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Resource allocation in cognitive wireless powered communication networks with wirelessly powered secondary users and primary users

Ding XU[1*] & Qun LI[2]

[1] *Wireless Communication Key Lab of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China;*
[2] *Jiangsu Key Lab of Big Data Security and Intelligent Processing, Nanjing University of Posts and Telecommunications, Nanjing 210023, China*

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Dear editor,
Wireless powered communication networks (WPCNs) are popular especially for wireless sensor networks where sensors can be wirelessly powered. For coordinating wireless power and information transfer, Ju and Zhang in their pioneer work [1] proposed a "harvest-then-transmit" protocol for WPCN, where the time for wireless power transfer (WPT) and wireless information transfer (WIT) is divided into two phases: the WPT phase and WIT phase. Meanwhile, cognitive radio (CR) is another important technology that can provide high spectrum efficiency [2]. In CR networks, unlicensed secondary users (SUs) are allowed to coexist with licensed primary users (PUs) under underlay, interweave, or overlay models. In contrast to underlay and interweave models where the PU does not benefit from the SU transmission, for overlay CR model, the SU improves the transmission quality of the PU, and in turn the SU gains transmission opportunities. Naturally, WPT and CR can be considered together to improve spectrum efficiency and provide continuous energy to user equipments [3, 4]. Specifically, a mutual benefit between the SU and PU can be achieved in WPT-based overlay CR networks. However, in existing studies on such networks, only the SU or PU is considered to be wirelessly powered [5, 6], and to the best of our knowledge, no work has considered that both the SU and PU are wirelessly powered in CR networks.

Motivated by the above discussion, this study considers that both the SU and PU are wirelessly powered in a multi-carrier WPT-based CR network, and adopts the "harvest-then-transmit" protocol for coordinating WPT and WIT for the SU and PU. The cognitive hybrid access point (CHAP) is assumed to wirelessly broadcast energy in the WPT phase and receive data from the SU on the subcarriers that are permitted to be used in the WIT phase, as long as the PU achieves a minimum rate in the WIT phase, which guarantees quality of service. Such cooperation leads to a win-win situation for both the SU and PU, and can be considered as an overlay CR model. Under the PU minimum rate constraint and the transmit power constraint at the CHAP, the SU rate is maximized by optimizing the transmit power of the CHAP in the WPT phase, the time allocation between the WPT phase and the WIT phase, the subcarrier allocation between the SU and PU in the WIT phase, and the transmit powers of the

* Corresponding author (email: xuding@ieee.org)

SU and PU in the WIT phase. A resource allocation scheme based on the dual optimization method is proposed. For comparison, a heuristic scheme is also proposed. It is shown that the proposed dual scheme is practically optimal with linear complexity in the number of subcarriers as opposed to the exponential complexity required by the optimal exhaustive search scheme. The dual scheme achieves a higher SU rate than the heuristic scheme, especially when the PU minimum rate constraint or the transmit power constraint at the CHAP is loose.

System model and problem formulation. We consider an uplink WPT-based CR network with a secondary link consisting of one CHAP and one wirelessly powered SU sharing N subcarriers with a primary link consisting of a wireless powered PU transmitter (PU-TX) and a PU receiver (PU-RX). The CHAP is able to wirelessly broadcast energy signals in the downlink and receive information signals from the SU in the uplink. The channel power gains between the CHAP and the SU, from the CHAP to the PU-TX, and from the PU-TX to the PU-RX on subcarrier i are denoted by $h_{\rm s}^i$, $h_{\rm sp}^i$, and $h_{\rm p}^i$, respectively. All the channels are assumed to be block fading.

The time for each transmission block is normalized to be one and divided into two phases, i.e., the WPT phase with duration τ_0 and the WIT phase with duration $1-\tau_0$. The WPT phase is dedicated for broadcasting energy signals by the CHAP using all the subcarriers. Let $p_{\rm c}^i$ denote the transmit power of the CHAP on subcarrier i in the WPT phase. The sum transmit power of the CHAP is restricted as $\sum_{i=1}^N p_{\rm c}^i \leqslant P$, where P denotes the maximum transmit power limit. In the WPT phase, the energies harvested by the SU and PU-TX can be written as $E_{\rm s} = \zeta \sum_{i=1}^N p_{\rm c}^i h_{\rm s}^i \tau_0$ and $E_{\rm p} = \zeta \sum_{i=1}^N p_{\rm c}^i h_{\rm sp}^i \tau_0$, respectively, where ζ denotes the energy harvesting efficiency.

The WIT phase is used for information transmission from the SU to CHAP and from the PU-TX to the PU-RX. In this phase, enough subcarriers are allocated to the PU for achieving the minimum rate $R_{\min}$, while the remaining subcarriers are allocated to the SU as a reward for broadcasting energy to the PU. Let $p_{\rm s}^i$ and $p_{\rm p}^i$ denote the transmit powers of the SU and PU-TX on subcarrier i in the WIT phase, respectively. Since each subcarrier is either allocated to the PU or SU, we have $p_{\rm s}^i p_{\rm p}^i = 0, i = 1, \ldots, N$. The energy causality constraint requires that the consumed energy cannot exceed the energy harvested in the WPT phase, as given by $\sum_{i=1}^N p_{\rm s}^i (1-\tau_0) \leqslant E_{\rm s}$ and $\sum_{i=1}^N p_{\rm p}^i (1-\tau_0) \leqslant E_{\rm p}$. The achievable rates of the SU and PU averaged over one transmission block can be written as $R_{\rm s} = \frac{1-\tau_0}{N} \sum_{i=1}^N \ln(1+\frac{p_{\rm s}^i h_{\rm s}^i}{\sigma^2})$ and $R_{\rm p} = \frac{1-\tau_0}{N} \sum_{i=1}^N \ln(1+\frac{p_{\rm p}^i h_{\rm p}^i}{\sigma^2})$, respectively, where σ^2 denotes the noise power. It is required that $R_{\rm p} \geqslant R_{\min}$.

We aim to maximize the SU rate under the aforementioned constraints by optimizing time and power allocation as given by P1:

$$\max_{0\leqslant\tau_0\leqslant1,\{p_{\rm c}^i\geqslant0\},\{p_{\rm s}^i\geqslant0\},\{p_{\rm p}^i\geqslant0\}} \quad R_{\rm s} \tag{1}$$

$$\text{s.t.} \sum_{i=1}^N p_{\rm c}^i \leqslant P, \tag{2}$$

$$p_{\rm s}^i p_{\rm p}^i = 0, i = 1, \ldots, N, \tag{3}$$

$$\sum_{i=1}^N p_{\rm s}^i (1-\tau_0) \leqslant E_{\rm s}, \sum_{i=1}^N p_{\rm p}^i (1-\tau_0) \leqslant E_{\rm p}, \tag{4}$$

$$R_{\rm p} \geqslant R_{\min}. \tag{5}$$

Resource allocation schemes. This section proposes schemes to solve the problem, P1. First, the problem, P1, with a given τ_0 is solved. Such problem may be infeasible because of the constraint in (5) (see Appendix A). In what follows, we propose a dual design for solving P1 with a given τ_0. For comparison, a heuristic design is proposed and the optimal design is derived.

First, we propose the dual design. It has been shown in [7] that the particular structure of the nonconvex problem, P1, with a given τ_0 satisfies the time-sharing condition when the number of subcarriers is infinity. This indicates that we can solve the problem in the dual domain [8].

Proposition 1. Using dual optimization method [8], the solution to the problem, P1, with a given τ_0 is $p_{\rm c}^k = P, k = \arg\max_i \mu_1 h_{\rm s}^i + \mu_2 h_{\rm sp}^i$, $p_{\rm c}^i = 0$, $i \neq k$, and $p_{\rm s}^i = \hat{p}_{\rm s}^i, p_{\rm p}^i = 0$ if $L_2(\hat{p}_{\rm s}^i, 0, \mu_1, \mu_2) \geqslant L_2(0, \hat{p}_{\rm p}^i, \mu_1, \mu_2) + \frac{\nu}{N} \ln(1+\frac{\hat{p}_{\rm p}^i h_{\rm p}^i}{\sigma^2})$ and $p_{\rm s}^i = 0, p_{\rm p}^i = \hat{p}_{\rm p}^i$ otherwise, where ν, μ_1, μ_2 are the dual variables, $\hat{p}_{\rm s}^i = (\frac{1}{\mu_1 N} - \frac{\sigma^2}{h_{\rm s}^i})^+, \hat{p}_{\rm p}^i = (\frac{\nu}{\mu_2 N} - \frac{\sigma^2}{h_{\rm p}^i})^+$ and

$$L_2(p_{\rm s}^i, p_{\rm p}^i, \mu_1, \mu_2) = \frac{1}{N} \ln\left(1+\frac{p_{\rm s}^i h_{\rm s}^i}{\sigma^2}\right) - \mu_1 p_{\rm s}^i - \mu_2 p_{\rm p}^i. \tag{6}$$

The variables, ν, μ_1, μ_2, can be obtained by the subgradient method [8].

Proof. Refer to Appendix B.

The complexity of the dual design is analyzed here. For a given ν, μ_1, μ_2, obtaining $\{p_{\rm c}^i\}, \{p_{\rm s}^i\}, \{p_{\rm p}^i\}$ requires $\mathcal{O}(N)$ operations. The subgradient method used to obtain ν, μ_1, μ_2 requires $\triangle$ operations, which is usually a small number. Therefore, the complexity of the dual scheme is $\mathcal{O}(N\triangle)$.

Then, we propose a heuristic design. Firstly, p_c^i is optimized to let the PU harvest more energy. Then, subcarriers are assigned to the PU with high priority in the WIT phase to satisfy the PU minimum rate constraint. If this is satisfied, subcarriers are reallocated in a certain order to the SU until any more reallocation would make the PU minimum rate constraint not to be satisfied. After that, the SU uses these allocated subcarriers to maximize its own rate. The detailed procedures of the heuristic design can be seen in Appendix C. From Appendix C, the time complexity of the heuristic design can be easily obtained as $\mathcal{O}(N^2)$ if $R_{\min}$ is small and $\mathcal{O}(N)$ if $R_{\min}$ is large.

Next, the optimal design is proposed. Firstly, for each subcarrier assignment, the problem, P1, with a given τ_0 without the constraint in (3) is convex, and thus, it can be solved using the convex optimization method similar to the dual design with complexity $\mathcal{O}(N\triangle)$. As finding optimal subcarrier assignment between the SU and PU for N subcarriers requires 2^N searches, the overall time complexity is $\mathcal{O}(2^N N\triangle)$. Therefore, the complexity of the optimal design is exponential in the number of subcarriers.

After the problem, P1, with a given τ_0 is solved, P1 can be solved by optimizing τ_0, which can be done by a simple one-dimensional search within the narrow interval $[0,1]$.

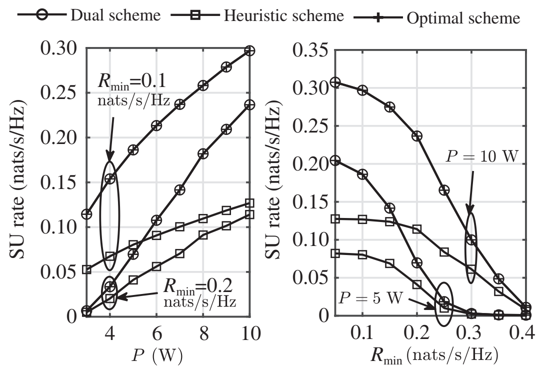

Figure 1 Comparison of the SU rates achieved by the three schemes.

Simulation results. In the simulation, it is assumed that all the channels follow Rayleigh fading with a unit mean, and noise power is normalized to be 1. Besides, we set $\zeta = 0.4$ and $N = 16$. Figure 1 compares the SU rates achieved by the three schemes. It is shown that the proposed dual scheme achieved the same SU rate as achieved by the optimal scheme. This indicates that the proposed dual scheme is practically optimal but with much lower complexity than the optimal scheme. It is also shown that the dual scheme achieved higher SU rate than the heuristic scheme, and the performance gap between them increases as P increases; this indicates that the proposed dual scheme is superior to the heuristic scheme especially when P is large. Besides, it is shown that the SU rate decreases as $R_{\min}$ increases. This is as expected since more subcarrier resources will be allocated to the PU with a higher $R_{\min}$. It is also shown that the SU rate achieved by the dual scheme is higher than that achieved by the heuristic scheme, especially when $R_{\min}$ is small. This indicates that the proposed dual scheme is superior to the heuristic scheme, especially when $R_{\min}$ is small.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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