Enhanced Secure Wireless Information and Power Transfer via Intelligent Reflecting Surface

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Aim

The aim of this paper is to devise an intelligent reflecting surface(IRS) aided secure wireless information and power transfer and maximise the harvested power.

Abstract

1. Optimize the secure transmit beamforming at the access point (AP) and phase shifts at the IRS subject to the secrecy rate (SR) and the reflecting phase shifts at the IRS constraints
2. convert the optimization problem into a semidefinite relaxation (SDR) problem and a sub-optimal solution is obtained.
3. To reduce the high-complexity of the proposed SDR method, a low-complexity alternating optimization (LC-AO) algorithm is proposed.
4. Simulation results show that the harvested power of the proposed SDR and LC-AO methods approximately double that of the existing method without IRS with the same SR.

Introduction

1. There have been some innovative studies on the IRS-assisted wireless communication systems by jointly optimizing the beamforming vector and the phase shifts at the IRS.
2. In a single-user multiple-input single-output (MISO) scenario [5], semidefinite relaxation (SDR) and Gaussian randomization algorithms were proposed to obtain a sub-optimal solution to maximize the total received signal power.
3. simultaneous wireless information and power transfer (SWIPT) could enhance the energy efficiency and solve energy-limited issues of wireless networks to some extent.
4. However, due to the severe path loss, wireless power transfer was only suitable for short distance transmission, hence the range of energy harvesting receivers (EHR) is limited.

System Model

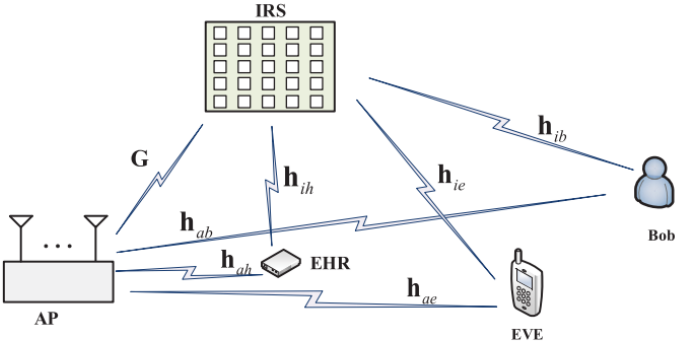

Figure: Fig. 1. An IRS-aided secure SWIPT wireless network.

System Model Contd.

Fig. 1 sketches a downlink MISO system with an IRS for SWIPT.In Fig. 1, there are an AP with M transmit antennas, an IRS with N reflecting units, an information receiver denoted as Bob, and an EHR in the presence of an EVE(eavesdropper).The minimum requirement for EHR such as the low-power sensors is -10 dBm, which is much higher than that for Bob (-60 dBm). Therefore, EHR should be placed close to the AP. Besides, as shown in Fig. 1, an IRS is deployed in the vicinity of EHR. The transmit signal from AP can be expressed as

$$\mathbf{x} = \mathbf{w}s \tag{1}$$

where w $\in \mathbb{C}^{M\times 1}$ denotes the transmit beamforming vector, which forces the confidential message (s) to the desired direction.

System Model Contd.

Suppose that P_s is the total transmission power constraint. Thus, we have $\mathbb{E}(x^H x) = \|\mathbf{w}\|^2 \leq P_s$. Let the baseband equivalent channel responses from the AP to the IRS, from the AP to Bob, from the AP to EHR, from the AP to EVE, from the IRS to Bob, from the IRS to the EHR, from the IRS to EVE are denoted by G $\in \mathbb{C}^{N\times M}$, $h_{ab}^H \in C^{1\times M}$, $h_{ah}^H \in C^{1\times M}$,h$_{ae}^H \in \mathbb{C}^{1\times M}$, $h_{ib}^H \in \mathbb{C}^{1\times N}$, $h_{ih}^H \in \mathbb{C}^{1\times N}$, $h_{ie}^H \in \mathbb{C}^{1\times N}$, respectively. The diagonal reflection-coefficient matrix of the IRS is denoted as
$\Theta = diag(\beta_1 e^{j\theta_1}, , \beta_n e^{j\theta_n})$,
where $\theta_n \in [0, 2)$ and $\beta_n \in (0, 1]$, $\forall$n .θ_n and β_n are the phase shift and amplitude reflection-coefficient of the nth unit, respectively. In this letter, $\beta_n = 1$.

System Model Contd.

The signal recieved by Bob can be written as

$$y_b(w, \theta) = \left(h_{ib}^H \Theta G + h_{ab}^H\right) ws + n_b \tag{2}$$

Where n_b is complex additive white Gaussian noise(AWGN).
The signals recived at EVE and EHR are

$$y_e(w, \theta) = \left(h_{ie}^H \Theta G + h_{ae}^H\right) ws + n_e \tag{3}$$

$$y_r(w, \theta) = \left(h_{ih}^H \Theta G + h_{ah}^H\right) ws + n_h \tag{4}$$

n_b, n_e and n_h are the AWGN which follow complex normal distribution with mean 0 and variance σ^2

Shannon-Hartley theorem

Theorem

The theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrarily low error rate using an average received signal power S through an analog communication channel subject to additive white Gaussian noise (AWGN) of power N:

$$C = Blog_2\left(1 + \frac{S}{N}\right) \tag{5}$$

1. *C is the channel capacity in bits per second, a theoretical upper bound on the net bit rate*
2. *B is the bandwidth of the channel in hertz (passband bandwidth in case of a bandpass signal)*
3. *S is the average received signal power over the bandwidth*
4. *N is the average power of the noise and interference over the bandwidth*

System Model Contd.

Using Shannon-Hartley theorem Bob and EVE can be expressed as

$$R_b\left(w,\Theta\right) = log_2\left(1 + \frac{|\left(h_{ib}^H \Theta G + h_{ab}^H\right) w|^2}{\sigma^2}\right) \tag{6}$$

$$R_e\left(w,\Theta\right) = log_2\left(1 + \frac{|\left(h_{ie}^H \Theta G + h_{ae}^H\right) w|^2}{\sigma^2}\right) \tag{7}$$

The achievable SR is

$$R_s\left(w,\Theta\right) = max\left(0, R_b\left(w,\Theta\right) - R_e\left(w,\Theta\right)\right) \tag{8}$$

The harvested power at EHR is

$$E_r\left(w,\Theta\right) = \zeta\left(|\left(h_{ih}^H \Theta G + h_{ah}^H\right) w|^2\right) \tag{9}$$

PROBLEM FORMULATION AND PROPOSED SOLUTION

We maximize the harvested power at EHR by jointly optimizing the secure transmit beamforming vector and phase shifts at the IRS to ensure that the achieved SR is greater than a predefined threshold.Then the optimization problem can be mathematically cast as

$$
\begin{aligned}
(P1): \quad & \max_{w,\Theta} E_r(w,\Theta) && (10)\\
\text{s.t.} \quad & R_s(w,\Theta) \geq r_0 && (11)\\
& \|w\|^2 \leq P_s && (12)\\
& |e^{j\theta_n}| = 1 && (13)
\end{aligned}
$$

Here r_0 is the minimum SR and P_s is the power budget at AP.

By defining $u = \left[e^{j\theta_1}, ..., e^{j\theta_N}\right]^H, v = [u; 1]$, $\mathrm{H}_r = \left[\mathrm{diag}\{h_{ih}^H\}G; h_{ah}^H\right], H_b = \left[\mathrm{diag}\{h_{ib}^H\}G; h^H ab\right], H_e = \left[\mathrm{diag}\{h_{ie}^H\}G; h_{ae}^H\right]$ $(P1)$ is equivalent to

$$(P2): \max_{w,v} |v^H H_r w|^2 \tag{14}$$

$$\text{s.t. } |v^H H_b w|^2 + \sigma^2 \geq 2^{r_0}\left(|v^H H_e w|^2 + \sigma^2\right) \tag{15}$$

$$\|w\|^2 \leq P_s \tag{16}$$

$$|v_n| = 1 \tag{17}$$

Proposed SDR based AO method

We define $f\left(W,V\right)$ and rewrite (14) and (30) as

$$f\left(W,V\right)=tr\{H_r^H V H_r W\} \tag{18}$$

$$tr\{H_b^H V H_b W\}+\sigma^2 \geq 2^{r_0}\left(tr\{H_c^H V H_c W\}+\sigma^2\right) \tag{19}$$

$$\text{where } V=vv^H \text{ and } W=ww^H. \tag{20}$$

After dropping the rank-one constraints(i.e rank(W)=1 and rank(V)=1), The SDR of problem (P2) is

$$(P3): \max_{w,v} f(W,V) \tag{21}$$

$$\text{s.t. } tr\left(W\right)\leq P_s \tag{22}$$

$$tr\left(E_n V\right)=1 \forall n=1...N+1 \tag{23}$$

$$W\geq 0, V\geq 0 \tag{24}$$

Proposed SDR based AO method

Problem (P3) is non-convex, it is difficult to solve this kind of non-convex problems directly. However, problem (P3) could be decomposed into two subproblems and solved by applying AO algorithm. By alternately fixing V and W, (P3) is reduced to two standard semidefinite programs (SDP), which can be solved by CVX directly. Making use of the AO algorithm, we obtain the solution to problem (P3). Considering that rank-one constraints are relaxed in problem (P3), the solutions to (P3) cannot be guaranteed to be rank-one. To recover the rank-one solution, we apply the standard Gaussian randomization method and obtain a high-quality sub-optimal solution of problem (P2).

Proposed Low-Complexity Alternating Optimization Method

To reduce computational complexity AO algorithm is proposed as follows. By fixing v problem (P2) is reduced to

$$(P4.1): \max_{w} |v^H H_r w|^2 \tag{25}$$

$$\text{s.t. } |v^H H_b w|^2 + \sigma^2 \geq 2^{r_0}\left(|v^H H_e w|^2 + \sigma^2\right) \tag{26}$$

$$\|w\|^2 \leq P_s \tag{27}$$

$$\tag{28}$$

Problem (P4.1) is still non-convex but the objective function (25) is convex.The first-order Taylor expansion of $x^H A x$ at point $\tilde{x}$ is $x^H A x \geq 2\mathbb{R}\{x^H A \tilde{x}\} - \tilde{x}^H A \tilde{x}$.

Proposed LC-AO Optimization Method Contd.

Therefore, problem (P4.1) can be further written as

$$\left(P4.1'\right): \max_{w} 2\mathbb{R}\{w^H H_{rv}\tilde{w}\} - \tilde{w} H_{rv}\tilde{w} \tag{29}$$

$$\text{s.t. } 2\mathbb{R}\{w^H H_{bv}\tilde{w}\} - \tilde{w}^H H_{bv}\tilde{w} + \sigma^2 \geq 2^{r_0}\left(w^H H_{rv}\tilde{w} + \sigma^2\right) \tag{30}$$

$$\|w\|^2 \leq P_s \tag{31}$$

$$\tag{32}$$

Here $H_{iv} = H_i^H V V^H H_i$ i takes r,e,b respectively. Problem 4.1' can be optimally solved using existing software such as CVX.

For any fixed w, problem (P2) is simplified as

$$(P4.2A): \max_{v} |v^H H_r w|^2 \tag{33}$$

$$\text{s.t. } |v^H H_b w|^2 + \sigma^2 \geq 2^{r_0}\left(|v^H H_e w|^2 + \sigma^2\right) \tag{34}$$

$$|v_n| = 1 \tag{35}$$

Where v$= [u; 1]$.

Proposed LC-AO Optimization Method Contd.

By separating out the constant term of vector v, problem (P4.2A) can be equivalently rewritten as

$$(P4.2): \ \max_{u} |u^H a + \alpha|^2 \tag{36}$$

$$\text{s.t. } |u^H b + \beta|^2 + \sigma^2 \geq 2^{r_0} \left(|u^H c + \gamma|^2 + \sigma^2 \right) \tag{37}$$

$$|u_n| = 1 \tag{38}$$

Where $a = \text{diag}\{h_{ih}^H\} Gw, \alpha = h_{ah}^H w \ \ b = \text{diag}\{h_{ib}^H\} Gw, \beta = h_{ab}^H w$, $c = \text{diag}\{h_{ie}^H\} Gw, \ \gamma = h_{ae}^H w$ By using first order Taylor expansion, (36) can be expressed as

$$|u^H a + \alpha|^2 \geq 2\mathbb{R}\{u^H d\} + c_1 \tag{39}$$

where $d = aa^H \tilde{u} + a\alpha^*$, $c_1 = \alpha\alpha^* \tilde{u}^H aa^H \tilde{u}$, where $\tilde{u}$ is phase shifts vector of previous iteration

Proposed LC-AO Optimization Method Contd.

Similarly (37) can be expressed as (using taylor expansion)

$$2\mathbb{R}\{u^H[M - A\tilde{u} + b\beta^* - 2^{r_0}c\gamma^*]\} \geq c_2 \quad (40)$$

$$\text{where } c_2 = N\lambda_{max}(A) + \tilde{u}^H(M - A)\tilde{u} + 2^{r_0}\gamma\gamma^* + \sigma^2 - \beta\beta^* - \sigma^2 \quad (41)$$

There always exists a non-negative μ such that (P4.2) can be formulated into the following equivalent problem.

$$(P4.2'): \max_{u} 2\mathbb{R}\{u^H d\} + 2\mu\mathbb{R}\{u^H f\} \quad (42)$$

$$\text{s.t. } (38) \quad (43)$$

where $f = (M - A)\tilde{u} + (b\beta^* - 2^{r_0}c\gamma^*)$.
When phase-shift vector u is equal to $d + \mu f$, the objective value is maximized. Therefore, the optimal solution to problem (P4.2) is

$$u(\mu) = e^{jarg(d+\mu f)} \quad (44)$$

Substituting $u(\mu)$ into constraint (40), μ can be obtained

Complexity Analysis

We will calculate the complexities of the two proposed methods and make a comparison. The total complexity of the proposed SDR-based AO algorithm without Gaussian randomization is

$$\mathbf{O}\Big(\mathrm{D}\Big[\sqrt{2+M}\left(M^2\left(2+M^3\right)+M^4\left(2+M^2\right)+M^6\right) \\ +\sqrt{2N+2}\left(N^2\left(N^3+N+2\right)+N^4\left(N^2+N+2\right)+N^6\right) \tag{45}$$

Where D denotes the number of alternating iterations.

Complexity Analysis

The complexity of the proposed LC-AO algorithm is

$$\mathbf{O}\left(\mathrm{L}\left[L_1\left(2\left(M\left(5^2+(M+1)^2\right)+M^3\right)\right)\right.\right. \tag{46}$$
$$\left.\left.+\left(L_2 N^3 log_2\left(\frac{(\lambda_{max}-\lambda_{min})}{\epsilon}\right)\right)\right)$$

20

where L denotes the maximum number of alternating iterations. L_1 and L_2 denote the iterative numbers of subproblems (P4.1) and (P4.2), respectively. λ_{max}, λ_{min} and ϵ are the upper-bound, lower-bound and the accuracy of bisection method respectively. Although the LC-AO algorithm has two-level iteration, the highest order of computational complexity is M^3 and N^3 FLOPS as compared to $M^{6.5}$ and $N^{6.5}$ FLOPS of the SDR-based AO algorithm.

Simulation results

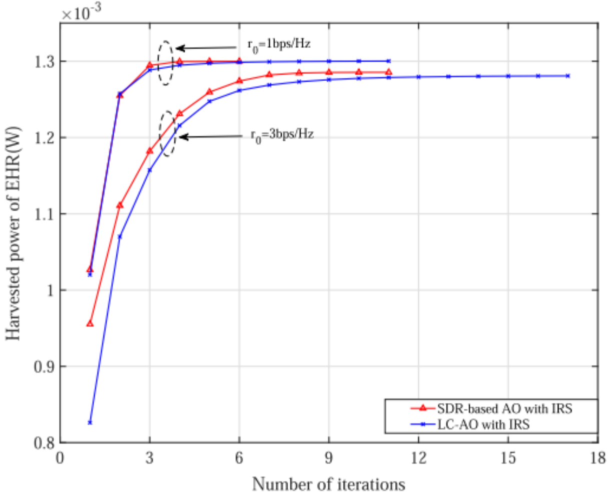

Figure: Fig. 2. Harvested power of EHR versus the number of iterations.

Simulation results

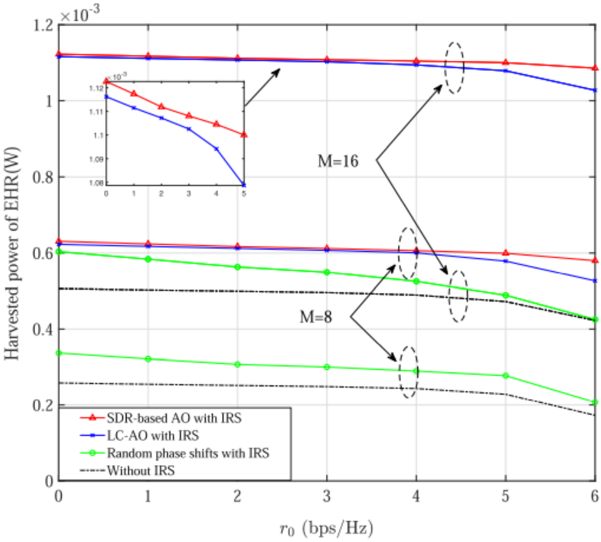

Figure: Fig. 3. Harvested power of EHR versus r_0

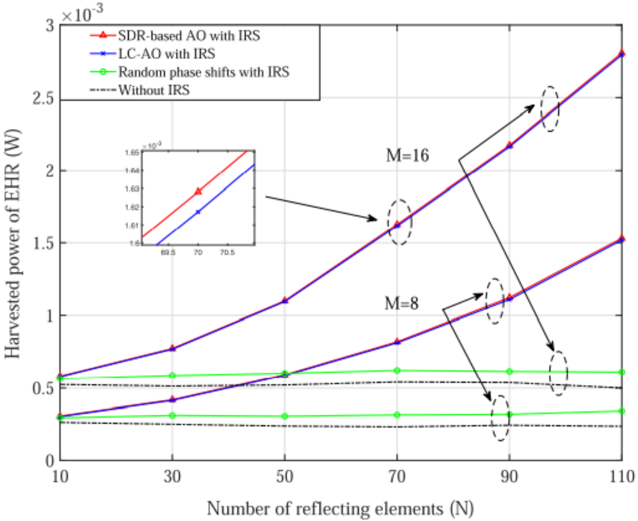

Figure: Fig. 4. Harvested power of EHR versus N

Conclusion

1. Two alternating iterative algorithms SDR and LC-AO were proposed to address the non-convex optimization problem.
2. With a much lower-complexity, the proposed LC-AO method can achieve almost the same performance as the proposed SDR method
3. the proposed two methods approximately double the harvested power compared to existing methods.