http://dx.doi.org/10.6109/ijice.2011.9.6.641

Cooperative Power Control Scheme for a Spectrum Sharing System

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***Abstract*— In this paper, we investigate a power control problem which is very critical in underlay-based spectrum sharing systems. Although an underlay-based spectrum sharing system is more efficient compared to an overlay-based spectrum sharing system in terms of spectral utilization, some practical problems obstruct its commercialization. One of them is a real-time-based power adaptation of secondary transmitters. In the underlay-based spectrum sharing system, it is essential to adapt secondary user's transmit power to interference channel states to secure primary users' communication. Thus, we propose a practical power control scheme for secondary transmitters. The feedback overhead of our proposed scheme is insignificant because it requires one-bit signaling, while the optimal power control scheme requires the perfect information of channel states. In addition, the proposed scheme is robust to feedback delay. We compare the performance of the optimal and proposed schemes in terms of primary user's outage probability and secondary user's throughput. Our simulation results show that the proposed scheme is almost optimal in terms of both primary user's outage probability and secondary user's throughput when the secondary user's transmit power is low. As the secondary user's transmit power increases, the primary user's outage probability of the proposed scheme is degraded compared with the optimal scheme while the secondary user's throughput still approaches that of the optimal scheme. If the feedback delay is considered, however, the proposed scheme approaches the optimal scheme in terms of both the primary user's outage probability and secondary user's throughput regardless of the secondary user's transmit power.**

***Index Terms*— Cognitive Radio, Power Control, Spectrum Sharing, Next-Generation Mobile Communication Systems**

I. INTRODUCTION

COMMUNICATIONS commission (FCC) introduced the spectrum sharing concept to improve spectral utilization. Based on this concept, secondary users can share spectra dedicated to primary users as long as the interference caused by the secondary users is regulated [2]. For the purpose of the interference regulation, the FCC also presented several recommendations, one of which is an underlay-based approach. The underlay-based spectrum sharing systems regulate interference caused by secondary users to primary users below a given interference temperature. Compared with an overlay-based concept, the underlay-based approach can dramatically improve spectral efficiency because secondary users can always share primary users' spectrum regardless of whether primary users occupy their spectrum or not. In addition, much higher spectral efficiency can be achieved by opportunistically allocating secondary user's transmit according to primary user's fading channel state information [8]

However, there is a serious drawback in the underlay-based approach in spite of its high spectral efficiency. Secondary users should assess the amount of interference in real-time base and adapt their transmit power based on actual environments. It is believed that this practical obstacle delays the commercialization of the underlay model. Unfortunately, there was, however, no previous work that studied practical power adaptation schemes in spite of this concern of practicality and feasibility on the underlay-based spectrum sharing system. To the best of our knowledge, most of previous studies including our own studies assumed that the real-time based interference measurement and power adaptation is perfect [3-6, 8-11]. Thus, further analysis and study of the power adaptation issue is urgently required to remove the practical obstacle because it can achieve much higher spectral efficiency than the overlay-based approach and is still attractive as a long strategy [12].

On the other hand, recently, the International Telecommunication Unit-Radio Communication Sector (ITU-R) recognized that CR can be one of promising technologies for the next generation-mobile communication systems and began feasibility studies on CR over international mobile telecommunication (IMT) systems which are based on infrastructure [13-16]. It is expected that next generation mobile communication systems will provide various multi-media contents and services through various radio access technologies. Thus, this infrastructure-based CR can improve the network efficiency, flexibility, and connectivity.

Based on these motivations, in this paper, we investigate a power adaptation problem in the

Manuscript received August 10, 2011; revised September 4, 2011; accepted September 17, 2011.

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underlay-based spectrum sharing system based on infrastructure and propose a practical power control scheme for unlay-based spectrum sharing systems which are based on the cooperation between secondary and primary systems.

The rest of this paper is organized as follows: In Section 2, an infrastructure-based spectrum sharing system model is described and an optimal power control scheme for secondary user is introduced. In Section 3, a cooperative power control scheme is proposed. In Section 4, simulation results are presented to compare the performance of the optimal and proposed schemes. Finally, conclusions are drawn in Section 5

II. SYSTEM AND CHANNEL MODELS

A. System Model

Fig. 1 shows an infrastructure based spectrum sharing system based on an underlay model, where primary and secondary receivers operate on the basis of infrastructure and they can exchange signaling messages to cooperate with each other. Although this signaling message can be exchanged through a wireless or wired link, we assume that they are connected through a wired link because base stations can be clustered to exploit cooperative communication in most of next generation mobile communication systems including 3GPP LTE-advanced [7] and IEEE 802.16m [1]. It should be noted that this assumption does not restrict the application of the proposed scheme. Using the notations listed in Table 1, the received signals at secondary and primary receivers, y_s and y_p can be described, respectively, as

$$
\begin{aligned}
y_p &= h_{pp}x_p + h_{sp}x_s + n \\
y_s &= h_{ss}x_s + h_{ps}x_p + n
\end{aligned} \tag{1}
$$

and their received SINRs can be obtained as

$$
\begin{aligned}
\gamma_p &= \frac{P_p |h_{pp}|^2}{P_s^{tx} |h_{ss}|^2 + 1} \\
\gamma_s &= \frac{P_s^{tx} |h_{ss}|^2}{P_p^{tx} |h_{ps}|^2 + 1}
\end{aligned} \tag{2}
$$

where we assume that the primary transmitter uses fixed transmit power while the secondary user adapts its transmit power to satisfy a given interference constraint and power is normalized by noise variance without loss of generality.

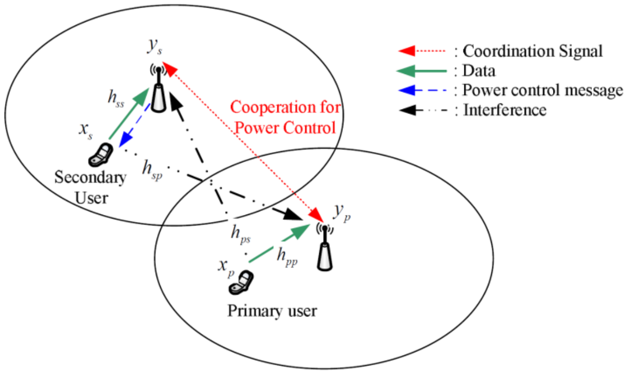


Fig. 1. Infrastructure-based spectrum sharing system

B. Optimal Power Control

Originally, Ghasemi et al. [1] proposed an optimal power allocation scheme in a fading environment to maximize the ergodic capacity of the secondary user given an interference temperature constraint at the primary receiver, which was also described in Eq. (1). They assumed that a secondary transmitter can obtain perfect information of the channel from secondary transmitter to primary receiver, h_{sp} . However, the power allocation scheme cannot exploit the fading effect of the channel from primary transmitter to primary receiver, h_{pp} . Fig. 2 shows the channel gains and the secondary user's transmit power. High channel gain value of the interference channel seriously decreases secondary transmitter's transmit power although the primary user's channel is good enough to tolerate higher interference from the secondary user. It is desirable to allow secondary user to use higher transmit power when the primary user's channel gain is good enough to satisfy its target SINR value in spite of the interference from the secondary user. Thus, the secondary user's performance can be improved if the secondary user can obtain the channel state information of the primary user, h_{pp} and exploit the fading effect of the channel [8]. Based on this fact, the optimal transmit power of the secondary transmitter can be obtained as a function of h_{pp}, as shown in Fig. 3.

TABLE I
NOTATIONS

Parameters	Description	Value
x_p	Transmitted signal from a primary transmitter	
x_s	Transmitted signal from a secondary transmitter	
P_p	Primary user's available transmit power[dB]	
P_s	Secondary user's available transmit power[dB]	
P_s^{tx}	Secondary user's transmit power[dB]	
y_p	Received signal at a primary receiver	
y_s	Received signal at a secondary receiver	
h_{ij}	Channel gain from transmitter i to receiver j (i and j can be primary, p or secondary, s)	$\mathcal{CN}(0, \sigma_{ij}^2)$
γ_p	Primary user's received SINR	
γ_s	Secondary user's received SINR	
n	AWGN at a receiver	$\mathcal{CN}(0, \sigma^2)$
Γ	Primary user target SINR[dB]	

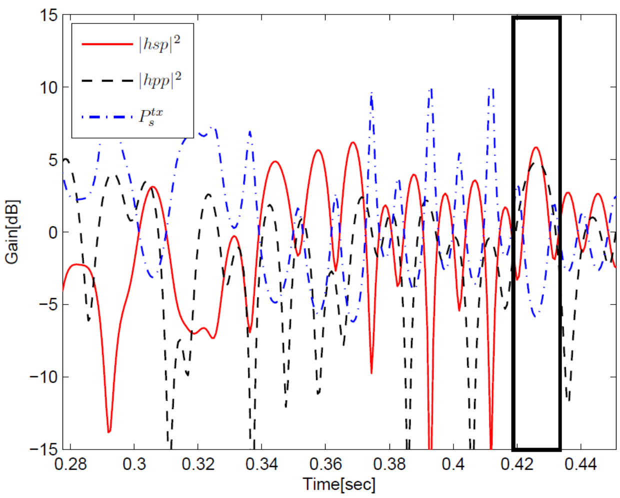


Fig. 2. Channel gains and secondary user's transmit power

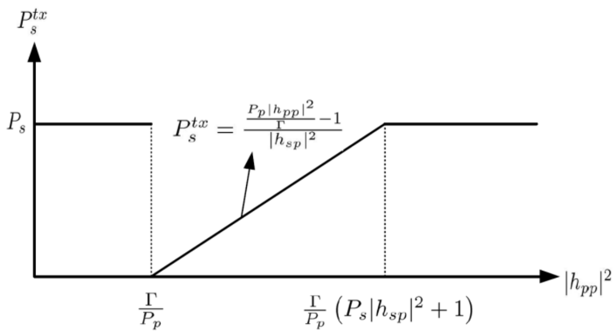


Fig. 3. Optimal power control scheme of secondary user

- When $|h_{pp}|^2 < \frac{\Gamma}{P_p}$ the primary user's target SINR can not be satisfied because of its own deep fading even if the secondary user does not transmit. In this case, it is optimal for secondary user to transmit its data using its peak transmit power, Ps.
- When $\frac{\Gamma}{P_p} \le |h_{pp}|^2 < \frac{\Gamma}{P_p}(P_s|h_{sp}|^2+1)$, the secondary transmitter should adaptively reduce its transmit power so that the primary user's target SINR is satisfied as follows:

$$\gamma_s = \frac{P_p |h_{pp}|^2}{P_s^{tx} |h_{sp}|^2 + 1} = \Gamma \tag{3}$$

Then, the secondary user's optimal transmit power is determined as

$$P_s^{tx} = \frac{\frac{P_p |h_{pp}|^2}{\Gamma} - 1}{|h_{sp}|^2} \tag{4}$$

which is linearly proportional to the value of $|h_{pp}|^2$. The secondary user should have the prior information of channel states, $|h_{pp}|^2$ and $|h_{pp}|^2$ to compute $|h_{pp}|^2$. It should be noted that P_s^{tx} can be obtained by measuring the pilot channel from the primary receiver, while $|h_{pp}|^2$ can only obtained through a direct feedback from the primary receiver.

- When $\frac{\Gamma}{P_p}(P_s|h_{sp}|^2+1) \le |h_{pp}|^2$, the primary user's target SINR can be unconditionally satisfied regardless of the secondary user's transmission because the channel state is good enough to tolerate the secondary user's peak power transmission. Thus, the secondary user can transmit its data using its peak power, Ps.

III. ANALYSIS OF OUTAGE PROBABILITY

Although the optimal transmit power of secondary transmitters can be determined as described in 2.2, it may be impractical because it requires direct communication between the primary receiver and the secondary transmitter for the feedback of channel state information, which is prohibitive in spectrum sharing systems because it can cause a serious burden to primary users. Thus, we propose an empirical power control scheme for secondary users, which is based on the cooperation between secondary and primary infrastructures. Fig. 4 shows the flow diagram of our proposed scheme, where Δ_u and Δ_d denote the power increment and decrement steps of secondary transmitters, respectively.

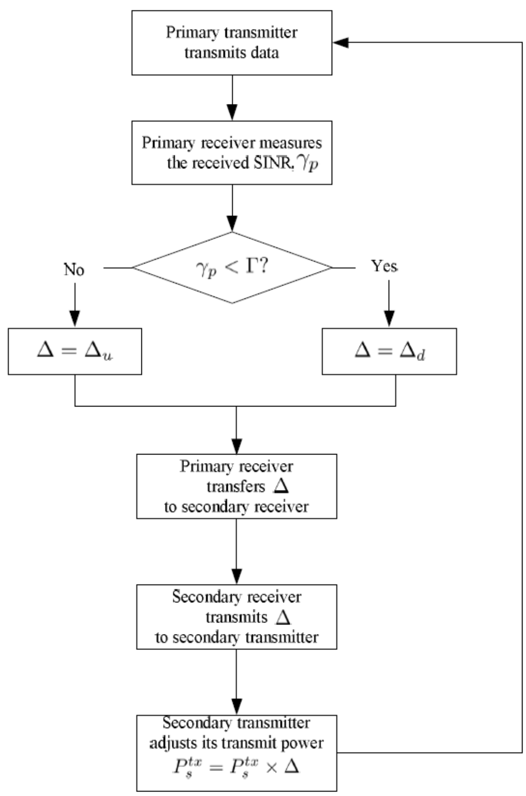


Fig. 4. Proposed power control scheme for a secondary user

Although the primary receiver is assumed to transfer the values of Δ_d and Δ_u to the secondary transmitter through the secondary receiver, they can be replaced with one bit indicator to reduce feedback overhead if the values of Δ_u and Δ_d are shared between the secondary transmitter and the primary receiver.

IV. SIMULATION RESULTS

Unfortunately, it is intractable to mathematically analyze the performance of the proposed scheme. Thus, we present simulation results to investigate the proposed power control scheme and compare the performance of the proposed scheme with that of the optimal power control scheme in terms of primary user's outage probability and secondary user's throughput, which are defined, respectively, as

$$P_p^{out} = \Pr\left[\gamma_p < \Gamma\right]$$

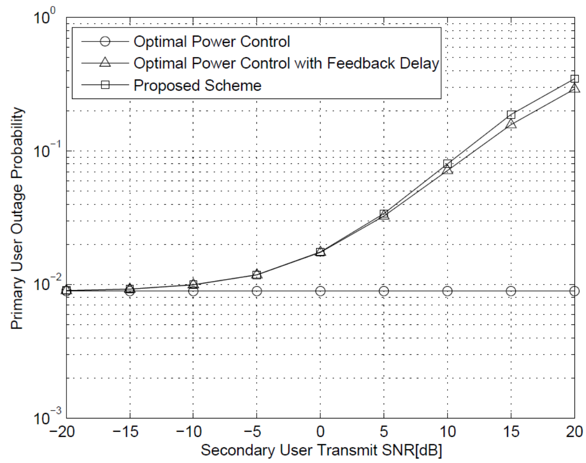
$$Th_s = \mathbb{E}\left[\log_2\left(1+\gamma_s\right)\right] \tag{5}$$

We assume that all average channel gains are equal to 1 to focus on the effect of small-scale fading, although the effect of large-scale channel fading can be incorporated by considering adequate average channel gains. The simulation parameters are summarized in Table II.

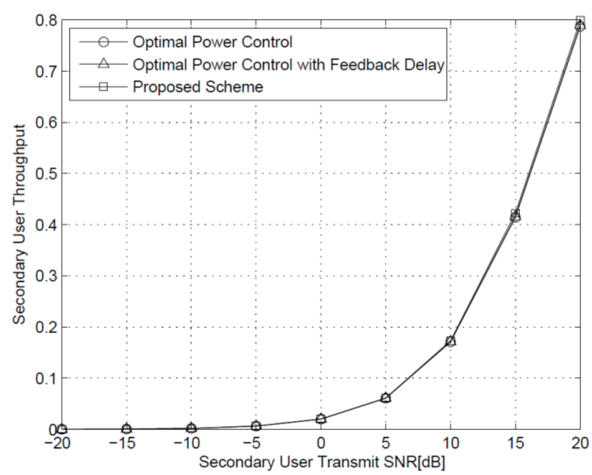
TABLE II
SIMULATION PARAMETERS

Parameters	Description	Value
Γ	Primary user target SINR[dB]	0
v	User velocity	30 km/h
f	Carrier frequency	2 GHz
c	Light velocity	3×10^8 m/s
f_d	Doppler shift	$\frac{vf}{c}$
Δ_u	Power increment step [dB]	1
Δ_d	Power decrement step [dB]	-3 or -1
f_{pc}	Power control frequency [Hz]	800 or 1600
d_{fb}	Feedback delay [sec]	1 sample=$\frac{1}{f_{pc}}$

Fig. 5 shows the primary user's outage probability and secondary user's throughput when $P_s = 20$ dB, $v = 30$ km/h, $\Delta_u = 1$ dB, $\Delta_d = -1$ dB and, $f_{pc} = 800$ Hz , The optimal power control scheme serves as theoretical upper-bound for the proposed scheme in terms of both primary user's outage and secondary user's throughput. As derived in Appendix D, the primary user's outage probability of the optimal scheme is independent of the secondary user's transmit power because the secondary user can always compute its optimal transmit power to secure the primary user's transmission if it can obtain the perfect channel state information. When the secondary user's transmit power is low, the proposed scheme approaches the optimal scheme in terms of both the primary user's outage probability and secondary user's throughput. As the secondary user's transmit power increases, the primary user's outage probability of the proposed scheme is degraded, while the secondary user's throughput of the proposed scheme is still optimal. In practice, the feedback of channel state information always accompanies with feedback delay. If the feedback delay is considered, the primary user's outage probability of the optimal power control scheme is degraded due to the inaccurate channel state information, while the secondary user's throughput is not degraded. On the other hand, the proposed scheme is very robust to the feedback delay and almost optimal regardless of the secondary user's transmit power in terms of both primary user's outage probability and secondary user's throughput.



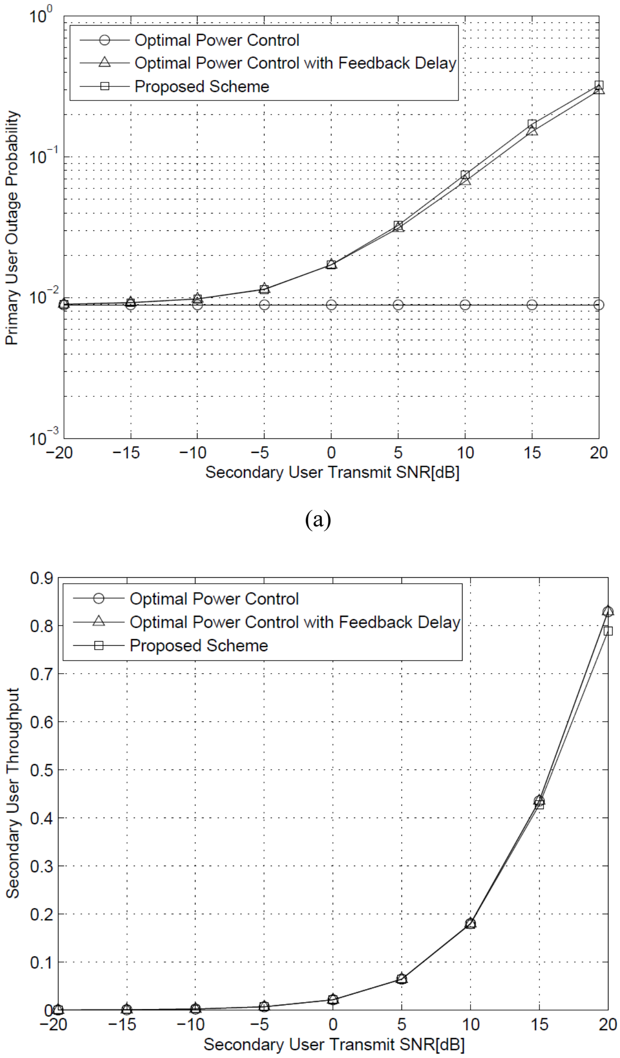
(a)



(b)

Fig. 5. Primary user's outage probability and secondary user's throughput when $P_s = 20$ dB, $v = 30$ km/h, $\Delta_u = 1$ dB, $\Delta_d = -1$ dB and $f_{pc} = 800$ Hz
(a) Primary user's outage Probability
(b) Secondary user's throughput

Fig. 6 shows the performance of both schemes when f_{pc} = 1600 Hz and all other parameters are the same as in Fig. 5. As the frequency of power control is doubled, the performance is slightly improved in terms of primary user's outage probability. However, the performance improvement is insignificant if the increased power control overhead is considered.

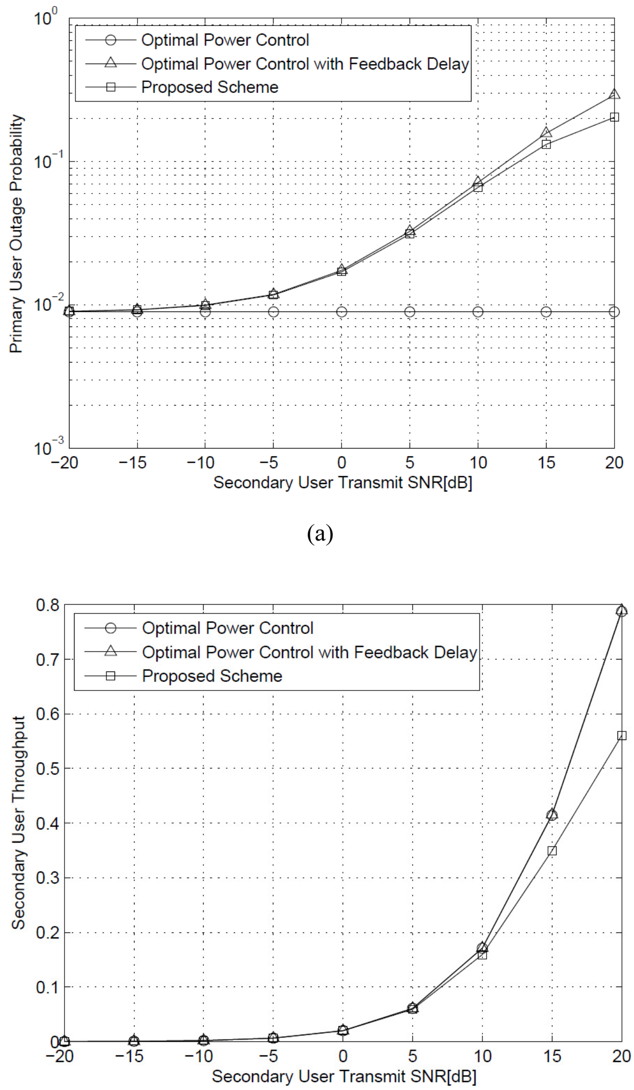


(a)

(b)

Fig. 6. Primary user's outage probability and secondary user's throughput when $P_s = 20$ dB, $v = 30$ km/h, $\Delta_u = 1$ dB, $\Delta_d = -1$ dB and f_{pc} = 1600Hz
(a) Primary user's outage Probability
(b) Secondary user's throughput

Fig. 7 shows the performance of both schemes when Δ_d = −3 dB and all other parameters are the same as in Fig. 5. It is shown that the primary user's outage probability can be greatly improved at the cost of secondary user's throughput. That is, secondary user should aggressively reduce its transmit power to secure primary user's communication when primary user is in outage state although its own throughput can be degraded. It should be noted that in order to improve the primary user's outage probability, the adjustment of Δ_d is much more efficient than the increase in the power control frequency. In addition, the adjustment of Δ_d does not cause any additional overhead while the increase in the power control frequency linearly increases signaling overhead.



(a)

(b)

Fig. 7. Primary user's outage probability and secondary user's throughput when $P_s = 20$ dB, $v = 30$ km/h, $\Delta_u = 1$ dB, $\Delta_d =$ -3dB and $f_{pc} = 800$ Hz
(a) Primary user's outage Probability
(b) Secondary user's throughput

V. SUMMARY

In this paper, we proposed a practical power control scheme for secondary users in an infrastructure-based underlay spectrum sharing system. Although the underlay-based spectrum sharing system can dramatically improve the spectral efficiency compared to the overlay model, it is challenging to regulate the interference caused by secondary users. Specially, it is very difficult to estimate interference channels and adapt secondary users' transmit power in real-time base. In spite of these practical obstacles, most of previous studies assumed that the channel estimation and real-time power adaptation are perfect. Thus, we proposed an empirical power control scheme based on an infrastructure where a primary receiver estimates its received SINR and transfers power control message to a secondary transmitter through a secondary receiver. Our simulation results show that the primary user's outage probability of the proposed scheme approaches that of the optimal scheme when the secondary user's transmit power is low and the proposed scheme is almost optimal in terms of the secondary user's throughput regardless of the secondary user's transmit power. It is also shown that our proposed scheme is very robust to the feedback delay, while the optimal power control scheme is very vulnerable to the feedback delay. If the feedback delay is considered, our proposed scheme yields almost optimal performance in terms of both primary user's outage probability and secondary user's throughput. It should be also noted that our proposed scheme requires one-bit signaling to control secondary user's transmit power while the optimal power control scheme requires full channel state information of both secondary and primary users.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by Ministry of Education, Science, and Technology (2010-0011140).

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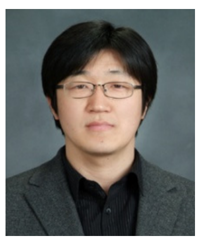

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