Optimization for DF Relaying Cognitive Radio Networks with Multiple Energy Access Points

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***Abstract*—Cognitive radio (CR) has been advocated to improve the network spectrum efficiency for decades, and the cooperation between the primary and secondary systems has become a new paradigm to further improve the spectrum utilization. Cooperative cognitive radio networks (CCRN) may be, nevertheless, prohibitive in the recent trend of 5G-enabling large scale and densely deployed heterogeneous networks due to energy constrained situation of secondary transmitters (STs). To circumvent this, in this paper, we consider a novel spectrum sharing CCRN wireless powered by energy access points (EAPs) that charge users in proportion to their harvested amount of energy, in which a multi-antenna secondary user (SU) pair seeks cooperation with a single-antenna primary user (PU) pair by offering DF relaying solely powered by wireless energy harvesting (WEH). For the interest of the ST, its payoff is maximized by joint optimization of its WEH strategies, DF relay beamforming, and PU's power allocations. To reduce the high complexity induced by integer programming (IP), we also design a greedy-based algorithm that assigns the ST with right EAPs to connect with in linear time. The proposed scheme is shown to be very promising by simulations in terms of little compromise to optimality.**

I. Introduction

With the rapid development of wireless services and applications, the demand for frequency resources has dramatically increased. How to accommodate these new wireless services and applications within the limited radio spectrum becomes a big challenge facing the modern society. A report published by Federal Communications Commission (FCC) shows that the current scarcity of spectrum resource is mainly due to the inflexible spectrum regulation policy rather than the physical shortage of spectrum [1]. Most of the allocated frequency bands are under-utilized, and the utilization of the spectrum varies in time and space. The compelling need to improve the spectrum utilization and establish more flexible spectrum regulations motivates the advent of cognitive radio (CR) [2].

In this paper, a spectrum sharing CR system is considered, where a secondary user (SU) is allowed to transmit concurrently with a primary users (PU) over the same frequency band provided that the PU's performance degradation caused by SUs interference is tolerable.

On another front, energy harvesting, with the great potential to provide clean and green power supplies, becomes a promising approach to power wireless communication networks. Besides the well-known energy sources such as solar and wind, ambient radio signal is now regarded as a new viable source for wireless energy harvesting due to the fact that the wireless signals carry energy as well as information [4]. Recently, wireless power technologies have evolved significantly to make wireless power transfer (WPT) for wireless applications a reality [5]. Wireless power can be harvested from the environment such as the TV broadcast signals [6]. In [6], a wireless peer-to-peer communication system powered solely by ambient radio signals has already been successfully implemented. As a result, wireless powered communication networks (WPCNs) [7], in which wireless devices are powered only by WPT, have been a hot topic.

In this paper, we consider a spectrum-sharing *decode-and-forward (DF)*-enabled CR relay networks with energy harvesting capabilities. The secondary transmitter is required to help with the primary transmission for the purpose of sharing the PU's spectrum. The main contribution of this paper is summarized as follows:

- The trade-off between the achievable rate for the PU and the amount of required harvested energy is formulated as an payoff maximization problem for the benefit of the SU, who weighs its revenue gained by assisting the SU pair with cognitive relaying against the energy consumption that is charged by EAPs.
- The optimum trade-off is achieved by jointly optimizing the SU's wireless energy harvesting (WEH) strategies, multi-antenna beamforming, and PU's power allocation over the two transmission phases of DF relaying.
- Driven by the trend of delegating ad hoc data to a cloud centre for fast online optimization, a greedy-based heuristic algorithm is developed to substantially reduce the integer programming (IP) induced complexity, and is also verified by simulations to well approach the optimal scheme.

A. Notation

We use the upper case boldface letters for matrices and lower case boldface letters for vectors. $(\cdot)^T$, $(\cdot)^H$, and $\mathsf{Tr}(\cdot)$ denote the transpose, conjugate transpose, and trace operations on matrices, respectively. $\|\cdot\|$ is the Euclidean norm of a vector. $\mathbb{E}[\cdot]$ stands for the statistical expectation of a random variable. $\boldsymbol{A} \succeq 0$ indicates that $\boldsymbol{A}$ is a positive semidefinite matrix and $\boldsymbol{I}$ denotes an identity matrix with appropriate size. $[x]^+$ represents $\max(0, x)$.

II. System Model

In this paper, we consider a WEH-enabled cooperative cognitive radio network (CCRN) operating with DF relaying that consists of a primary transmitter-receiver pair, a secondary transmitter-receiver pair, and K energy access points (EAPs). The primary transmitter and receiver are denoted by PT and PR, respectively. The secondary transmitter and receiver are denoted by ST and SR, respectively. PT and PR are equipped with one antenna each, while ST and SR are equipped with N and M antennas, respectively. The number of antennas at the kth EAP is denoted by N_k, $\forall k \in \mathcal{K} = \{1, \cdots, K\}$.

In order to share the spectrum with the PUs, we assume that ST is required to assist with the primary transmission via *decode-and-forward* (DF) relaying, by which the ST receives the PT's signal in the first time slot, re-encodes it with its own message, and broadcasts the superimposed signal to the PR and the SR in the second time slot. In this paper, we assume that the ST is battery limited, and thus it resorts to WEH as its only means of power supply for the spectrum-sharing cooperative transmission. As illustrated by Fig. 1, a two-equal slot transmission protocol is assumed to be adopted.

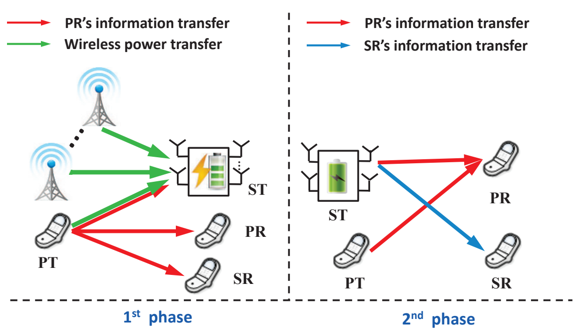

Fig. 1. Transmission protocol for a wireless powered CCRN.

In the first time slot, EAPs and the PT transfer energy signal to the ST. The PT also simultaneously transmits its message to the PR, which will also be received by the ST and the SR. In the secondary time slot, the ST broadcasts the superimposed signal (PT's signal and its own signal) to both the SR and the PR. At the same time, the PT continues transmitting to the PR.

A. The First Time Slot

Received signal at the PR. Let s denote PT's transmitted signal, and $\boldsymbol{x}_k s_k$ denote the kth EAP's energy signal where $\boldsymbol{x}_k \in \mathbb{C}^{N_k \times 1}$ is the beamforming vector for the kth EAP. For the convenience of exposition, we introduce an indicator function ρ_k for the kth EAP$k \in \mathcal{K}$, which is defined as

$$\rho_k = \begin{cases} 1 & \text{the } k\text{th EAP is selected for WPT,} \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

Accordingly, the signal received at the PR can be expressed as

$$y_{PR}^{(1)} = h_{pp}\sqrt{\beta P_p} s + \sum_{k=1}^{K} \rho_k \boldsymbol{h}_{k,p}^H \boldsymbol{x}_k s_k + n_{PR}^{(1)}, \quad (2)$$

where h_{pp} denotes the complex channel from the PT to the PR; $\boldsymbol{h}_{k,p}$'s represent the complex channels from the kth EAP to the PR; β is a power allocation factor that decides the amount of power used to transmit the primary information in the first time slot; P_p is the total power available to the PT for two time slots; and $n_{PR}^{(1)}$ denotes the circularly symmetric complex Gaussian (CSCG) additive noise at the PR, i.e., $\boldsymbol{n}_{PR}^{(1)} \sim \mathcal{CN}(0, \sigma_{PR}^2)$.

It is worthy pointing out that $\sum_{k=1}^{K} \rho_k \boldsymbol{h}_{k,p}^H \boldsymbol{x}_k s_k$ can be perfectly cancelled out by the PR if the kth EAP transmits an *a priori* constant signal s_k, $\forall k \in \mathcal{K}$. This is doable since these energy signals are dedicated for WPT bearing no information, which will facilitate the decoding of the PT's signal s without interference.

Received signal at the SR. The received signal at the SR, with EAP's energy signals perfectly cancelled, is given by

$$\boldsymbol{y}_{SR}^{(1)} = \boldsymbol{h}_{ps}\sqrt{\beta P_p} s + \boldsymbol{n}_{SR}^{(1)}, \quad (3)$$

where $\boldsymbol{h}_{ps}$ denotes the complex channels from the PT to the SR, and $\boldsymbol{n}_{SR}^{(1)}$ is the CSCG noise received at the SR, denoted by $\boldsymbol{n}_{SR}^{(1)} \sim \mathcal{CN}(0, \sigma_{SR}^2 \boldsymbol{I})$.

Received signal at the ST. In this paper, we assume that the ST employs a dynamic power splitting (DPS) receiver for concurrent energy harvesting (EH) and information decoding (ID) from the same stream of received signal, where ϱ portion of the received signal power is used to feed the energy supply versus the remaining $1-\varrho$ portion reserved for ID. As a result, the signal received by the ST available for ID is given by

$$\boldsymbol{y}_{ST}^{(1)} = \sqrt{1-\varrho}(\boldsymbol{h}_{p,ST}\sqrt{\beta P_p} s + \boldsymbol{n}_a) + \boldsymbol{n}_c, \quad (4)$$

where $\boldsymbol{h}_{p,ST}$ denotes the complex channels from the PT to the ST; $\boldsymbol{n}_a$ denotes the antenna noise at the RF-band with zero mean and a variance of $\sigma_{n_a}^2$; and $\boldsymbol{n}_c$ is the RF-band to baseband signal conversion noise, denoted by $\boldsymbol{n}_c \sim \mathcal{CN}(0, \sigma_{n_c}^2 \boldsymbol{I})$. Note that the simultaneously received energy signals $\sqrt{1-\varrho}\sum_{k=1}^{K} \rho_k \boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k$, where $\boldsymbol{H}_{k,ST} \in \mathbb{C}^{N \times N_k}$ represents the complex channels from the kth EAP to the ST, are assumed to have been cancelled by the ST for the same reason as that for the PR and the SR.

B. The Second Time Slot

Transmitted signal at the ST. In the second time slot, the ST extracts the PR's desired message and superimposes it with its own message as follows.

$$\boldsymbol{x}_{ST}^{(2)} = \boldsymbol{w}_p s + \boldsymbol{q}_s, \quad (5)$$

where $\boldsymbol{w}_p$ denotes the beamforming vector for the PR's desired signal s, while $\boldsymbol{q}_s$ is the transmit signal conveying the SR's information aimed for multiplexing MIMO transmission, the covariance matrix of which is $\mathbb{E}[\boldsymbol{q}_s \boldsymbol{q}_s^H] = \boldsymbol{Q}_s$. As mentioned before, the transmit power for the ST is solely supplied by its harvest power, i.e.,

$$\mathsf{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta\varrho P_{\mathrm{EH}}(\beta), \quad (6)$$

where $P_{\mathrm{EH}}(\beta) = \sum_{k=1}^{K} \rho_k \|\boldsymbol{H}_{k,ST}\boldsymbol{x}_k\|^2 + \beta P_p \|\boldsymbol{h}_{p,ST}\|^2$ denotes the maximum wireless transferred power without any hardware limitation, and η is the actual energy harvesting efficiency.

Received signal at the PR. In the second time slot, PT uses the rest of its available power to transmit a duplicate copy of its previously transmitted signal given by $\sqrt{(1-\beta)P_p}s$. Thus, the received signal at the PR is given by

$$y_{PR}^{(2)} = h_{pp}\sqrt{(1-\beta)P_p}s + \boldsymbol{g}_{sp}^H \boldsymbol{x}_{ST}^{(2)} + n_{PR}^{(2)}, \quad (7)$$

where $\boldsymbol{g}_{sp}$ denotes the conjugate transpose of the complex channel from the ST to the PR, and $n_{PR}^{(2)}$ denotes the additive noise at the PR. Plugging (5) into (7), $y_{PR}^{(2)}$ can be rewritten in a more compact form as follows.

$$y_{PR}^{(2)} = \boldsymbol{g}_{sp}^H \boldsymbol{q}_s + \boldsymbol{h}_{pp}'^H \boldsymbol{w}_p' s + n_{PR}^{(2)}, \quad (8)$$

where $\boldsymbol{h}'_{pp} = [\boldsymbol{g}_{sp}^H, \ h_{pp}]^H$ is an equivalent channel carrying the primary information s, and $\boldsymbol{w}'_p = [\boldsymbol{w}_p^H, \ \sqrt{(1-\beta)P_p} \ ]^H$ is an equivalent beamforming vector corresponding to $\boldsymbol{h}'_{pp}$.

Received signal at the SR. The received signal at the SR is given by

$$\boldsymbol{y}_{SR}^{(2)} = \boldsymbol{G}_{ss}\boldsymbol{q}_s + \left(\boldsymbol{G}_{ss}\boldsymbol{w}_p + \boldsymbol{h}_{ps}\sqrt{(1-\beta)P_p}\right)s + \boldsymbol{n}_{SR}^{(2)}, \quad (9)$$

where $\boldsymbol{G}_{ss} \in \mathbb{C}^{M\times N}$ denotes the MIMO channel between the ST and the SR, and $\boldsymbol{n}_{SR}^{(2)}$ is the receiving noise at the SR, denoted by $\boldsymbol{n}_{SR}^{(2)} \sim \mathcal{CN}(0, \sigma_{SR}^2 \boldsymbol{I})$.

III. Problem Formulation

In this paper, we assume that the PR performs maximum ratio combining (MRC) on its received signal in (2) and (7) to jointly decode s, which yields its maximum achievable signal-to-interference-plus-noise ratio (SINR) given by

$$\mathrm{SINR}_{PR} = \frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}_{pp}'^H \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s \boldsymbol{g}_{sp} + \sigma_{PR}^2}. \quad (10)$$

Then, taking the DF relay effect into account, the achievable rate for the PR is given by

$$r_{PR} = \min\left\{\frac{1}{2}\log_2\left(1 + \frac{(1-\varrho)\beta P_p \|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2 + \sigma_{n_c}^2}\right), \frac{1}{2}\log_2\left(1 + \frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}_{pp}'^H \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s \boldsymbol{g}_{sp} + \sigma_{PR}^2}\right)\right\}. \quad (11)$$

Note here we assume the interfere introduced by the EAPs' signal is perfectly cancelled out.

The achievable rate for the underlaying MIMO secondary transmission pair, denoted by r_{SR}, is given by

$$r_{SR} = \frac{1}{2}\log_2 \det\left(\boldsymbol{I} + \frac{\boldsymbol{G}_{ss}\boldsymbol{Q}_s\boldsymbol{G}_{ss}^H}{\sigma_{SR}^2}\right). \quad (12)$$

Note here we assume the interference introduced by the PT's signal is perfectly cancelled out due to the fact that the SR can perform successive interfere cancellation (SIC) to cancel out the interference introduced by the PT's signal taking advantage of the received signal in (3).

In this paper, we assume the SR will be rewarded by the PR in proportional to PR's rate, i.e., $c_1 r_{PR}$ (c.f. (11)), where c_1 is a reward conversion factor which relates the PR's rate with SR's revenue. As mentioned before, SR needs to harvest energy from EAPs and the PT, and use the harvested energy to transmit its own signal and help the primary transmission. We assume that the SR has to pay for the energy that it harvests from both the EAPs and the PR, and this becomes the cost of the SR, i.e., $c_2\eta\varrho P_{\mathrm{EH}}(\beta)$, where c_2 is a cost conversion factor that relates the amount of harvested energy with SR's cost. Thus, the payoff for the ST is given by $c_1 r_{PR} - c_2\eta\varrho P_{\mathrm{EH}}(\beta)$.

In this paper, we investigate the payoff maximization problem for the ST, which can be formulated as follows

$$\begin{aligned}
(\mathrm{P1}): \max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \varrho, \beta, \{\rho_k\}} \quad & c_1 r_{PR} - c_2\eta\varrho P_{\mathrm{EH}}(\beta) && (13\mathrm{a})\\
\mathtt{s.t.} \quad & r_{PR} \geq R_{PR}, && (13\mathrm{b})\\
& r_{SR} \geq R_{SR}, && (13\mathrm{c})\\
& \boldsymbol{w}'_p = [\boldsymbol{w}_p^H, \ \sqrt{(1-\beta)P_p} \ ]^H, && (13\mathrm{d})\\
& \rho_k \in \{0,1\}, \ \forall k, && (13\mathrm{e})\\
& 0 \leq \varrho \leq 1, \ 0 \leq \alpha \leq 1, \ (6), && (13\mathrm{f})
\end{aligned}$$

where R_{PR} and R_{SR} are QoS-required transmission rate for the PR and the SR, respectively.

IV. Proposed Solutions

To solve (P1), we first consider EAPs' optimal transmission strategy. For each EAP, if it is selected for transmission, its optimal transmission strategy can be obtained by solving the following problem

$$\begin{aligned}
(\mathrm{P2}): \mathtt{Maximize}_{\boldsymbol{x}_k} \quad & \|\boldsymbol{H}_{k,ST}\boldsymbol{x}_k\|^2, && (14\mathrm{a})\\
\mathtt{Subject\ to} \quad & \|\boldsymbol{x}_k\|^2 \leq P_0, && (14\mathrm{b})
\end{aligned}$$

where P_0 denotes the transmit power of the EAP once connected. The solution to Problem (P0) is the well-known eigenmode EB [8], and can be explicitly expressed as $\boldsymbol{x}_k^* = \sqrt{P_0}\boldsymbol{v}_{\max}(\boldsymbol{H}_{k,ST})$, for $k \in \{k \in \mathcal{K} \mid \bar{\rho}_k = 1\}$, where $\boldsymbol{v}_{\max}(\cdot)$ denotes the right singular vector that corresponds to the largest singular value of the given matrix. The (reduced) SVD of $\boldsymbol{H}_{k,ST}$ (assuming $N \leq L$) is expressed as $\boldsymbol{H}_{k,ST} = \boldsymbol{U}_k \boldsymbol{\Sigma}_k^{1/2} \boldsymbol{V}_k^H$, where $\boldsymbol{\Sigma}_k = diag(\lambda_{k,1}, \ldots, \lambda_{k,N})$.

When ρ_k's are given, the maximum amount of WPT received at the ST is given by $\bar{P}_{\mathrm{EH}}(\beta) = P_0\sum_{k=1}^{K} \bar{\rho}_k \lambda_{k,\max} + \beta P_p \|\boldsymbol{h}_{p,ST}\|^2$, where $\lambda_{k,\max} = \max_n\{\lambda_{k,n}\}_{n=1}^{N}$ and $\bar{\rho}_k$'s denote the given indicator functions. Thus, when ρ_k's are given as $\bar{\rho}_k$, P1 can be reduced to

$$\text{(P3)}: \max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \varrho, \beta} \ c_1 r_{PR} - c_2 \eta \varrho \bar{P}_{\rm EH}(\beta) \tag{15a}$$

$$\text{s.t.}\ r_{PR} \geq R_{PR}, \tag{15b}$$

$$r_{SR} \geq R_{SR}, \tag{15c}$$

$$\mathsf{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta \varrho \bar{P}_{\rm EH}(\beta), \tag{15d}$$

$$\boldsymbol{w}_p' = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}\ ]^H, \tag{15e}$$

$$0 \leq \varrho \leq 1,\ \ 0 \leq \beta \leq 1. \tag{15f}$$

As a step stone to solving (P1), we first investigate the solution of (P3).

A. Feasibility

First, we investigate the feasibility issue of (P3). We need to investigate the feasible rate region, i.e. (R_{PR}, R_{SR}) paris, which are supported by the system. Hence, we consider to characterize its Pareto boundary by first looking into the maximum achievable R_{PR}, and then given any feasible R_{PR}, determining the maximum achievable R_{SR}. First, the following problem is formulated so as to find the maximum R_{PR} achieved by the system.

$$\text{(P0-1)}: \max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \varrho, \beta} \ r_{PR}(c.f.\ (11)) \tag{16a}$$

$$\text{s.t.}\ \mathsf{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta \varrho \bar{P}_{\rm EH}(\beta), \tag{16b}$$

$$\boldsymbol{w}_p' = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}\ ]^H, \tag{16c}$$

$$0 \leq \varrho \leq 1,\ \ 0 \leq \beta \leq 1. \tag{16d}$$

Denoting the optimum value for (16a) by R_{PR}^*, then given any $R_{PR} \in [0, R_{PR}^*]$, consider the maximum-R_{SR} problem as follows.

$$\text{(P0-2)}: \max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \varrho, \beta} \ \frac{1}{2} \log_2 \det \left(\boldsymbol{I} + \frac{\boldsymbol{G}_{ss} \boldsymbol{Q}_s \boldsymbol{G}_{ss}^H}{\sigma_{SR}^2} \right) \tag{17a}$$

$$\text{s.t.}\ r_{PR} \geq R_{PR}, \tag{17b}$$

$$\mathsf{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta \varrho \bar{P}_{\rm EH}(\beta), \tag{17c}$$

$$\boldsymbol{w}_p' = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}\ ]^H, \tag{17d}$$

$$0 \leq \varrho \leq 1,\ \ 0 \leq \beta \leq 1. \tag{17e}$$

It is also worthy of noting that in the sequel we constrain ourself to the channels related to $\boldsymbol{h}_{p,ST}$ and h_{pp} satisfying the following condition

$$|h_{pp}|^2 \leq \frac{\sigma_{PR}^2}{\sigma_{n_a}^2 + \sigma_{n_c}^2} \|\boldsymbol{h}_{p,ST}\|^2, \tag{18}$$

since otherwise (18) implies that the direct transmission has already outperforms the upper-bound of the CR-aided DF relaying, which reduces to a trivial case that is out of the main focus of this paper.

To solve (P0-1), we rewrite its objective function into a tractable form associated with the SINR of the DF relaying in two phases, respectively, as follows.

$$\text{(P0-1}'\text{)}: \max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \varrho, \beta, t} \ t \tag{19a}$$

$$\text{s.t.}\ \frac{(1-\varrho)\beta P_p \|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2 + \sigma_{n_c}^2} \geq t, \tag{19b}$$

$$\frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}_{pp}'^H \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s \boldsymbol{g}_{sp} + \sigma_{PR}^2} \geq t, \tag{19c}$$

$$\mathsf{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta \bar{P}_{\rm EH}(\beta), \tag{19d}$$

$$\boldsymbol{w}_p' = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}\ ]^H, \tag{19e}$$

$$0 \leq \varrho \leq 1,\ \ 0 \leq \beta \leq 1. \tag{19f}$$

Since (P0-1$'$) and (P0-2) are both hard to solve in terms of the coupling of β and ϱ. We propose to attain the feasible rate region as follows. First, given any $\bar{\beta} \in [0,1]$, we exploit the following proposition to find the maximum R_{PR}, denoted by $\bar{R}_{PR}^*$; next, plugging any feasible R_{PR} into problem (P0-2), we obtain the optimum R_{SR}, denoted by $\bar{R}_{SR}^*(R_{PR})$; then we specify the feasible rate regions with different $\bar{\beta}$'s by identifying their respective Pareto boundary consisting of $(R_{PR}, \bar{R}_{SR}^*(R_{PR}))$'s; at last, we characterize the feasible rate region for (P3) by taking their union sweeping over $\bar{\beta} \in [0,1]$.

Proposition 4.1: For any $\bar{\beta} \in [0,1]$, the optimum $t(\bar{\beta})$ to (P0-1$'$) is uniquely determined by the following equation w.r.t. t.

$$\frac{\left(\sqrt{\eta\varrho(t)\bar{P}_{\rm EH}(\bar{\beta})}\,\|\boldsymbol{g}_{sp}\| + \sqrt{(1-\beta)P_p}|h_{pp}|\right)^2}{\sigma_{PR}^2} + \frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} - t = 0, \tag{20}$$

where $\varrho(t)$ is given by

$$\varrho(t) = 1 - \frac{\sigma_{n_c}^2 t}{\bar{\beta} P_p \|\boldsymbol{h}_{p,ST}\|^2 - \sigma_{n_a}^2 t}. \tag{21}$$

Proof: A sketch of the proof is outlined herein. First we show that the constraints in (19b)-(19c) are always active when (P0-1$'$) admits its optimum value by contradiction. Hence, (19c) implies that $t^*(\bar{\beta})$ is achieved when there is no QoS requirement for the SR. Next, given $\boldsymbol{Q}_s^* = 0$, looking into a subproblem of maximizing the left-hand side (LHS) of (19b) subject to (19e), $\boldsymbol{w}_p^*$ proves to be aligned to the same direction as $\boldsymbol{g}_{sp}$ given by $\boldsymbol{w}_p'^* = [\sqrt{\eta\varrho(t)P_{\rm EH}(\bar{\beta})}\frac{\boldsymbol{g}_{sp}}{\|\boldsymbol{g}_{sp}\|}\exp -j\measuredangle h_{pp}; \sqrt{(1-\beta)P_p}]$. Then, substituting $\boldsymbol{Q}_s^*$ and $\boldsymbol{w}_p'^*$ into (20), we yield (20), where $\varrho(t)$ is simply obtained from (19b) with the inequality active. ■

With $t^*(\bar{\beta})$ in (20) numerically solved, the maximum achievable R_{PR} is consequently given by $R_{PR}^* = \frac{1}{2}\log_2(1+t^*)$. Next, given any $R_{PR} \in [\frac{1}{2}\log_2(1+\frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2}), R_{PR}^*]$, we consider to solve (P0-2) with β fixed as $\bar{\beta}$ as follows. By introducing $\boldsymbol{W}_p' = \boldsymbol{w}_p' \boldsymbol{w}_p'^H$ and ignoring the rank constraint that $\boldsymbol{W}_p'$ is subject to, (P0-2) is recast as follows.

(P0-2-sub) :

$$\max_{\boldsymbol{W}_p',\boldsymbol{Q}_s,\varrho} \frac{1}{2}\log_2\det\left(\boldsymbol{I}+\frac{\boldsymbol{G}_{ss}\boldsymbol{Q}_s\boldsymbol{G}_{ss}^H}{\sigma_{SR}^2}\right) \tag{22a}$$

$$\text{s.t.} \ \frac{(1-\varrho)\bar{\beta}P_p\|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2+\sigma_{n_c}^2} \geq \left(2^{2R_{PR}}-1\right), \tag{22b}$$

$$\mathsf{Tr}(\boldsymbol{H}_{pp}\boldsymbol{W}_p') \geq \left(2^{2R_{PR}}-1-\frac{\bar{\beta}P_p|h_{pp}|^2}{\sigma_{PR}^2}\right)$$
$$\left(\mathsf{Tr}(\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s\boldsymbol{g}_{sp})+\sigma_{PR}^2\right), \tag{22c}$$

$$\mathsf{Tr}(\boldsymbol{Q}_s)+\mathsf{Tr}(\bar{\boldsymbol{E}}\boldsymbol{W}_p') \leq \eta\varrho\bar{P}_{\text{EH}}(\bar{\beta}), \tag{22d}$$

$$\mathsf{Tr}(\boldsymbol{U}_{N+1}\boldsymbol{W}_p') = (1-\bar{\beta})P_p, \tag{22e}$$

$$0\leq\varrho\leq 1, \ \ \boldsymbol{W}_p'\succeq\boldsymbol{0}, \ \ \boldsymbol{Q}_s\succeq\boldsymbol{0}, \tag{22f}$$

where $\boldsymbol{H}_{pp}=\boldsymbol{h}_{pp}\boldsymbol{h}_{pp}^H$, $\bar{\boldsymbol{E}}=\boldsymbol{E}^H\boldsymbol{E}$, in which $\boldsymbol{E}=[\boldsymbol{I}_N \ \boldsymbol{0}]$, and $\boldsymbol{U}_{N+1}=diag(\boldsymbol{e}_{N+1})$, in which $\boldsymbol{e}_{N+1}\in\mathbb{R}^{(N+1)\times 1}$ denotes an element vector with the $N+1$th entry being 1 and all the other 0. Since ((P0-2-sub)) turns out to be a convex problem, it can be efficiently solved by some convex optimization toolbox facilities. It is worthy of noting that whether or not $\boldsymbol{W}_p'^*$ is achievable by a beamforming vector $\boldsymbol{w}_p'$ lies in the tightness of the SDR used in (P0-2-sub), which turns out to be tight and the proof will be discussed in the next subsection.

B. Optimal Solution to (P1)

In this subsection, we study the optimal solution to (P1). For any set of given integer variables $\{\bar{\rho}_k\}$, assuming that (P3) proves to be feasible in accordance with Section IV-A, denote its optimum value as $f_1(\{\bar{\rho}_k\})$. The optimal solution to (P1) can thus be obtained by $\{\rho_k^*\}=\arg\max_{\{\bar{\rho}_k\}\in\boldsymbol{\Pi}} f_1(\{\bar{\rho}_k\})$, where $\boldsymbol{\Pi}=\{0,1\}^K$ is defined by length-K Cartesian product. Hence, we only focus on solving (P3) in the sequel.

We commence with recasting (P3) into a two-stage problem. First, with a fixed $\bar{\beta}\in[0,1]$, we solve the epigraph reformulation of (P3) as follows.

$$\text{(P3.1)}: \max_{\boldsymbol{w}_p,\boldsymbol{Q}_s,\varrho,t} \frac{c_1}{2}\log_2(1+t)-c_2\eta\varrho\bar{P}_{\text{EH}}(\bar{\beta}) \tag{23a}$$

$$\text{s.t.} \ \frac{(1-\varrho)\bar{\beta}P_p\|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2+\sigma_{n_c}^2}\geq t, \tag{23b}$$

$$\frac{\bar{\beta}P_p|h_{pp}|^2}{\sigma_{PR}^2}+\frac{|\boldsymbol{h}_{pp}'^H\boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s\boldsymbol{g}_{sp}+\sigma_{PR}^2}\geq t, \tag{23c}$$

$$t\geq 2^{R_{PR}}-1, \tag{23d}$$

$$\frac{1}{2}\log_2\det\left(\boldsymbol{I}+\frac{\boldsymbol{G}_{ss}\boldsymbol{Q}_s\boldsymbol{G}_{ss}^H}{\sigma_{SR}^2}\right)\geq R_{SR}, \tag{23e}$$

$$\mathsf{Tr}(\boldsymbol{Q}_s)+\|\boldsymbol{w}_p\|^2\leq\eta\varrho\bar{P}_{\text{EH}}(\bar{\beta}), \tag{23f}$$

$$\boldsymbol{w}_p'=[\boldsymbol{w}_p^H, \ \sqrt{(1-\bar{\beta})P_p} \ ]^H, \tag{23g}$$

$$0\leq\varrho\leq 1. \tag{23h}$$

Denoting the optimum value of (P3.1) by $f_3(\bar{\beta})$, (P3) can be equivalently solved by (P3.2) : $\max_{0\leq\bar{\beta}\leq 1} f_3(\bar{\beta})$, which allows for a simple one-dimension search over $\bar{\beta}$, assuming that $f_3(\bar{\beta})$ is attainable. As a result, we aim for solving (P3.1) in the sequel.

It is observed from (P3.1) that the maximum payoff is always attained when $\mathsf{Tr}(\boldsymbol{Q}_s)$ takes on its minimum value such that (23e) holds. This can also be intuitively seen from the fact that the ST is rewarded only by the PR's achievable rate, and thus it attempts to fulfill its own user's QoS requirement, i.e., R_{SR}, with as little power it can such that the remaining harvested power allocated for assisting with PR's transmission is larger, which may lead to a larger achievable rate for the PR and thus a higher payoff. Hence, problem (P3.1) is readily decoupled into two subproblems without loss of any optimality as follows.

$$\text{(P3.1-1)}: \max_{\boldsymbol{Q}_s} \ \mathsf{Tr}(\boldsymbol{Q}_s) \tag{24a}$$

$$\text{s.t. (23e)}. \tag{24b}$$

Next, plugging its optimal solution, $\boldsymbol{Q}_s^*$, into (P3.1), (P3.1) reduces to the following problem.

$$\text{(P3.1-2)}: \max_{\boldsymbol{w}_p,\varrho,t} \frac{c_1}{2}\log_2(1+t)-c_2\eta\varrho\bar{P}_{\text{EH}}(\bar{\beta}) \tag{25a}$$

$$\text{s.t.} \ \frac{(1-\varrho)\bar{\beta}P_p\|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2+\sigma_{n_c}^2}\geq t, \tag{25b}$$

$$\frac{\bar{\beta}P_p|h_{pp}|^2}{\sigma_{PR}^2}+\frac{|\boldsymbol{h}_{pp}'^H\boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s^*\boldsymbol{g}_{sp}+\sigma_{PR}^2}\geq t, \tag{25c}$$

$$t\geq 2^{R_{PR}}-1, \tag{25d}$$

$$\|\boldsymbol{w}_p\|^2\leq\eta\varrho\bar{P}_{\text{EH}}(\bar{\beta})-\mathsf{Tr}(\boldsymbol{Q}_s^*), \tag{25e}$$

$$\boldsymbol{w}_p'=[\boldsymbol{w}_p^H, \ \sqrt{(1-\bar{\beta})P_p} \ ]^H, \tag{25f}$$

$$0\leq\varrho\leq 1. \tag{25g}$$

Subproblem (P3.1-1) is straightforward to be seen as a dual problem of the achievable rate maximization subject to the total transmit power for point-to-point MIMO channel, which thus yields the standard "water-filling" solution given by $\boldsymbol{Q}_s^*=\boldsymbol{V}diag(P_1,\ldots,P_r)\boldsymbol{V}^H$ [T. Cover], where $\boldsymbol{V}\in\mathcal{C}^{N\times r}$ is the precoding matrix given by the (reduced) SVD of $\boldsymbol{G}_{ss}=\boldsymbol{U}_G\boldsymbol{\Sigma}_G^{1/2}\boldsymbol{V}_G^H$ with $\boldsymbol{\Sigma}_G=diag(\lambda_{G,1},\ldots,\lambda_{G,r})$, $r=\min\{M,N\}$, $p_i=(\frac{\nu}{\ln 2}-\frac{\sigma_{SR}^2}{\lambda_{G,i}})^+$, $i=1,\ldots,r$, and ν is constant determining the "water-level" such that $\frac{1}{2}\sum_{i=1}^r\log_2(1+\frac{p_i\lambda_{G,i}}{\sigma_{SR}^2})=R_{SR}$. Subproblem (P3.1-2) is nevertheless non-convex, since (25c) is concave w.r.t. $\boldsymbol{w}_p'$. To circumvent this, we continue with devising the technique of SDR as is done for (P0-2-sub) such that (P3.1-2) can be reformulated as follows.

$$\text{(P3.1-2-SDR)}:$$

$$\max_{\boldsymbol{W}'_p,\varrho,t} \ \frac{c_1}{2}\log_2(1+t) - c_2\eta\varrho\bar{P}_{\rm EH}(\bar{\beta}) \quad (26a)$$

$$\text{s.t.} \ \frac{(1-\varrho)\bar{\beta}P_p\|\boldsymbol{h}_{p,ST}\|^2}{(1-\varrho)\sigma_{n_a}^2+\sigma_{n_c}^2} \geq t, \quad (26b)$$

$$\frac{\bar{\beta}P_p|h_{pp}|^2}{\sigma_{PR}^2} + \frac{\mathsf{Tr}(\boldsymbol{H}_{pp}\boldsymbol{W}'_p)}{\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s^*\boldsymbol{g}_{sp}+\sigma_{PR}^2} \geq t, \quad (26c)$$

$$t \geq 2^{R_{PR}}-1, \quad (26d)$$

$$\mathsf{Tr}(\bar{\boldsymbol{E}}\boldsymbol{W}'_p) \leq \eta\varrho\bar{P}_{\rm EH}(\bar{\beta}) - \mathsf{Tr}(\boldsymbol{Q}_s^*), \quad (26e)$$

$$\mathsf{Tr}(\boldsymbol{U}_{N+1}\boldsymbol{W}'_p) = (1-\bar{\beta})P_p, \quad (26f)$$

$$0 \leq \varrho \leq 1, \ \ \boldsymbol{W}'_p \succeq \boldsymbol{0}. \quad (26g)$$

As stated in Section IV-A, the upper-bound solution of $\boldsymbol{W}'_p$ by relaxing its rank constraint can be achieved if and only if $\text{rank}(\boldsymbol{W}'_p) = 1$, which is guaranteed by the following proposition.

Proposition 4.2: The optimal solution to (P3.1-2-SDR) always satisfies $\text{rank}(\boldsymbol{W}'^*_p) \leq 1$.

Proof: Please refer to Appendix A. ■

C. Proposed Solution to (P1)

In this subsection, we study a suboptimal solution to (P1). It is known from Section IV-B that the optimal solution to (P1) requires exhaustive search over $\boldsymbol{\Pi}$, which induces computational complexity up to $\mathcal{O}(2^K)$ and thus quite prohibitive in practical system, especially when the number of RAP, K, becomes large. Hence, we propose to reduce this integer programming-induced complexity to $\mathcal{O}(\mathcal{K})$ by designing a bi-direction greedy-based algorithm as shown in Table I.

The main thrust of this scheme includes two parts. On one hand, we aim to be "greedy" in terms of the ST's revenue by incrementally decreasing its value from an all-on state ($\{\bar{\rho}_k = 1\}$), i.e., turning off each time one EAP that corresponds to presently the least $\lambda_{H,k,\max}$, until the payoff begins to decrease. On the other hand, we aim to be "greedy" in terms of saving cost by incrementally increasing $P^*_{\rm EAP}$ from an all-off state ($\{\bar{\rho}_k = 0\}$) vice versa. At last, the ST chooses $\{\bar{\rho}_k\}$ from the above two directions that yields a larger payoff.

TABLE I
A GREEDY-BASED ALGORITHM FOR SOLVING (P1)

Require: (R_{PU}, R_{SU})
sort $diag(\boldsymbol{\Sigma}_{H,k})$ s.t. $\lambda_{H,n_1,\max} \geq \lambda_{H,n_2,\max} \geq \dots \lambda_{H,n_K,\max}$
$ii \leftarrow K$, $\bar{\rho}_{n_k}^{(ii)} \leftarrow 1$, $k = 1,\dots,K$
solve (P0) given $\{\bar{\rho}_{n_k}^{(ii)}\}$, and obtain $f_1(\{\bar{\rho}_{n_k}^{(ii)}\})$
if $R_{PU} > R^*_{PU}$ OR $R_{SU} > R^*_{SU}$ **then**
  return ('Infeasible')
else
  repeat
    $ii \leftarrow ii-1$, $\bar{\rho}_{n_{ii+1}}^{(ii)} \leftarrow 0$, and update $\{\bar{\rho}_{n_k}^{(ii)}\}$, $f_1(\{\bar{\rho}_{n_k}^{(ii)}\})$
  until $f_1(\{\bar{\rho}_{n_k}^{(ii)}\}) < f_1(\{\bar{\rho}_{n_k}^{(ii+1)}\})$ OR $ii = 0$
end if
return $ii^* = \arg\max_{ii \leq \bar{ii} \leq K} f_1(\{\bar{\rho}_{n_k}^{(\bar{ii})}\})$
sort $diag(\boldsymbol{\Sigma}_{H,k})$ s.t. $\lambda_{H,n'_1,\max} \leq \lambda_{H,n'_2,\max} \leq \dots \lambda_{H,n'_K,\max}$
$jj \leftarrow 0$, $\bar{\rho}_{n'_k}^{(jj)} \leftarrow 0$, $k = 1,\dots,K$
solve (P0) given $\{\bar{\rho}_{n'_k}^{(jj)}\}$, and obtain $f_1(\{\bar{\rho}_{n'_k}^{(jj)}\})$
repeat
  $jj \leftarrow jj+1$, $\bar{\rho}_{n'_{jj}}^{(jj)} \leftarrow 1$, and update $\{\bar{\rho}_{n'_k}^{(jj)}\}$, $f_1(\{\bar{\rho}_{n'_k}^{(jj)}\})$
until $f_1(\{\bar{\rho}_{n'_k}^{(jj)}\}) < f_1(\{\bar{\rho}_{n'_k}^{(jj-1)}\})$ OR $jj = K$
return $jj^* = \arg\max_{1 \leq \bar{jj} \leq jj} f_1(\{\bar{\rho}_{n'_k}^{(\bar{jj})}\})$
Ensure: $f_1^{(\rm grd)} = \max\{f_1(\{\bar{\rho}_{n_k}^{(ii^*)}\}), f_1(\{\bar{\rho}_{n'_k}^{(jj^*)}\})\}$, $\{\rho_k^{(\rm grd)}\} = \arg\max\{f_1(\{\bar{\rho}_{n_k}^{(ii^*)}\}), f_1(\{\bar{\rho}_{n'_k}^{(jj^*)}\})\}$

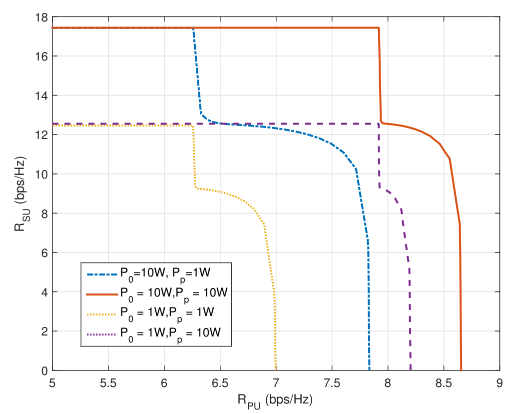

Fig. 2. The feasible rate region of (R_{PR}, R_{SR}), $K = 10$, $L = 10$, $M = N = 3$ under different P_0 and P_p.

V. NUMERICAL RESULTS

In this section, we provide numerical results to validate the proposed complexity reduced joint EAP selection and DF beamforming scheme for the considered wireless powered spectrum-sharing CRN, referred to as *-proposed*. Denoted by *-optimal*, the optimal solutions to problem (P1), in spite of their exponential complexity, serve as achievable performance upper-bound.

Taking the position of the ST as the origin of a polar coordinate, the PT, PR and SR are assumed to be located at $(-5, 0)$, $(5, \frac{pi}{6})$ and $(5, \frac{11pi}{6})$, respectively, with the default unit for distance m. We also assume that K EAPs are uniformly located within a circle of radius $R_{\max}$m centered at the ST. The channel models are assumed to consist of both large-scale and small-scale fading, the former of which is given by a simple path loss model with a path loss exponent of 2.5 in addition to 30dB free space attenuation, and the latter of which is assumed to be multi-path fading following $i.i.d.$ complex Gaussian distribution with zero mean and unit variance. Unless otherwise specified, the simulation parameters are set as follows: $R_{\max} = 8$m, $P_p = 30$dBm, $P_0 = 40$dBm, $K = 5$, $M = 3$, $N = 3$, $\eta = 0.5$, $\sigma_{n_a}^2 = -170$dBm, $\sigma_{n_c}^2 = -130$dBm, $\sigma_{PR}^2 = \sigma_{SR}^2 = \sigma_{n_a}^2 + \sigma_{n_c}^2$, $\eta = 0.5$, $c_1 = 1$, and $c_2 = 100$. N_k's are all set to be 10.

Fig. 2 depicts the Pareto boundaries of the feasible rate region by setting $\bar{\rho}_k = 1$, $\forall k \in \mathcal{K}$. The feasible rate region

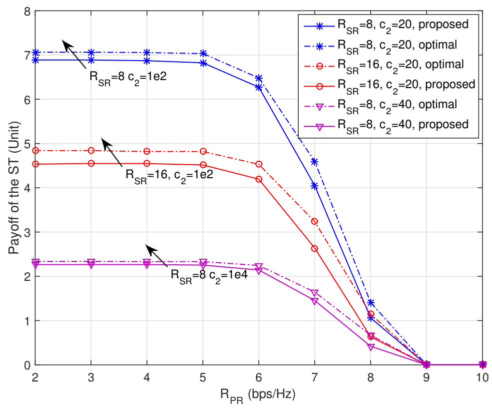

Fig. 3. The average payoff of the ST by different schemes vs R_{PR}, $K = 5$.

is accordingly given by $\{(r_{PR}, r_{SR}) \mid r_{PR} \leq R_{PR}, r_{SR} \leq R_{SR}\}$, in which, given any R_{PR}'s, R^*_{SR}'s are the maximum achievable $\bar{R}^*_{SR}(R_{PR})$ by sweeping over $\beta \in [0, 1]$.

It is observed from Fig. 2 that the same R_{SR} can be supported by a large range of R_{PR}. This is because a mild value R_{PR}, which is subject to the minimum of the ST's SINR and the PR's SINR (c.f. (11)), can always be achieved by increasing β. However, since $\boldsymbol{w}'_p$ is subject to $\sqrt{(1-\beta)}P_p$, continuously increasing β might be detrimental, and thus larger R_{PR} must be achieved at the cost of decreasing $\mathsf{Tr}(\boldsymbol{Q}_{\mathsf{s}})$, which results in a lower R_{SR}. It is also seen that given the same P_p, both R^*_{PR}'s and R^*_{SR}'s response positively with the increase in P_0, which implies that both PR and SR can benefit from the WPT phase.

Fig. 3 shows the average ST's payoff versus the PR's transmission rate requirement. As expected intuitively, the average payoff of the ST remains stable for small and mild value of R_{PR}, and is seen to first prominently climb down with higher QoS requirement on PR's achievable rate and then to arrive at zero (infeasible) when R_{PR} increases to 9bps/Hz. Given the same cost conversion factor c_2, a larger transmission rate required by the SR also results in an obvious decrease in the ST's payoff for both the proposed and optimal schemes due to a shrinking feasible region for problem (P3.1-2). Furthermore, the proposed schemes do not exhibit much performance loss from the optimal solutions. In particular, when the cost conversion factor c_2 increases by 20dB, the optimal scheme outperforms the proposed one with negligible gap. This can be explained as follows. When c_2 is large, the ST attempts to connect to as fewer EAPs as possible, as long as the required R_{PR} and R_{SR} are satisfied. Accordingly, the optimum selection scheme tends to activate only one EAP that corresponds to $\min\limits_{k \in \mathcal{K}} \lambda_{H,k,\max}$, which can be easily reached by one of our greedy direction that starts from harvesting minimum amount of power from the EAPs.

VI. Conclusion

This paper considered a novel WEH-enabled CCRN operating with DF relaying solely powered by the WPT-enabled PT and multiple EAPs. Assuming that direct links are active, the multi-antenna SU pair assisted with the transmission of a single-antenna PU pair by wireless powered DF relaying, and in return superimposed its own message by spectrum-sharing CR. A joint optimization of EAP-selection scheme, WEH-enabled information reception as well as the DF relay beamforming for the ST, and the power allocations for the PT has been investigated to maximize the ST;s payoff, subject to QoS requirements on achievable rates of PR and SR, and the total harvested power for the ST to perform DF relaying. We optimally solved this IP-mixed non-convex optimization using the technique of SDR that is proved to be tight. We also proposed a low complexity suboptimal algorithm based on greedy EAP-selection, the effectiveness of which is validated by numerical results.

Appendix A

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