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Secrecy energy efficiency optimization for AN-aided SWIPT system with power splitting receiver

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Dear editor,

Two emerging technologies of fifth generation wireless systems (5G), i.e., simultaneous wireless information and power transmission (SWIPT) and physical layer (PHY) security, are attracting considerable attention because they can reduce system energy consumption and can enhance network communication security, respectively [1–3]. These technologies have been jointly studied as secure SWIPT, and recent literatures have investigated the problems of secrecy rate maximization (SRM), harvested energy maximization, and transmission power minimization [4–6]. However, since SRM and harvested energy maximization have conflicting goals, secrecy energy efficiency (SEE) is considered to be the best tradeoff between them. A dearth of research in the SEE problem in secure SWIPT motivates this work.

This study considers secure SWIPT with one base station (BS) and multiple users, where the message intended for a legitimate user (LU) should be kept secure from eavesdroppers (Eves). For improving communication security, artificial noise (AN) is transmitted together with the confidential message for LU, and all users (Eves and LU) implement a power splitting (PS) scheme for energy harvesting (EH). Due to the coupling of variables, the formulated SEE maximization (SEEM) problem is intractable. We propose to solve this using a low-complexity, two-stage SEEM algorithm that incorporates a slack variable and Dinkelbach method. The simulation results validate the efficiency of the proposed algorithm and show the advantage of AN in improving the SEE of the system.

System model and problem formulation. We consider a downlink AN-aided secure SWIPT system, which consists of one BS with $N_t \geqslant 1$ antennas, one LU and K Eves, each of which is equipped with a single antenna. The perfect channel state information (CSI) of LU and Eves is assumed to be available at BS, and AN lies in the null space of LU's channel [7]. The worst case, i.e., Eve uses the entire received signal for information decoding (ID) to achieve the maximum signal to interference plus noise ratio (SINR), is considered in this study. Thus, the PS ratio of the k-th Eve is $\rho_k = 1$, while that of LU is ρ $(0 \leqslant \rho \leqslant 1)$. Let us denote the index set of Eves as $\mathcal{K} = \{1, 2, \ldots, K\}$. Subsequently, the SINR for ID at LU and the k-th Eve can be expressed respectively as

$$\Gamma_{\rm LU} = \frac{\rho|\boldsymbol{h}_{\rm LU}\boldsymbol{w}|^2}{\rho\sigma_{\rm LU}^2 + \delta_{\rm LU}^2}, \quad (1)$$

$$\Gamma_{e,k} = \frac{|\boldsymbol{h}_{e,k}\boldsymbol{w}|^2}{p_v|\boldsymbol{h}_{e,k}\boldsymbol{v}|^2 + \sigma_{e,k}^2 + \delta_{e,k}^2}, \ \forall k, \quad (2)$$

where $\boldsymbol{h}_{\rm LU}$ (resp. $\boldsymbol{h}_{e,k}$) is the channel vector of LU (resp. k-th Eve), $\sigma_{\rm LU}^2$ (resp. $\sigma_{e,k}^2$) is antenna noise power, and $\delta_{\rm LU}^2$ (resp. $\delta_{e,k}^2$) is the additional noise

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power introduced by ID. $\boldsymbol{v}$ is the AN vector with $\|\boldsymbol{v}\|^2 = 1$ and p_v is AN power. Maximum ratio transmission precoding scheme is adopted for the confidential message, where the precoding vector $\boldsymbol{w} = \sqrt{p_w}\frac{\boldsymbol{h}_{\rm LU}^H}{||\boldsymbol{h}_{\rm LU}||}$, p_w is the power of the transmitted confidential signal.

On the other hand, the harvested power at LU is given by

$$E_{\rm LU} = \theta_{\rm LU}(1-\rho)(p_w||\boldsymbol{h}_{\rm LU}||^2 + \sigma_{\rm LU}^2), \quad (3)$$

where $\theta_{\rm LU} \in [0,1]$ represents the EH efficiency at LU. Therefore, the SEEM problem can be formulated as

$$\begin{aligned} \max_{p_w,p_v,\rho} \ & \frac{R_{\rm LU}(p_w,p_v,\rho)}{P_{\rm LU}(p_w,p_v,\rho)} \\ \text{s.t.} \ & C1: R_{\rm LU} \geqslant r_0, \\ & C2: E_{\rm LU} \geqslant e_{\min}, \\ & C3: 0 \leqslant p_w + p_v \leqslant P_{\rm total}, \\ & C4: 0 \leqslant \rho \leqslant 1, \end{aligned} \quad (4)$$

where $R_{\rm LU} = [\log(1+\Gamma_{\rm LU}) - \max_{k\in\kappa}\log(1+\Gamma_{e,k})]^+$, $P_{\rm LU} = \tau(p_w+p_v) + P_C - E_{\rm LU}$, P_C represents the circuit power consumption and τ is the efficiency of the power amplifier. The constraints $C1$–$C4$ represent the secrecy rate requirement for LU using r_0 as the corresponding quality of service (QoS) target, the harvested energy at LU using $e_{\min}$ as the minimum requirement, the total transmission power constraint using $P_{\rm total}$ as the allowed maximum transmission power, and the boundary constraint of the PS ratio, respectively.

An efficient two-stage SEEM algorithm. To simplify the objection function of (4), a slack variable $\lambda \geqslant 1$ is introduced and the numerator of the objection function is given as follows:

$$R'_{\rm LU} = \log(1+\Gamma_{\rm LU}) - \log\lambda, \quad (5)$$

where $\log\lambda$ represents the maximum rate among all Eves, and the boundary of λ can be derived from the constraint $C1$ as $\Lambda = [1, \frac{1}{2^{r_0}}(1+\frac{P_{\rm total}||\boldsymbol{h}_{\rm LU}||^2}{\sigma_{\rm LU}^2+\delta_{\rm LU}^2})]$. Subsequently, the problem can be rewritten as

$$\max_{\lambda} \ \psi(\lambda) \quad \text{s.t. } \lambda \in \Lambda, \quad (6)$$

where $\psi(\lambda)$ can be expressed as

$$\begin{aligned} \psi(\lambda) \triangleq \max_{p_w,p_v,\rho} \ & \frac{R'_{\rm LU}(p_w,p_v,\rho)}{P_{\rm LU}(p_w,p_v,\rho)} \\ \text{s.t. } & C1', C2\text{–}C4, \end{aligned} \quad (7)$$

where $C1'$ is $(\lambda-1)(p_v||\boldsymbol{h}_{e,k}||^2 + \sigma_{e,k}^2 + \delta_{e,k}^2) - \frac{p_w|\boldsymbol{h}_{e,k}\boldsymbol{h}_{\rm LU}^H|^2}{||\boldsymbol{h}_{\rm LU}||^2} \geqslant 0, \forall k$.

It is obvious that problem (6) is a two-stage optimization problem. The outer one is a single variable optimization problem, which can be efficiently solved by one-dimensional search of λ. The inner one, problem (7), is still a non-convex fractional programming problem and can be solved by the Dinkelbach method. The objective function of (7) can be transformed into a subtractive form as

$$\begin{aligned} \Phi(\omega) = & \max_{\{p_w,p_v,\rho\}\in\Omega} R'_{\rm LU}(p_w,p_v,\rho) - \omega\tau(p_w+p_v) \\ & + \omega E_{\rm LU}(p_w,\rho), \end{aligned} \quad (8)$$

where $\omega \geqslant 0$ and Ω is the feasible region of problem (7). The optimal objective value, $\{p_w^*, p_v^*, \rho^*\}$, can be found by seeking the root of $\Phi(\omega) = 0$. Since the Dinkelbach method is an iterative algorithm, which can generate a new ω on each iteration, the maximum SEE ω^* can be obtained when ω converges to a fixed value. Since the parametric subtractive problem (8) is non-convex, it is inefficient to use one-dimension search for ρ, p_w and p_v, respectively. Thus, problem (8) can be expressed as

$$\begin{aligned} \max_{0\leqslant\rho\leqslant1} \max_{p_w,p_v} \ & R'_{\rm LU}(p_w,p_v,\rho) - \omega\tau(p_w+p_v) \\ & + \omega E_{\rm LU}(p_w,\rho) \\ \text{s.t. } & p_w \leqslant p_1(p_v), \ p_w \geqslant p_2(\rho), \\ & 0 \leqslant p_w \leqslant p_3(p_v), \ 0 \leqslant \rho \leqslant 1, \end{aligned} \quad (9)$$

where $p_1(p_v) = \frac{(\lambda-1)||\boldsymbol{h}_{\rm LU}||^2(p_v||\boldsymbol{h}_{e,k}||^2+\sigma_{e,k}^2+\delta_{e,k}^2)}{|\boldsymbol{h}_{e,k}\boldsymbol{h}_{\rm LU}^H|^2}$, $p_2(\rho) = \frac{e_{\min}}{\theta_{\rm LU}(1-\rho)||\boldsymbol{h}_{\rm LU}||^2} - \frac{\sigma_{\rm LU}^2}{||\boldsymbol{h}_{\rm LU}||^2}$, $p_3(p_v) = P_{\rm total} - p_v$ (abbreviated as p_1, p_2, p_3).

Since ρ is practically discrete influenced by the digital circuit, and divisible equally into M intervals in the domain $[0,1]$, it is possible to solve the outer problem in (9) by searching the entire domain of ρ. The inner problem in (9) is convex and $R'_{\rm LU}(p_w,p_v,\rho)$ is a strictly concave function of p_w with fixed p_v, which indicates that the inner problem has a unique solution for p_w. The closed-form expression of p_w^* can be derived by comparing the stationary point $p_w^s(\rho)$ (abbreviated as p_w^s) with the boundary of p_w, as shown in

$$p_w^* = \begin{cases} p_2, & \text{if } p_w^s \leqslant p_2 \leqslant \min(p_1,p_3), \\ p_1, & \text{if } p_2 \leqslant p_1 \leqslant \min(p_w^s,p_3), \\ p_3, & \text{if } p_2 \leqslant p_3 \leqslant \min(p_1,p_w^s), \\ p_w^s, & \text{if } p_2 \leqslant p_w^s \leqslant \min(p_1,p_3). \end{cases} \quad (10)$$

On the other hand, the objective function is a linear function of p_v with fixed p_w, which decreases with an increase in p_v. Hence, it is reasonable to choose a smaller p_v, which is

$$p_v^* = \left[\frac{p_w^*|\boldsymbol{h}_{e,k}\boldsymbol{h}_{\rm LU}^H|^2}{(\lambda-1)\|\boldsymbol{h}_{e,k}\|^2\|\boldsymbol{h}_{\rm LU}\|^2} - \frac{\sigma_{e,k}^2+\delta_{e,k}^2}{\|\boldsymbol{h}_{e,k}\|^2}\right]^+.$$

Simulation Results. Numerical results are provided to evaluate the performance of the proposed SEEM algorithm. The number of Eves is $K = 4$ and number of antennas at BS is $N_t = 5$. The antenna noise and additional noise introduced by ID are $\sigma^2_{\rm LU} = -40$ dBm (resp. $\sigma^2_{e,k} = -40$ dBm) and $\delta^2_{\rm LU} = -60$ dBm (resp. $\delta^2_{e,k} = -60$ dBm), respectively. Moreover, we set $\theta_{\rm LU} = 1$, $\tau = 3$, $P_C = 654$ mW, and $r_0 = 1$ bit/s/Hz. A Rician flat fading channel is applied [8].

Figure 1 shows the comparison between average SEE for SEEM and SRM algorithms over 10000 random channel realizations. The average SEE generated by the SEEM algorithm increases initially with the maximum transmission power. When SEE reaches its maximum value, it tends to get stable. As the maximum transmission power increases, the average SEE for SRM algorithm increases gradually, and decreases after reaching its maximum value. It can also be observed that the performance for the SEEM and SRM algorithms with AN is better than that without AN. In addition, simulation results of the exhaustive search (ES) method are also given for comparison. Note that while the ES method exhibits a higher SEE, its computational complexity is much greater than that of the SEEM algorithm.

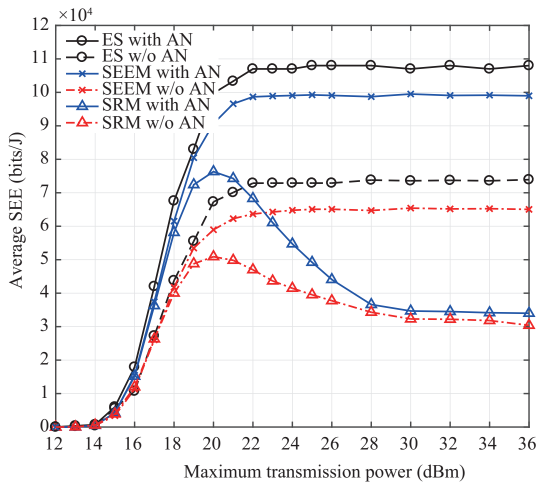

Figure 1 (Color online) Comparison of average SEE for SEEM, SRM and ES algorithms with and without AN.

Conclusion. The AN-aided SEEM problem has been considered for a downlink secure SWIPT system under perfect CSI. Since the SEEM problem is difficult to solve due to its non-convex feature, by introducing a slack variable, the complexity of the SEEM algorithm is reduced. With the Dinkelbach method, the closed-form expressions for the power of the confidential signal and AN power are further derived. Simulation results indicate that the SEEM algorithm is efficient in tackling the problem, and AN plays a crucial role in improving the SEE performance of the system.

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