ENERGY EFFICIENT BEAMFORMING FOR SECURE COMMUNICATION IN COGNITIVE RADIO NETWORKS

Jian Ouyang[1,2] *Min Lin*[3] *Wei-Ping Zhu*[1] *Daniel Massicotte*[4] *A. Lee Swindlehurst*[5]

[1]Department of Electrical and Computer Engineering, Concordia University, Montreal, QC, Canada
[2]College of Telecommunications and Information Engineering,
Nanjing University of Posts and Telecommunications, Nanjing, China
[3]Nanjing Institute of Telecommunication Technology, Nanjing, China
[4]Department of Electrical and Computer Engineering, Universit du Qubec Trois-Rivires, QC, Canada
[5]Center for Pervasive Communications and Computing, University of California, Irvine, USA

ABSTRACT

In this paper, we study the energy efficiency of secure communication in an underlay cognitive radio network (CRN). We first formulate an optimization problem to maximize the secrecy energy efficiency (SEE) while meeting the quality-of-service (QoS) requirement for the primary user and the transmit power constraint at each base station. Since the problem is non-convex and very difficult to solve, we then convert the original fractional form into a subtractive one, and adopt the difference of two-convex functions (D.C.) approximation method to obtain an equivalent convex problem. Furthermore, a two-layer iterative algorithm is presented to solve the problem and obtain the optimal beamforming (BF) weight vectors. Finally, numerical results are provided to demonstrate the superiority of the proposed scheme.

Index Terms— beamforming, cognitive radio network, energy efficiency, secure communication, optimization

1. INTRODUCTION

Recently, physical layer secrecy has received much attention in cognitive radio networks (CRNs) [1–4]. For example, in [2], the authors studied the secrecy capacity maximization problem for multi-antenna CRNs by optimizing the downlink transmit covariance matrix under transmit power and interference constraints. By employing artificial noise at the cognitive user (CU), the authors of [3] designed downlink beamforming (BF) to achieve maximum secrecy throughput for the primary user (PU). In addition, the authors of [4] presented a multiuser scheduling strategy to improve security against both coordinated and uncoordinated eavesdroppers for multi-user multi-eavesdropper CRNs.

More recently, energy efficiency (EE) has been considered as a crucial issue for CRNs, since it can balance the need for both a high spectral efficiency (SE) and power consumption [5]. For this situation, the authors of [6] used the water-filling method and proposed an EE power allocation (PA) scheme to improve the SE for unit-energy consumption in OFDM-based CRNs. In [7], the authors developed a PA strategy for CU to maximize its mean EE while guaranteeing the outage probability of the PUs. In [8], the trade-off between SE and EE for CRN was also analyzed, and joint secrecy rate (SR) and EE schemes for CRNs were studied in [9–11], where either of the two criteria, namely, SR maximization subject to the EE constraint, or EE maximization under secure quality-of-server (QoS) constraint, has been used.

However, it should be pointed out that the work of [2–4] only considers SR, while the work of [6–11] only focuses on EE. Although a definition of secrecy energy efficiency (SEE) was given in [12] to evaluate the number of available secret bits per unit energy, and has been used as a criterion by [13] and [14] for resource allocation and BF design, respectively, it has to date never been investigated in CRNs. Motivated by this fact, we first formulate an SEE maximization problem with the constraint of the PU's QoS requirement and the limitation of the transmit power at each base station. Then, we propose a method to convert this non-convex problem to a convex one with the help of the difference of two-convex functions (D.C.) approximation method and develop a two-layer iterative algorithm to solve this problem. Finally, numerical results are given to demonstrate the effectiveness of the proposed scheme.

2. PROBLEM FORMULATION

As shown in Fig.1, we consider a scenario where a CRN coexists with a primary network (PN). Here, the PN consists of

This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Regroupement stratgique en microsystmes du Qubec (ReSMiQ), the National Natural Science Foundation of China (61271255, 61372122), the China Postdoctoral Science Foundation (2015M571784), the Jiangsu Planned Projects for Postdoctoral Research Funds (1402068B) and the NUPTSF (NY214140, NY215135).

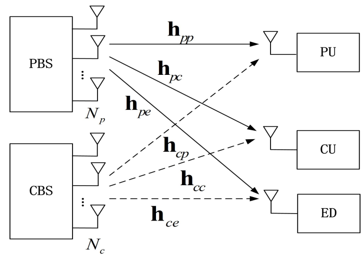

Fig. 1. System model for secure communication in CRN.

a primary base station (PBS) and a PU, and the CRN consists of a cognitive base station (CBS), a CU, and an eavesdropper (ED) who attempts to intercept the confidential messages between CBS and CU. It is assumed that CBS and PBS have N_c and N_p antennas, respectively, while CU, ED and PU are each equipped with a single antenna. At time t, the PBS sends its signals $x_p(t)$ satisfying $\mathrm{E}[|x_p(t)|^2] = 1$ to the PU, while the CBS simultaneously transmits its confidential signals $x_c(t)$ obeying $\mathrm{E}[|x_c(t)|^2] = 1$ to the CU with the same spectrum. Due to the broadcast nature of the wireless channels, the signal received by the CU, ED and PU can be respectively expressed as

$$y_c(t) = \mathbf{h}_{cc}^H \mathbf{w}_c x_c(t) + \mathbf{h}_{pc}^H \mathbf{w}_p x_p(t) + n_c(t) \qquad (1)$$

$$y_e(t) = \mathbf{h}_{ce}^H \mathbf{w}_c x_c(t) + \mathbf{h}_{pe}^H \mathbf{w}_p x_p(t) + n_e(t) \qquad (2)$$

$$y_p(t) = \mathbf{h}_{pp}^H \mathbf{w}_p x_p(t) + \mathbf{h}_{cp}^H \mathbf{w}_c x_c(t) + n_p(t) \qquad (3)$$

where $\mathbf{w}_\alpha$ denotes the $N_\alpha \times 1$ downlink BF weight vector, $\mathbf{h}_{\alpha\beta} = \sqrt{\vartheta_{\alpha\beta}} \widetilde{\mathbf{h}}_{\alpha\beta}$ with $\widetilde{\mathbf{h}}_{\alpha\beta}$ and $\vartheta_{\alpha\beta}$ being the $N_\alpha \times 1$ fading channel vector and the corresponding path loss of the $\alpha - \beta$ link. Here, $\alpha \in \{c, p\}$ stands for CBS or PBS, and $\beta \in \{c, e, p\}$ for CU, ED or PU. In addition, $n_\beta(t)$ is additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_\beta^2 = \triangle f N_0$, where $\triangle f$ denotes the system bandwidth and N_0 the single-sided noise spectral density. By using (1)-(3), the instantaneous output signal-to-interference-plus-noise ratios (SINRs) at the CU, ED and PU can be, respectively, written as

$$\gamma_c(\mathbf{w}_c, \mathbf{w}_p) = \frac{\mathbf{h}_{cc}^H \mathbf{w}_c \mathbf{w}_c^H \mathbf{h}_{cc}}{\mathbf{h}_{pc}^H \mathbf{w}_p \mathbf{w}_p^H \mathbf{h}_{pc} + \sigma_c^2} \qquad (4)$$

$$\gamma_e(\mathbf{w}_c, \mathbf{w}_p) = \frac{\mathbf{h}_{ce}^H \mathbf{w}_c \mathbf{w}_c^H \mathbf{h}_{ce}}{\mathbf{h}_{pe}^H \mathbf{w}_p \mathbf{w}_p^H \mathbf{h}_{pe} + \sigma_e^2} \qquad (5)$$

$$\gamma_p(\mathbf{w}_c, \mathbf{w}_p) = \frac{\mathbf{h}_{pp}^H \mathbf{w}_p \mathbf{w}_p^H \mathbf{h}_{pp}}{\mathbf{h}_{cp}^H \mathbf{w}_c \mathbf{w}_c^H \mathbf{h}_{cp} + \sigma_p^2} \qquad (6)$$

According to [15], the available SR of the CRN is given by

$$R_{sec}(\mathbf{w}_c, \mathbf{w}_p) = \left[\log_2 \left(\frac{1 + \gamma_c(\mathbf{w}_c, \mathbf{w}_p)}{1 + \gamma_e(\mathbf{w}_c, \mathbf{w}_p)} \right) \right]^+ \qquad (7)$$

where $[x]^+ = \max\{x, 0\}$. In most of the related works, such as [2–4], maximization of the SR is often used as a criterion to design the optimal BF. However, to balance the available SR and the power consumption of the CRN, we adopt the SEE performance metric as [12]

$$\eta_{SEE} = \frac{R_{sec}(\mathbf{w}_c, \mathbf{w}_p)}{P_T(\mathbf{w}_c)} \qquad \text{(bit/Joule/Hz)} \qquad (8)$$

where $P_T(\mathbf{w}_c) = \rho \|\mathbf{w}_c\|_F^2 + N_c P_A + P_B$ is the total power consumption at the CBS with $\rho \geq 1$ being the power amplifier inefficiency factor, P_A the circuit power used by each antenna, and P_B the basic power consumed by the CBS. Meanwhile, considering that the maximal transmit powers of the CBS and PBS are fixed, and the QoS of the PU must be satisfied in CRNs, a constrained SEE maximization problem can be mathematically formulated as

$$\text{(P1)} \qquad \max_{\mathbf{w}_c, \mathbf{w}_p} \eta_{SEE}$$

$$\text{s.t.} \quad \gamma_p(\mathbf{w}_c, \mathbf{w}_p) \geq \gamma_p^{th} \text{ and } \|\mathbf{w}_\alpha\|_F^2 \leq P_\alpha^{max},\ \alpha \in \{c, p\}$$

where γ_p^{th} denotes the minimal acceptable SINR for the PU, and P_c^{max} and P_p^{max} the given transmit power limits for the CBS and PBS, respectively. In the following section, we will propose an iterative method to solve the above problem.

3. OPTIMAL SOLUTION

Due to the fractional form and logarithmic function in the objective function (8), optimization problem (P1) is strictly non-convex and very difficult to solve. To tackle it, we first consider the following non-fractional form

$$\text{(P2)}\ f(\eta_{SEE}) = \max_{\mathbf{w}_c, \mathbf{w}_p} \{R_{sec}(\mathbf{w}_c, \mathbf{w}_p) - \eta_{SEE} P_T(\mathbf{w}_c)\}$$

$$\text{s.t.}\ \gamma_p(\mathbf{w}_c, \mathbf{w}_p) \geq \gamma_p^{th} \text{ and } \|\mathbf{w}_\alpha\|_F^2 \leq P_\alpha^{max},\ \alpha \in \{c, p\}$$

and give the following theorem.

Theorem 1: Let η_{SEE}^* be the maximum SEE. The optimization problems (P1) and (P2) are equivalent if and only if $f(\eta_{SEE}^*) = 0$ holds.

Proof: Please see Appendix A.

The above theorem reveals that if we can find η_{SEE}^* satisfying $f(\eta_{SEE}^*) = 0$, the solution to optimization problem (P1) can be obtained by solving the equivalent problem (P2). By defining $\mathbf{W}_\alpha = \mathbf{w}_\alpha \mathbf{w}_\alpha^H$ and $\mathbf{H}_{\alpha\beta} = \mathbf{h}_{\alpha\beta} \mathbf{h}_{\alpha\beta}^H$, (P2) can be rewritten as (P3) at the top of next page. However, since (P3) is still non-convex, we apply the D.C. approximation method [16] and express the objective function in (P3) as

$$f_1(\mathbf{W}_c, \mathbf{W}_p, \eta_{SEE}) - f_2(\mathbf{W}_c, \mathbf{W}_p) \qquad (9)$$

where

$$\begin{aligned} f_1(\mathbf{W}_c, \mathbf{W}_p, \eta_{SEE}) &= \log_2\left(\mathrm{Tr}(\mathbf{W}_p \mathbf{H}_{pe}) + \sigma_c^2\right) \\ &+ \log_2\left(\mathrm{Tr}(\mathbf{W}_c \mathbf{H}_{cc}) + \mathrm{Tr}(\mathbf{W}_p \mathbf{H}_{pc}) + \sigma_c^2\right) \\ &- \eta_{SEE}\left(\rho \mathrm{Tr}(\mathbf{W}_c) + N_c P_A + P_B\right) \qquad (10) \end{aligned}$$

$$\begin{aligned} f_2(\mathbf{W}_c, \mathbf{W}_p) &= \log_2\left(\mathrm{Tr}(\mathbf{W}_p \mathbf{H}_{pc}) + \sigma_c^2\right) \\ &+ \log_2\left(\mathrm{Tr}(\mathbf{W}_c \mathbf{H}_{ce}) + \mathrm{Tr}(\mathbf{W}_p \mathbf{H}_{pe}) + \sigma_e^2\right) \qquad (11) \end{aligned}$$

$$\text{(P3)} \max_{\mathbf{W}_c,\mathbf{W}_p} \left\{ \log_2\left(1+\frac{\text{Tr}(\mathbf{W}_c\mathbf{H}_{cc})}{\text{Tr}(\mathbf{W}_p\mathbf{H}_{pc})+\sigma_c^2}\right) - \log_2\left(1+\frac{\text{Tr}(\mathbf{W}_c\mathbf{H}_{ce})}{\text{Tr}(\mathbf{W}_p\mathbf{H}_{pe})+\sigma_e^2}\right) - \eta_{SEE}\left(\rho\text{Tr}(\mathbf{W}_c)+N_cP_A+P_B\right)\right\}$$
$$\text{s.t.} \quad \frac{\text{Tr}(\mathbf{W}_p\mathbf{H}_{pp})}{\text{Tr}(\mathbf{W}_c\mathbf{H}_{cp})+\sigma_p^2} \geq \gamma_p^{th}, \quad \text{Tr}(\mathbf{W}_c) \leq P_c^{max}, \quad \text{Tr}(\mathbf{W}_p) \leq P_p^{max}, \quad \text{rank}(\mathbf{W}_c)=1 \quad \text{and} \quad \text{rank}(\mathbf{W}_p)=1$$

$$\text{(P4)} \max_{\mathbf{W}_c,\mathbf{W}_p} \left\{ f_1(\mathbf{W}_c,\mathbf{W}_p,\eta_{SEE}) - f_2(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p) - \frac{\text{Tr}\left(\mathbf{H}_{pc}^H\left(\mathbf{W}_p-\bar{\mathbf{W}}_p\right)\right)}{\varphi(\bar{\mathbf{W}}_p)\ln 2} - \frac{\text{Tr}\left(\mathbf{H}_{ce}^H\left(\mathbf{W}_c-\bar{\mathbf{W}}_c\right)+\mathbf{H}_{pe}^H\left(\mathbf{W}_p-\bar{\mathbf{W}}_p\right)\right)}{\phi(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p)\ln 2}\right\}$$
$$\text{s.t.} \quad \text{Tr}(\mathbf{W}_p\mathbf{H}_{pp}) - \gamma_p^{th}\text{Tr}(\mathbf{W}_c\mathbf{H}_{cp}) \geq \gamma_p^{th}\sigma_p^2, \quad \text{Tr}(\mathbf{W}_c) \leq P_c^{max} \quad \text{and} \quad \text{Tr}(\mathbf{W}_p) \leq P_p^{max}$$

Furthermore, we approximate $f_2(\mathbf{W}_c, \mathbf{W}_p)$ by its first-order Taylor series expansion at the feasible solution $(\bar{\mathbf{W}}_c, \bar{\mathbf{W}}_p)$, i.e.,

$$\begin{aligned} f_2(\mathbf{W}_c,\mathbf{W}_p) &\approx f_2(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p) \\ &+ \langle \nabla f_2(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p), (\mathbf{W}_c,\mathbf{W}_p)-(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p)\rangle \end{aligned} \tag{12}$$

where $\langle \mathbf{A}, \mathbf{B}\rangle = \text{Tr}\left(\mathbf{A}^H\mathbf{B}\right)$ and $\nabla f_2(\bar{\mathbf{W}}_c, \bar{\mathbf{W}}_p)$ is the gradient of $f_2(\mathbf{W}_c, \mathbf{W}_p)$ at $(\bar{\mathbf{W}}_c, \bar{\mathbf{W}}_p)$, given by

$$\begin{aligned} &\nabla f_2(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p) \\ &= \frac{1}{\ln 2}\left[\frac{\mathbf{H}_{ce}^H}{\phi(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p)}, \frac{\mathbf{H}_{pe}^H}{\phi(\bar{\mathbf{W}}_c,\bar{\mathbf{W}}_p)} + \frac{\mathbf{H}_{pc}^H}{\varphi(\bar{\mathbf{W}}_p)}\right]^H \end{aligned} \tag{13}$$

with $\phi(\bar{\mathbf{W}}_c, \bar{\mathbf{W}}_p) = \text{Tr}(\bar{\mathbf{W}}_c\mathbf{H}_{ce}) + \text{Tr}(\bar{\mathbf{W}}_p\mathbf{H}_{pe}) + \sigma_e^2$ and $\varphi(\bar{\mathbf{W}}_p) = \text{Tr}(\bar{\mathbf{W}}_p\mathbf{H}_{pc}) + \sigma_c^2$. By substituting (12) and (13) into the objective function in (P3) and dropping the rank-one constraints on $\mathbf{W}_c$ and $\mathbf{W}_p$, we can obtain the convex optimization problem (P4) above. Now, (P4) can be efficiently handled by available convex software, such as CVX [17].

Finally, by combining Theorem 1 with the D.C. approximation, we propose a two-layer iterative algorithm to find the optimal BF solution for the considered SEE maximization problem as summaried in Algorithm 1. At the outer layer, the golden search method is applied to find η_{SEE}^* in the interval $[0, \eta_{SEE}^{up}]$. Here, $\eta_{SEE}^{up} = \log_2\left(1+\frac{P_c^{max}\|\mathbf{h}_{cc}\|_F^2}{(N_cP_A+P_B)\sigma_c^2}\right)$ is an upper bound for η_{SEE} that can be obtained by using the inequality $\text{Tr}(\mathbf{AB}) \leq \text{Tr}(\mathbf{A})\text{Tr}(\mathbf{B})$ and the constraint $\|\mathbf{w}_c\|_F^2 \leq P_c^{max}$. At the inner layer, for the given η_{SEE}, we solve (P4) to obtain the optimal solution $(\mathbf{W}_c, \mathbf{W}_p)$, which is used to update the value of $f(\eta)$ for the next outer iteration. The convergence behavior of the outer iteration based on the golden search method has been well studied in [18] and the convergence of the inner iteration is guaranteed by Theorem 2 below.

Theorem 2: The inner iteration of Algorithm 1 generates an increasing sequence of feasible solutions which converge to the optimal solution of (P4).

Proof: Please see Appendix B.

In addition, the randomization technique (RT) [19] is used at step 8 to obtain the rank-one solution of $\mathbf{W}_\alpha$ and to ensure no loss of optimality from (P3) to (P4).

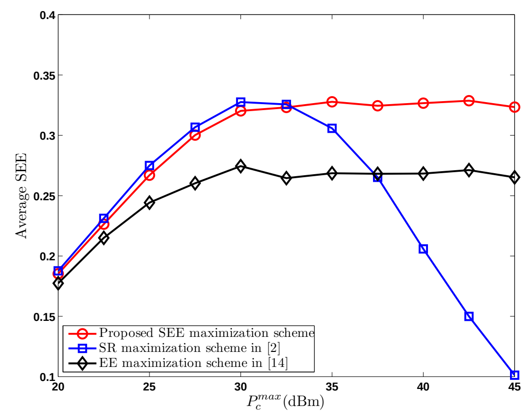

Fig. 2. Average SEE versus P_c^{max}.

4. SIMULATION RESULTS

This section provides numerical results to evaluate the performance of the proposed BF scheme. Here, the simulation parameters are chosen as: $N_c = N_p = 4$, $\rho = 2.6$, $P_A = 30$dBm, $P_B = 40$dBm, $\triangle f = 10$MHz and $N_0 = -174$dBm/Hz. The path loss is $\log_{10}(\vartheta) = -34.5 - 38\log_{10}(d_{\alpha\beta}[m])$ with $d_{\alpha\beta} = 200$m and the convergence threshold is set to $\delta = 10^{-3}$.

Fig. 2 depicts the average SEE versus the CBS transmit power constraint P_c^{max} for 1000 random channel realizations, where $P_p^{max} = 30$dBm and $\gamma_p^{th} = 8$dB. Here, the curves for the BF schemes in [2] focusing on SR maximization and that in [14] based on the criterion of EE maximization are also given for comparison. It is observed that the SEE performance of the proposed BF scheme is similar to that of the SR Maximization scheme in the 20-30dBm region, revealing that both algorithms can achieve the maximum SEE with full transmit power. After attaining the maximum SEE, the proposed BF scheme outperforms the SR maximization scheme with increasing of P_c^{max}. This is because the proposed method ceases allocating transmit power to avoid sacrificing the achieved maximum SEE while the SR maximization

Algorithm 1: The proposed BF scheme

Function *OuterIteration*
Initialize $\tau = (\sqrt{5}-1)/2$, $\eta_l = 0$ and $\eta_u = \eta_{SEE}^{up}$.
Set $t_l = \eta_u - \tau(\eta_u - \eta_l)$ and $t_u = \eta_l + \tau(\eta_u - \eta_l)$.
repeat
  (i) Call **Function** *InnerIteration* with η_l and η_u respectively to find $(\mathbf{w}_c^l, \mathbf{w}_p^l)$ and $(\mathbf{w}_c^u, \mathbf{w}_p^u)$, and compute corresponding $f(\eta_l)$ and $f(\eta_u)$.
  (ii) **If** $f(\eta_l) \le f(\eta_u)$: $f(\eta_l) = f(\eta_u)$, $\eta_l = t_l$, $t_l = t_u$ and $t_u = \eta_l + \tau(\eta_u - \eta_l)$.
  (iii) **Else**: $f(\eta_u) = f(\eta_l)$, $\eta_u = t_u$, $t_u = t_l$ and $t_l = \eta_l + (1-\tau)(\eta_u - \eta_l)$.
until $|\eta_u - \eta_l| \le \delta$, *where* δ *is the tolerance*;
Set $\eta_{SEE}^* = (\eta_u - \eta_l)/2$ and apply again **Function** *InnerIteration* with η_{SEE}^* to obtain the optimal solution $(\mathbf{w}_c^*, \mathbf{w}_p^*)$.
end
Function *InnerIteration(η)*
Initialize $\left(\bar{\mathbf{W}}_c^0, \bar{\mathbf{W}}_p^0\right) = \left(\mathbf{0}_{N_c}, \mathbf{0}_{N_p}\right)$ and $f^0 = 0$.
Set $i = 0$.
repeat
  (i) Find the optimal solution $(\mathbf{W}_c, \mathbf{W}_p)$ of (P4) for given $\bar{\mathbf{W}}_c^i$ and $\bar{\mathbf{W}}_p^i$.
  (ii) Set $i = i + 1$.
  (iii) Update $\left(\bar{\mathbf{W}}_c^i, \bar{\mathbf{W}}_p^i\right) = (\mathbf{W}_c, \mathbf{W}_p)$, and compute $f^i = f_1\left(\bar{\mathbf{W}}_c^i, \bar{\mathbf{W}}_p^i, \eta\right) - f_2\left(\bar{\mathbf{W}}_c^i, \bar{\mathbf{W}}_p^i\right)$.
until $|f^i - f^{i-1}| \le \delta$, *where* δ *is the tolerance*;
Apply RT method [19] to obtain the optimal rank-one solution $(\mathbf{w}_c, \mathbf{w}_p)$ from $\left(\bar{\mathbf{W}}_c^i, \bar{\mathbf{W}}_p^i\right)$.
return $(\mathbf{w}_c, \mathbf{w}_p)$.
end

scheme continues increasing the transmit power to achieve a higher SE. In addition, we can see that the proposed scheme achieves a significant improvement in the SEE performance as compared with the EE maximization approach, which can be attributed to the optimized BF weight vector increasing the secrecy capacity.

5. CONCLUSION

We have investigated the SEE maximization problem in CRN. To solve this optimization problem, we first presented a method to convert this non-convex formulation to a convex one. Then, a two-layer iterative algorithm was designed to solve the problem and obtain the optimal BF weight vectors. Finally, by comparing with previous SR and EE maximization schemes, numerical results were given to show that the proposed BF scheme can significantly improve both the security and energy efficiency of CRN, thus demonstrating the superiority of our proposed BF scheme.

6. APPENDIX

A. PROOF OF THEOREM 1

First, assuming that there exists an optimal solution $(\hat{\mathbf{w}}_c, \hat{\mathbf{w}}_p)$ for (P1), we have

$$\eta_{SEE}^* = \frac{R_{sec}(\hat{\mathbf{w}}_c, \hat{\mathbf{w}}_p)}{P_T(\hat{\mathbf{w}}_c)} \ge \frac{R_{sec}(\mathbf{w}_c, \mathbf{w}_p)}{P_T(\mathbf{w}_c)} \tag{A.1}$$

Due to the fact that $P_T(\mathbf{w}_c) \ge 0$, we can further obtain

$$R_{sec}(\hat{\mathbf{w}}_c, \hat{\mathbf{w}}_p) - \eta_{SEE}^* P_T(\hat{\mathbf{w}}_c) = 0 \tag{A.2}$$
$$R_{sec}(\mathbf{w}_c, \mathbf{w}_p) - \eta_{SEE}^* P_T(\mathbf{w}_c) \le 0 \tag{A.3}$$

Combining (A2) and (A3), it is easy to see that the maximum value of (P3) can be zero at the optimal solution $(\hat{\mathbf{w}}_c, \hat{\mathbf{w}}_p)$. Second, let $(\tilde{\mathbf{w}}_c, \tilde{\mathbf{w}}_p)$ be the optimal solution of (P3) satisfying $R_{sec}(\tilde{\mathbf{w}}_c, \tilde{\mathbf{w}}_p) - \eta_{SEE}^* P_T(\tilde{\mathbf{w}}_c) = 0$. Then, we can obtain the following inequality

$$\begin{aligned} & R_{sec}(\mathbf{w}_c, \mathbf{w}_p) - \eta_{SEE}^* P_T(\mathbf{w}_c) \\ & \quad \le R_{sec}(\tilde{\mathbf{w}}_c, \tilde{\mathbf{w}}_p) - \eta_{SEE}^* P_T(\tilde{\mathbf{w}}_c) = 0 \end{aligned} \tag{A.4}$$

which yields

$$\frac{R_{sec}(\mathbf{w}_c, \mathbf{w}_p)}{P_T(\mathbf{w}_c)} \le \frac{R_{sec}(\tilde{\mathbf{w}}_c, \tilde{\mathbf{w}}_p)}{P_T(\tilde{\mathbf{w}}_c)} = \eta_{SEE}^* \tag{A.5}$$

Hence, $(\tilde{\mathbf{w}}_c, \tilde{\mathbf{w}}_p)$ is also the optimal solution of (P1). This completes the proof of Theorem 1.

B. PROOF OF THEOREM 2

Letting $\left(\bar{\mathbf{W}}_c^i, \bar{\mathbf{W}}_p^i\right)$ and $\left(\bar{\mathbf{W}}_c^{i+1}, \bar{\mathbf{W}}_p^{i+1}\right)$ be the feasible solutions in (P3) at iterations i and $i+1$, respectively, and following the inner iteration in Algorithm 1, we have the following relations:

$$\begin{aligned} & f_1\left(\bar{\mathbf{W}}_c^{i+1}, \bar{\mathbf{W}}_p^{i+1}\right) - f_2\left(\bar{\mathbf{W}}_c^{i+1}, \bar{\mathbf{W}}_p^{i+1}\right) \\ & \approx f_1\left(\bar{\mathbf{W}}_c^{i+1}, \bar{\mathbf{W}}_p^{i+1}\right) - f_2\left(\bar{\mathbf{W}}_c^{i}, \bar{\mathbf{W}}_p^{i}\right) \\ & - \frac{\mathrm{Tr}\left(\mathbf{H}_{pc}^H\left(\mathbf{W}_p^{i+1} - \bar{\mathbf{W}}_p^i\right)\right)}{\varphi\left(\bar{\mathbf{W}}_p^i\right)\ln 2} \\ & - \frac{\mathrm{Tr}\left(\mathbf{H}_{ce}^H\left(\mathbf{W}_c^{i+1} - \bar{\mathbf{W}}_c^i\right) + \mathbf{H}_{pe}^H\left(\mathbf{W}_p^{i+1} - \bar{\mathbf{W}}_p^i\right)\right)}{\phi\left(\bar{\mathbf{W}}_p^i, \bar{\mathbf{W}}_p^i\right)\ln 2} \\ & \ge f_1\left(\bar{\mathbf{W}}_c^{i}, \bar{\mathbf{W}}_p^{i}\right) - f_2\left(\bar{\mathbf{W}}_c^{i}, \bar{\mathbf{W}}_p^{i}\right) \end{aligned} \tag{B.1}$$

which shows that the algorithm produces a monotonically non-decreasing sequence as the solution is updated. Hence $\left(\bar{\mathbf{W}}_c, \bar{\mathbf{W}}_p\right)$ converges to the optimal solution.

7. REFERENCES

[1] Z. Shu, Y. Qian, and S. Ci, "On physical layer security for cognitive radio networks," *IEEE Network*, vol. 27, no. 3, pp. 28-33, 2013.

[2] Y. Pei, Y.-C. Liang, L. Zhang, et al., "Secure communication over MISO cognitive radio channels," *IEEE Trans. Wireless Commun.*, vol. 9, no. 4, pp. 1494-1502, Apr. 2010.

[3] C. Wang, and H.-M. Wang, "On the secrecy throughput maximization for MISO cognitive radio network in slow fading channels," *IEEE Trans. Inf. Foren. Sec.*, vol. 9, no.11, pp. 1814-1827, Nov. 2014.

[4] Y. Zou, X. Li, and Y.-C. Liang, "Secrecy outage and diversity analysis of cognitive radio systems," *IEEE J. Sel. Areas Commun.*, vol. 32, no.11, pp. 2222-2236, Nov. 2014.

[5] S. Eryigit, G. Gur, S. Bayhan, et al., "Energy efficiency is a subtle concept: Fundamental trade-offs for cognitive radio networks," *IEEE Commun. Mag.*, vol. 52, no.7, pp. 30-36, Jul. 2014.

[6] J. Mao, G. Xie, J. Gao, et al., "Energy efficiency optimization for OFDM-based cognitive radio systems: A water-filling factor aided search method," *IEEE Trans. Wireless Commun.*, vol. 12, no.5, pp. 2366-2375, May 2013.

[7] L. Wang, M. Sheng, X. Wang, et al., "Mean energy efficiency maximization in cognitive radio channels with PU outage constraint," *IEEE Commun. Lett.*, vol. 19, no.2, pp. 287-290, Feb. 2015.

[8] F. Haider, C.-X. Wang, H. Haas, et al., "Spectral and energy efficiency analysis for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 14, no.6, pp. 2969-2980, Jun. 2015.

[9] S. Althunibat, V. Sucasas, H. Marques, et al., "On the trade-off between security and energy efficiency in cooperative spectrum sensing for cognitive radio," *IEEE Commun. Lett.*, vol. 17, no.8, pp. 1564-1567, Aug. 2013.

[10] F. Gabry, A. Zappone, R. Thobaben, et al, "Energy efficiency analysis of cooperative jamming in cognitive radio networks with secrecy constraints," *IEEE Wireless Commun. Lett.*, vol. 4, no.4, pp. 437-440, Aug. 2015.

[11] X. Hong, C. Zheng, J. Wang, et al., "Optimal resource allocation and EE-SE trade-off in hybrid cognitive gaussian relay channels," *IEEE Trans. Wireless Commun.*, vol. 14, no.48, pp. 4170-4181, Aug. 2015.

[12] M. El-Halabi, T. Liu, and C. N. Georghiades, "Secrecy capacity per unit cost," *IEEE J. Sel. Areas Commun.*, vol. 31, no.9, pp. 1909-1920, Sep. 2013.

[13] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-efficient resource allocation for secure OFDMA systems," *IEEE Trans. Veh. Technol.*, vol. 61, no.6, pp. 25722585, Jul. 2012.

[14] X. Chen and L. Lei, "Energy-efficient optimization for physical layer security in multi-antenna downlink networks with QoS guarantee," *IEEE Commun. Let.*, vol. 17, no.4, pp. 637-640, Apr. 2013.

[15] A. Mukherjee, S. Fakoorian, J. Huang and A. L. Swindlehurst, "Principles of physical layer security in multiuser wireless networks: A survey," *IEEE Commun. Surv. Tut.*, vol. 16, no.3, pp. 1550-1573, 2014.

[16] H. H. Kha, H. D. Tuan, and H. H. Nguyen, "Fast global optimal power allocation in wireless networks by local DC programming," *IEEE Trans. Wireless Commun.*, vol. 11, no.2, pp. 510-515, Feb. 2012.

[17] Michael Grant and Stephen Boyd, "CVX: Matlab Software for Disciplined Convex Programming, version 2.1," [Online:] http://cvxr.com/cvx, Mar. 2014.

[18] T. H. Cormen, *Introduction to algorithms*, MIT press, 2009.

[19] Z.-Q. Luo, W.-K. Ma, A. M.-C. So, et al., "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Process. Mag.*, vol. 27, no.3, pp. 20-34, May 2010.