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Power Allocation Scheme for Secondary User under Primary Full Duplex Relay System in Cognitive Radio Network

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Abstract

A power allocation scheme for the secondary user when the primary user employs the full duplex relay (FDR) is proposed in cognitive radio system. When the FDR is deployed in primary system, the primary relay and receiver suffers the interference from the secondary transmitter in order to share the spectrum of the primary user. Therefore, the power allocation scheme to satisfy the interference constraint is needed for the spectrum sharing. Thus, we propose a new power allocation scheme to satisfy the quality of service (QoS) of the primary user. Since the proposed power allocation scheme does not need the instantaneous channel state information (CSI), the proposed scheme not only has feedback burden, but also can be robust the outdated CSI environment.

Keywords: *Cognitive Radios, Random Access, Energy Saving*

1. Introduction

Cognitive radios have been being actively studied recently since it was reported that licensed spectra exclusively allocated to some wireless communication systems were under-utilized [1, 2]. Technical issues of cognitive radios are categorized into two subjects, which are spectrum sharing and spectrum sensing. In spectrum sensing, secondary users search for unused spectra which are originally allocated to a primary communication system. In spectrum sharing, secondary users utilize primary spectra under a condition which is that secondary users only can give a predetermined amount of the interference to primary users. In both issues, this paper focuses on the spectrum sharing.

In spectrum sharing, secondary users can coexists with primary users if the quality of service (QoS) of primary communications is not degraded by the interference due to secondary communications [3, 4]. Hence, secondary users should control its transmission power in order to satisfy the interference constraint set at primary users. If the interference constraint is satisfied by secondary users, we can easily expect better spectrum utilization because two communication systems coexist in a spectrum.

Accordingly, technical problems for secondary users to achieve better capacity have been studied in spectrum sharing. In [5-7], transmission power allocations of secondary users were firstly studied for the capacity enhancement of secondary users. In those literatures, the transmission power is simply determined by measuring the interference channel between the secondary transmitter and the primary receiver. In [5], the general capacity derivation was developed in various fading channel using the average transmission power and the peak transmission power. Another capacity derivation was made in [6]. In [7], outage capacity was newly adopted in the spectrum sharing. In such cases, secondary users can transmit a signal with strong or weak transmission power when the interference channel is weak and strong, respectively. However, they commonly consider only the interference channel.

After that, two-hop relaying systems were adopted to secondary communication systems in spectrum sharing, which results in increasing the capacity of secondary users [8-9]. Different from the conventional works in [5-7], the secondary transmitter has to determine the transmission power depending on not only the interference channel between the secondary transmitter and the primary receiver but also another interference channel between the secondary transmitter and the primary relay if the primary system is a two-hop relay system. However, those works only consider a situation that primary users do a peer-to-peer communication. In addition to that, various transmission schemes of primary users are not taken into account in the conventional works.

This work considers primary users using a full duplex relay (FDR). In this case, signal transmission of secondary users becomes interference to not only primary receiver not also primary FDR simultaneously. Therefore, secondary transmission power has to be controlled to satisfy interference constraints set at primary FDR and receivers. In this paper, power allocation scheme is newly proposed not to violate the interference constraint at primary FDR and receiver. Capacity of secondary users using the proposed scheme is also derived in a closed form.

2. System Model

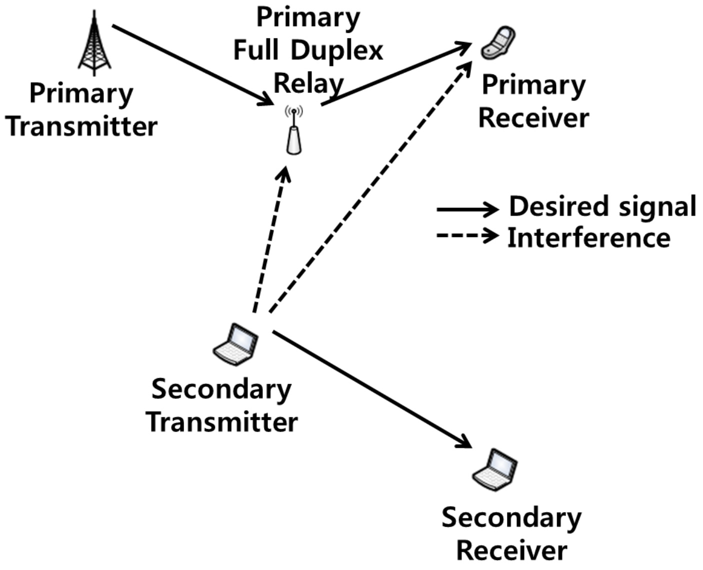

Figure 1. System Model: Primary User using a FDR

It is assumed that a primary user uses a FDR and a secondary user shares the primary spectrum. Figure 1 shows the system model considered in this paper. In Figure 1, Stx and Srx are a secondary transmitter and receiver, respectively. PTx, PR, and PRx are a primary transmitter, relay, and receiver, respectively. PR is a decode-and-forward FDR [10]. A FDR can simultaneously transmit and receive signal. Hence, in spectrum sharing environments, Stx should be able to satisfy the interference constraint set at PR and PRx simultaneously, too.

For the sake of the secondary communication, Stx measures the interference channel between Stx and PRx and another interference channel between Stx and PR. Usually, in this area of research [5-7], the secondary transmitter has knowledge to the primary system. Therefore, the channel measurement information can be exchanged between the secondary transmitter and the primary receiver. A band-manager can help to let them exchange the channel measurement information [5].

In this paper, we assume a full-duplex relay. Hence, PR simultaneously receives from PTx and transmits the received signal to PRx. It is assumed that a direct link between PTx and PRx does not exist. Echo signal between antennas for signal transmission and reception can be cancelled just as in [11].

In Figure 1, h_s is the channel between a secondary transmitter and receiver h_{SR} and h_{RD} are channels between a primary transmitter and relay, and a relay and receiver, respectively. Additionally, h_{IR} and h_{ID} are interference channel between a secondary transmitter and a primary relay, and a primary receiver, respectively. Those channels are complex Gaussian random variables with zero mean and unit variance. Hence, channel gains of those channels are expressed as:

$$g_i = |h_i|^2, i \in \{S, SR, RD, IR, ID\}, \tag{1}$$

which become exponential random variables with unit mean.

In a spectrum sharing, a secondary transmitter controls its transmission power to satisfy a QoS constraint set at the primary relay and receiver. In this paper, the QoS constraint is the outage probability as:

$$P_{out} = \Pr\{\min(\gamma_R, \gamma_D) \le \eta_F\} \le Q, \tag{2}$$

where γ_R and γ_R are signal-to-interference-and-noise ratios (SINR), respectively. η_F is the minimum required SINR value for the primary user maintain its QoS. Q is the allowable outage probability of the primary user. This equation means that the secondary transmission can be made only if, even in the worst case of the primary communication due to the secondary spectrum utilization, the quality of the primary communication remains above the predetermined value. From this equation, we can know that the primary communication is primarily protected from the interference generated by the secondary communication.

If the condition in (2) is met, the secondary user can transmit a signal in a spectrum while primary transmitter and relay are transmitting signals. Surely, the secondary transmission power changes depending on the interference channel between Stx and PR, and Stx and PRx. In this paper, a power allocation scheme is proposed to satisfy the outage probability constraint, and the capacity of a secondary link using the power allocation scheme is derived.

As we can see in (2), we set an outage constraint in order to protect the primary communication. Actually, in the conventional works such as [5-7], a received interference power level is used for the constraint value for the primary communication protection. However, it was revealed that the conventional way of the primary communication protection using the received interference power level cannot be practically applied to the real world because of the feedback latency [12]. In [5-7], the secondary transmitter does not give any harmful interference if the value of the channel between Stx and PRx is exact. However, the value of the channel is not exact any more when Stx receives it from PRx due to the feedback latency. If not considering the secondary spectrum utilization, the feedback latency results in small capacity degradation. However, in the spectrum sharing, under-estimated channel due to the feedback latency might make harmful interference to PRx. As shown in [12], the probability that the channel value between Stx and PRx is under-estimated or overestimated is exactly 0.5, which means fifty percentage of secondary transmissions five harmful interference to PRx. This is a serious violation of the primary communication protection policy. The schematic process of the proposed power allocation is summarized as Figure 2.

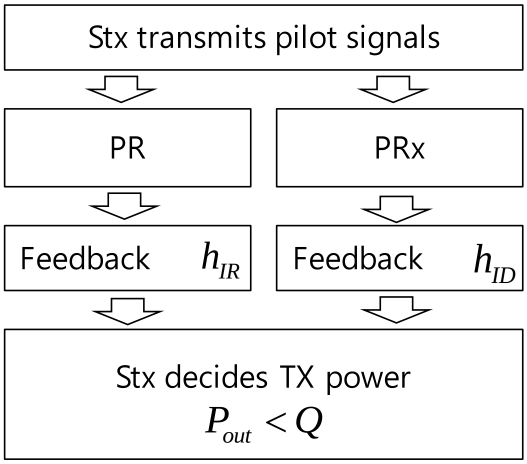

Figure 2. Schematic Process of the Proposed Power Allocation Scheme

Therefore, we adopt the primary communication protection policy by using the outage probability. Although the secondary communication cannot help giving harmful interference to PRx, we can control the probability that the harmful interference occurs at PRx by adopting the outage probability constraint.

3. Power Allocation Scheme

In this system model, a secondary user has to satisfy the outage probability for both PRx and PR as:

$$P_{out} = 1-(1-\Pr\{\gamma_R \le \eta_F\})(1-\Pr\{\gamma_D \le \eta_F\}) \tag{3}$$

This equation means that outage occur if one link, at least, between the PTx-PR link and the PR-PRx link cannot maintain the predetermined signal quality. In (3), one can know that the outage event at PRx depends on not only SINR at the receiver (γ_R) but also SINR at the FDR (γ_D) because this is a two-hop relaying system. Hence, the outage probability of the channel h_{SR} is firstly expressed as:

$$\Pr\{\gamma_R \le \eta_F\} = \Pr\left\{\frac{g_{SR}P_{PT}}{g_{IR}P_{ST}+\sigma^2} \le \eta_F\right\}, \tag{4}$$

where P_{PT} and P_{ST} are transmission power values of the primary transmitter and secondary transmitter, respectively, and σ^2 is the variance of the thermal noise. From (4), the outage probability of the PTx-PR link can be calculated as:

$$\begin{aligned}\mathrm{P}_{out}^{SR} &= \int_0^\infty e^{-g_{IR}} \int_0^{\frac{\eta_F}{P_{PT}}\left(g_{IR}P_{ST}+\sigma^2\right)} e^{-g_{SR}} dg_{SR} dg_{IR} \\ &= \int_0^\infty \left(1-e^{-\frac{\eta_F}{P_{PT}}\left(g_{IR}P_{ST}+\sigma^2\right)}\right) e^{-g_{IR}} dg_{IR} = 1-\frac{e^{-\frac{\eta_F\sigma^2}{P_{PT}}} P_{PT}}{\eta_F P_S + P_{PT}}.\end{aligned} \tag{5}$$

Similar to (5), the outage probability of the PR-PRx link can be also derived as:

$$\mathrm{P}_{out}^{RD} = 1-\frac{e^{-\frac{\eta_F\sigma^2}{P_{PR}}} P_{PR}}{\eta_F P_S + P_{PR}}. \tag{6}$$

Substituting (5) and (6) into (3), resultant outage probability of the primary user, when the secondary user shares the primary spectrum, can be derived as:

$$P_{out} = 1-(1-\mathrm{P}_{out}^{SR})(1-\mathrm{P}_{out}^{RD}) = 1-\frac{e^{-\eta_F\sigma^2\left(\frac{P_{PT}+P_{PR}}{P_{PT}P_{PR}}\right)} P_{PT}P_{PR}}{(\eta_F P_S + P_{PT})(\eta_F P_S + P_{PR})}. \tag{7}$$

Therefore, if the secondary user can share the primary spectrum only if the outage probability of the primary user is maintained below value Q, the maximum secondary transmission power P_S can be derived from (7) as:

$$P_S(Q) = -\frac{P_{PT}+P_{PT}}{2\eta_F} + \frac{e^{-\eta_F\sigma^2\left(\frac{P_{PT}+P_{PR}}{2P_{PT}P_{PR}}\right)}}{2\eta_F}\sqrt{\frac{4P_{PT}P_{PR}}{1-Q}+(P_{PT}-P_{PR})^2 e^{\eta_F\sigma^2\left(\frac{P_{PT}+P_{PR}}{P_{PT}P_{PR}}\right)}} \tag{8}$$

Observing the secondary transmission power $P_S(Q)$ in (8), it is a function of transmission powers of primary transmitter and relay, the variance of the thermal noise, the required SINR of primary users, and the outage constraint. Compared with the conventional spectrum sharing schemes requiring instantaneous channel state information (CSI), it is shown that the transmission power in (8) does not require instantaneous CSI. Therefore, this spectrum sharing system can reduce the signaling overhead for the CSI feedback, which means robustness in channel environments with outdated CSI feedback. Using (8), secondary users can share the primary spectrum while the QoS of primary users is satisfied.

Next, let us derive the capacity of secondary users which use the transmission power value in (8). Using (8), the capacity of a secondary user can be expressed as:

$$C_S = E\left[\log\left(1+\frac{g_S P_S}{\sigma^2}\right)\right], \tag{9}$$

where $E[\cdot]$ is the expectation operation. Applying the probability density function of g_S to (9), the capacity of the secondary user can be calculated as:

$$C_S = \int_0^{\infty} \log\left(1+\frac{g_S P_S}{\sigma^2}\right) f_{g_S}(g_S)dg_S = e^{-\frac{\sigma^2}{P_S}} E_i\left(-\frac{\sigma^2}{P_S}\right), \tag{10}$$

where $E_i(x) = -\int_{-x}^{\infty} e^{-t}t^{-1}dt$ is the exponential integral function.

4. Numerical Results

In this section, using the power allocation in (8), the capacity of the secondary user is depicted. Figure 3 shows capacity comparison between when using the power allocation value in (8) and when using conventional power allocation value determined by instantaneous channel information. In the conventional way to determine the secondary transmission power value, the interference to both primary relay and receiver must be below the predetermined interference threshold I_{th}. Hence, the conventional power allocation value can be calculated as:

$$P_S^{Conv} = \frac{I_{th}}{\min(g_{IR}, g_{ID})}. \tag{11}$$

Comparing fairly with the proposed power allocation scheme, the interference threshold for the proposed one can be derived as:

$$I_{th} = -\frac{\eta\sigma^2(P_{PR}+P_{PD}) + P_{PT}P_{PR}\log(Q)}{\eta P_{PT}P_{PR}} \tag{12}$$

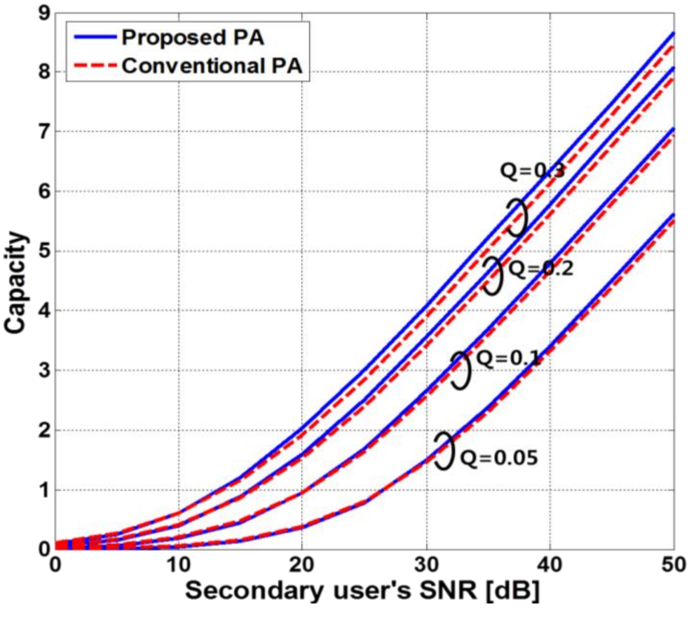

Figure 3. Capacity of Secondary User

As we can see in Figure 3, the proposed power allocation scheme slightly outperforms the conventional power allocation scheme in terms of the capacity as signal-to-noise ratio increases. Although the performance gap looks very small, we have to pay attention on the difference of the CSI burden between the two schemes. While the proposed power allocation scheme does not need any instantaneous CSI, the conventional scheme should consume a considerable amount of radio resource for CSI measurements and feedback.

In spectrum sharing, it is very important to get the precise channel information between Stx and PRx or PR because wrong channel information between them means harmful interference to the primary system while wrong channel information means just throughput degradation in the conventional wireless systems, However, considering the mobility of primary or secondary nodes, it can be easily shown that to obtain an exact channel information between Stx and PRx or PR is practically not possible due to feedback latency which is the time difference between the channel measurement time and the reporting time. Accordingly, results depicted in Figure 3 shows us an important fact to practically implement the secondary system without the channel measurement and feedback while the capacity performance of the secondary system is not sacrificed.

Figure 4 shows that conventional power allocation scheme does not satisfy the outage probability of primary users while the proposed scheme tightly satisfies the primary outage condition when the channel is outdated. In this result, a general outdated channel model is used as follows:

$$h_i = r\breve{h}_i + \sqrt{1-r^2}\hat{h}_i,\ i \in \{IR, ID\}, \tag{13}$$

where $\breve{h}_i$ and $\hat{h}_i$ are the outdated channel and complex Gaussian random variable, respectively. The value r is the correlation coefficient depending on the latency for the CSI feedback.

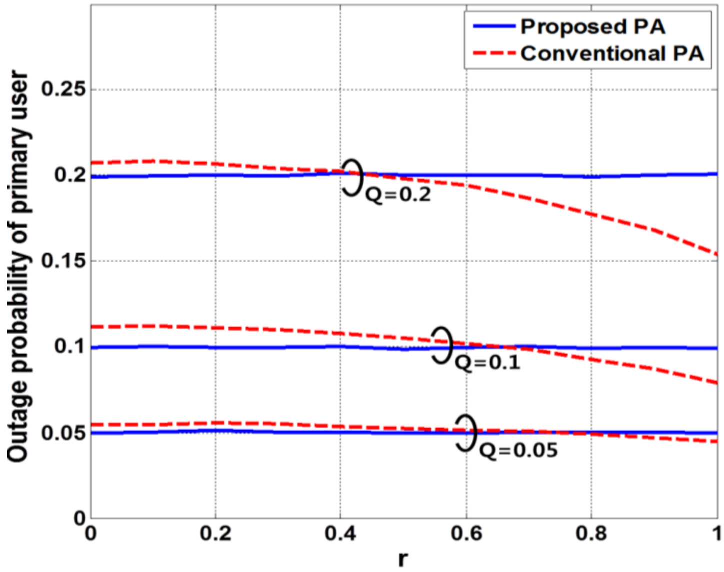

Figure 4. Primary QoS Guaranteed by the Proposed Power Allocation Scheme

Therefore, the proposed power allocation scheme has robustness to satisfy the primary outage condition in order to share the primary spectrum in wireless communication environments with CSI feedback latency. If the value of the correlation coefficient is very low, the conventional power allocation scheme makes more harmful interference due to feedback latency. However, if the value of the correlation coefficient is very high, feedback latency does not matter for the outage probability. In the real world, it is very difficult to get the value of the correlation coefficient. Therefore, the outage event cannot be predictable. Therefore, the proposed outage-probability-predictable power allocation scheme should be useful for the practical implementation of the secondary communication system.

In Figure 5, the capacity of the secondary user is plotted as the variance of the background noise varies. σ_S^2, σ_D^2, and σ_R^2 are background noise variance of the secondary receiver, primary receiver and relay, respectively. In this result, it can be observed that zero capacity points of secondary users are different depending on values of the allowable outage probability Q because the requirement of the allowable outage probability cannot be satisfied if the variance of the background noise is below a certain value. However, the secondary user can share the primary spectrum if the variance of the background noise is larger than a value. In this case, we can also observe that the proposed scheme outperforms the conventional spectrum sharing schemes.

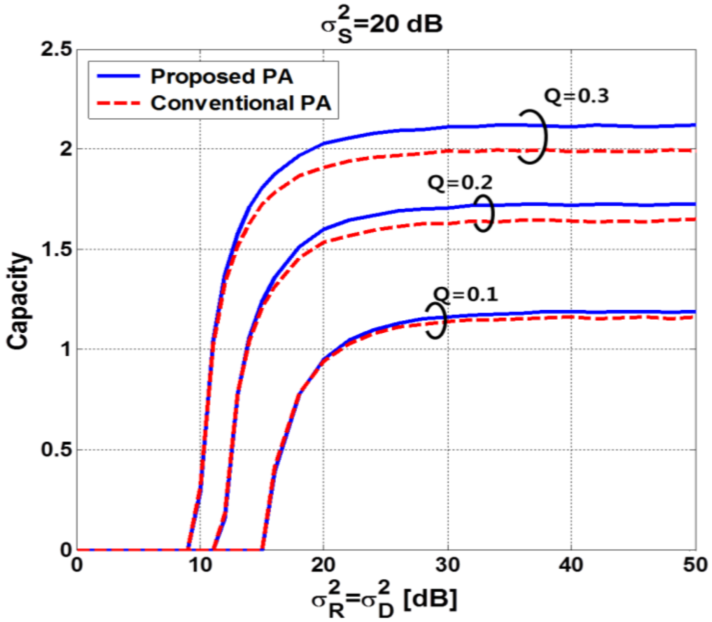

Figure 5. Secondary User's Capacity Depending on Noise Variance

In Figure 6, the capacity of the secondary user is plotted as the allowable outage probability Q increases. As we can see in this figure, the capacity of the secondary user increases as the value of Q increases, which is because the larger value of Q means that more amount of the interference is allowable at the primary user. In this result, the capacity performance gap between the proposed scheme and the conventional scheme increases as the value of Q increases.

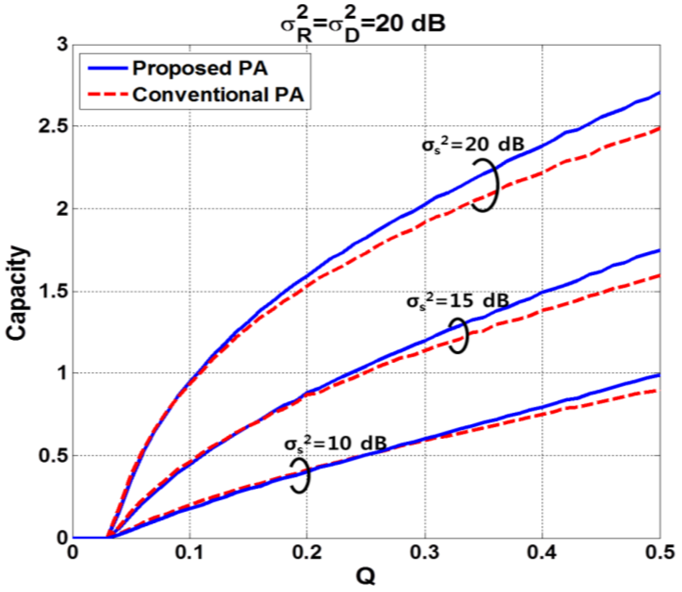

Figure 6. Secondary User's Capacity Depending on Values of Q

However, the performance gap is practically meaningless because no primary system allows over ten percentage of outage. Therefore, the proposed power allocation scheme almost has the same capacity performance.

Through the results shown in this paper, it is known that the proposed power allocation scheme even performs better without the feedback of the instantaneous channel information than the conventional power allocation scheme requiring the feedback of the instantaneous channel information in the spectrum sharing environment with the primary FDR if the primary system allows the capacity outage due to the secondary communication.

5. Conclusion

In this paper, a new power allocation scheme of secondary users was proposed in spectrum sharing environments where primary users use FDR. The closed form solution for the secondary power allocation was derived. Based on the secondary power allocation, secondary capacity could be calculated and compared with that by the conventional power allocation. As a result, the proposed power allocation scheme outperforms the conventional one in terms of capacity even though the proposed power allocation does not need instantaneous CSI feedback which is indispensable to the conventional power allocation scheme. Therefore, it can be concluded that the proposed power allocation scheme is practically implementable under the outdated channel condition in spectrum sharing environments.

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