Information and Energy Cooperation in Overlay Hierarchical Cognitive Radio Networks

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Abstract—**In overlay hierarchical cognitive radio (HCR) networks, the primary system (PS) and the secondary system (SS) can cooperate to exploit the spectrum resource more efficiently. In this paper, we propose a new HCR, in which an energy harvesting (EH) device is additionally deployed at the primary receiver (PR) such that the PS can not only share the spectrum resources with the SS, but also harvest energy from the SS, achieving a new simultaneous wireless information and power transfer (SWIPT) paradigm. In the considered structure, the secondary base station (SB) can help relay the PS's signal via an amplify-and-forward (AF) protocol, and a power splitting EH device is adopted at the PR. A cooperative strategy is proposed for maximizing the efficiency of the information and power transfer. We optimize two precoders at the SB (for the PS and SS, respectively) and the power splitting factor for the PR. Since the optimization problem is non-convex, it is a real challenge. To facilitate the optimization process, a precoding structure is first proposed to reduce the number of parameters. The resultant optimization problem can then be equivalently solved using a semidefinite relaxation (SDR) approach. Numerical results show that the proposed strategy provides a promising improvement for information and energy cooperation, as compared with existing methods.**

Index Terms **– Hierarchical radio networks (HCRs), Energy harvesting (EH), Overlay, Convex optimization, Amplify-and-forward (AF), Semidefinite relaxation (SDR).**

I. INTRODUCTION

Wireless power transfer (WPT) has been a promising technology to offer stable and sustainable power to low-power wireless systems [1]. Applying WPT in hierarchical cognitive radio (HCR) networks is invented to further improve the spectrum utilization and prolong the battery lifetime [1]-[10].

The WPT technologies used in HCR are mainly divided into two categories, the wireless powered communication networks (WPCN) and the simultaneously wireless information and power transfer (SWIPT) systems. In WPCN-based HCR networks, the energy harvesting device is usually allocated at the secondary transmitter (ST) to perform the harvest-then-transmit protocol [2]-[4], in which the communication equipment is powered by WPT. In [2], an energy harvesting (EH) device is placed at the ST to store energy in rechargeable batteries with the finite capacity. The cognitive sensing and access policies are studied to maximize the SS's transmission rate. The authors in [3] and [4] proposed strategies that the ST can opportunistically harvest RF energy from nearby primary transmitters (PTs) to maximize the total throughout.

An alternative design is based on SWIPT, where the information signal is involved in the radiated RF waveform [5], [6]. The authors in [5] deploy power splitting EH devices at the ST so that the PT conducts the SWIPT and the ST jointly transmits the signals of the SS and the PS with the additional harvested energy. In [6], the authors extend the design in [5] to the orthogonal frequency division multiplexing (OFDM) based scenario, where the additional degree of subcarriers is utilized in the joint information and energy cooperation schemes.

The above-mentioned design deploys the EH devices at the transmitter. It is noted that the harvested energy at the EH device is generally much smaller than the transmit power. For instance, the maximum harvested power at a freespace distance of 40 meters is just $7\mu W$ and $1\mu W$ for 2.4 GHz and 900 MHz [7]. Hence, the transmitters with energy harvested devices are suitable for the sensor networks that do not frequently transmit the information signals. The alternative design is to deploy the EH device at the receiver to offer the additional power for information decoding (ID), effectively prolonging the lifetime of the receiver [8]-[10]. In [8], the designed SR can receive the RF radiation to perform either the EH or the ID. The authors in [9] studied the SRs which can be divided into two categories, the ID and EH receivers. The ST uses an artificial noise (AN)-aided precoding method to maximize the secrecy rate under the limited interference in the PR. In [10], the time-switching EH device is placed at the PR and it can harvest the energy from the transmitted information signals in the SS. The time-switching factor and the beamforming technology are jointly optimized to improve the amount of the harvested power at the PR and the SS's transmission rate. However, in some situations, the PB-PR channel link may be poor, which seriously degrades the uplink/downlink performance of the PS. It motivates us to develop a new information and energy cooperation strategy to overcome the dilemma.

In this paper, we study a new information and energy cooperation strategy for an EH-based HCR network [10]. In the proposed scenario, the ST and PT are the secondary base station (SB) and the primary base station (PB), respectively. The SB can not only act as a relay node to help the PS convey its signals but also transmit its own signals to the SR; meanwhile, the SB offers wireless energy to the PR, achieving a new win-win situation. Specifically, the SB uses an amplify-and-forward (AF) protocol to help relay the PS's signal. The signal transmission in the considered system is then performed in two phases. In the first phase, the PB sends its signal to both the SB and PR. In the second phase, the SB helps the PB relay the PS's signal, and the SB simultaneously transmits its signal to the SR. In addition, the PR divides the received signal into EH and ID portion accordance with a power splitting factor. We use two precoders at the SB (one for the PS and the other for the SS) to improve the information and energy transfer efficiency. A zero-forcing (ZF) precoder is then adopted at the SB to prevent the interference resulted from the SS in the PR. Hence, the PR can use the maximum ratio combining (MRC) scheme to optimally combine the received two-phase signals. Consequently, the cooperation strategy is commenced to jointly optimize the two precoders and power splitting factor such that the SS's transmission rate is maximized, and the information rate of the PS is guaranteed. Owing to the inclusion of relaying capability, the formulated optimization problem cannot be easily solved in its original form. To find a tractable solution, we then formulate the problem as semidefinite programming (SDP). The objective function, however, is not convex due to its fractional form. Hence, the Charnes-Cooper transformation is used to transfer the problem into a series of equivalent optimizations which are finally conducted with semidefinite relaxation (SDR) [11]. We further rigorously prove that the solution of the SDR approach is a rank-one solution which means the proposed SDR approach is equivalent to the original problem. Finally, some simulations are carried out to show the performance of the proposed cooperation strategy, and it indicates that the proposed information and energy cooperation outperforms the design in [10], especially when the channel quality of the PB-SB-PR link is getting better.

The rest of this paper is organized as follows. In Section II, the signal model of the proposed HCR and the corresponding information and energy cooperation strategy are presented. The optimization process is detailed in Section III. Simulation results are given in Section IV. Finally, we draw conclusions in Section V.

II. System Model

We study a novel information and energy cooperation strategy for EH-based HCR network proposed in [10]. In the considered design, the SB can further help the PS to convey its signals; meanwhile, the SB transmits its own signals to the SR. Hence, this structure is benefit when the PB-PR link is poor and PB-SB-PR is well, compared with the design in [10]. Specifically, the PS's signals are transmitted into two phases. In the first phase, the PB transmits its signals to the PR and SB, respectively. In the second phase, the SB helps the PS conduct SWIPT, where the SB is treated not only as an AF relay node but also a WPT, as shown in Fig. 1. Herein, the SB and PR are equipped with N_{SB} and N_{PR} antennas, respectively, to enhance the transmission rate and harvested energy with beamforming technology. The associated received signals models are detailed as follows.

Assume the PB broadcast its signal x_p with power q_p to both the PR and the SB. Without loss of generality, we assume $E\left[\left|x_p\right|^2\right] = 1$. The received signals at the PR and SB in the first phase can be expressed as

$$\mathbf{y}_{PB,PR} = \sqrt{q_p}\mathbf{h}_{PB,PR}x_p + \mathbf{n}_{PR,1} \tag{1}$$

and

$$\mathbf{y}_{PB,SB} = \sqrt{q_p}\mathbf{h}_{PB,SB}x_p + \mathbf{n}_{SB}\,, \tag{2}$$

where $\mathbf{h}_{PB,PR} \in \mathbb{C}^{N_{PR}\times 1}$ and $\mathbf{h}_{PB,SB} \in \mathbb{C}^{N_{SB}\times 1}$ are the BP-PR and the PB-SB channel links; $\mathbf{n}_{PR,1} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_{n,PR}^2\mathbf{I}_{N_{PR}}\right)$ and $\mathbf{n}_{SB} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_{n,SB}^2\mathbf{I}_{N_{SB}}\right)$ are the noise vectors at the PR and SB, accordingly.

In the second phase, the SB forwards the received signal from the PB; meanwhile, the SB sends the signal, x_s, to the SR. The transmitted signal at the SB is thus given by

$$\mathbf{t} = \mathbf{w}_S x_s + \mathbf{W}_P\left(\sqrt{q_q}\mathbf{h}_{PB,SB}x_p + \mathbf{n}_{SB}\right), \tag{3}$$

with an average power value of

$$E\left[\left\|\mathbf{t}\right\|^2\right] = \left\|\mathbf{w}_S\right\|^2 + q_p\left\|\mathbf{W}_P\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{n,SB}^2\left\|\mathbf{W}_P\right\|^2, \tag{4}$$

where $\mathbf{W}_P \in \mathbb{C}^{N_{SB}\times N_{SB}}$ is the precoder used to enhance the performance of the EH and ID at the PR, and $\mathbf{w}_S \in \mathbb{C}^{N_{SB}\times 1}$ is the dedicated precoder for the SR. Here, $E\left[\left|x_s\right|^2\right] = 1$. Denote $\mathbf{h}_{SB,SR} \in \mathbb{C}^{1\times N_{SB}}$ and $\mathbf{H}_{SB,PR} \in \mathbb{C}^{N_{PR}\times N_{SB}}$ are the SB-SR and the SB-PR channel links, respectively. The received signals at the SR and PR, denoted as $y_{SB,SR}$ and $\mathbf{y}_{SB,PR}$, respectively, are thus given as

$$y_{SB,SR} = \mathbf{h}_{SB,SR}\mathbf{t} + n_{SR} \tag{5}$$

$$\mathbf{y}_{SB,PR} = \mathbf{H}_{SB,PR}\mathbf{t} + \mathbf{n}_{PR,2} \tag{6}$$

with a power splitting EH device at the PR. The received signals are then divided into two portions, one for ID and the other for EH. Here, $\mathbf{n}_{PR,2} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_{n,PR}^2\mathbf{I}_{N_{PR}}\right)$. By defining a power splitting factor ρ and from (6), the signal for EH can be expressed as

$$\mathbf{y}_e = \sqrt{1-\rho}(\mathbf{H}_{SB,PR}(\mathbf{w}_S x_s + \mathbf{W}_p(\sqrt{q_p}\mathbf{h}_{PB,SB}x_p + \mathbf{n}_{SB})) + \mathbf{n}_{PR,2}) \tag{7}$$

and the harvested energy is given by

$$\begin{aligned} P_{EH} = \frac{1}{2}\eta(1-\rho)(q_p\left\|\mathbf{H}_{SB,PR}\mathbf{W}_p\mathbf{h}_{PB,SB}\right\|^2 + \\ \left\|\mathbf{H}_{SB,PR}\mathbf{w}_S\right\|^2 + \sigma_{n,SB}^2\left\|\mathbf{H}_{SB,PR}\mathbf{W}_P\right\|^2 + N_{PR}\sigma_{n,PR}^2), \end{aligned} \tag{8}$$

where the factor 2 is due to the two-phase transmissions, and η denotes the efficiency of energy transfer. In addition, the signal for ID is given as

$$\sqrt{\rho}\mathbf{y}_{SB,PR} + \mathbf{n}_{RF} = \sqrt{\rho}(\mathbf{H}_{SB,PR}(\mathbf{w}_S x_s + \mathbf{W}_P(\sqrt{q_p}\mathbf{h}_{PB,SB}x_p + \mathbf{n}_{SB})) + \mathbf{n}_{PR,2}) + \mathbf{n}_{RF} \tag{9}$$

where $\mathbf{n}_{RF}$ is the noise during the RF-to-baseband conversion process with $\mathcal{CN}\left(\mathbf{0}, \sigma_{RF}^2\mathbf{I}\right)$ [5]. Concatenating (1) and (9) into a vector, the two-phase received signals at the PR can be given by

$$\begin{bmatrix} \mathbf{y}_{PB,PR} \\ \sqrt{\rho}\mathbf{y}_{SB,PR} \end{bmatrix} = \begin{bmatrix} \sqrt{q_p}\mathbf{h}_{PB,PR} \\ \sqrt{\rho q_p}\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{h}_{PB,SB} \end{bmatrix} x_p + \begin{bmatrix} \mathbf{0} \\ \sqrt{\rho}\mathbf{H}_{SB,PR}\mathbf{w}_S \end{bmatrix} x_s + \mathbf{n}, \tag{10}$$

where

$$\mathbf{n} = \begin{bmatrix} \mathbf{n}_{PR,1} \\ \sqrt{\rho}(\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{n}_{SB} + \mathbf{n}_{PR,2}) + \mathbf{n}_{RF} \end{bmatrix} \tag{11}$$

is the equivalent noise with a covariance $\mathbf{R}_n = E\left[\mathbf{n}\mathbf{n}^H\right]$.

For simplicity, a ZF precoder is employed for the precoder $\mathbf{w}_S$ to avoid the interference at the PR. To facilitate the later derivation, a noise whitening process is adopted for (9) by using the whitening matrix $\mathbf{W} = \mathbf{R}_n^{1/2}$. The MRC receiver is optimum for the received signals after whitening process, and the signal after MCR can be written as

$$\begin{aligned} \hat{y}_{PR} = \mathbf{m}^H\tilde{\mathbf{y}}_{PR} = &\Big(q_p\sigma_{n,PR}^{-2}\left\|\mathbf{h}_{PB,SB}\right\|^2 + \rho q_p\mathbf{h}_{PB,SB}^H\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H \times \\ &\left(\sigma_{n,SB}^2\rho\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H + \rho\sigma_{n,PR}^2\mathbf{I}_{N_{PR}} + \sigma_{RF}^2\mathbf{I}_{N_{PR}}\right)^{-1} \\ &\mathbf{H}_{SB,PR}\mathbf{W}_p\mathbf{h}_{PB,SB}\Big)x_p \\ &+\Big[\sqrt{q_p}\sigma_{n,PR}^{-2}\mathbf{h}_{PB,SB}^H\mathbf{n}_{PR,1} + \sqrt{\rho q_p}\mathbf{h}_{PB,SB}^H\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H \times \\ &\left(\sigma_{n,SB}^2\rho\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H + \rho\sigma_{n,PR}^2\mathbf{I}_{N_{PR}} + \sigma_{RF}^2\mathbf{I}_{N_{PR}}\right)^{-1}\Big] \\ &\left(\sqrt{\rho}(\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{n}_{SB} + \mathbf{n}_{PR,2}) + \mathbf{n}_{RF}\right)\Big] \end{aligned} \tag{12}$$

The related signal-to-noise power ratio (SNR) can then be computed as

$$\begin{aligned} SNR_{PS} = &\frac{q_p}{\sigma_{n,PR}^2}\left\|\mathbf{h}_{PB,SB}\right\|^2 + \rho q_p\Big\|(\rho\sigma_{n,SB}^2\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H \\ &+\sigma_{n,PR}^2\mathbf{I}_{N_{PR}} + \rho\sigma_{RF}^2\mathbf{I}_{N_{PR}})^{-1/2}\mathbf{H}_{SB,PR}\mathbf{W}_P\mathbf{h}_{PB,SB}\Big\|^2 \end{aligned} \tag{13}$$

which is the function of ρ and $\mathbf{W}_P$. The achievable rate of the PS is then obtained as

$$R_p = \frac{1}{2}\log\left(1 + SINR_{PS}\right). \tag{14}$$

From (5), the achievable rate of the SS can be computed as

$$R_s = \frac{1}{2}\log\left(1 + \frac{\left\|\mathbf{h}_{SB,SR}\mathbf{w}_S\right\|^2}{q_p\left\|\mathbf{h}_{SB,SR}\mathbf{W}_P\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{n,SB}^2\left\|\mathbf{h}_{SB,SR}\mathbf{W}_P\right\|^2 + \sigma_{n,SR}^2}\right). \tag{15}$$

III. PROPOSED EH-BASED HCR NETWORKS

A. Problem Formulation

The energy and information strategy is conducted by jointly designing power splitting factor ρ and the two precoders $\mathbf{W}_P$ and $\mathbf{w}_S$ for maximizing the achievable rate of the SS, providing that the information rate and harvested energy as the PR must exceed present threshold values of γ_{PS} and Γ_{PS}, respectively. The optimization problem is thus formulated as follows

$$\max_{\rho,\mathbf{w}_S,\mathbf{W}_P} R_s \tag{16a}$$

s.t.

$$R_p \geq \gamma_{PS}; \tag{16b}$$

$$P_{EH} \geq \Gamma_{PS}; \tag{16c}$$

$$\mathbf{H}_{SB,PR}\mathbf{w}_S = \mathbf{0}; \tag{16d}$$

$$q_p\left\|\mathbf{W}_P\mathbf{h}_{PB,SB}\right\|^2 + \left\|\mathbf{w}_S\right\|^2 + \sigma_{n,SB}^2\left\|\mathbf{W}_P\right\|^2 \leq Q_{SB}; \tag{16e}$$

$$0 \leq \rho \leq 1. \tag{16f}$$

Here, (16d) indicates that the SB does not interfere with the PR, and (16e) represents the power constraint at the SB. Herein, R_s, R_p, and P_{EH} are represented in (15), (14), and (8), respectively.

B. Optimum Solution

As shown in (16), the optimization problem is not jointly convex in $(\rho, \mathbf{W}_P, \mathbf{w}_S)$. To make the problem tractable, a series of equivalent optimization problems are cast to facilitate the finding of the optimum solution. First, define $\tilde{\mathbf{h}}_{PB,SB} = \mathbf{h}_{PB,SB} / \left\|\mathbf{h}_{PB,SB}\right\|$ and

$$\mathbf{B} = \left\|\mathbf{h}_{PB,SB}\right\|^2 \mathbf{H}_{SB,PR}\mathbf{W}_P\tilde{\mathbf{h}}_{PB,SB}\tilde{\mathbf{h}}_{PB,SB}^H\mathbf{W}_P^H\mathbf{H}_{SB,PR}^H, \tag{17}$$

where $\mathbf{B}$ is rank-one matrix. Invoking the singular value decomposition (SVD), we have

$$\mathbf{H}_{SB,PR} = \mathbf{U}_{SB,PR}\mathbf{\Sigma}_{SB,PR}\mathbf{V}_{SB,PR}^H, \tag{18}$$

where $\mathbf{U}_{SB,PR} \in \mathbb{C}^{N_{PR}\times N_{PR}}$, $\mathbf{\Sigma}_{SB,PR} \in \mathbb{R}^{N_{PR}\times N_{SB}}$ and $\mathbf{V}_{SB,PR} \in \mathbb{C}^{N_{SB}\times N_{SB}}$ are the left-singular eigenvectors, singular matrix, and right-singular vectors corresponding to $\mathbf{H}_{SB,PR}$. The following precoding structure is proposed for $\mathbf{W}_P$ to simplify the optimization problem.

Proposition I: The precoding structure of $\mathbf{W}_P$ for the problem (16),

$$\mathbf{W}_P = \sigma_{p,1} \mathbf{V}_{SB,PR}(:,1) \tilde{\mathbf{h}}_{PB,SB}^H, \quad (19)$$

is able to maximize the achievable rate (14) and the harvested energy (8) at the PR simultaneously. Here, $\sigma_{p,1}$ is a scalar that should be further determined.

Proof: We ignore the detailed derivation due to the limited space.

Substituting the $\mathbf{W}_P$ in (19) into (16) and denoting λ_p = $\sigma_{p,1}^2$ and $\mathbf{Q}_S = \mathbf{w}_S \mathbf{w}_S^H$, the optimization problem (16) can be restated as the SDP given by

$$\max_{\rho, \mathbf{Q}_S, \lambda_p} \frac{\operatorname{tr}\left\{\mathbf{h}_{SB,SR}^H \mathbf{h}_{SB,SR} \mathbf{Q}_S\right\}}{\lambda_p \left(q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{n,SB}^2\right) \left\|\mathbf{h}_{SB,SR} \mathbf{V}_{SB,PR}(:,1)\right\|^2 + \sigma_{n,SR}^2}$$

$$\text{s.t. } \frac{\rho q_p \lambda_p \sigma_{SB,PR,1}^2 \left\|\mathbf{h}_{PB,SB}\right\|^2}{\sigma_{n,SB}^2 \rho \lambda_p \sigma_{SB,PR,1}^2 + \left(\rho \sigma_{n,PR}^2 + \sigma_{RF}^2\right)}$$

$$\geq 2^{\gamma_{PS}} - 1 - \frac{q_p}{\sigma_{n,PR}^2} \left\|\mathbf{h}_{PB,PR}\right\|^2$$

$$\eta(1-\rho)\Big(\operatorname{tr}\left\{\mathbf{H}_{SB,PR}^H \mathbf{H}_{SB,PR} \mathbf{Q}_S\right\} + q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 \lambda_p \sigma_{SB,PR,1}^2$$

$$+ \sigma_{n,SB}^2 \lambda_p \sigma_{SB,PR,1}^2 + N_{PR} \sigma_{n,PR}^2\Big) \geq 2\Gamma_{PS}$$

$$\mathbf{H}_{SB,PR} \mathbf{Q}_S = \mathbf{0}, \quad 0 \leq \rho \leq 1, \ \lambda_p \geq 0,$$

$$\operatorname{rank}(\mathbf{Q}_S) = 1$$

$$\operatorname{tr}\{\mathbf{Q}_S\} + \lambda_p \left(q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 \sigma_{n,SB}^2\right) \left\|\mathbf{V}_{SB,PR}(:,1)\right\|^2 \leq Q_{SB} \quad (20)$$

Even though the objective function now becomes linear fractional form of the designed parameters, the transferred optimization problem can not be easily solved in its current form. Resorting to the Charnes-Cooper transformation [11], we can equivalently transfer the linear fractional programming into a linear programming problem. Accordingly, by setting $u\mathbf{Q}_S = \mathbf{D}_S$ and $u\lambda_p = g_p$, the problem (20) can be transformed to an optimization problem shown as follows

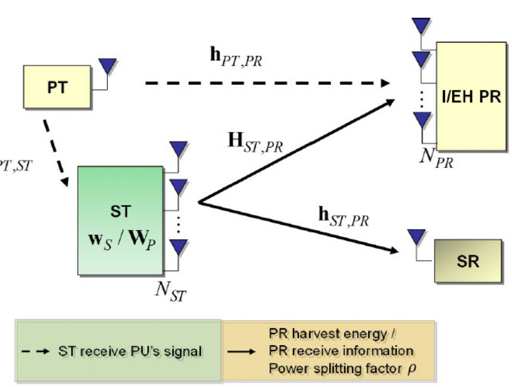

Fig. 1 The proposed EH-based HCR.

$$\max_{u, \rho, \mathbf{D}_S, g_p} \operatorname{tr}\left\{\mathbf{h}_{SB,SR}^H \mathbf{h}_{SB,SR} \mathbf{D}_S\right\}$$

s.t.

$$g_p \left(q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{n,SB}^2\right) \left\|\mathbf{h}_{SB,SR} \mathbf{V}_{SB,PR}(:,1)\right\|^2 + u\sigma_{n,SR}^2 = 1$$

$$g_p \rho \left(q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{SB,PR,1}^2 - \sigma_{n,SB}^2 \sigma_{SB,PR,1}^2 \left(2^{\gamma_{PS}} - 1 - \frac{q_p}{\sigma_{n,PR}^2} \left\|\mathbf{h}_{PB,PR}\right\|^2 \right) \right)$$

$$\geq u\left(\rho \sigma_{n,PR}^2 + \sigma_{RF}^2\right) \left(2^{\gamma_{PS}} - 1 - \frac{q_p}{\sigma_{n,PR}^2} \left\|\mathbf{h}_{PB,PR}\right\|^2 \right)$$

$$\eta(1-\rho)\Big(\operatorname{tr}\left\{\mathbf{H}_{SB,PR}^H \mathbf{H}_{SB,PR} \mathbf{D}_S\right\} + q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 g_p \sigma_{SB,PR,1}^2$$

$$+ \sigma_{n,SB}^2 g_p \sigma_{SB,PR,1}^2 + u N_{PR} \sigma_{n,PR}^2\Big) \geq 2u\Gamma_{PR}$$

$$\mathbf{H}_{SB,PR} \mathbf{D}_S = \mathbf{0}, \quad 0 \leq \rho \leq 1, \ g_p \geq 0,$$

$$\mathbf{D} \succeq \mathbf{0}, \quad \operatorname{rank}(\mathbf{D}_S) = 1,$$

$$\operatorname{tr}\{\mathbf{D}_S\} + g_p \left(q_p \left\|\mathbf{h}_{PB,SB}\right\|^2 + \sigma_{n,SB}^2\right) \left\|\mathbf{V}_{ST,PR}(:,1)\right\|^2 \leq uQ_{SB} \quad (21)$$

Herein, λ_p is replaced by g_p and the additional variable u is involved in the optimization. It is noted that (21) is not jointly convex in $(u, \rho, g_p, \mathbf{D}_S)$, whereas it is a standard SDP problem if ρ is foxed and rank relaxation is adopted for $\mathbf{D}_S$. Then, ρ can be solved numerically via one-dimensional search [12]. Accordingly, the SDP can be solved by using interior-point method. Generally, the SDR approach does not guarantee the rank-one solution. However, it is shown that the optimum solution for $\mathbf{D}_S$ is indeed rank-one, and thereby, the obtained solution is also optimum for the problem (21). The detailed derivation can be referred to Appendix.

IV. Numerical Results

The performance of the proposed information and energy cooperation strategy (marked as power splitting) is compared with that derived in [10] (marked as time switching). In the simulation, the channel links are assumed to be Rayleigh flat fading, and N_{SB} = 4 and N_{PR} = 3. The power value of the noise components are all normalized to unity, i.e., $\sigma_{n,SB}^2$ = $\sigma_{n,SR}^2$ = $\sigma_{n,PR}^2$ = 1.

The simulations are commenced by evaluating the performance of the two information and energy cooperation strategies with different values of the energy transfer efficiency. For both schemes, the system parameters are set as q_p = 20 dB, γ_{PS} = 1 bps/Hz, Γ_{PS} = 1, and ($\sigma_{PB,PR}^2$, $\sigma_{PB,SB}^2$, $\sigma_{SB,PR}^2$, $\sigma_{SB,SR}^2$) = (1,1,1,1). Fig. 2 shows the SS's information rate for various SB transmission power value. As shown in this figure, the SS's information rate increases with an increasing value of Q_{SB} in both strategies. This result is reasonable since the QoS requirement of the PS is easily satisfied, given a higher SB transmission power value, and hence, more power resource can be allocated to the SS. For the same reason, the SS's information rate also increases as the energy-transfer efficiency is increased for any fixed SB transmission power value. The results also reveal that the design in [10] outperforms the proposed strategy in low transmission power region of Q_{SB} , whereas the reverse is true in high transmission power region. This result arises since (i) the AF protocol is essentially non-beneficial in low transmission power region, yielding poor SNR values in the considered system; (ii) in [10], the PB can adaptively adjust the time switching factor governing the periods for ID and EH, respectively, whereas the time periods for which the relay receives or transmits the signals are fixed in the considered system. In contrasts, in high transmission power region, where the SB has sufficient power to meet the QoS requirements, the SB of the proposed design can use two different precoders with different directions and power values, leading to a better performance. The SB in [10], however, can only use a beamforming to maintain the EH QoS at the PR and to enhance the SS'S information rate.

Fig. 3 indicates the effect of the channel quality on the SS's information rate. Herein, q_p = 20 dB, γ_{PS} = 3 bps/Hz, Γ_{PS} = 10 and ($\sigma^2_{PB,PR}$, $\sigma^2_{PB,SB}$, $\sigma^2_{SB,PR}$, $\sigma^2_{SB,SR}$) = (1,1,1,1), (2,1,1,1), (0.5,1,1,1), (1,2,1,1), (1,0.5,1,1), (1,1,2,1),(1,1,0.5,1), (1,1,1,2) and (1,1,1,0.5). It is seen that channel qualities of (1,1,1,2) and (1,1,1,0.5) yield the best and worst performance, respectively. This is due to the fact two cases differ only in the variance of the SB-PR link, and the SS's information rate is improved with an increasing SB-SR channel quality, and vice versa. Also, we can observe that in the low-to-medium SB transmission power region, the proposed strategy achieves the best performance given the channel quality of (1,1,2,1). The reason follows from the fact that a larger value of Q_{SB} can dramatically improve the SNR at the PR and facilitate the QoS satisfaction in the low SNR region.

V. CONCLUSIONS

In this paper, an information and energy cooperation strategy is proposed for an EH-based HCR network. The basic premise of the proposed strategy is that the SS provides energy to the PS, while the PS offers an opportunity to access the spectrum to the SS in return. Owing to the overlay protocol, the EH device operates in a power splitting mode, and the information and energy transfer are optimized through the joint design of the two precoders at the SB and the power splitting factor at the PR. The optimum precoder is determined by means of an SDR approach. The numerical results have shown that the proposed cooperation strategy can improve both the information rate and energy transfer efficiency, especially for a better PB-SB-PR link.

VI. APPENDIX

Let $\mathbf{A}_1 = \mathbf{h}^H_{SB,SR}\mathbf{h}_{SB,SR}$ and $\mathbf{A}_2 = \mathbf{H}^H_{SB,PR}\mathbf{H}_{SB,PR}$. For a fixed value of ρ , the problem (21) can be restated as

$$\begin{aligned}&\min_{u,g_p,\mathbf{D}_S} \operatorname{tr}\{\mathbf{A}_1\mathbf{D}_S\}\\ &h_1(g_p,u)=0;\ \ \mathbf{H}_{SB,PR}\mathbf{D}_S=\mathbf{0};\\ &g_1(g_p,u)\le 0;\ \ g_2(\mathbf{D}_S,g_p,u)\le 0;\ \ g_3(\mathbf{D}_S,g_p,u)\le 0\\ &-g_p\le 0;\ \ \mathbf{D}_S\succeq 0,\end{aligned} \tag{22}$$

where h_1 , g_1 , g_2 , g_3 are defined as follows.

$$h_1(g_p,u)=g_p\left(q_p\left\|\mathbf{h}_{PB,SB}\right\|^2+\sigma^2_{n,SB}\right)\left|\mathbf{h}_{SB,SR}\mathbf{V}_{SB,PR}(:,1)\right|^2+u\sigma^2_{n,SR}-1 \tag{23-1}$$

$$\begin{aligned}g_1(g_p,u)&=u\left(\rho\sigma^2_{n,PR}+\sigma^2_{RF}\right)\left(2^{\gamma_{PS}}-1-\frac{q_p}{\sigma^2_{n,PR}}\left\|\mathbf{h}_{PB,PR}\right\|^2\right)\\ &-\rho\left(q_p\left\|\mathbf{h}_{PB,SB}\right\|^2\sigma^2_{SB,PR,1}-\sigma^2_{n,SB}g_p\sigma^2_{SB,PR,1}\left(2^{\gamma_{PS}}-1-\frac{q_p}{\sigma^2_{n,PR}}\left\|\mathbf{h}_{PB,PR}\right\|^2\right)\right)\end{aligned} \tag{23-2}$$

$$\begin{aligned}g_2(\mathbf{D}_S,g_p,u)&=2u\Gamma_{PS}-\eta(1-\rho)\Big(\operatorname{tr}\{\mathbf{H}^H_{SB,PR}\mathbf{H}_{SB,PR}\mathbf{D}_S\}+\\ &q_pg_p\sigma^2_{SB,PR,1}\left\|\mathbf{h}_{PB,SB}\right\|^2+\sigma^2_{n,SB}g_p\sigma^2_{SB,PR,1}+uN_{PR}\sigma^2_{n,PR}\Big)\end{aligned} \tag{23-3}$$

$$g_3(\mathbf{D}_S,g_p,u)=\operatorname{tr}\{\mathbf{D}_S\}+g_p\left(q_p\left\|\mathbf{h}^2_{PB,SB}\right\|^2+\sigma^2_{n,SB}\right)\left\|\mathbf{V}_{SB,PR}(:,1)\right\|^2-uQ_{SB} \tag{23-4}$$

The corresponding Lagrangian function is then written as

$$\begin{aligned}L(\mathbf{D}_S,g_p,u)&=-\operatorname{tr}\{\mathbf{A}_1\mathbf{D}_S\}+\mu_1h_1(g_p,u)+\\ &\mu_2^T\operatorname{vec}(\mathbf{H}_{SB,PR}\mathbf{D}_S)+\lambda_1g_1(g_p,u)+\lambda_2g_2(\mathbf{D}_S,g_p,u)\\ &+\lambda_3g_3(\mathbf{D}_S,g_p,u)-\lambda_4g_p-\operatorname{tr}\{\mathbf{\Lambda}_5\mathbf{D}_S\},\end{aligned} \tag{24}$$

where $\mu_1\in\mathbb{R}$, $\mu_2\in\mathbb{R}^{N_{SB}N_{PR}\times 1}$, $\lambda_i\ge 0$, i=1,⋯,4, and $\mathbf{\Lambda}_5\succeq\mathbf{0}$ are the Lagrangian multipliers. The dual function for (22) is then given by

$$\begin{aligned}&g(\mu_1,\mu_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,\Lambda_5)\\ &=\inf_{\mathbf{D}_S\succeq\mathbf{0},g_p,\mu}L(\mathbf{D}_S,g_p,u)=-\mu_1,\end{aligned} \tag{25}$$

providing that those KKT conditions in (26)-(29) are held.

$$\begin{aligned}&\mu_1\sigma^2_{n,SR}+\lambda_1\left(\eta\sigma^2_{n,PR}+\sigma^2_{RF}\right)\left(2^{\gamma PS}-1-\frac{q_p}{\sigma^2_{n,PR}}\left\|\mathbf{h}_{PB,PR}\right\|^2\right)\\ &+\lambda_2\left(2\Gamma_{PS}-\eta(1-\rho)N_{PR}\sigma^2_{n,PR}\right)-\lambda_3Q_{SB}=0\end{aligned} \tag{26}$$

$$\begin{aligned}&\mu_1\left(q_p\left\|\mathbf{h}_{PB,SB}\right\|^2+\sigma^2_{n,SB}\right)\left|\mathbf{h}_{SB,SR}\mathbf{V}_{SB,PR}(:,1)\right|-\\ &\lambda_1\rho q_p\left\|\mathbf{h}_{PB,SB}\right\|^2\sigma^2_{SB,PR,1}-\lambda_2\eta(1-\rho)\left(q_p\left\|\mathbf{h}_{PB,SB}\right\|^2\sigma^2_{SB,PR,1}+\sigma^2_{n,SB}\sigma^2_{SB,PR,1}\right)\\ &-\lambda_3\left(q_p\left\|\mathbf{h}_{PB,SB}\right\|^2+\sigma^2_{n,SB}\right)\left\|\mathbf{V}_{SB,PR}(:,1)\right\|^2-\lambda_4\ge 0\end{aligned} \tag{27}$$

$$\mathbf{H}_{SB,PR}\mathbf{D}_S=\mathbf{0} \tag{28}$$

$$\mathbf{\Lambda}_5 = \lambda_3 \mathbf{I} + \lambda_2 \eta (1-\rho) \mathbf{A}_2 - \mathbf{A}_1 \tag{29}$$

Conditions (26)-(29) make the dual problem feasible. The corresponding dual problem is then given by

$$\begin{aligned} &\max_{\mu_1,\mu_2,\lambda_1,\lambda_2,\lambda_3,\lambda_4,\mathbf{\Lambda}_5 \succeq \mathbf{0}} -\mu_1 \\ &\text{s.t.} \\ &(26),\ (27),\ (28), \\ &\mathbf{\Lambda}_5 = \underbrace{\lambda_3 \mathbf{I} + \lambda_2 \eta (1-\rho) \mathbf{A}_2}_{:=\mathbf{\Phi}} - \mathbf{A}_1 \succeq \mathbf{0} \end{aligned} \tag{30}$$

From the complementary slackness condition of (22), we have

$$\mathbf{\Lambda}_5 \mathbf{D}_S = \mathbf{0}. \tag{31}$$

If the optimum dual variables λ_2 and λ_3, denoted as λ_2^* and λ_3^*, respectively, are λ_2^* = λ_3^* = 0, then μ_1 = λ_1 = 0 by (26) and (27). Therefore, λ_2^* and λ_3^* cannot be zero simultaneously, and $\mathbf{\Phi}$ is a full-rank matrix consequently. Since $\mathbf{A}_1$ is a rank-one matrix, the rank of $\mathbf{\Lambda}_5$ is either N_{SB} or N_{SB} - 1. If the rank of $\mathbf{\Lambda}_5$ is N_{SB}, then $\mathbf{D}_S$ = 0 which violates the constraint g_2 or does not reach to the optimum value of the primal problem. Therefore, the rank of $\mathbf{\Lambda}_5$ must be N_{SB} - 1. Thus, $\mathbf{D}_S$ have to lies in the null space of $\mathbf{\Lambda}_5$ whose dimension is one.

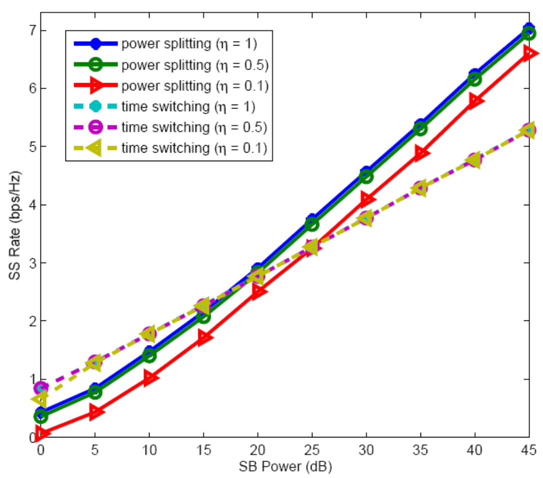

Fig 2. SS's rate v.s. SB's power (γ_{PS} = 1 bps/Hz, Γ_{PS} = 1).

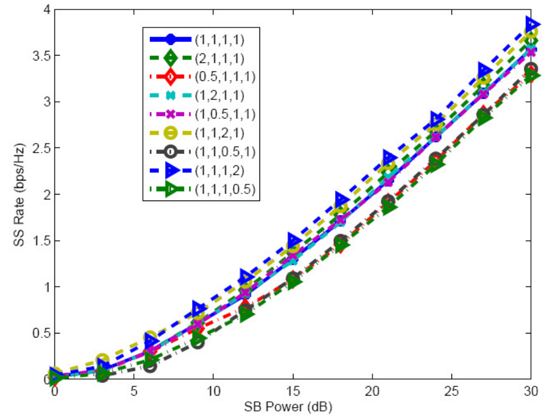

Fig. 3 SS's rate v.s. SB's power in the proposed overlay HCR (γ_{PS} = 3 bps/Hz, Γ_{PS} = 10).

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