outage probability of the primary network by the cooperating secondary users while leasing the spectrum. At the same time, we propose a spectrum sharing policy that maximizes the outage capacity of the secondary users. Unlike [8], in the proposed scheme, a single secondary user (relay) selection is utilized for cognitive cooperation. It has been shown in [9] that, a single relay selection significantly reduces the bandwidth penalty of orthogonal transmissions and synchronization diffi-

Manuscript received July 23, 2009; approved for publication by Sanghoon Lee, Division II Editor, May 02, 2010.

This research was supported by Basic Science Research Program through the National Research Foundation (NRF) of Korea funded by the Ministry of Education, Science, and Technology (No. 2009-0073895).

The authors are with the Department of Electrical Engineering, University of Ulsan, Korea, email: {asad78, hkong, iskoo}@mail.ulsan.ac.kr.

H. Y. Kong is the corresponding author of this paper.

culties of DSTC [10]. Moreover, the relay selection schemes, where a single relay is selected to cooperate on information transmission, can efficiently use the transmit power which leads to an outage optimality of the protocols [9], [11]. Subsequently, we adopt a single secondary user relay selection and propose an opportunistic relaying based spectrum leasing scheme for cognitive radio network. The DSTC scheme, used in [8], also requires a strict symbol level synchronization which is very difficult to obtain among the distributed nodes. In our work, we consider cooperative transmission via single relay selection, hence there is no need of symbol level synchronization among the nodes for simultaneous transmission.

In the proposed scheme, the primary and secondary users share the communication resource in time. The primary transmits with a fixed rate and the secondary tries to find a positive time for its own transmission. We present an information theoretic analysis to evaluate the outage probability of primary users and the probability of achieving a positive time for secondary data transmission. Our analysis and simulation show that these probabilities improve as the number of cooperating secondary nodes increases. We also show that the achievable secondary user's transmission time is a function of several network parameters for example, signal-to-noise-ratio (SNR), the number of secondary relays, primary target rate, channel parameters, etc.

This paper is organized as follows. In Section II, we describe the system and channel models. Section III gives the description and Section IV presents the performance analysis of the proposed protocol. Simulation results and discussions are given in Section V, and finally we conclude this paper in Section VI.

II. SYSTEM MODEL

We consider an ad-hoc cognitive radio network which is colocated with a primary network as shown in Fig. 1. The primary network is aware of the secondary network and ready to lease a portion of its communication resource. As a remuneration of the spectrum leasing, the primary network will operate with improved outage probability without sacrificing other QoSs. The secondary network is ready to assist the primary network, whenever possible, to achieve cooperative diversity. And the secondary network opportunistically utilizes the redundant communication resource for its own transmission. Without losing generality, we consider a single pair of primary transmitter (P_{TX}) and receiver (P_{RX}) and a group of M secondary nodes (S_m) are available within their common transmission range; here, $m \in \{1, 2, \cdots, M\}$. Assume that the secondary network has a centralized control unit (CCU) to control the network operations. To select the best secondary node that maximizes the secondary transmission time, we consider a MAC layer signaling based distributed relay selection scheme proposed in [9].

Consider that the channels between any two nodes (primary or secondary) are subjected to flat Rayleigh fading plus additive white Gaussian noise (AWGN). Each node has a single half duplex radio and a single antenna. The baseband equivalent received signal at node j due to the transmission of node i for symbol n is given by

$$r_{i,j}(n) = h_{i,j}s(n) + \eta_j(n) \tag{1}$$

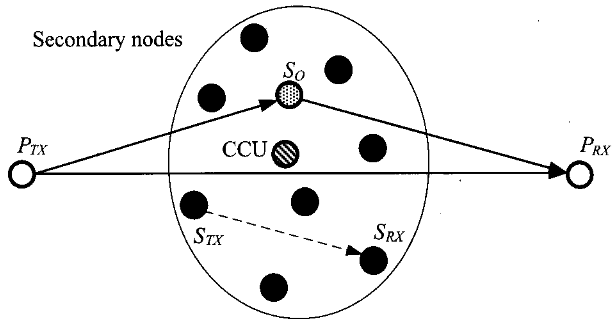


Fig. 1. A single hop model of the proposed system.

where $\eta_j(n)$ are the AWGN samples with variance $N_0/2$ per dimension at terminal j, $h_{i,j}$ is the fading coefficient between node i and j, and $s(n)$ is the signal transmitted by node i with normalized unit transmit power. We consider flat Rayleigh fading, hence, $h_{i,j}$ is modeled as independent samples of zero mean complex Gaussian random variable with variance $\sigma^2_{i,j}$.

The fading coefficients are assumed to be constant over the channel coherent time. Because of slow fading, channel estimation is possible at the receivers. Assume that perfect channel state information are available at both the primary and secondary receivers but not at the transmitters. Due to the perfect CSI at the receivers coherent detection is possible. We also assume that the secondary nodes are capable to measure partial CSI, in the form of channel state amplitude, from the received control signals, for example ready-to-transmit (RTS) and clear-to-transmit (CTS). Therefore, the length of the RTS and CTS signals should be long enough to measure the instantaneous channel state amplitude.

III. PROTOCOL DESCRIPTION

A. Selection of the Best Secondary Node

We propose a similar approach of opportunistic relaying [9] to select the best secondary node from M available secondary nodes. In opportunistic relaying, the best cognitive relay is selected based on the equivalent instantaneous channel state information (CSI) of the links. For the best secondary selection, we use the mutual information of each cooperative link instead of instantaneous CSI of the links. The mutual information of the links P_{TX}-to-P_{RX}, P_{TX}-to-S_m and S_m-to-P_{RX} are given by

$$r_{P_{TX},P_{RX}} = \log_2(1 + \gamma_{P_{TX},P_{RX}}) \tag{2}$$

$$r_{P_{TX},S_m} = \frac{1}{2}\log_2(1 + \gamma_{P_{TX},S_m}) \tag{3}$$

$$r_{S_m,P_{RX}} = \frac{1}{2}\log_2(1 + \gamma_{S_m,P_{RX}}) \tag{4}$$

where the scaling factor $1/2$ in eqs. (3) and (4) is due to the half-duplex operation of the relay nodes. The instantaneous received signal to noise ratio (SNR) at node j due to the transmission of node i can be given as

$$\gamma_{i,j} = \frac{P_i}{N_0}|h_{i,j}|^2 \tag{5}$$

where P_i is the transmit power of terminal i. For Rayleigh fading, $\gamma_{i,j}$ is exponential random variable with hazard rate $1/\Gamma_{i,j}$. Here, $\Gamma_{i,j} = (P_i/N_0)\,\sigma_{ij}^2$ represents the average SNR of the corresponding link.

Similar to opportunistic relaying protocol, primary transmitter and receiver transmit the link layer signals such as, RTS and CTS to access the channel. All the secondary nodes receive these RTS and CTS packets. Using these two control packets all available secondary relays, S_m for $m \in \{1, 2, \cdots, M\}$, in the network, estimate the instantaneous channel state amplitude $|h_{P_{TX},S_m}|^2$ and $|h_{S_m,P_{RX}}|^2$. We assume that secondary nodes can measure the channel state amplitude from the received control signals RTS and CTS.

By using (3) and (4), secondary node m can calculate r_{P_{TX},S_m} and $r_{S_m,P_{RX}}$. The equivalent end-to-end data rate of the two-hop cooperative link is the minimum one of the two hops [11]. Therefore, instantaneous rate between P_{TX} and P_{RX} when S_m is used as cognitive relay can be given as

$$r_m = \min\{r_{P_{TX},S_m}, r_{S_m,P_{RX}}\}. \tag{6}$$

If the equivalent end-to-end data rate is greater than the primary target rate, i.e., $r_m > R_P$, then secondary node-m (S_m) set its timer with initial value

$$T_m = \frac{\Omega}{\min\{r_{P,S_m}, r_{S_m,P}\}} \tag{7}$$

where Ω is a constant and dependent on the unit of time. From (7), it is clear that the best secondary node has reduced its timer to zero first since it started with a smaller initial value. We term the best secondary node as opportunistic secondary (S_O) throughout the paper. As soon as the timer of the opportunistic secondary reduces to zero it transmits a flag signal to inform the other secondary nodes to back off. This protocol selects an opportunistic secondary node that satisfies the following condition

$$S_O = \arg \max_{m\in\{1,2,\cdots,M\}} \left(\min\{r_{P_{TX},S_m}, r_{S_m,P_{RX}}\}\right). \tag{8}$$

The collision probability of this kind of timer based relay selection scheme i.e., the probability of there being two or more relay timers expire within the same time interval has been discussed in [9] and shows that this probability is very small.

B. Resource Sharing Policy

Without losing generality, we assume that the communication resource is shared between primary and secondary network in time domain. The primary network has its own fixed target rate R_P bits/sec/Hz which is assumed to be known to the secondary nodes. This means that we have 1 second to transmit R_P bits/Hz. Now the opportunistic secondary node divides this time in three portions (A, B, and C) as shown in Fig. 2. It is clear from Fig. 2 that the fraction of time ($A + B$) is used for the primary data transmission and fraction of time C is used for the secondary data transmission. By knowing R_P, the opportunistic secondary (S_O) can easily calculate the corresponding transmission time A, B, and C as

$$A = R_P/r_{P_{TX},S_o}, \tag{9}$$

$$B = R_P/r_{S_o,P_{RX}}, \tag{10}$$

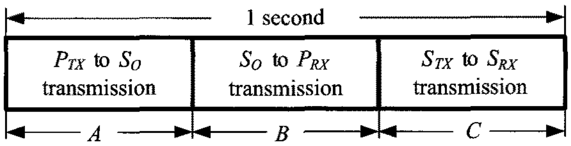


Fig. 2. Fraction of time used for primary and secondary transmission.

$$C = 1 - (A + B). \tag{11}$$

The opportunistic secondary node includes the values of A, B, and C in the best relay flag so that the primary can act properly. If r_m is less than the primary target rate R_P, for all $m \in \{1, 2, \cdots, M\}$, then a direct transmission between P_{TX} and P_{RX} takes place.

The transmission of the secondary network is assumed to be controlled by a centralized controller. Due to the broadcast nature of the wireless transmission, the centralized controller can receive the best relay flag that contains the values of A, B, and C for current round. Assume that the medium access control of the secondary network is handled by the centralized controller. A pair of secondary nodes that want to exchange the information is selected by the centralized controller for current round. The detail of the medium access control policy is beyond the scope of our physical layer analysis.

It is clear that the secondary transmission is fully dependent on the transmission time C. The achievable transmission rate between a secondary transmitter and receiver, conditioned on $C > 0$, can be given as

$$r_{S_{TX},S_{RX}} = C \log_2 (1 + \gamma_{S_{TX},S_{RX}}). \tag{12}$$

It has been shown in [12] that the good measure of the capacity of a fading channel is the outage capacity. We defined the outage probability of secondary network as the probability that $C \le 0$. Now the outage capacity of the secondary network can be given as

$$\begin{aligned} R_S &= r_{S_{TX},S_{RX}} \Pr[C > 0] \\ &= r_{S_{TX},S_{RX}} (1 - \Pr[C \le 0]). \end{aligned} \tag{13}$$

The closed form expression of $\Pr[C \le 0]$ is derived in the next section.

C. Implementation Issues

In this work, we consider a property-rights model (or spectrum leasing) in which the primary license users own the spectral resource and agree to lease part of it to secondary users in exchange for appropriate remuneration. To implement such spectrum leasing primary system requires some extra control signal to ensure effective collaboration (for example, best relay flag). The data rate of the primary transmitter is dependent on values of A, B, and C that are function of the instantaneous channel gains. To adapt the transmission rate, the primary system needs adaptive transmitter and receiver radios. Such requirement of adaptive transmitter and receiver radios will increase the size and cost of the primary users. In spectrum sharing systems, the cognitive users receive the signal from the primary and therefore, there is an obvious question of the privacy and security of the primary systems. In property-rights model primary users are aware about the CR-users. Hence, the licensed system can take the proper actions which are necessary to overcome these drawbacks to get the remunerations offered by the CR systems.

Obviously, for the implementation of the proposed resource sharing in time domain, packet/frame synchronization among the primary and secondary nodes is required. We assume that all the nodes (primary and secondary) are synchronized in packet/frame level but not in symbol level. Such synchronization can be achieved through MAC layer control signals such as RTS, CTS, and the best relay flag. Throughout this paper, we assume that the control signals required to measure the instantaneous CSI and to achieve time synchronization are the MAC layer control signals. Therefore, a proper crosslayer design between physical layer and MAC layer is needed to minimize the signaling overhead to implement the proposed protocol.

IV. PERFORMANCE ANALYSIS

In this section we derive the closed form expression of outage probability of the primary and secondary networks of the proposed protocol. The primary network operates on a fixed transmission rate R_P bits/sec/Hz. Hence, the outage event for primary network can be defined as the event of the end-to-end transmission rate between P_{TX} and P_{RX} is less than R_P. On the other hand, the secondary network operates on an adaptive transmission rate. Hence, we define the secondary network is in outage, when the secondary transmission time C is less than or equal to zero. The proposed system achieves a positive value of C when the capacity (mutual information) of the cooperative link through the S_O is greater than the primary target rate. Now, the probability that C is less than or equal to zero can be written as

$$\begin{aligned}\Pr(C \leq 0) &= \Pr[\min\{r_{P_{TX},S_o}, r_{S_o,P_{RX}}\} \leq R_P] \\ &= \Pr\left[\min\left\{\frac{1}{2}\log_2(1+\gamma_{P_{TX},S_o}),\right.\right. \\ &\qquad \left.\left.\frac{1}{2}\log_2(1+\gamma_{S_o,P_{RX}})\right\} < R_P\right] \\ &= \Pr\left[\min\{\gamma_{P_{TX},S_o}, \gamma_{S_o,P_{RX}}\} < 2^{2R_P}-1\right] \quad (14)\end{aligned}$$

where

$$\min\{\gamma_{P_{TX},S_o}, \gamma_{S_o,P_{RX}}\} = \max_{m\in\{1,\ldots,M\}} \min\{\gamma_{P_{TX},S_m}, \gamma_{S_m,P_{RX}}\}. \quad (15)$$

The random variables, γ_{P_{TX},S_m} and $\gamma_{S_m,P_{RX}}$ are exponentially distributed with hazard rate $1/\Gamma_{P_{TX},S_m}$ and $1/\Gamma_{S_m,P_{RX}}$; hence, $\min\{\gamma_{P_{TX},S_m}, \gamma_{S_m,P_{RX}}\}$ is an exponential random variable with hazard rate $1/\Gamma_{eq,m} = 1/\Gamma_{P_{TX},S_m} + 1/\Gamma_{S_m,P_{RX}}$ [13]. Finally, $\min\{\gamma_{P_{TX},S_o}, \gamma_{S_o,P_{RX}}\}$ is a random variable which is maximum one of M exponential random variables. By considering these distributions of random variables, we can write

$$\Pr(C \leq 0) = \prod_{m=1}^{M}\left[1-\exp\left(-\frac{2^{2R_P}-1}{\Gamma_{eq,m}}\right)\right]. \quad (16)$$

The primary user is in outage when the cooperative link through opportunistic secondary and the direct link between the P_{TX} and P_{RX} is in outage and can be written as

$$\begin{aligned}P_{OUT}^{P} &= \Pr[r_{P_{TX},P_{RX}} < R_P] \\ &\quad \cdot \Pr[\min\{r_{P_{TX},S_o}, r_{S_o,P_{RX}}\} < R_P] \\ &= \Pr[\gamma_{P_{TX},P_{RX}} < 2^{R_P}-1] \\ &\quad \cdot \Pr[\min\{\gamma_{P_{TX},S_o}, \gamma_{S_o,P_{RX}}\} < 2^{2R_P}-1] \quad (17)\end{aligned}$$

The second probability of (17) is same as (16) and the first probability of (17) can be easily calculated by using the fact that $\gamma_{P_{TX},P_{RX}}$ is exponential random variable with hazard rate $1/\Gamma_{P_{TX},P_{RX}}$, as

$$\Pr[\gamma_{P_{TX},P_{RX}} < 2^{R_P}-1] = 1-\exp\left(-\frac{2^{R_P}-1}{\Gamma_{P_{TX},P_{RX}}}\right). \quad (18)$$

Replacing (16) and (18) in (17), we can get the exact expression of the outage probability of the primary network.

V. SIMULATION RESULTS

In this section, we provide some numerical results of the outage probabilities that have been developed in Section IV and verify these results with simulations. We also perform Monte Carlo simulations to find the average value of the secondary transmission time, C, and the achievable transmission rate of the secondary for various network parameters. For simplicity, we avoid optimal power allocation techniques that require CSI at transmitters [14], and assume equal power allocation. Hence, the primary and secondary transmit power, P_P and P_S are same, i.e., $P_P = P_S = P$. The variance of fading coefficients between primary to secondary and secondary to primary, $\sigma^2_{P_{TX}S_m}$ and $\sigma^2_{S_mP_{RX}}$ are generated as uniformly distributed random values between 1 and 2. The variance of primary transmitter to primary receiver channel $\sigma^2_{P_{TX}P_{RX}}$ is considered as 1.

Fig. 3 shows the outage probability of primary network as a function of SNR (P/N_0) in dB with different number of secondary relays (M). This figure shows that the outage behavior of the primary network is similar to the conventional cooperative networks. The outage probability decreases with SNR as well as with the number of cooperating secondary nodes. In Fig. 3, we also verified the simulation results with the analytical outage probability developed in Section IV. In all cases, the simulation and numerical results are well matched with each other. Both simulation and numerical results clearly indicate that the diversity order improves as the number of secondary relays increase. Hence, our proposal preserves all the benefits of conventional cooperative communication for the primary network.

Fig. 4 shows the outage probability of the secondary network (probability that the secondary transmission time, C is less than or equal to zero) as a function of SNR. The secondary outage probability shows the same behavior as the outage probability of the primary network. Fig. 4 indicates that the probability of secondary transmission opportunity is very high at the high SNR region. As we expected, the probability of secondary transmission opportunity improves as the number of cooperating secondary nodes increases.

In the following figures, we evaluate the average value of secondary transmission time (C) and the outage capacity of the

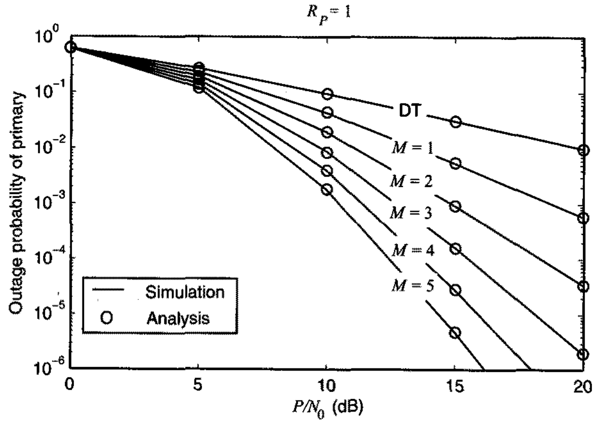


Fig. 3. Outage probability of the primary network.

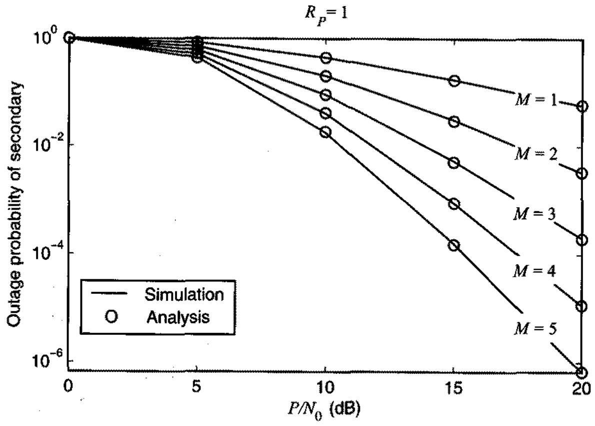


Fig. 4. Probability of C less than or equal to zero.

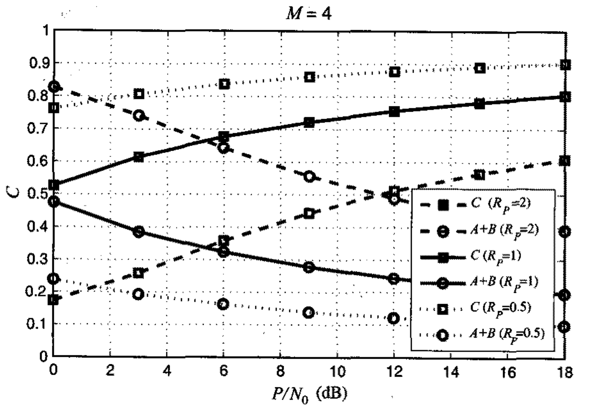


Fig. 5. Comparison of primary and secondary transmission time.

secondary network using the definition of (9)–(11) and (13). In Fig. 5, we compare the primary transmission time $(A + B)$ with the secondary transmission time (C) for different values of R_P, when $C > 0$. For R_P equal to 0.5 and 1, the secondary transmission time is greater than the primary transmission time over the whole range of P/N_0 under investigation. And for R_P equal to 2 the secondary transmission time is greater than the primary transmission time when P/N_0 is greater than 12 dB. For all cases, the secondary transmission time C increases with

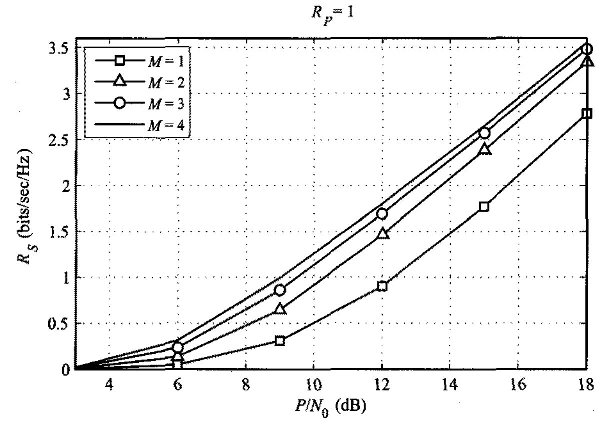


Fig. 6. Average secondary outage capacity for different value of M.

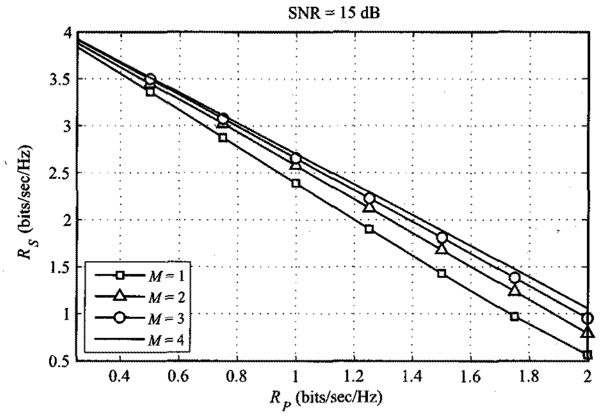


Fig. 7. Average secondary outage capacity versus primary transmission rate.

the SNR of cooperative transmission.

Fig. 6 shows the outage capacity of the secondary network with respect to P/N_0 for different numbers of secondary nodes that are cooperating with the primary transmitter. As expected, the outage capacity monotonically increases with the average signal to noise ratio. The outage capacity increases as the number of cooperating secondary nodes (M) increases. At high value of M, this improvement is small because of the fixed value of primary rate (R_P).

In Fig. 7, we investigate the capacity region of the collocated primary and secondary network. Two networks operate on the same frequency by sharing the time on the condition that the primary network satisfies its own QoS. Fig. 7 shows that the capacity of the secondary network R_S is highly dependent on the primary target rate R_P. At low value of R_P the secondary outage capacity is very high and it linearly decreases as R_P increases. Hence, our proposal offers a good tradeoff between R_P and R_S. Moreover, the area of the capacity region increases as the number of cooperating secondary nodes M increases.

VI. CONCLUSION

In this paper, we investigate the spectrum leasing for cognitive radio networks when the secondary users act as a relay for the primary users. Most of the recent research on cognitive radio focused the Commons model where the secondary users search for a spectrum hole for data transmission. But, the alternative spectrum leasing model has not been investigated in depth. We show that the cooperation based spectrum leasing can provide a significant amount of communication resource for the secondary users without sacrificing the performance of the primary users. As a remuneration of the spectrum the secondary users assist the primary network to achieve cooperative diversity which leads to an improvement in the outage probability of the primary network. The approach presented in this work can be viewed as a cross layer approach between physical layer and data link layer. We only presented the physical layer analysis in this paper and the link layer analysis would be a good topic for future research.

REFERENCES

[1] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, 2005.

[2] J. M. Peha, "Approaches to spectrum sharing," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. 10–12, 2005.

[3] G. R. Faulhaber and D. Farber, "Spectrum management: Property rights, markets, and the commons," in *Proc. Telecommun. Policy Research Conf.*, Oct. 2003.

[4] Z. Qing and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, 2007.

[5] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[6] S. S. C. Rezaei, S. O. Gharan, and A. K. Khandani, "Cooperative strategies for the half-duplex gaussian parallel relay channel: Simultaneous relaying versus successive relaying," in *Proc. Ann. Allerton Conf. Commun., Control, and Comput.*, 2008, pp. 1309–1316.

[7] O. Simeone, J. Gambini, Y. Bar-Ness, and U. Spagnolini, "Cooperation and cognitive radio," in *Proc. IEEE ICC*, 2007, pp. 6511–6515.

[8] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 203–213, 2008.

[9] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, 2006.

[10] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, 2003.

[11] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wireless Commun.*, vol. 6, no. 9, pp. 3450–3460, 2007.

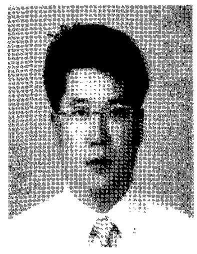
[12] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Trans. Inf. Theory*, vol. 43, no. 6, pp. 1986–1992, 1997.

[13] A. Papoulis and S. U. Pillai, *Probability, Random Variables, and Stochastic Processes*. Boston: McGraw-Hill, 4th ed., 2002.

[14] S. Weifeng, A. K. Sadek, and K. J. R. Liu, "Ser performance analysis and optimum power allocation for decode-and-forward cooperation protocol in wireless networks," in *Proc. IEEE WCNC*, vol. 2, 2005, pp. 984–989.

Asaduzzaman received the B.Sc. engineering degree in Electrical and Electronics Engineering from Chittagong University of Engineering and Technology, Bangladesh, in 2001. From 2001 to 2005, he was a Faculty member of the same University. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, University of Ulsan, Korea. His major research interests include wireless communication systems with emphasis on cooperative communications and MIMO systems, wireless sensor networks, modulation, and coding techniques, cognitive radio, etc.

Hyung Yun Kong received the M.E. and Ph.D. degrees in Electrical Engineering from Polytechnic University, Brooklyn, New York, USA, in 1991 and 1996. And he received the B.E. in Electrical Engineering from New York Institute of Technology, New York in 1989. Since 1996, he was with LG electronics Co., Ltd., in the multimedia research lab, and from 1997 the LG chairman's office planning future satellite communication systems. Currently, he is a Professor in Electrical Engineering at University of Ulsan, Korea. His research area includes high data rate modulation, channel coding, detection and estimation, cooperative communications, and sensor networks. He is a member of IEEK, KICS, KIPS, IEEE, and IEICE.



Insoo Koo received the B.E. degree from the Kon-Kuk University, Seoul, Korea, in 1996, and received the M.S. and Ph.D. degrees from the Gwangju Institute of Science and Technology (GIST), Gwangju, Korea, in 1998 and 2002, respectively. From 2002 to 2004, he was with Ultrafast Fiber-Optic Networks (UFON) research center in GIST, as a Research Professor. For one year from September 2003, he was a Visiting Scholar at Royal Institute of Science and Technology, Sweden. In 2005, he joined University of Ulsan where he is now Associate Professor. His research interests include next generation wireless communication systems, and wireless sensor networks.