

Research Article

Power Allocation in Nonselish Symbiotic Cognitive Relaying with Partial Channel State Information

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Received 3 October 2013; Revised 12 December 2013; Accepted 13 December 2013; Published 9 January 2014

Academic Editor: Yanmin Zhu

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We first address the problem of power allocation at cognitive users (CUs) to maximize the throughput of a nonselish symbiotic cognitive radio scheme, in which the CUs may assist the data transmission of primary users (PUs) via nonorthogonal amplify-and-forward (AF) cognitive relaying and obtain an incentive time for their own data transmission in a nonselish manner. Then, an optimal power allocation algorithm is proposed based on the full channel state information (CSI) among PUs, CUs, and base station (BS). In order to reduce the feedback overhead, another power allocation algorithm is devised based only on the partial CSI, that is, the CSI of BS-PU and the CSI of BS-CUs. Simulation results demonstrate that, compared with the optimal power allocation algorithm, the power allocation algorithm with only the partial CSI can achieve a similar performance with a smaller channel feedback overhead.

1. Introduction

With underutilized time or frequency resources, the Federal Communications Commission (FCC) has recommended that more efficient spectrum utilization could be realized by implementing devices that can coexist with licensed users or PUs [1]. In consequence, cognitive radio (CR) has been considered as an essential candidate for exploiting spectrum at a higher efficiency [2, 3]. Based on the original CR concept [2], the data transmission of a conventional cognitive radio scheme (CCR) [1] is performed as a passive approach. The CUs need to sense the spectrum and wait for spectrum holes for their data transmission without any interaction between primary and cognitive networks. In this case, there is no need for any modification in the primary network, but, instead, the achievable performance, for example, spectrum efficiency, is quite limited.

The relay systems have been actively studied to increase the throughput as well as to increase the service coverage in wireless networks [4–6]. In order to further enhance the performance of the cognitive network, the relay function is actively enabled at the CUs to assist the primary transmission, which may bring the benefits to the CUs, for example,

creating more spectrum holes for the cognitive network. As the CUs with relay function come into play, the optimal power allocation at CUs to increase the spectrum efficiency becomes a critical issue for coexisting primary and cognitive networks [7–13]. However, to efficiently utilize the spectrum holes created by cognitive relaying, some interaction between primary and cognitive networks is inevitable, despite that it may break the rule of original CR concept. (Strictly speaking, this may not be said CR from its original point of view. However, we call it cognitive relaying herein, since CR concept and relay function are combined together.) For instance, rather than a passive approach in CCR, a spectrum leasing algorithm was introduced as an active approach, in which a common control channel was assumed for the CSI exchange and the decision delivery, for example, cooperation parameters and cooperation decision [7]. As a reward for the decode-and-forward (DF) cooperation from CUs, the PU might lease part of its own time slot to the cooperative CUs; herein, a CU that cooperates with a PU is called a cooperative CU, and is the only user that can immediately access the channel in the leased time; accordingly, this type of CU is called a *selfish* one.

For the selfish scheme in [7], the cooperative CUs might not be the CUs with the best link quality in the leased time. So, allocation of leased time only to the cooperative CUs is inefficient for maximizing the overall throughput of coexisting primary and cognitive networks, especially for the cognitive network. Thus, a nonselfish symbiotic cognitive relaying scheme (NSCRS) [8] was introduced. Owing to the nonselfish behavior, the CUs can selflessly grant a concession to give the incentive time to a CU with the best link quality for better utilization of the incentive time than that in [7]. However, only the constant transmit power is assumed at each CU for the cooperative transmission in [8], which is inefficient at managing the received signal power at the receiver side and controlling the potential interference to the neighbor cell. Even though a suboptimal power allocation algorithm was introduced for a symbiotic cognitive relaying scheme to maximize the throughput of cognitive network in [9], the problem for maximizing the throughput of primary and cognitive networks by optimally allocating power at CUs has not been taken into account.

Originated from the symbiosis in [8, 9], the suboptimal algorithms for joint power allocation, subcarrier allocation, and routing selection were investigated in an orthogonal frequency division multiplexing (OFDM) based symbiotic cognitive relaying architecture to maximize the incentive time [10]. This work was further extended to develop an optimum utility-based decision-making process to allocate the fraction of time to the PU and CUs [11]. In addition, a closed form expression of the outage probability for data transmissions at CUs was presented under the constraint of a target outage probability of primary transmissions [12]. A cross-layer approach was presented to jointly consider optimal relay selection, adaptive modulation and coding, and data-link layer frame size to maximize the transmission control protocol throughput in cognitive networks with limited interference to the primary link [13]. However, all the cognitive relaying schemes in [7, 10–13] assumed the orthogonal transmission at the CUs and the power allocation problem with nonorthogonal AF relaying was not considered.

In this paper, we intend to maximize the overall throughput of NSCRS with the nonorthogonal AF relaying by optimally allocating the power among CUs, while minimizing the required interaction between primary and cognitive networks as well as the overhead of CSI feedback. We first formulate the power allocation problem to maximize the throughput of NSCRS under a sum power constraint at CUs. With the nonorthogonal AF cognitive relaying transmission at CUs, all the amplified noise and interference from multiple CUs are taken into account at PUs, since all the CUs are simultaneously transmitting their amplified signals to PUs. Then, an optimal power allocation algorithm is proposed based on the full CSI feedback. To alleviate the overhead of CSI feedback, another power allocation algorithm is additionally proposed based only on the partial CSI, that is, CSI of BS-PU and BS-CUs. We investigate the performances of NSCRS in three cases: with ideal assumption of full CSI, with partial CSI, and with no CSI for comparative purpose.

The rest of this paper is organized as follows. Section 2 gives a preliminary description of CCR and NSCRS. In

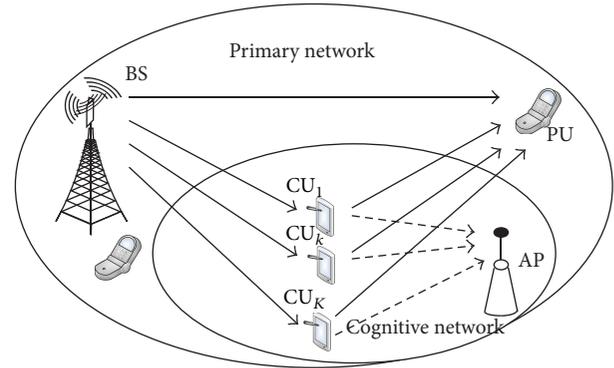


FIGURE 1: System architecture with coexisting primary and cognitive networks.

Section 3, we formulate the power allocation problems for NSCRS. In Sections 4 and 5, the proposed algorithms are presented and evaluated by intensive simulations, respectively. Finally, Conclusions are drawn in Section 6.

2. Preliminary

In this section, we introduce the system architecture for the coexistence of primary and CR networks as well as the transmission approaches for both CCR and NSCRS.

2.1. System Architecture for Coexistence of Primary and Cognitive Networks. We consider a system architecture with coexistence of primary and cognitive networks, as shown in Figure 1. The primary network is assumed to be a time division multiple access (TDMA)-based cellular network, where the BS transmits the data to the PUs in different time slots. In the cognitive network, the CUs seek opportunities to access the AP of cognitive network. For the cognitive network, only the AP can communicate with the BS and all the CUs can only communicate with the AP. For the symbiotic architecture, the data transmission of CU itself happens only when such CU is allocated with an incentive time, which can be obtained when the CUs provide cooperation to the PUs. In addition, a control channel for CSI exchange and decision delivery, for example, cooperation parameters and incentive time allocation, is considered [7, 8]. In the relay assisted networks, the BS makes the decision for cooperation, for example, power allocation at relays, with the aid of the dedicated pilots for CSI estimation and the specific channels for CSI feedback [14, 15]. However, in the case of NSCRS, to alleviate the overhead of primary network, for example, in terms of signaling exchange, CSI feedback, and decision delivery for cooperation, an AP of the cognitive network is assumed to coordinate the cooperation between primary and cognitive networks rather than the BS or the PU as in [7, 10–15]. In other words, only the AP in the cognitive network can communicate with the BS and all the CUs can only communicate with the AP. For the NSCRS, the CUs are assumed to be able to estimate the CSI of BS-CUs for the cooperation for the PU by sensing the radio environment and

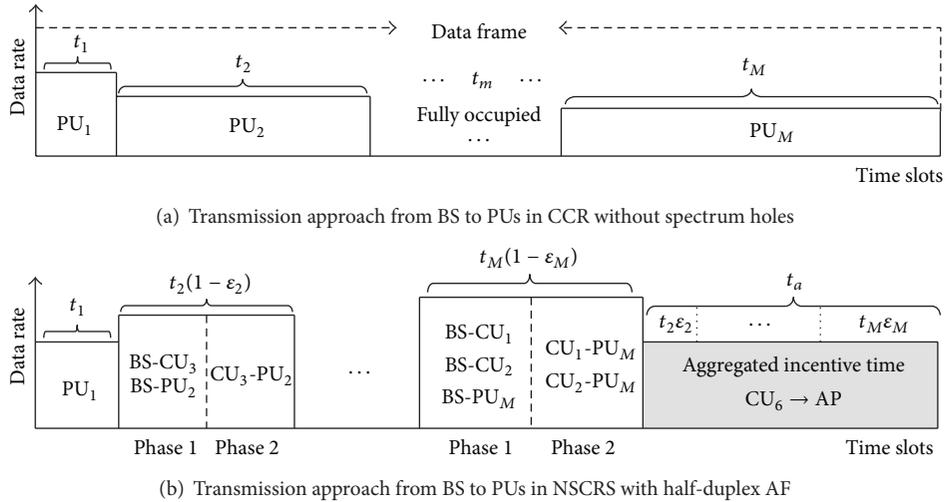


FIGURE 2: Transmission approaches for CCR and NSCRS.

detecting the transmitted pilots in the primary network [16]. The CUs may fail to estimate the CSI of CUs-PU, for example, when the PU may report the channel quality information instead of sending the pilots to the BS [17]. In addition, the incentive time in [8–10] was utilized in a segregated manner; that is, CUs immediately take the incentive time after each primary transmission, which requires the CUs to frequently access the AP via signaling for their own data transmission in the segregated incentive times. Thus, the segregated manner in [8–10] may bring a serious amount of overhead on signaling exchange between CUs and the AP of the cognitive network.

2.2. Transmission Approaches for CCR and NSCRS. Figure 2 shows an example of transmission approaches for both CCR and NSCRS. In the CCR, the M PUs, even with poor link quality, fully occupy the time of a data frame, as shown in Figure 2(a). With different number of information bits to receive, dissimilar time durations are reserved for different PUs, for example, t_m for the m th ($m = 1, 2, \dots, M$) PU. Additionally, due to the different link qualities from the BS to PUs, the achievable transmission data rates for PUs are different. In this case, the CUs have to wait, since no spectrum hole is available. Considering downlink primary transmission without symbiosis, the received signal-to-noise ratio (SNR) at the m th PU, γ_m^{bs} , can be given as

$$\gamma_m^{\text{bs}} = \frac{P_{\text{bs}} \alpha_m^{\text{bs}}}{N}, \quad (1)$$

where α_m^{bs} denotes the channel gain from the BS to the m th PU due to fading, path loss, and shadowing. N is the power of additive white Gaussian noise (AWGN). A constant transmit power, P_{bs} , is considered at the BS. In this paper, for performance evaluation purpose, the Shannon formula is used for simplicity, which is widely used for performance evaluation and was found to well match with practical case

with a large MCS code set [18]. Hence, the rate of the m th PU for the direct primary transmission can be given as

$$R_m^{\text{bs}} = \log_2(1 + \gamma_m^{\text{bs}}). \quad (2)$$

Figure 2(b) shows an example of the transmission approach of NSCRS with a conventional half-duplex (HD) AF relaying, where two phases with identical time duration exist. In the NSCRS, the PUs can obtain the half-duplex AF cooperation from the CUs and, then, a higher level of modulation and coding rate may be adopted to achieve a higher transmission rate; thus, the required time for transmitting the same amount of information from BS to the PU_M can be reduced compared to that in the CCR; that is, it is reduced from t_M in the CCR to $t_M(1 - \epsilon_M)$ in the NSCRS, and the remaining time of the PU_M , $t_M \epsilon_M$, is given to the CUs as an incentive time, where ϵ_m ($0 \leq \epsilon_m < 1$) is introduced as the proportion of incentive time in the reserved time for the m th PU in the CCR. However, if the cooperation from CUs cannot provide a higher transmission rate for the PU in the NSCRS, the PU will take up the originally reserved time for its data transmission as in the CCR, for example, for the case of PU_1 , as shown in Figure 2(b). After finishing all the data transmission to PUs, the incentive time from PUs is given to the CU in an aggregated manner. Compared to the segregated manner of incentive time utilization in [8–10], the utilization of aggregated incentive time is more efficient for the CUs due to less signaling overhead among AP and CUs. With nonselfish behaviors at CUs, the incentive time can be assigned to a more appropriate CU with the best link quality among the entire set of CUs, that is, CU_6 .

3. Problem Formulation for Nonselfish Symbiotic Cognitive Relaying Scheme

3.1. Cooperative Transmission for PU. Figure 3 describes an example of data transmission to the m th ($m = 1, 2, \dots, M$) PU with the cooperation of K CUs. The transmit power

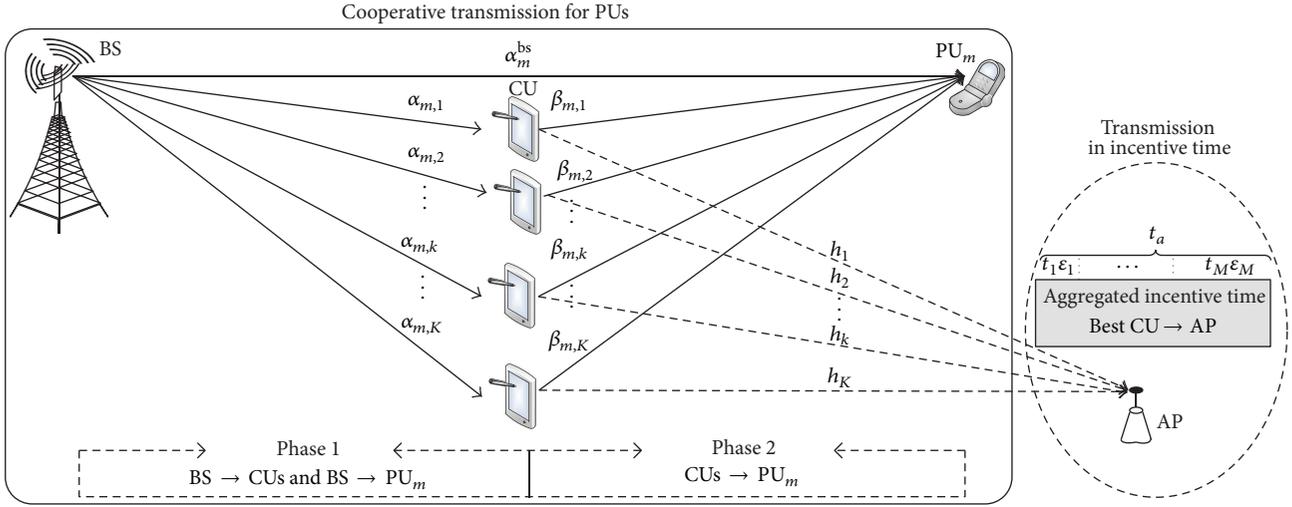


FIGURE 3: Cooperative transmission for PU.

at the k th CU for data transmission to the m th PU is denoted by $P_{cu}^{m,k}$. $\alpha_{m,k}$ and $\beta_{m,k}$, respectively, denote the instantaneous channel gains from the BS to the k th CU and from the k th CU to the m th PU. An independent and identically distributed (i.i.d.) block Rayleigh fading channel model, in which the channel state remains quasistatic within a fading block but becomes independent across different fading blocks, is considered among PUs, CUs, AP, and BS. In addition, the slow Rayleigh fading channel is assumed, where the fading channel remains almost unchanged during long enough time for channel estimation, cooperation, and data transmission.

In phase 1, the BS transmits a signal to CUs and the m th PU. Then, in phase 2, the received signals at CUs are, respectively, amplified and retransmitted to the m th PU, where the nonorthogonal AF relaying is considered and all the CUs are allowed to transmit their signals simultaneously [6]. Delay diversity can be used to combine the received signals from CUs in phase 2; it is assumed that the transmitted signals from CUs may arrive at the PU with different delays. Then, the m th PU can coherently combine the entire received signals along the paths by the Rake receiver with maximum ratio combining (MRC) in phase 2 [19]. Thanks to the excellent autocorrelation property of well-designed spreading code or interference cancellation, the interference at the PU from CUs can be neglected [19, 20]. Then, the received SNR at the m th PU with cooperation from CUs, γ_m^{cu} , and the corresponding transmission rate, R_m^{cu} , after combining the received signals in phases 1 and 2 with MRC can be expressed, respectively, as

$$\gamma_m^{cu} = \gamma_m^{bs} + \frac{\sum_{k=1}^K P_{bs} P_{cu}^{m,k} \alpha_{m,k} w_{m,k} \beta_{m,k}}{\sum_{k=1}^K P_{cu}^{m,k} w_{m,k} \beta_{m,k} N + N}, \quad (3)$$

$$R_m^{cu} = \frac{1}{2} \cdot \log_2 (1 + \gamma_m^{cu}), \quad (4)$$

where $1/2$ in the right side of (4) results from the HD AF relaying with two identical phases and $w_{m,k} \equiv (P_{bs} \alpha_{m,k} +$

$N)^{-1}$ is the power normalization factor at the k th CU for data transmission of the m th PU. The first term of (3) is the received SNR at the m th PU in phase 1 and the second term represents the received SNR of the retransmitted signals from CUs in phase 2. The amplified noise received from the other CUs still remains in the denominator of the second term on the right side of (3), while the interference from the other CUs is neglected. This is different from the conventional nonorthogonal AF schemes.

For the NSCRS, if $R_m^{cu} > R_m^{bs}$, the cooperation of CUs can provide a higher transmission rate for the PU and, then, an incentive time is to be given to CUs as a reward by the m th PU. However, if $R_m^{cu} \leq R_m^{bs}$, the m th PU occupies the entire time duration, as in CCR, and no incentive time is given to CUs. Thus, the cooperative transmission rate for the m th PU in NSCRS, R_m , can be given as

$$R_m = \max(R_m^{bs}, R_m^{cu}), \quad (5)$$

where the function $\max(\cdot, \cdot)$ returns the maximum value of its arguments.

3.2. Transmission in Incentive Time. Let t_m represent the reserved time for the m th PU in the CCR. Then, $t_m R_m^{bs}$ information bits are transmitted to the m th PU by the BS in the CCR. Owing to a higher data transmission capability in a symbiotic approach, an incentive time can be yielded for the case of effective cooperation from CUs to the m th PU. During the time of $(1 - \varepsilon_m)t_m$, the same amount of information bits as that is transmitted in the CCR, $t_m R_m^{bs}$, is guaranteed to be transmitted to the m th PU at the rate R_m ; that is, $R_m^{bs} = (1 - \varepsilon_m)R_m$. So ε_m can be alternatively expressed as

$$\varepsilon_m = 1 - \left(\frac{R_m^{bs}}{R_m} \right). \quad (6)$$

Then, the remaining time of the m th PU, $\varepsilon_m t_m$, is given to CUs as an incentive time. After finishing all the data

transmission of PUs, the aggregated incentive time, t_a , can be expressed as

$$t_a = \sum_{m=1}^M \varepsilon_m t_m. \quad (7)$$

To maximize the transmission rate in the aggregated incentive time, the aggregated incentive time is allocated to a CU with the highest transmission rate to the AP among the entire set of CUs.

Thus, the k_1 th CU, which satisfies (8), is selected to be given the incentive time

$$k_1 = \arg \max_{i \in \{1, 2, \dots, K\}} \frac{P'_{cu} h_i}{N}, \quad (8)$$

where h_i represents the channel gain from the i th CU to the AP as in Figure 3 and P'_{cu} is the maximal transmit power of the CU. It implies that once a CU is selected to transmit in the incentive time for cognitive network, it always transmits signals at its maximum power. So the transmission rate in the incentive time, R_{inc} , can be represented as $R_{inc} = \log_2(1 + P'_{cu} h_{k_1}/N)$.

3.3. Problem Formulation for NSCRS. Now, we intend to maximize the throughput of NSCRS by optimally allocating the power to the CUs, where the throughput is defined as the total number of transmitted bits divided by the measurement time. In the NSCRS, the same amount of information of PUs as that is transmitted in the CCR, for example, $R_m^{bs} t_m$ for the m th PU, is first transmitted. Then, the selected CU, that is, the k_1 th CU, transmits its data to the AP during the aggregated incentive time, t_a , at a rate of R_{k_1} . So, the throughput maximization problem of NSCRS can be formulated as

$$\max_{\mathbf{P}_m, m=1, \dots, M} \frac{\sum_{m=1}^M R_m^{bs} t_m + R_{inc} \sum_{m=1}^M \varepsilon_m t_m}{\sum_{m=1}^M t_m}, \quad (9a)$$

$$\text{s.t.} \quad \sum_{k=1}^K P_{cu}^{m,k} \leq P_C, \quad 0 \leq P_{cu}^{m,k}, \quad k = 1, \dots, K. \quad (9b)$$

The objective function of (9a) aims to maximize the throughput of NSCRS by optimally allocating the power of \mathbf{P}_m ($m = 1, 2, \dots, M$) to the CUs for the data transmission of the m th ($m = 1, 2, \dots, M$) PU; \mathbf{P}_m is the power allocation vector at the CUs for the data transmission of the m th PU and is denoted by $\mathbf{P}_m = [P_{cu}^{m,1}, P_{cu}^{m,2}, \dots, P_{cu}^{m,k}, \dots, P_{cu}^{m,K}]$.

With the assumption of slow fading, the value of R_m^{bs} remains unchanged and accordingly, t_m remains constant. \mathbf{P}_m ($m = 1, 2, \dots, M$) is determined for each PU independently. In addition, the best user selection scheduling is adopted in the incentive time and the selected CU always transmits its signals to the AP at its maximal transmit power.

Thus, R_{inc} remains unchanged. So the problem of (9a)-(9b) can be rewritten as

$$\max_{\mathbf{P}_m, m=1, \dots, M} \sum_{m=1}^M \varepsilon_m t_m, \quad (10a)$$

$$\text{s.t.} \quad \sum_{k=1}^K P_{cu}^{m,k} \leq P_C, \quad 0 \leq P_{cu}^{m,k}, \quad k = 1, \dots, K. \quad (10b)$$

Due to the TDMA nature for the cooperative transmissions to PUs, ε_m ($m = 1, 2, \dots, M$) are independent. Thus, the problem of (10a)-(10b) can be decomposed and simplified into M optimization problems as

$$\max_{\mathbf{P}_m} \varepsilon_m(1, 2, \dots, M) \quad (11a)$$

$$\text{s.t.} \quad \sum_{k=1}^K P_{cu}^{m,k} \leq P_C, \quad 0 \leq P_{cu}^{m,k}, \quad k = 1, \dots, K. \quad (11b)$$

According to (6), we can further simplify the problem of (11a)-(11b) as

$$\max_{\mathbf{P}_m} R_m(1, 2, \dots, M) \quad (12a)$$

$$\text{s.t.} \quad \sum_{k=1}^K P_{cu}^{m,k} \leq P_C, \quad 0 \leq P_{cu}^{m,k}, \quad k = 1, \dots, K. \quad (12b)$$

Thus, the optimization problem of (9a)-(9b) finally can be simplified into the power allocation problems to individually maximize the transmission rate to PUs by optimally allocating the power at CUs as in (12a)-(12b).

According to (5), we can decompose the optimization problem of (12a)-(12b) into two cases.

Case 1. Consider $R_m = R_m^{bs}$ as BS transmits the signals to the m th PU without the cooperation from CUs as in CCR.

Case 2. Consider $R_m = R_m^{cu}$ as BS transmits the signals to the m th PU with the cooperation of CUs.

In Case 1, the objective function of (12a) becomes a constant value of R_m^{bs} regardless of the constraints. It corresponds to the zero power allocation at each CU; that is, $P_{cu}^{m,k} = 0$ ($k = 1, 2, \dots, K$). Consequently, no incentive time is generated; that is, $\varepsilon_m = 0$. However, for Case 2, based on (3), we can simplify the problem of (12a)-(12b) as

$$\max_{\mathbf{P}_m} \gamma_m^{cu} \quad (13a)$$

$$\text{s.t.} \quad \sum_{k=1}^K P_{cu}^{m,k} \leq P_C, \quad 0 \leq P_{cu}^{m,k}, \quad k = 1, \dots, K. \quad (13b)$$

4. Proposed Power Allocation Algorithm with Full or Partial CSI Feedback

If the CUs can estimate the CSI of $\alpha_{m,k}$ and $\beta_{m,k}$, the full CSI of α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$ is available at the AP, which

can be considered as an ideal scenario (called ‘‘Scenario 1’’) for NSCRS. However, $\beta_{m,k}$ may not be available at the AP; thus, a ‘‘Scenario 2’’ is additionally considered for the NSCRS with only the partial CSI, that is, α_m^{bs} and $\alpha_{m,k}$. In this section, the power allocation algorithms for both scenarios are investigated. In addition, an equal power allocation algorithm (EPA), in which the total available power of the CUs is equally distributed to the CUs, that is, $P_{\text{cu}}^{m,k} = P_C/K$, is also considered.

4.1. Optimal Power Allocation Algorithm in Scenario 1. For Case 1, we have the optimal solution of $P_{\text{cu}}^{m,k} = 0$ ($k = 1, 2, \dots, K$) and $R_m = R_m^{\text{bs}}$ for the m th PU. However, in Case 2, due to the nonlinear objective function of (12a), the problem of (13a)-(13b) is difficult to solve and to be transformed into a linear programming problem. Instead, Proposition 1 is established.

Proposition 1. *With a sum power constraint at CUs, that is, $\sum_{k=1}^K P_{\text{cu}}^{m,k} = P_C$, the γ_m^{cu} for the optimization problem of (13a)-(13b) satisfies*

$$\max_{\sum_{k=1}^K P_{\text{cu}}^{m,k} = P_C} \gamma_m^{\text{cu}} = \max_{k=1,2,\dots,K} \left(\gamma_m^{\text{bs}} + \frac{P_{\text{bs}} P_C \alpha_{m,k} \omega_{m,k} \beta_{m,k}}{P_C \omega_{m,k} \beta_{m,k} N + N} \right). \quad (14)$$

Proof. Owing to the constant power consumption of P_{bs} at BS, γ_m^{bs} is constant for the m th PU and we can easily prove this proposition by the Proposition 4 in [6].

Proposition 1 implies that the optimal solution for the problem of (13a)-(13b) can be obtained by allocating full available power of CUs to a single CU, as shown in (14), rather than allocating the power in a shared manner among CUs. Consequently, a complicated power allocation problem is reduced to a simple CU selection problem, which is very desirable for practical implementation. For Case 2, the highest transmission rate is achieved at the m th PU by allocating full power of P_C to the best CU, for example, the k'_m th CU, which satisfies

$$k'_m = \arg \max_{k=1,2,\dots,K} \left(\gamma_m^{\text{bs}} + \frac{P_{\text{bs}} P_C \alpha_{m,k} \omega_{m,k} \beta_{m,k}}{P_C \omega_{m,k} \beta_{m,k} N + N} \right). \quad (15)$$

Thus, the corresponding transmission rate at the m th PU can be calculated as $R_m^{k'_m} = 0.5 \log_2(1 + \gamma_m^{k'_m})$, where $\gamma_m^{k'_m}$ is the received SNR at m th PU and is given by $\gamma_m^{k'_m} = \max_{k=1,2,\dots,K} (\gamma_m^{\text{bs}} + (P_{\text{bs}} P_C \alpha_{m,k} \omega_{m,k} \beta_{m,k} / P_C \omega_{m,k} \beta_{m,k} N + N))$. Thus, based on α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$, an optimal power allocation algorithm (OPA) is proposed in Scenario 1, as in Algorithm 1. \square

For the OPA, since only the index of the selected CU, that is, k'_m , is required to be fed back to the CUs, only $\lceil \log_2(K) \rceil$ bits for the power allocation are needed for the data transmission of each PU, which is simple and desirable for OPA implementation. The function $\lceil \cdot \rceil$ returns the smallest integer value not less than the argument.

4.2. Power Allocation Algorithm in Scenario 2. Although the proposed optimal power allocation algorithm in Scenario 1 maximizes the throughput of NSCRS, the full CSI of α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$ is required. If the CSI of $\beta_{m,k}$ is not available at AP, then the efficient power allocation algorithm in Scenario 2, with only the partial CSI of α_m^{bs} and $\alpha_{m,k}$, needs to be developed.

For Case 2, if the link qualities from CUs to the m th PU are assumed to be much better than those from BS to CUs, that is, $P_C \beta_{m,k} \gg P_{\text{bs}} \alpha_{m,k}$ and $P_C \beta_{m,k} \gg N$ ($k = 1, 2, \dots, K$), which implies that the noise amplification effect at CUs for the data transmission of the m th PU is negligible, we can derive a suboptimization problem for (14) or (13a)-(13b) as

$$\max_{\sum_{k=1}^K P_{\text{cu}}^{m,k} = P_C} \gamma_m^{\text{cu}} = \max_{k=1,2,\dots,K} \left(\gamma_m^{\text{bs}} + \frac{P_{\text{bs}} \alpha_{m,k}}{N} \right). \quad (16)$$

Obviously, the solution for the problem of (16) can be obtained by allocating P_C to the best CU, for example, the k''_m th CU, which satisfies

$$k''_m = \arg \max_{k=1,2,\dots,K} \left(\frac{P_{\text{bs}} \alpha_{m,k}}{N} \right). \quad (17)$$

And the corresponding received SNR at the m th PU can be given as

$$\gamma_m^{k''_m} = \gamma_m^{\text{bs}} + \frac{P_{\text{bs}} P_C \alpha_{m,k''_m} \omega_{m,k''_m} \beta_{m,k''_m}}{P_C \omega_{m,k''_m} \beta_{m,k''_m} N + N}. \quad (18)$$

Thus, a power allocation algorithm based only on partial CSI, that is, α_m^{bs} and $\alpha_{m,k}$, (PPA) is proposed in scenario 2, as in Algorithm 2. (For the proposed PPA, the PU is just required to estimate the received SNR. Then, a CQI can be fed back to the BS as in a LTE system and the modulation and coding set can be adaptively selected).

Similar to the OPA, only one CU, that is, the k''_m th CU, is selected to utilize the full power of the CUs, P_C , for the cooperative transmission to the m th PU, so the PPA also just needs $\lceil \log_2(K) \rceil$ bits for the power allocation in the NSCRS.

4.3. Working Procedure for NSCRS with OPA or PPA. Figure 4 shows the working procedure for NSCRS with OPA or PPA. A BS intends to transmit data to M PUs in a TDMA manner and the CUs can actively monitor the radio environment and estimate the CSI by detecting the transmitted pilots in the primary network [16]. We also assume the system works at a time division duplex (TDD) manner to alleviate the CSI feedback overhead, where the channel reciprocity is preserved [21]. The CUs are able to estimate $\alpha_{m,k}$ and $\beta_{m,k}$ by detecting the pilots from the primary network. And the AP is informed of α_m^{bs} by the BS. In the case of OPA, α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$ are available at the AP for determining the allocated power at CUs. However, $\beta_{m,k}$ is not available at the AP for the case of PPA. Thus, in real situation, depending on whether $\beta_{m,k}$, which is needed to be fed back from PUs, is available at the AP or not, the OPA and the PPA can be dynamically selected for the power allocation at CUs. With the full CSI,

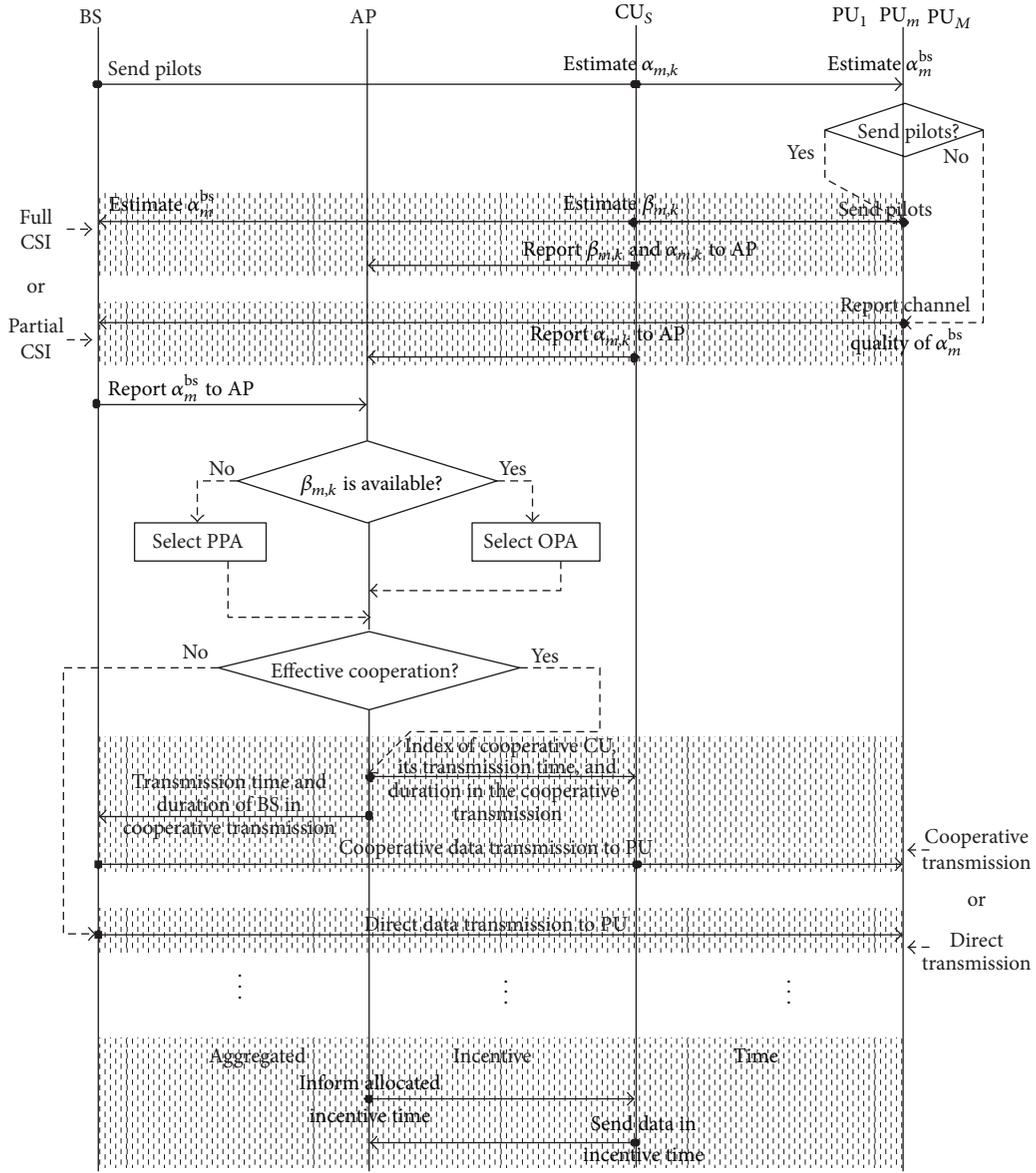
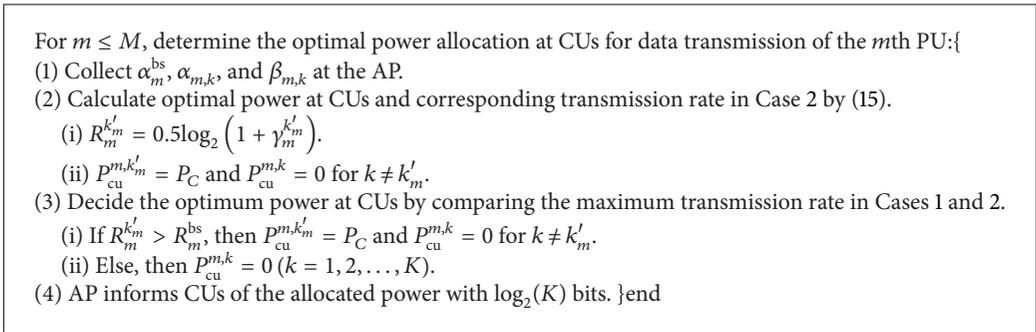


FIGURE 4: Working procedure for NSCRS with OPA or PPA.



ALGORITHM 1: Optimal power allocation algorithm (OPA) in Scenario 1.

For $m \leq M$, determine the optimal power allocation at CUs for the data transmission of the m th PU: {

- (1) Collecting α_m^{bs} and $\alpha_{m,k}$ at the AP.
- (2) Calculate optimal power at CUs and corresponding transmission rate in Case 2 by (17).
 - (i) $R_m^{k''} = 0.5 \log_2 (1 + \gamma_m^{k''})$.
 - (ii) $P_{\text{cu}}^{m,k''} = P_C$ and $P_{\text{cu}}^{m,k} = 0$ for $k \neq k''$.
- (3) Decide on the optimum power at CUs by comparing $(\alpha_{m,k''}/\alpha_m^{\text{bs}})$ with ρ , where ρ is a predetermined threshold for deciding whether the cooperation from CUs to the m th PU is effective or not.
 - (i) If $(\alpha_{m,k''}/\alpha_m^{\text{bs}}) > \rho$, then $P_{\text{cu}}^{m,k''} = P_C$ and $P_{\text{cu}}^{m,k} = 0$ for $k \neq k''$.
 - (ii) Else, then $P_{\text{cu}}^{m,k} = 0$ ($k = 1, 2, \dots, K$).
- (4) AP informs CUs of the allocated power by $\log_2(K)$ bits. }end

ALGORITHM 2: Partial CSI based power allocation algorithm (PPA) in Scenario 2.

that is, α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$, or the partial CSI, that is, α_m^{bs} and $\alpha_{m,k}$, the AP can check whether the cooperation from CUs is effective for the PU or not. (In this paper, effective cooperation means that cooperation from CUs can provide a higher transmission rate to the PU compared to the direct transmission from the BS to the PU.) If the cooperation from CUs is effective for the PU, the AP feeds back the cooperation parameters, for example, index of cooperative CU, cooperation time, and duration of cooperative CU, to CUs, while the corresponding transmission time and duration of BS in the cooperative transmission are sent to the BS. It is noted that the BS can know the existence of CUs serving as relays indirectly, since the received SNR at PU(s) increases as CUs relay the signals, compared with the direct transmission without relaying. Owing to the effective cooperation from CUs, an incentive time is to be given to the cognitive network after finishing the data transmission of each PU. Finally, the AP allocates the aggregated incentive time to a CU with the best link quality among the entire set of CUs and the CU with the allocated incentive time begins its data transmission to the AP.

5. Simulations and Results

Figure 5 shows the simulation model for the coexistence of primary and cognitive networks. BS, PU, AP, and CUs are placed within a 2-dimensional region (1 km \times 1 km). BS and AP are, respectively, fixed at the coordinates of (0,0) and (500,0). 10 CUs and 10 PUs are randomly placed within the 1000 m \times 1000 m region. A path loss model of $(1/d^2)$, where d is the Euclidean distance in meter between transmitting and receiving devices, is considered and shadowing is not considered. $P_{\text{bs}} = 30$ dBm and $P_{\text{cu}}^l = 20$ dBm are considered. The AWGN powers at PU, AP, and CUs are assumed to be identical at $N = -40$ dBm. BS and CUs always have the data for transmission and this situation can be regarded as the worst condition for the CUs in CCR, since PUs always take the entire time and CUs can never transmit data to the AP. In simulations, a measurement time of 60 ms is considered. For simplicity, 60 ms is assumed to be equally occupied by 10 PUs in the case of CCR, that is, 6 ms per

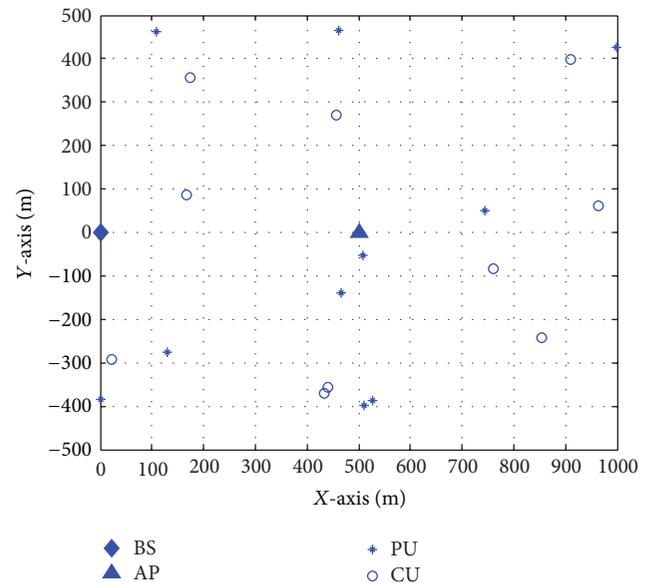


FIGURE 5: Simulation model for coexistence of primary and cognitive networks.

PU. We evaluate the performance of CCR and NSCRS with different power allocation algorithms, that is, OPA, PPA, and EPA, in terms of average throughput, average ratio of aggregated incentive time in the measurement time, and normalized average power consumption at the BS. In this paper, to find the optimal threshold of ρ for a given pair of (P_{bs}, P_C) and given numbers of PUs and CUs, we first obtain the performance in terms of throughput of NSCRS with perfect CSI feedback. Then, we consider the PPA case without CSI of $\beta_{m,k}$, by varying ρ in the range of $[10^{-10} \leq \rho \leq 10^{10}]$ at a fixed (P_{bs}, P_C) P through an exhaustive search method. By comparing the performance of ideal case with that of PPA, we can find the optimal threshold value of ρ , at which the performance gap between PPA and OPA is minimized, for a pair of (P_{bs}, P_C) with given numbers of PUs and CUs. In practical systems, the optimal value of ρ for each pair of (P_{bs}, P_C) can be predetermined and can be stored as a lookup table at the AP. The locations of the BS and the AP are usually

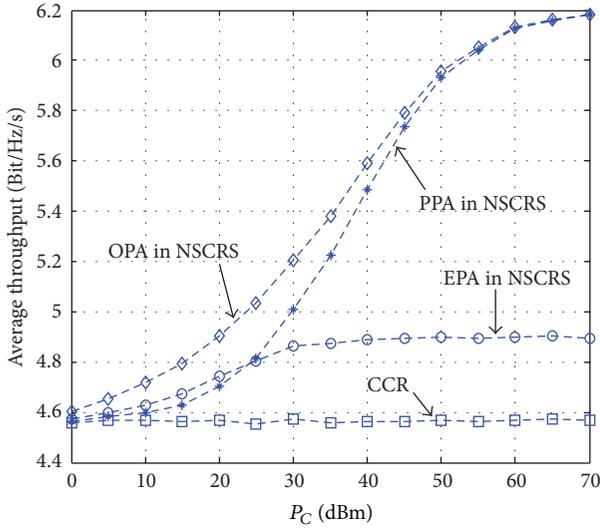


FIGURE 6: Average throughput for CCR and NSCRS in the cases of OPA, PPA, and EPA by varying the power constraint of P_C .

fixed and the numbers of CUs and PUs in their served areas can be known at the AP or the BS. So the optimal value ρ can be obtained by referring to the lookup table with given values of (P_{bs}, P_C) and numbers of PUs and CUs.

Figure 6 compares the average throughput of CCR and NSCRS with different power allocation algorithms, that is, OPA, PPA, and EPA, by varying the power constraint of P_C . With the fixed power consumption at the BS, a constant average throughput of PUs can be observed in the case of CCR. Owing to the possibility of additional data transmission at CUs, a higher average throughput can be achieved by the NSCRS compared to the CCR. Undoubtedly, OPA always outperforms both PPA and EPA for the entire range of P_C . Even though the EPA is slightly better than the PPA at low P_C , as the P_C increases, for example, $P_C > 25$ dBm, the PPA becomes much better than the EPA due to the usage of CSI in the power allocation rather than the equal power allocation method in the EPA. Without any CSI for the power allocation, the performance of the EPA finally becomes a constant regardless of P_C . Since the approximations of $P_C\beta_{m,k} \gg P_{bs}\alpha_{m,k}$ and $P_C\beta_{m,k} \gg N$ are not valid with a low P_C , the PPA achieves a lower throughput compared with that of the OPA. As the P_C increases, however, the gap in the average throughput between OPA and PPA becomes smaller and finally diminishes at high P_C , for example, $P_C = 55$ dBm. This implies that if CUs maintain the high link qualities to the PU, the PPA can be a good choice for NSCRS with only marginal degradation in terms of average throughput.

Figure 7 compares the average ratio of aggregated incentive time in a frame in the cases of OPA and PPA as a function of the number of CUs. The average ratio of aggregated incentive time in the measurement time is defined as $E[\sum_{m=1}^M \varepsilon_m t_m / \sum_{m=1}^M t_m]$, where the function $E[\bullet]$ returns the mean value of argument. As the number of CUs increases, a CU with good channel quality for cooperation has a higher probability of existence. Hence, the maximum transmission

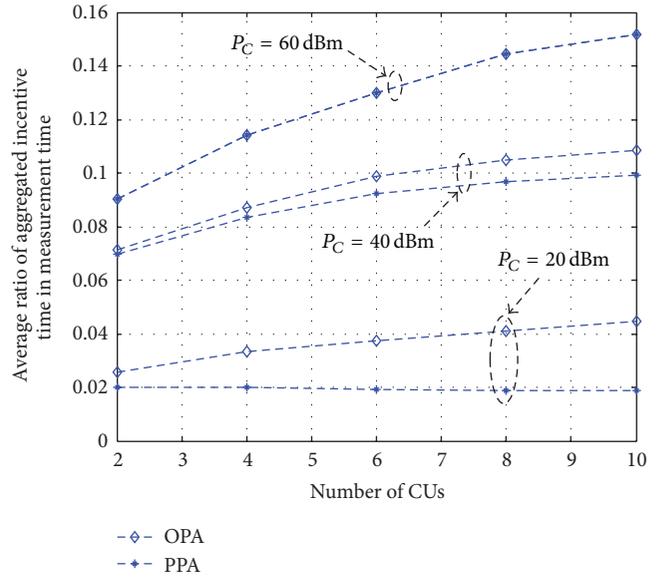


FIGURE 7: Average ratio of aggregated incentive time in the measurement time for both OPA and PPA as a function of the number of CUs.

rate for the primary transmission becomes higher as the number of CUs increases for both OPA and PPA, which results in a larger average ratio of aggregated incentive time or equivalently, a longer transmission time for cognitive network. Since the link qualities from CUs to the PU fail to satisfy the assumption of much better than those from the BS to CUs at $P_C = 20$ dBm and the CSI of CUs-PU, $\beta_{m,k}$, is not available in PPA, a gap in the average ratio of aggregated incentive time can be observed between OPA and PPA. However, with a higher P_C , for example, $P_C = 60$ dBm, both OPA and PPA provide an identical average ratio of aggregated incentive time, since the link qualities from CUs to the PU are much better than those from the BS to CUs and the assumption in scenario 2, from which the PPA is obtained, is satisfied.

Figure 8 shows the normalized average power consumption at the BS for both OPA and PPA with different numbers of CUs. The average transmitting power consumption at the BS in the case of OPA or PPA is normalized to that of CCR, where the same amounts of information bits are assumed to be transmitted to the PUs in the cases of CCR, OPA, and PPA. With a larger number of CUs, the possibility to achieve a higher transmission rate for the PUs increases, which results in a shorter transmission time at the BS. Thus, the power consumption at the BS decreases as the number of CUs increases. At low P_C , for example, $P_C = 20$ dBm, a gap in the normalized average power consumption at the BS is observed between OPA and PPA. However, this gap diminishes at high P_C , for example, $P_C = 60$ dBm. Thus, in practice, when the link qualities from CUs to the PU are much better than those from the BS to CUs, which results in a negligible noise amplification effect at CUs, the PPA can be selected for NSCRS based only on the partial CSI feedback, rather than the OPA with full CSI feedback.

TABLE I: Comparisons of OPA, PPA, and EPA in NSCRS.

Algorithm	Radio environment monitoring at CUs	Necessary condition for CUs	Required CSI feedback to AP	Applicable scenario
OPA	Required	CUs can fully detect the transmitted pilots in the primary network	$\alpha_m^{\text{bs}}, \alpha_{m,k}, \beta_{m,k}$	AP with full CSI
PPA	Required	At least, CUs can detect the pilots from the BS	$\alpha_m^{\text{bs}}, \alpha_{m,k}$	Much better link qualities of CUs-PU than those of BS-CUs
EPA	None	None	None	AP without any CSI

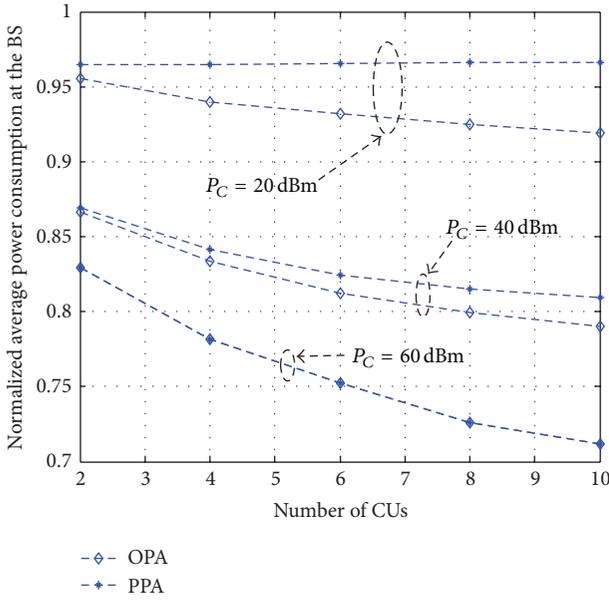


FIGURE 8: Normalized average power consumption of PU in OPA and PPA as a function of the number of CUs.

Table 1 compares the three algorithms of OPA, PPA, and EPA in detail. Owing to the full CSI feedback to the AP, that is, α_m^{bs} , $\alpha_{m,k}$, and $\beta_{m,k}$, the optimal algorithm, OPA, outperforms the other algorithms. However, the full CSI in OPA requires larger feedback overhead than the other algorithms. On the other hand, the EPA needs none of CSI feedback but huge degradation in average throughput can be observed compared to the OPA as in Figure 6. In order to reduce the feedback overhead while maintaining a similar performance as the OPA, the PPA is proposed only based on partial CSI, α_m^{bs} and $\alpha_{m,k}$. As shown in Figures 6 and 7, we can observe that the PPA with only the partial CSI feedback still can achieve a comparable throughput as that of the OPA when, for example, $P_{\text{bs}} \geq 55$ dBm.

We can consider the OPA as the ideal cognitive relaying case, since all of the CSI is available for power allocation. However, in the NSCRS, the CSI of BS-CUs and the CSI of CUs-PU mainly rely on the radio environment monitoring and the detection on the pilots from primary networks at CUs [16]. In addition, the selection criterion for the PPA depends on the long-term observation of link qualities among

BS, CUs, and PUs and whether the CUs can estimate the CSI of CUs-PU by detecting the pilots from PUs or not. In practice, the PPA may just need to measure the path loss and the shadowing attenuations by some kind of sliding window measurement and then periodically reports the link qualities to the AP of cognitive network, especially in a slow fading environment. When the link qualities from CUs to PUs are much better than those from BS to CUs in a long-term observation, the PPA can be chosen to reduce the complexity in terms of the CSI feedback compared to the OPA. When the CUs fail to estimate the CSI of CUs-PU, for example, when the PU sends the CQI rather than the pilots [17], the PPA can be a more appropriate power allocation algorithm for the NSCRS.

6. Conclusions

We first devised an optimal power allocation algorithm for the throughput maximization of NSCRS with nonorthogonal AF cognitive relaying based on the full CSI among BS, PUs, and CUs. Moreover, a suboptimal power allocation algorithm was further proposed for the NSCRS with only the partial CSI, that is, CSI of BS-PU and CSI of BS-CUs. Simulation results demonstrated that the proposed power allocation algorithm based only on the partial CSI is able to work effectively with a smaller feedback overhead compared to the optimal power allocation algorithm with full CSI. In addition, we also found that the optimal power allocation problem among CUs can be simplified into a single CU selection problem. So, only the index of the selected CU is required to be fed back in both proposed power allocation algorithms, which results in a smaller feedback overhead and makes those methods desirable for the practical implementation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was supported in part by Basic Science Research Program through the NRF (NRF-2013R1A1A2A10059215), National Natural Science Foundation of China (the no. 61201180), Beijing Natural Science Foundation (the no. 4132055), and the Excellent Young Scholars Research Fund of Beijing Institute of Technology.

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