Energy Harvesting In Cellular Underlay Cognitive Networks: Rate-Energy Trade-off Characterization

Ali Kariminezhad and Aydin Sezgin
Institute of Digital Communication Systems
RUB, 44780 Bochum, Germany
Email: ali.kariminezhad@rub.de, aydin.sezgin@rub.de

***Abstract*—In classical communications, information massage has been considered as the only entity to be transferred between communicating pairs. However, recently by the feasibility of energy harvesting at the hand-held devices, the power transmission is of great importance as well. Thus, the users demand for both information rate and radio frequency (RF) signal energy. Due to the natural trade-off between rate and energy demands, we study the optimal transmission in underlay cognitive cellular networks, where the primary users demand information and energy at a particular time instant. On one hand, in order to satisfy the energy demands of the primary users, the transmitters of the secondary users are activated which deteriorates the achievable rates of the primary users on the other hand. The rate region of the primary users is studied while utilizing power splitting at the receivers for joint information detection and energy harvesting purposes. In order to deliver the outer-most boundary of the rate region, we formulate the weighted max-min optimization problem well-known as weighted Chebyshev problem. Numerically, we show the influence of energy harvesting constraint on the rate region of primary users.**

***Index Terms*—Gaussian signaling, cognitive networks, TIN, energy harvesting, achievable rate region.**

I. INTRODUCTION

Future wireless networks are expected to fulfil ever-increasing demands of the mobile customers. In classical communication networks, the demands are limited to information rates. However, the users might demand energy in order to remain functional in the network. This energy can not be provided by plug-in recharging sometimes and it needs to be provided in a wireless fashion. Hence, power transmission is of particular interest recently [1]. The energy of RF signals can be captured by various receiver realizations. For instant, by implementing a power splitter at the receivers, the incident RF signal is split into two portions. The energy of one portion diverted to the energy harvesting chain in order to load the energy buffer, while the other portion is diverted to the information detection chain [1]. Time sharing (TS) is an alternative for joint information detection and energy harvesting purposes. In the TS receiver structure, information detection and energy harvesting chains are activated in separate time instants. Yet another receiver structure is antenna separation which allows joint information detection and energy harvesting. Here, at one antenna the energy of the incident signal is captured, while at the other antenna the information out of the received signal is extracted [1].

The incident RF signal contains desired signal energy and the energy of the interference. This interference is due to sharing the resources between different communicating pairs, which deteriorates the achievable information rates of the users. However we can exploit the energy of the interference to fulfil the energy demands. This trade-off requires the study of the optimal operating states of communication network [2].

The authors in [3] propose small cell deployment for future communication networks. In such networks, the users located in small cells are served by the local base stations, e.g. radio access points (RAPs). In this paper we consider this network structure and study the achievable rates with energy harvesting constraints. Furthermore, we prioritize the user by assuming cognition in the network, so that a multiple-antenna main base station serves single-antenna primary users. As shown in Fig. 1, multiple-antenna radio access-points (RAPs) are deployed to support single-antenna secondary users located in sub-regions (femto cells). The communication in a femto cell takes place only under constraint set by the quality of service (QoS) demands of the primary users, i.e., the secondary users underlay the primary system. This kind of cognitive network is well-known as underlay cognitive networks [4], [5], [6]. In this underlay cognitive network with femto cell deployment, the primary users are equipped with PS receiver structure for joint information detection and energy harvesting.

In such a network, the outer-most boundary of the rate region achieved by the primary users is studied. In order to characterize this boundary, we formulate a weighted max-min optimization problem [7]. The proposed problem is non-convex due to certain constraints. The problem is reformulated as a semi-definite program (SDP) [8]. The non-convex constraints are relaxed and the semi-definite relaxation (SDR) is solved by joint bisection and interior-point methods [9].

II. SYSTEM MODEL

In this work, we consider an underlay cognitive network, where the primary users in a macro-cell are served by the BS, while the secondary users in femto-cells are served by RAPs, Fig. 1. The channel input-output relationship is

$$y_i = \mathbf{h}_{iB}^H \mathbf{x}_B + \sum_{k=1}^{K} \mathbf{g}_{ib_k}^H \mathbf{x}_{b_k} + n_i, \tag{1}$$

$$z_{jk} = \mathbf{h}_{jkB}^H \mathbf{x}_B + \sum_{k=1}^{K} \mathbf{g}_{jkb_k}^H \mathbf{x}_{b_k} + w_j, \tag{2}$$

where y_i and z_{jk} are the received signals at the i^{th} primary user and the j^{th} secondary user located in the k^{th} femto cell,

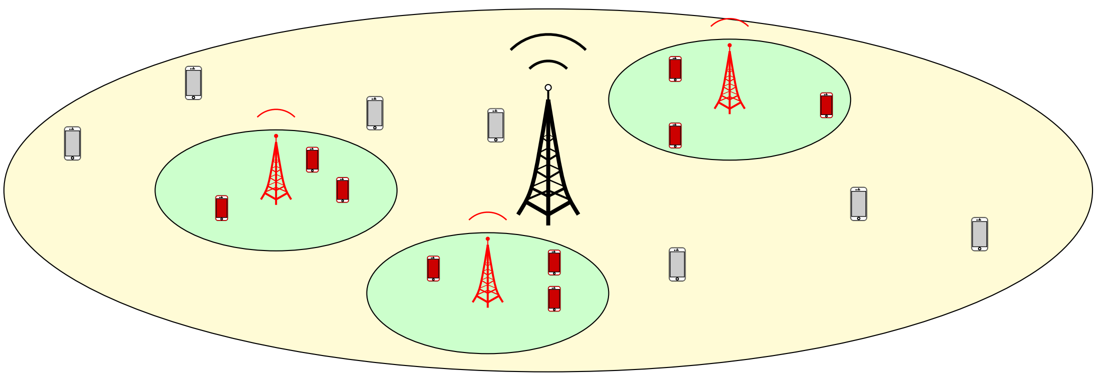


Fig. 1. The primary users in the macro-cell are served by the BS. They demand both information and energy. Furthermore, the secondary users in the femto cells underlay the primary system, i.e., the secondary users are allowed to be active if they fulfil the demands of the primary system. The transmitters are equipped with multiple antennas, while the receivers have single antenna each.

respectively. The associated receiver noises are represented by n_i and w_j which are zero-mean AWGN with variance σ_n^2 and σ_w^2, respectively. The channel vector between the i^{th} primary user and the RAP of the k^{th} femto cell is represented by $\mathbf{g}_{ib_k}$, while the channel between the i^{th} primary user and the BS is represented by $\mathbf{h}_{iB}$. The channel from the BS and the k^{th} RAP to the j^{th} secondary user located in the k^{th} femto cell are given by $\mathbf{h}_{jkB}$ and $\mathbf{g}_{jkb_k}^H$, respectively. The transmitted signal from the BS and the k^{th} femto cell RAP are denoted as $\mathbf{x}_B$ and $\mathbf{x}_{b_k}$, respectively. Assuming linear beamforming at the transmitters, we can formulate the transmit signals as

$$\mathbf{x}_B = \sum_{i=1}^{N_B} \mathbf{v}_i d_i = \mathbf{V}\mathbf{d}, \tag{3}$$

$$\mathbf{x}_{b_k} = \sum_{j=1}^{N_{b_k}} \mathbf{u}_{kj} d_{kj}^{'} = \mathbf{U}_k \mathbf{d}_k^{'}, \tag{4}$$

where the information symbols intended for the i^{th} user in the macro-cell and the j^{th} user in the k^{th} femto-cell are represented by d_i and $d_{kj}^{'}$, respectively. These information symbols are beamformed in direction of $\mathbf{v}_i$ and $\mathbf{u}_{kj}$, which are the i^{th} and j^{th} columns of $\mathbf{V}$ and $\mathbf{U}_k$, respectively. The vectors $\mathbf{d}$ and $\mathbf{d}_k$ are the information vectors for the primary users and the secondary users in the k^{th} femto cell, respectively. We assume that the users demand independent information and the primary users demand energy at a particular time instant as well. The quantity of transmit antennas at the BS and the k^{th} RAP are denoted by N_B and N_{b_k}, respectively.

The achievable rates of any communicating pairs in the network depends on the variance of the desired signal and interference-plus-noise. The received signal variances at the users are written is (5) and (6) on top of the next page, where the first terms, C_{d_i} and $C_{d_{jk}^{'}}$ are the desired signal variances at the i^{th} primary user and j^{th} secondary user located in the k^{th} femto cell, respectively. The terms C_{n_i} and $C_{w_{jk}}$ are the variances of interference-plus-noise. It is important to note that,

$$\mathbf{C}_{B_i} = \mathbf{v_i}\mathbb{E}\{d_i d_i^H\}\mathbf{v}_i^H, \tag{7}$$

$$\mathbf{C}_{b_{kj}} = \mathbf{u}_{kj}\mathbb{E}\{d_{kj}^{'} d_{kj}^{'H}\}\mathbf{u}_{kj}^H, \tag{8}$$

are the transmit covariance matrices of the i^{th} signal vector in the macro-cell and the j^{th} signal vector in the k^{th} femto-cell, respectively. The transmit signal power at the BS and k^{th} femto cell RAP are represented by $\mathbb{E}\{\mathbf{d}\mathbf{d}^H\}$ and $\mathbb{E}\{\mathbf{d}_k^{'}\mathbf{d}_k^{'H}\}$, respectively. Moreover, notice that the BS and the k^{th} RAP transmit covariance matrices are

$$\mathbf{C}_B = \sum_{i=1}^{M} \mathbf{C}_{B_i}, \tag{9}$$

$$\mathbf{C}_{b_k} = \sum_{j=1}^{Q_k} \mathbf{C}_{b_{kj}}, \tag{10}$$

respectively for M primary users and Q_k secondary users located in k^{th} femto cell. For convenience, we assume that the transmit signal power is embedded into the beamforming vectors, thus

$$\mathbb{E}\{\mathbf{d}\mathbf{d}^H\} = 1, \quad \mathbb{E}\{\mathbf{d}_k^{'}\mathbf{d}_k^{'H}\} = 1, \tag{11}$$

$$P_B = \mathrm{Tr}(\mathbf{V}_B\mathbf{V}_B^H), \tag{12}$$

$$P_{b_k} = \mathrm{Tr}(\mathbf{V}_{b_k}\mathbf{V}_{b_k}^H), \tag{13}$$

where P_B and P_{b_k} are the transmit power of BS and the RAP located in the k^{th} femto cell. In order to formulate the achievable rates we assume Gaussian signaling at the transmitters while the incident interference is treated a noise (TIN). Thus, the achievable rates are formulated as

$$r_i \leq \log\left(1 + \frac{C_{d_i}}{C_{n_i}}\right) = R_i, \tag{14}$$

$$r_{jk}^{'} \leq \log\left(1 + \frac{C_{d_{jk}^{'}}}{C_{w_{jk}}}\right) = R_{jk}^{'}, \tag{15}$$

where C_{d_i}, C_{n_i}, $C_{d_{jk}^{'}}$ and $C_{w_{jk}}$ are given in (5) and (6).

The amount of RF energy captured by the users are given by

$$e_i \leq C_{y_i} - \sigma_n^2 = E_i, \tag{16}$$

$$e_{jk}^{'} \leq C_{z_{jk}} - \sigma_w^2 = E_{jk}^{'}. \tag{17}$$

By formulating the achievable information rates and harvested RF energies at the users, we can proceed with the optimization problem in the next section.

$$C_{y_i} = \underbrace{\mathbf{h}_{iB}^H \mathbf{C}_{B_i} \mathbf{h}_{iB}}_{C_{d_i}} + \underbrace{\sum_{\substack{m=1 \\ m \neq i}}^{M} \mathbf{h}_{iB}^H \mathbf{C}_{B_m} \mathbf{h}_{iB} + \sum_{k=1}^{K} \mathbf{g}_{ib_k}^H \mathbf{C}_{b_k} \mathbf{g}_{ib_k} + \sigma_n^2}_{C_{n_i}}, \tag{5}$$

$$C_{y'_{jk}} = \underbrace{\mathbf{g}_{jkb_k}^H \mathbf{C}_{b_{kj}} \mathbf{g}_{jkb_k}}_{C_{d'_{jk}}} + \underbrace{\sum_{\substack{q=1 \\ q \neq j}}^{Q_k} \mathbf{g}_{jkb_k}^H \mathbf{C}_{b_{kq}} \mathbf{g}_{jkb_k} + \sum_{\substack{l=1 \\ l \neq k}}^{K} \mathbf{g}_{jkb_k}^H \mathbf{C}_{b_k} \mathbf{g}_{jkb_k} + \mathbf{h}_{jkB}^H \mathbf{C}_B \mathbf{h}_{jkB} + \sigma_w^2}_{C_{w_{jk}}}, \tag{6}$$

$$R_i^{(\eta)} = \log \left(1 + \frac{\eta \mathbf{h}_{iB}^H \mathbf{C}_{B_i} \mathbf{h}_{iB}}{\eta \left(\sum_{\substack{m=1 \\ m \neq i}}^{M} \mathbf{h}_{iB}^H \mathbf{C}_{B_m} \mathbf{h}_{iB} + \sum_{k=1}^{K} \mathbf{g}_{ib_k}^H \mathbf{C}_{b_k} \mathbf{g}_{ib_k} \right) + \sigma_n^2} \right), \tag{18}$$

$$E_i^{(\eta)} = (1-\eta) \left(\mathbf{h}_{iB}^H \mathbf{C}_{B_i} \mathbf{h}_{iB} + \sum_{k=1}^{K} \mathbf{g}_{ib_k}^H \mathbf{C}_{b_k} \mathbf{g}_{ib_k} \right). \tag{19}$$

III. Optimization Problems

In this section, we formulate the appropriate optimization problems in order to characterize the achievable rate region of the primary users with EH constraints. The achievable rate regions are characterized by formulating the appropriate Chebyshev objective functions. The primary users demand information and energy at the same time and as already mentioned, this can be achieved, for instance by PS receivers. The rate region of the primary users' are enlarged in case of silent RAPs, however the energy demands might not be satisfied in this case. Thus, depending on the demands of the primary users', the secondary users' beamforming strategy change. By defining $0 < \eta < 1$ as the power splitting factor, a portion of the received signal power is diverted to the EH chain which is ηC_{y_i} and the other portion is diverted to the ID chain, $(1-\eta) C_{y_i}$. Hence, considering the power splitting coefficient, the primary users' achievable information rates and harvested energies are formulated in (18) and (19), respectively on top of the page.

Now, we formulate the weighted max-min problem [7], as

$$\max_{\substack{\eta, \mathbf{C}_{B_i}, \mathbf{C}_{b_{kj}} \\ \forall i,j,k}} \min_i \left(\frac{R_i^{(\eta)}}{\alpha_i} \right), \tag{20}$$

$$\text{s.t. } \psi_i \leq E_i^{(\eta)}, \quad \forall i, \tag{20a}$$
$$0 \leq \text{Tr}(\mathbf{C}_B) \leq P_B^{\max}, \tag{20b}$$
$$0 \leq \text{Tr}(\mathbf{C}_{b_k}) \leq P_{b_k}^{\max}, \quad \forall k, \tag{20c}$$
$$\mathbf{C}_B \succeq 0, \tag{20d}$$
$$\mathbf{C}_{b_k} \succeq 0, \quad \forall k, \tag{20e}$$
$$\text{rank}(\mathbf{C}_{B_i}) = 1, \quad \forall i, \tag{20f}$$
$$\text{rank}(\mathbf{C}_{b_k}) = 1, \quad \forall k, \tag{20g}$$

where $P_B^{\max}$ and $P_{b_k}^{\max}$ are the maximum available transmit power at the BS and the RAP located in the k^{th} femto cell, respectively. The first constraint in (20) manifests the energy demands $\psi_i, \forall i$, of the primary users, $1 \leq i \leq M$. In order to get feasible beamforming solutions, the covariance matrices should be rank-1 Hermitian positive semi-definite as stated in (20d) and (20e). We will solve this problem for given $0 < \alpha_i < 1, \forall i$, $\sum_{i=1}^{M} \alpha_i = 1$, to obtain an outer-most achievable rate tuples in the direction of $\boldsymbol{\alpha} = [\alpha_1, ..., \alpha_M]$. Thus, the outer-most boundary of the rate region can be obtained by solving the problem in different directions of $\boldsymbol{\alpha}$ which cover the positive quadrant of $\mathbb{R}^M$, [7]. We can merge the objective function into the constraint set by defining an auxiliary variable $\Gamma = \min_i \left(\frac{R_i^{(\eta)}}{\alpha_i} \right)$. Then the optimization problem is written as

$$\max_{\substack{\Gamma, \eta, \mathbf{C}_{B_i}, \\ \mathbf{C}_{b_{kj}}, \forall i,j,k}} \Gamma \tag{21}$$

$$\text{s.t. } \Gamma \leq \frac{R_i^{(\eta)}}{\alpha_i}, \quad \forall i \tag{21a}$$
$$\text{s.t.} (20a) - (20g).$$

The optimization problem (21) is a non-convex problem due to the non-convex constraints, e.g. (21a).

By defining $\mathbf{H}_{iB} = \mathbf{h}_{iB} \mathbf{h}_{iB}^H$ and $\mathbf{G}_{ib_k} = \mathbf{g}_{ib_k} \mathbf{g}_{ib_k}^H$ we can formulate problem (21) as a semi-definite program (SDP) as stated in (22) on top of the next page. By relaxing the rank-1 constraints and bisecting over Γ, the problem simplifies to a convex problem for a given η. Hence, the problem can be efficiently solved by a feasibility check [7]. Further, outer-most boundary can be obtained by exhaustive search over the scalar variable η. The feasibility of (22) for a given η and Γ with relaxed constraints is expressed as

$$\text{find} \quad \mathbf{C}_{B_i}, \mathbf{C}_{b_{kj}}, \quad \forall i,j,k \tag{23}$$
$$\text{s.t.} (22a), \ (22b), \ (20b) - (20e).$$

If a solution exists for a fixed η and given Γ, then the acquired solutions are feasible but not optimal. Obtaining of the optimal

$$\max_{\substack{\Gamma,\eta,\mathbf{C}_{B_i},\\ \mathbf{C}_{b_{kj}},\ \forall i,j,k}} \quad \Gamma \tag{22}$$

$$\text{s.t. } \Gamma \leq \frac{1}{\alpha_i}\log\left(1+\frac{\eta \mathrm{Tr}(\mathbf{H}_{iB}\mathbf{C}_{B_i})}{\eta\left(\sum_{\substack{m=1\\ m\neq i}}^{M}\mathrm{Tr}(\mathbf{H}_{iB}\mathbf{C}_{B_m})+\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{G}_{ib_k}\mathbf{C}_{b_k})\right)+\sigma_n^2}\right), \quad \forall i \tag{22a}$$

$$\psi_i \leq (1-\eta)\left(\mathrm{Tr}(\mathbf{H}_{iB}\mathbf{C}_{B})+\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{G}_{ib_k}\mathbf{C}_{b_k})\right), \quad \forall i \tag{22b}$$

$$(20b)-(20g)$$

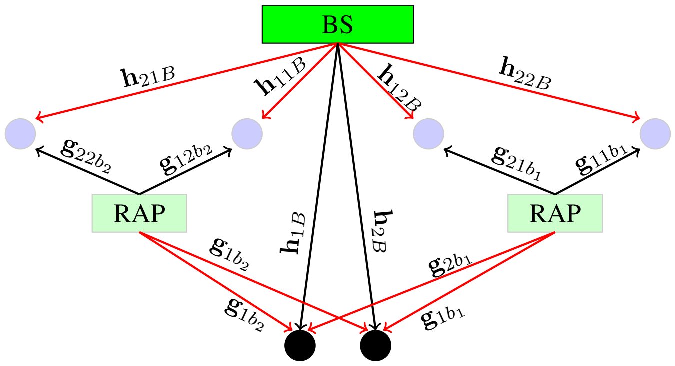


Fig. 2. The channel vectors between the transmitters and receivers are shown in case of limiting the number of primary users, Femto-cells, and number of users in each femto cell to two. For clarity in illustration, the inter-femto cell interference is not depicted. The transmitters are equipped with multiple transmit antennas.

solution requires bisection over Γ and exhaustive search over η. If the solutions are intrinsically rank-1, then the optimal beamforming vectors can be extracted out of rank-1 solutions by eigen-value decomposition (EVD), otherwise we get a sub-optimal rank-1 solution out of the higher rank solutions by Gaussian randomization [8], [10], [11], [12].

IV. Numerical Results

Without loss of generality and for convenience is presentation, we assume $M = Q_k = K = N_B = N_{b_k} = 2$. The illustration of the system with the respective channels is given in Fig. 2. The channels are known at the transmitters and given in Table I.

The performance of the system is evaluated by determining the outer-most boundary of the achievable rate region of the primary users with energy harvesting constraints. Practically, by splitting the signal into two portions by an optimal power splitting factor η, the rate region boundary is examined. In order to satisfy the energy constraints of the primary users, the RAPs need to transmit power in an optimal direction. If the RAPs form their beams in the direction of the primary users' channels, the maximum energy will be delivered to the primary users, but the achievable rate deteriorates. Thus the optimal direction neither favours rate nor energy solely, but considers both of them jointly. Figure 3, compares the achievable rates of the primary users with and without energy

Primary users' channels	
$\mathbf{h}_{1B}$	$[0.94e^{2.61i} \quad 0.34e^{-1.61i}]^T$
$\mathbf{h}_{2B}$	$[0.92e^{0.44i} \quad 0.4e^{1.6i}]^T$
$\mathbf{g}_{1b_1}$	$[0.63e^{-0.16i} \quad 0.77e^{0.42i}]^T$
$\mathbf{g}_{1b_2}$	$[0.61e^{-0.22i} \quad 0.79e^{0.33i}]^T$
$\mathbf{g}_{2b_1}$	$[0.80e^{-1.39i} \quad 0.60e^{-1.12i}]^T$
$\mathbf{g}_{2b_2}$	$[0.97e^{1.95i} \quad 0.25e^{-1.21i}]^T$
secondary users' channels	
$\mathbf{h}_{11B}$	$[0.37e^{-0.94i} \quad 0.93e^{2.88i}]^T$
$\mathbf{h}_{12B}$	$[0.98e^{0.21i} \quad 0.78e^{-1.87i}]^T$
$\mathbf{h}_{21B}$	$[0.68e^{-0.36i} \quad 0.73e^{0.83i}]^T$
$\mathbf{h}_{22B}$	$[0.57e^{1.66i} \quad 0.82e^{0.76i}]^T$
$\mathbf{g}_{11b_1}$	$[0.43e^{0.82i} \quad 0.9e^{2.21i}]^T$
$\mathbf{g}_{12b_1}$	$[0.56e^{1.25i} \quad 0.83e^{-2.17i}]^T$
$\mathbf{g}_{21b_1}$	$[0.63e^{0.98i} \quad 0.77e^{-0.28i}]^T$
$\mathbf{g}_{22b_1}$	$[0.88e^{-1.91i} \quad 0.47e^{2.08i}]^T$
$\mathbf{g}_{11b_2}$	$[0.60e^{1.34i} \quad 0.80e^{-1.99i}]^T$
$\mathbf{g}_{12b_2}$	$[0.78e^{-0.67i} \quad 0.62e^{0.07i}]^T$
$\mathbf{g}_{21b_2}$	$[0.65e^{1.88i} \quad 0.76e^{2.23i}]^T$
$\mathbf{g}_{22b_2}$	$[0.54e^{-3.14} \quad 0.84e^{2.20i}]^T$

TABLE I
CHANNEL REALIZATION H1 (UNIT-NORM CHANNEL)

harvesting constraints for two channel realizations (see Table I and Table II). Power transmission by the RAPs help the primary users in satisfying their energy demands, however it reduces the achievable rates of the primary system (for channel realization H1). We explain the two extreme points on the curves that have analytical solutions. The maximum rate of the 1^{st} primary user is achieved in case of full power allocation and maximum ratio transmission (MRT) by the BS for the signal of that user. This operating point is named "A" on the figure. Note that, in order to achieve this point, the RAPs have two options,

- Remain silent: This case is not optimal for the secondary users, since they achieve zero information rates.
- Zero-Forcing: This case is rate-optimal for the secondary users, while on one side point "A" is still achievable and

Primary users' channels	
$\mathbf{h}_{1B}$	$[1.90e^{2.75i} \quad 2.31e^{2.15i}]^T$
$\mathbf{h}_{2B}$	$[1.09e^{2.51i} \quad 2.79e^{-1.33i}]^T$
$\mathbf{g}_{1b_1}$	$[0.76e^{-3.08i} \quad 0.64e^{0.42i}]^T$
$\mathbf{g}_{1b_2}$	$[0.21e^{-0.33i} \quad 0.97e^{-0.89i}]^T$
$\mathbf{g}_{2b_1}$	$[0.49e^{1.12i} \quad 0.86e^{1.72i}]^T$
$\mathbf{g}_{2b_2}$	$[0.78e^{-2.26i} \quad 0.61e^{1.62i}]^T$
secondary users' channels	
$\mathbf{h}_{11B}$	$[0.29e^{-0.71i} \quad 0.95e^{-1.54i}]^T$
$\mathbf{h}_{12B}$	$[0.59e^{0.92i} \quad 0.80e^{1.16i}]^T$
$\mathbf{h}_{21B}$	$[0.75e^{-2.93i} \quad 0.65e^{1.08i}]^T$
$\mathbf{h}_{22B}$	$[0.63e^{0.18i} \quad 0.77e^{-1.10i}]^T$
$\mathbf{g}_{11b_1}$	$[2.66e^{-1.24i} \quad 1.38e^{2.00i}]^T$
$\mathbf{g}_{12b_1}$	$[0.91e^{-1.93i} \quad 0.40e^{-0.13i}]^T$
$\mathbf{g}_{21b_1}$	$[2.74e^{-2.31i} \quad 1.20e^{-2.73i}]^T$
$\mathbf{g}_{22b_1}$	$[0.35e^{0.19i} \quad 0.93e^{0.68i}]^T$
$\mathbf{g}_{11b_2}$	$[0.36e^{-1.11i} \quad 0.93e^{-0.40i}]^T$
$\mathbf{g}_{12b_2}$	$[1.84e^{-1.13i} \quad 2.36e^{0.56i}]^T$
$\mathbf{g}_{21b_2}$	$[0.67e^{0.95i} \quad 0.73e^{-2.38i}]^T$
$\mathbf{g}_{22b_2}$	$[2.35e^{1.77i} \quad 1.85e^{1.48i}]^T$

TABLE II
CHANNEL REALIZATION H2

on the other side, the secondary system achieves non-zero rates. By zero-forcing, the RAPs direct their beams in a direction which is orthogonal to the channel of the 1^{st} primary user. Hence, does not deteriorate the achievable rate of the primary user.

The same arguments can be made for the achievable rate depicted by "B" on the figure. Moreover, the achievable rate of our linear precoding is compared with a complex non-linear scheme which is dirty-paper coding (DPC).It is of importance to mention that, DPC is the capacity achieving scheme for our setup in absence of energy harvesting constraints [13], [14]. In the presence of EH constraints, the convex hull of the achievable rate region by DPC and TS can be considered as an upper-bound for the linear scheme used in this paper.
It is important to note that, EH constraints of 5, 10, 15 are fulfilled by channel realization H2 without degradation in the achievable rate region in case of linear precoding. This is due to satisfying the energy constraints while remaining in the optimal performance from the rate perfective. It is interesting to see that, the rate region achieved by DPC is degraded for this channel realization. Table III compares the achievable rates in the network for the channel realization H1. For the case that the primary users demand 10 units of energy, the secondary system's achievable rates are improved due to information-embedded power transmission. Information-embedded power transmission helps the primary system by energy and favours the secondary users by information rates.

Without EH constraints					
r_1	r_2	r'_{11}	r'_{21}	r'_{12}	r'_{22}
0.00	3.46	0.02	0.2	0.16	0.11
0.75	1.62	0.00	0.00	0.00	0.00
1.21	1.1	0.00	0.00	0.00	0.00
3.46	0.00	0.11	0.23	0.15	0.0064
With EH constraints=10					
r_1	r_2	r'_{11}	r'_{21}	r'_{12}	r'_{22}
0.00	1.19	0.15	0.08	0.04	0.15
0.21	0.74	0.03	0.15	0.03	0.25
0.82	0.21	0.10	0.11	0.02	0.34
1.20	0.00	0.04	0.16	0.05	0.28

TABLE III
SOME ACHIEVABLE RATES OF THE PRIMARY AND THE SECONDARY USERS. NOISE VARIANCE IS UNITY. THE SIMULATED CHANNEL IS GIVEN IN TABLE I.

V. CONCLUSION

In this paper, we studied the achievable rate region of the primary users of an underlay cognitive cellular network, where the primary users demand both information and energy. For high energy demands of the primary system, the RAPs in the femto cells help satisfying them. This transmission helps fulfilling primary users' energy demands on one hand and improves the secondary users' information rates on the other hand. The achievable rate region of our linear precoding is compared with the rate region delivered by non-linear DPC scheme. It is numerically shown that for a broadcast channel with high-enough energy demands, DPC scheme does not improve the rate performance significantly.

REFERENCES

[1] R. Zhang and C. K. Ho, "Mimo broadcasting for simultaneous wireless information and power transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[2] A. Kariminezhad and A. Sezgin, "Harvesting the (self-)interference in heterogeneous full-duplex networks for joint rate-energy optimization," *Arxiv*.

[3] A. Laya, K. Wang, A. A. Widaa, J. A.-Zarate, J. Markendahl, and L. Alonso, "Device-To-Device Communications And Small Cells: Eabling Spectrum Reuse For Dense Networks," *IEEE Wireless Communications Mag*, August 2014.

[4] Y.-C. Liang, K.-C. Chen, G. Li, and P. Mahonen, "Cognitive radio networking and communications: an overview," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 7, pp. 3386–3407, Sept 2011.

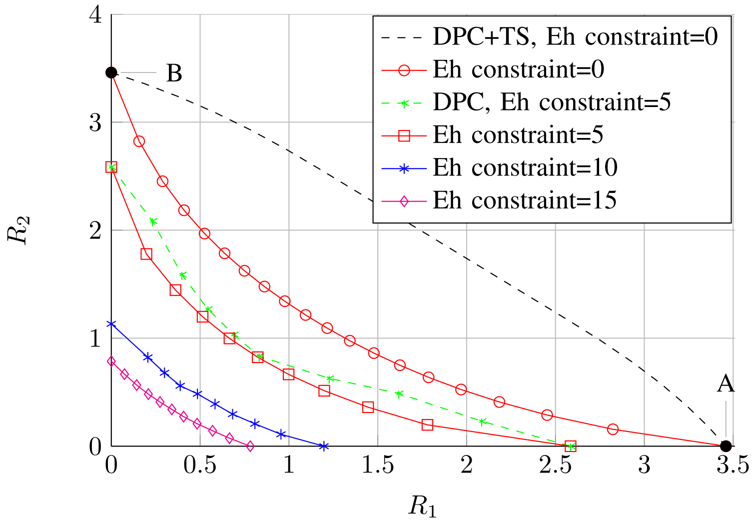
[5] S. Geirhofer, L. Tong, and B. Sadler, "Cognitive medium access: Constraining interference based on experimental models," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 95–105, Jan 2008.

[6] N. Devroye, P. Mitran, and V. Tarokh, "Achievable rates in cognitive radio channels," *IEEE Transactions on Information Theory*, vol. 52, no. 5, pp. 1813–1827, 2006.

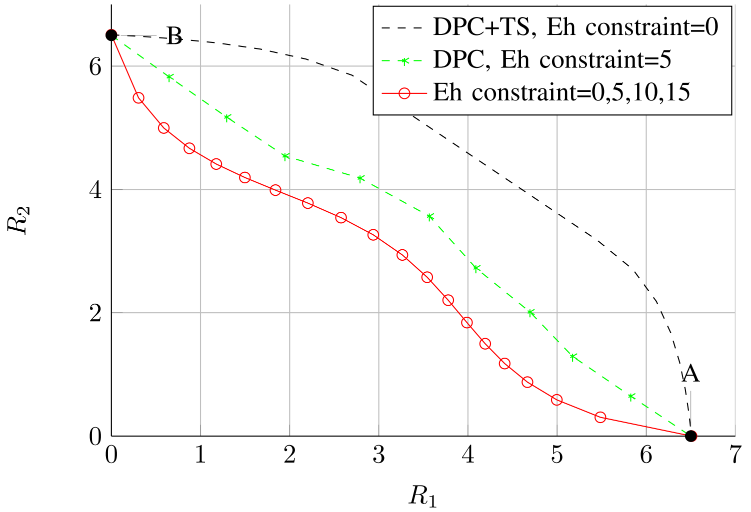
[7] E. Bjornson, E. Jorswieck, M. Debbah, and B. Ottersten, "Multiobjective signal processing optimization: The way to balance conflicting metrics in 5G systems," *IEEE Signal Processing Magazine*, vol. 31, no. 6, pp. 14–23, Nov 2014.

[8] Z.-Q. Luo, W.-K. Ma, A.-C. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 20–34, May 2010.

[9] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.



(a) Channel realization H_1 (unit-norm channel)



(b) Channel realization H_2

Fig. 3. Achievable rate region of the primary users with and without energy harvesting constraints. Each primary user demands certain energy while the BS and RAPs have the maximum power of 10 and 5 units, respectively. The noise variance is unity. Dashed curve is the outer-most boundary of the capacity region of the primary users in case of zero energy demands.

[10] Z.-Q. Luo and W. Yu, "An introduction to convex optimization for communications and signal processing," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1426–1438, Aug 2006.

[11] N. Sidiropoulos, T. Davidson, and Z.-Q. Luo, "Transmit beamforming for physical-layer multicasting," *IEEE Transactions on Signal Processing*, vol. 54, no. 6, pp. 2239–2251, June 2006.

[12] Z. Luo, N. D. Sidiropoulos, P. Tseng, and S. Zhang, "Approximation bounds for quadratic optimization with homogeneous quadratic constraints," *SIAM Journal on Optimization*, vol. 18, no. 1, pp. 1–28, 2007.

[13] S. Vishwanath, N. Jindal, and A. Goldsmith, "Duality, achievable rates, and sum-rate capacity of Gaussian MIMO broadcast channels," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2658–2668, Oct 2003.

[14] P. Viswanath and D. Tse, "Sum capacity of the vector Gaussian broadcast channel and uplink-downlink duality," *IEEE Transactions on Information Theory*, vol. 49, no. 8, pp. 1912–1921, Aug 2003.