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Secrecy Rate Optimization for RF Powered Two-Hop Untrusted Relay Networks with Non-Linear EH Model

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SUMMARY In this letter, we investigate the secure transmission in radio frequency (RF) powered two-hop untrusted relay networks, where the source node and untrusted relay are both wireless powered by an RF power supplier. Specifically, considering the non-linear energy-harvesting (EH) model, the two-process communication protocol is proposed. The secrecy rate is maximized by jointly designing the beamforming vector at source and beamforming matrix at relay, under the constraints of transmit power at RF power supplier and destination. The secrecy rate maximization (SRM) is non-convex, hence we propose an alternative optimization (AO) based iterative algorithm. Numerical results demonstrate that the proposed scheme can significantly increase the secrecy rate compared to the baseline schemes.

key words: *RF powered networks, non-linear EH model, untrusted relay, secrecy rate, physical layer security*

1. Introduction

Radio frequency (RF) energy-harvesting (EH) paradigms are promising in energy-constraint networks, which contain nodes with finite-capacity battery to maintain operation [1]. Under the RF-EH scheme, the lifetime of wireless nodes can be prolonged by converting the RF transmission into available power supply [2].

On the other hand, due to the limited transmit range of wireless communication or the blocking of obstacles, cooperative relay technology is widely employed [3], [4]. However, the introduction of cooperative relay results in weak anti-eavesdropping capability, because the relay willing to forward the information-bearing signal may be also curious about the secret information. To prevent information leakage, the physical layer security (PLS) has been widely studied [5], [6].

For the RF powered relay networks, the external jammer was introduced to interfere the untrusted relay and the optimal power allocation was studied to maximize the secrecy rate in [7]. A destination-assisted-jamming-based transmit scheme was proposed in [8], where the destination node not only generates the jamming but also provides the RF energy for the relay. Reference [9] studied the two-hop secure simultaneous wireless information and power transfer (SWIPT) transmission, where the source and relay are both RF powered.

However, most current works concentrate on linear EH model. Actually, the practical power conversion circuit results in a non-linear end-to-end power transfer [10]. Hence, the non-linear EH model was proposed recently [11]. The secure beamforming was designed for cognitive radio networks in [10], while the energy efficiency was maximized for the SWIPT networks based on non-linear EH model in [12].

In this letter, we study the destination-assisted-jamming-based secure transmit scheme for the RF powered two-hop untrusted relay networks with non-linear EH model. Supposing the source and relay are both RF powered, an RF power supplier is employed, which can avoid the path loss during RF energy transmission from the destination to the relay and source in [9]. Reference [5] also studied the joint secure beamforming scheme, but the RH-EH paradigm was not considered therein.

Notations: Boldface lowercase and uppercase letters are used to denote vectors and matrices, respectively. $\mathbf{I}$ and $\mathbf{0}$ denote the identity matrix and zero matrix, respectively. $\mathbf{X} \succeq \mathbf{0}$ means that $\mathbf{X}$ is a Hermitian positive semidefinite matrix. The operators $(\cdot)^T, (\cdot)^\dagger, (\cdot)^H$, and $Tr(\cdot)$ represent the transpose, conjugate, conjugate transpose, and trace operations, respectively. The symbol $E\{\cdot\}$ represents the statistical expectation of the argument and $[x]^+ = max(0, x)$. $\otimes$ and $vec(\cdot)$ denote the Kronecker product and vectorization operation, respectively.

2. System Model and Problem Formulation

Consider a two-hop untrusted relay network which is comprised of a source ($\mathcal{S}$), an untrusted relay ($\mathcal{R}$), a destination ($\mathcal{D}$) and an RF power supplier ($\mathcal{P}$). The antenna numbers of $\mathcal{S}$ and $\mathcal{R}$ are N_s and N_r, respectively. The node $\mathcal{D}$ and $\mathcal{P}$ are both single-antenna. Each node operates in a half-duplex mode. Since there is no direct link from $\mathcal{S}$ to $\mathcal{D}$, the communication is established through the relay $\mathcal{R}$. Meanwhile, $\mathcal{R}$ which conducts amplify-and-forward (AF) protocol, is untrusted and may wiretap the secret information in passive way.

As shown in Fig. 1, we design a two-process communication protocol for a transmission slot (of duration T_0). In the first process lasting for $T_0/2$, the wireless power transfer is conducted from $\mathcal{P}$ to $\mathcal{S}$ and $\mathcal{R}$. The signals received at $\mathcal{S}$ and $\mathcal{R}$ can be represented as

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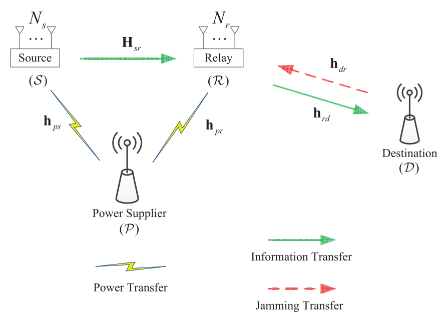

Fig. 1 System model.

$$\begin{aligned}\mathbf{y}_{ps} &= \mathbf{h}_{ps}\sqrt{P_p}x_p + \mathbf{n}_s \\ \mathbf{y}_{pr} &= \mathbf{h}_{pr}\sqrt{P_p}x_p + \mathbf{n}_{pr}\end{aligned} \tag{1}$$

where $\mathbf{h}_{ps} \in \mathbb{C}^{N_s\times 1}$ and $\mathbf{h}_{pr} \in \mathbb{C}^{N_r\times 1}$ represent the channel gains from $\mathcal{P}$ to $\mathcal{S}$ and $\mathcal{R}$, respectively. $\mathbf{n}_s \sim \mathcal{CN}(0, {\sigma_s}^2\mathbf{I})$ and $\mathbf{n}_{pr} \sim \mathcal{CN}(0, {\sigma_{pr}}^2\mathbf{I})$ denote the independent and identical distributed (i.i.d.) circular symmetric complex additive white Gaussian (AWGN) noises. x_p is the unit RF power signal and P_p is the transmit power at $\mathcal{P}$. Hence, the received RF power at $\mathcal{S}$ and $\mathcal{R}$ can be represented as

$$\begin{aligned}P_{rec\_s} &= \eta_s(P_p\|\mathbf{h}_{ps}\|^2 + N_s{\sigma_s}^2) \\ P_{rec\_r} &= \eta_r(P_p\|\mathbf{h}_{pr}\|^2 + N_r{\sigma_{pr}}^2)\end{aligned} \tag{2}$$

where $0 < \eta_s < 1$ and $0 < \eta_r < 1$ are the energy transfer efficiency, respectively.

In this letter, we employ a recently proposed non-linear EH model [11]. Thus, the harvesting power at $\mathcal{S}(\mathcal{R})$ is

$$\begin{aligned}P_{hst\_i} &= \frac{\Psi_E - M_E\Omega_E}{1-\Omega_E} \\ \Psi_E &= \frac{M_E}{1+e^{-a_E(P_{rec\_i}-b_E)}} \\ \Omega_E &= \frac{1}{1+e^{a_E b_E}}\end{aligned} \tag{3}$$

where $i \in \{s, r\}$ and e denotes the base of natural logarithms. In this model, M_E is a constant denoting the maximum harvested power when the EH circuit is saturated, a_E and b_E are parameters related to the detailed circuit specifications.

In the second process lasting for $T_0/2$, $\mathcal{S}$ transmits information-bearing signal to $\mathcal{D}$ through $\mathcal{R}$ using the energy harvested. This process is divided into two phases with equal duration of $T_0/4$. In the first phase, $\mathcal{S}$ sends information-bearing signal to $\mathcal{R}$. Meanwhile, to prevent information leakage, $\mathcal{D}$ generates jamming to interfere $\mathcal{R}$. The signal received at $\mathcal{R}$ is represented as

$$\mathbf{y}_{sr} = \mathbf{H}_{sr}\mathbf{w}_s x_s + \mathbf{n}_r + \mathbf{h}_{dr}\sqrt{P_d}x_d \tag{4}$$

where $\mathbf{H}_{sr} \in \mathbb{C}^{N_r\times N_s}$ is the channel gain from $\mathcal{S}$ to $\mathcal{R}$ and $\mathbf{h}_{dr} \in \mathbb{C}^{N_r\times 1}$ is the channel gain from $\mathcal{D}$ to $\mathcal{R}$. $x_s \in \mathbb{C}$ denotes the secret information and $\mathbf{w}_s \in \mathbb{C}^{N_s\times 1}$ denotes the corresponding beamforming vector. Without loss of generality, we assume that $E\{|x_s|^2\} = 1$. $x_d \sim \mathcal{CN}(0, 1)$ denotes the jamming signal and P_d is the transmit power at $\mathcal{D}$. $\mathbf{n}_r \sim \mathcal{CN}(0, {\sigma_r}^2\mathbf{I})$ denotes the i.i.d. AWGN noise at $\mathcal{R}$.

In the next phase, $\mathcal{R}$ transmits information to $\mathcal{D}$. The signal at $\mathcal{D}$ is

$$\begin{aligned}\mathbf{y}_{rd} =& \mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{H}_{sr}\mathbf{w}_s x_s + \mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{n}_r \\ &+ \mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{h}_{dr}\sqrt{P_d}x_d + n_d\end{aligned} \tag{5}$$

where $\mathbf{h}_{rd} \in \mathbb{C}^{N_r\times 1}$ is the channel gain from $\mathcal{R}$ to $\mathcal{D}$, $\mathbf{W}_r \in \mathbb{C}^{N_r\times N_r}$ denotes the beamforming matrix at $\mathcal{R}$ and $n_d \sim \mathcal{CN}(0, {\sigma_d}^2)$ denotes the i.i.d. AWGN noise. Due to x_d is the jamming signal generated by $\mathcal{D}$, the third item on the right hand of (5) can be eliminated for decoding.

In this way, the secrecy rate of this network can be calculated as [13]

$$R_s = \frac{1}{4}[R_d - R_r]^+ \tag{6}$$

where R_d denotes the achievable rate of main channel with

$$R_d = \log\left(1+\frac{\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{H}_{sr}\mathbf{w}_s\mathbf{w}_s{}^H\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H\mathbf{h}_{rd}}{{\sigma_r}^2\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{W}_r{}^H\mathbf{h}_{rd} + {\sigma_d}^2}\right) \tag{7}$$

and R_r denotes the achievable rate of wiretap channel with

$$\begin{aligned}R_r &= \log|\mathbf{I} + \mathbf{H}_{sr}\mathbf{w}_s\mathbf{w}_s{}^H\mathbf{H}_{sr}{}^H\mathbf{G}^{-1}| \\ \mathbf{G} &= P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H + {\sigma_r}^2\mathbf{I}\end{aligned} \tag{8}$$

The energy consumed by $\mathcal{S}$ and $\mathcal{R}$ in the information transfer process can be represented as

$$\begin{aligned}E_s =& \frac{T_0}{4}Tr(\mathbf{w}_s\mathbf{w}_s{}^H) \\ E_r =& \frac{T_0}{4}[Tr(\mathbf{W}_r\mathbf{H}_{sr}\mathbf{w}_s\mathbf{w}_s{}^H\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H) \\ &+{\sigma_r}^2Tr(\mathbf{W}_r\mathbf{W}_r{}^H)+P_d Tr(\mathbf{W}_r\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H\mathbf{W}_r{}^H)]\end{aligned} \tag{9}$$

In this letter, with given transmit power P_p at $\mathcal{P}$ and P_d at $\mathcal{D}$, we jointly design the beamforming vector $\mathbf{w}_s$ at $\mathcal{S}$ and beamforming matrix $\mathbf{W}_r$ at $\mathcal{R}$ for the secrecy rate maximization (SRM), i.e.,

$$\max_{\mathbf{w}_s,\mathbf{W}_r} R_s \tag{10a}$$

$$s.t.\ \ E_s \le \frac{T_0}{2}P_{hst\_s},\ E_r \le \frac{T_0}{2}P_{hst\_r} \tag{10b}$$

As $\mathcal{S}$ and $\mathcal{R}$ are both RF powered by $\mathcal{P}$, the energy constraint should be satisfied in (10b).

3. Joint Beamforming Design

In this section, we derive the suboptimal solution of the SRM problem (10). The original problem is non-convex, hence we propose an alternative optimization (AO) based iterative algorithm by dividing the original problem into two sub-problems.

3.1 Optimizing $\mathbf{w}_s$ with Given $\mathbf{W}_r$

When the beamforming matrix at $\mathcal{R}$ is given as $\mathbf{W}_r = \tilde{\mathbf{W}}_r$, the SRM can be expressed as

$$\max_{\mathbf{Q}_s} R_s = \frac{1}{4}\{\log(1+\frac{\mathbf{h}_{rd}{}^H\tilde{\mathbf{W}}_r\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H\mathbf{h}_{rd}}{\sigma_r{}^2\mathbf{h}_{rd}{}^H\tilde{\mathbf{W}}_r\tilde{\mathbf{W}}_r^H\mathbf{h}_{rd}+\sigma_d{}^2}) - \log|\mathbf{I}+\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}{}^H\mathbf{G}^{-1}|\} \tag{11a}$$

$$s.t.\ Tr(\mathbf{Q}_s) \leq 2P_{hst\_s} \tag{11b}$$

$$Tr(\tilde{\mathbf{W}}_r\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H)+\sigma_r{}^2Tr(\tilde{\mathbf{W}}_r\tilde{\mathbf{W}}_r^H) + P_dTr(\tilde{\mathbf{W}}_r\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H\tilde{\mathbf{W}}_r^H) \leq 2P_{hst\_r} \tag{11c}$$

$$\mathbf{Q}_s \succeq \mathbf{0}, rank(\mathbf{Q}_s) = 1 \tag{11d}$$

where $\mathbf{Q}_s$=$\mathbf{w}_s\mathbf{w}_s{}^H$. (11) is still non-convex mainly for (11a), hence the sequential parametric convex approximation (SPCA) method [14] is employed. By employing the first order Taylor series approximation [15], the low bound of (11a) can be expressed as

$$\tilde{R}_s = \frac{1}{4}\{\log(1+\frac{\mathbf{h}_{\mathrm{rd}}{}^{\mathrm{H}}\tilde{\mathbf{W}}_{\mathrm{r}}\mathbf{H}_{\mathrm{sr}}\mathbf{Q}_{\mathrm{s}}\mathbf{H}_{\mathrm{sr}}{}^{\mathrm{H}}\tilde{\mathbf{W}}_{\mathrm{r}}^{\mathrm{H}}\mathbf{h}_{\mathrm{rd}}}{\sigma_{\mathrm{r}}{}^2\mathbf{h}_{\mathrm{rd}}{}^{\mathrm{H}}\tilde{\mathbf{W}}_{\mathrm{r}}\tilde{\mathbf{W}}_{\mathrm{r}}^{\mathrm{H}}\mathbf{h}_{\mathrm{rd}}+\sigma_{\mathrm{d}}{}^2}) - \log|\mathbf{M}_0| - Tr[\frac{\mathbf{H}_{sr}(\mathbf{Q}_s-\mathbf{Q}_{s0})\mathbf{H}_{sr}{}^H}{\mathbf{M}_0}] + \log|P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H+\sigma_r{}^2\mathbf{I}|\} \tag{12}$$

where $\mathbf{M}_0 = P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H + \sigma_r{}^2\mathbf{I} + \mathbf{H}_{sr}\mathbf{Q}_{s0}\mathbf{H}_{sr}{}^H$ and $\mathbf{Q}_{s0}$ is a constant matrix. With semidefinite relaxation (SDR) technique by neglecting the rank constraint in (11d), (11) can be approximated as a semidefinite programming (SDP)

$$\begin{aligned} &\max_{\mathbf{Q}_s} R_s \\ &s.t.\ (11b), (11c) \\ &\quad \mathbf{Q}_s \succeq \mathbf{0} \end{aligned} \tag{13}$$

(13) is convex and can be solved efficiently [16]. Although employing the SDR, the following proposition implies that the solution of (13) is tight.

Proposition 1: Given the SDR problem (13), we can always get the optimal solution $\mathbf{Q}_s{}^*$ which satisfies $rank(\mathbf{Q}_s{}^*) = 1$.

The proof is in Appendix A.

The algorithm of solving (11) by SPCA method is summarized in Algorithm 1.

Algorithm 1 SPCA procedure for (11)

1: **Initialize** the constant matrix $\mathbf{Q}_{s0} = 0.5\mathbf{I}$.
2: **repeat**
3: Solve (13), get the optimal solution $\mathbf{Q}_s{}^*$ and $\tilde{R}_s$.
4: Set $\mathbf{Q}_{s0}$=$\mathbf{Q}_s{}^*$.
5: **until** $\tilde{R}_s$ converges.
Output:
6: The optimal solution $\mathbf{Q}_s{}^*$ and corresponding secrecy rate $\tilde{R}_s^*$.

3.2 Optimizing $\mathbf{W}_r$ with Given $\mathbf{w}_s$

When the beamforming vector at $\mathcal{S}$ is given as $\mathbf{w}_s = \tilde{\mathbf{w}}_s$, the secrecy rate only depends on the signal-to-interference-and-noise ratio (SINR) at $\mathcal{D}$. Hence, this SRM problem is equivalent to

$$\max_{\mathbf{W}_r} \frac{\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H\mathbf{h}_{rd}}{\sigma_r{}^2\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{W}_r{}^H\mathbf{h}_{rd}+\sigma_d{}^2} \tag{14a}$$

$$s.t.\ Tr(\mathbf{W}_r\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H)+\sigma_r{}^2Tr(\mathbf{W}_r\mathbf{W}_r{}^H) + P_dTr(\mathbf{W}_r\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H\mathbf{W}_r{}^H) \leq 2P_{hst\_r} \tag{14b}$$

where $\tilde{\mathbf{Q}}_s = \tilde{\mathbf{w}}_s\tilde{\mathbf{w}}_s^H$.

With the fact [17],

$$\begin{aligned} &Tr(\mathbf{A}\mathbf{B}^T) = vec^T(\mathbf{A})vec(\mathbf{B}) \\ &vec(\mathbf{ABC}) = (\mathbf{C}^T \otimes \mathbf{A})vec(\mathbf{B}) \\ &(\mathbf{A}\otimes\mathbf{B})^T = \mathbf{A}^T \otimes \mathbf{B}^T \end{aligned} \tag{15}$$

it follows that

$$\begin{aligned} &\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H\mathbf{h}_{rd} \\ &= vec^T(\mathbf{W}_r)\mathbf{F}_1vec(\mathbf{W}_r{}^\dagger) \end{aligned} \tag{16}$$

$$\begin{aligned} &\sigma_r{}^2\mathbf{h}_{rd}{}^H\mathbf{W}_r\mathbf{W}_r{}^H\mathbf{h}_{rd} \\ &= \sigma_r{}^2vec^T(\mathbf{W}_r)\mathbf{F}_2vec(\mathbf{W}_r{}^\dagger) \end{aligned} \tag{17}$$

with $\mathbf{F}_1 = \mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H \otimes \mathbf{h}_{rd}{}^\dagger\mathbf{h}_{rd}{}^T$, $\mathbf{F}_2 = \mathbf{I}\otimes\mathbf{h}_{rd}{}^\dagger\mathbf{h}_{rd}{}^T$. For the constraint (14b), it can be obtained that

$$\begin{aligned} &Tr(\mathbf{W}_r\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H\mathbf{W}_r{}^H) + \sigma_r{}^2Tr(\mathbf{W}_r\mathbf{W}_r{}^H) \\ &\quad + P_dTr(\mathbf{W}_r\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H\mathbf{W}_r{}^H) \\ &= Tr[\mathbf{W}_r(\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H + \sigma_r{}^2\mathbf{I} + P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H)\mathbf{W}_r{}^H] \\ &= vec^T(\mathbf{W}_r)\mathbf{F}_3vec(\mathbf{W}_r{}^\dagger) \end{aligned} \tag{18}$$

with $\mathbf{F}_3 = (\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H + \sigma_r{}^2\mathbf{I} + P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H)\otimes\mathbf{I}$.

Defining $\xi_r = vec(\mathbf{W}_r{}^\dagger)$ and $\mathbf{Q}_r = \xi_r\xi_r{}^H$, combined with (16), (17) and (18), (14) can be re-expressed as

$$\max_{\mathbf{Q}_r} \frac{Tr(\mathbf{Q}_r\mathbf{F}_1)}{\sigma_r{}^2Tr(\mathbf{Q}_r\mathbf{F}_2)+\sigma_d{}^2} \tag{19a}$$

$$s.t.\ Tr(\mathbf{Q}_r\mathbf{F}_3) \leq 2P_{hst\_r} \tag{19b}$$

$$\mathbf{Q}_r \succeq \mathbf{0}, rank(\mathbf{Q}_r) = 1 \tag{19c}$$

Neglecting the rank constraint in (19c), (19) is a quasi-convex problem, which can be equivalently reformulated via Charnes-Cooper transformation [17], i.e.,

$$\max_{\bar{\mathbf{Q}}_r, t} Tr(\bar{\mathbf{Q}}_r\mathbf{F}_1) \tag{20a}$$

$$s.t.\ \sigma_r{}^2Tr(\bar{\mathbf{Q}}_r\mathbf{F}_2) + t\sigma_d{}^2 = 1 \tag{20b}$$

$$Tr(\bar{\mathbf{Q}}_r\mathbf{F}_3) - 2tP_{hst\_r} \leq 0 \tag{20c}$$

$$\bar{\mathbf{Q}}_r \succeq \mathbf{0}, t \geq 0 \tag{20d}$$

where $\bar{\mathbf{Q}}_r = t\mathbf{Q}_r$. (20) is a SDP and can be solved. Still the following proposition implies that the SDR solution of (20) is tight for the original problem (14).

Proposition 2: Given the SDR problem (20), we can always get the optimal solution $\bar{\mathbf{Q}}_r^*$ which satisfies $rank(\bar{\mathbf{Q}}_r^*) = 1$.

The proof is in Appendix B.

Overall, combining the procedure in the two subproblems above, the iterative optimization algorithm for the SRM can be summarized as follows.

Algorithm 2 AO based iterative algorithm for SRM

Initialize the beamforming matrix $\tilde{\mathbf{W}}_r = 0.5\mathbf{I}$.
repeat
Calculate the optimal $\mathbf{Q}_s{}^*$ using Algorithm 1, set $\tilde{\mathbf{Q}}_s$=$\mathbf{Q}_s{}^*$.
Calculate the optimal $\bar{\mathbf{Q}}_r^*$ using (20), obtain $\xi_r{}^*$ and $\mathbf{W}_r{}^*$, set $\tilde{\mathbf{W}}_r = \mathbf{W}_r{}^*$.
Obtain the secrecy rate $\tilde{R}_s$ using (6) with $\tilde{\mathbf{Q}}_s, \tilde{\mathbf{W}}_r$.
until $\tilde{R}_s$ converges.
Output:
The optimal solution $\mathbf{Q}_s{}^*, \mathbf{W}_r{}^*$ and corresponding secrecy rate $\tilde{R}_s^*$.

Complex analysis: Problem (13) and (20) are SDP and can be solved using interior-point method. Thus, the computational complexity of Algorithm 1 is about $O(N_1 N_s{}^7 \log(1/\varepsilon))$, where ε is the given solution accuracy and N_1 is the average iteration number for the convergence of Algorithm 1. The total complexity of Algorithm 2 is $O(N_2[N_1 N_s{}^7 + (N_r{}^4 + 1)^{3.5}]\log(1/\varepsilon))$, where N_2 is the average iteration number of Algorithm 2.

4. Simulation Results

In this section, we provide the numerical simulation results to validate our proposed AO based iterative algorithm (AO scheme). The distances from $\mathcal{P}$ to $\mathcal{S}$, from $\mathcal{P}$ to $\mathcal{R}$, from $\mathcal{S}$ to $\mathcal{R}$ and from $\mathcal{R}$ to $\mathcal{D}$ are denoted as d_1, d_2, d_3 and d_4, respectively. They are set $d_1 = d_2 = 2m, d_3 = 3m$. Every entry of the channels is assumed as i.i.d. complex Gaussian random variable with zero mean and variance d^{-2}, where d denotes the distance between the two nodes. We set the noise power as $\sigma_s{}^2 = \sigma_{pr}{}^2 = \sigma_r{}^2 = \sigma_d{}^2 = -30dBm$ and transmission slot as $T_0 = 1$. The parameters of the non-linear EH model are $a_E = 150, b_E = 0.0014, M_E = 24mW$ and $\eta_s = \eta_r = 0.5$ [10]. For comparison, we introduce the destination-powered scheme (D-powered scheme) [9], the non-cooperative scheme [5], and the transmit scheme with linear EH model (linear model). For the linear model, we set that $P_{hst\_i} = \rho P_{rec\_i}, i \in \{s, r\}$, where $\rho = 0.5$ denotes the power conversion efficiency [6].

Figure 2 demonstrates the average secrecy rate R_s versus transmit power P_p at $\mathcal{P}$ for different transmit schemes. Compared with the D-powered scheme, the performance improvement of the proposed AO scheme reaches about $1.7bps/Hz$ at most, as $\mathcal{S}$ and $\mathcal{R}$ can harvest more RF energy using this scheme. The AO scheme also outperforms the non-cooperative scheme especially for high P_p and the gap is about $0.3bps/Hz$ when $P_p \geq 16dBm$, which verifies the advantages in beamforming design of the AO scheme.

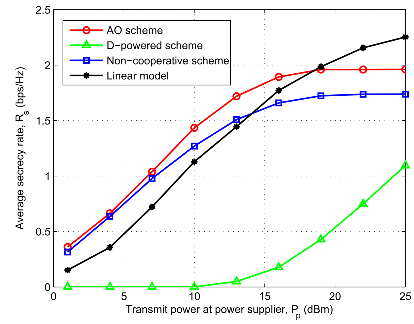

Fig. 2 Comparison of different transmit schemes with $P_d = 100\,mW, N_s = N_r = 4$ and $d_4 = 10\,m$.

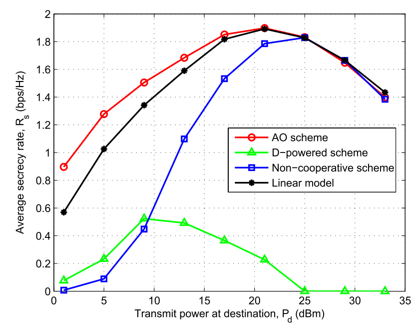

Fig. 3 Comparison of different transmit schemes with $P_p = 50\,mW, N_s = N_r = 4$ and $d_4 = 10\,m$.

Besides, we also compare the secrecy performance with the linear model. According to (3), the harvesting power of non-linear model is higher for low P_p, hence it shows better performance compared with linear model. But with (3), it can be obtained that $\lim_{P_{rec\_i}\to\infty} P_{hst\_i} = M_E$. Hence, the secrecy rate of non-linear model tends to be saturated as P_p goes to $20dBm$, and it shows worse performance compared with linear model for high P_p. This implies the existence of optimal power supply for $\mathcal{P}$ with practical non-linear model.

Figure 3 demonstrates the average secrecy rate R_s versus transmit power P_d at $\mathcal{D}$ for different transmit schemes. It shows that R_s increases with P_d at first, because the enhanced interfere degrades the wiretap channel. When P_d continues to increase, the secrecy performance decreases dramatically, because $\mathcal{R}$ has to forward the jamming signal using more harvesting energy in the information transfer process. It can also be found that the AO scheme outperforms the D-powered scheme and non-cooperative scheme. For the linear model, when P_p is low the nodes $\mathcal{S}$ and $\mathcal{R}$ harvest less energy than the non-linear model, hence the secrecy performance is shown worse. When $P_d \geq 25dBm$, most harvesting energy of $\mathcal{R}$ is used for forwarding jamming signal, which leads to the near performance of AO scheme, non-cooperative scheme and linear scheme.

Figure 4 investigates the average secrecy rate R_s versus the distance d_4 between $\mathcal{R}$ and $\mathcal{D}$ with $P_p = 50mW, P_d = 100mW$. It can be found that for the AO and non-cooperative schemes, the R_s decreases with d_4 slowly at first, as $\mathcal{R}$ allocates less energy for forwarding jamming signal although

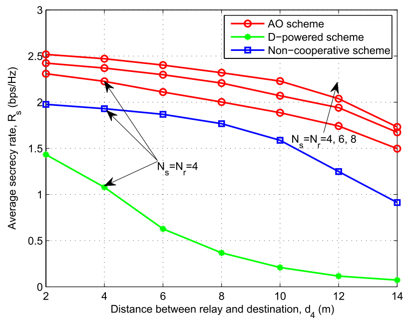

Fig. 4 Secrecy rate versus distance d_4 for different antenna numbers with different transmit schemes.

the path loss between $\mathcal{R}$ and $\mathcal{D}$ gets enhanced. But the path loss of D-powered scheme is more severe, hence the R_s decreases with d_4 rapidly. The AO scheme outperforms the non-cooperative scheme with performance gain about $0.5bps/Hz$ at most for $N_s = N_r = 4$. The performance gap between the AO scheme and the D-powered scheme increases with d_4 at first, because the larger d_4 leads to more severe path loss for the D-powered scheme. With d_4 further increasing, the performance gap decreases as both the two schemes tend toward $R_s = 0$. In addition, it also can be found that increasing the antenna number will lead to better secrecy performance as more spatial diversity is provided.

5. Conclusion

In this letter, we have addressed joint beamforming design for the RF powered two-hop untrusted relay networks with non-linear EH model. The original SRM problem is nonconvex, hence an AO based iterative algorithm was proposed to make it tractable. Finally, simulation results verified the effectiveness of the proposed algorithm in secrecy performance improvement.

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Appendix A: Proof of Proposition 1

The Lagrangian function of (13) can be expressed as

$$\begin{aligned} l_1 &= log(1+\frac{Tr(\mathbf{Q}_s\mathbf{A})}{b})-log|\mathbf{M}_0| \\ &-Tr[\frac{\mathbf{H}_{sr}(\mathbf{Q}_s-\mathbf{Q}_{s0})\mathbf{H}_{sr}{}^H}{\mathbf{M}_0}]+log|P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H+\sigma_r{}^2\mathbf{I}| \\ &-\nu_1[Tr(\tilde{\mathbf{W}}_r\mathbf{H}_{sr}\mathbf{Q}_s\mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H)+\sigma_r{}^2Tr(\tilde{\mathbf{W}}_r\tilde{\mathbf{W}}_r^H) \\ &+P_dTr(\tilde{\mathbf{W}}_r\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H\tilde{\mathbf{W}}_r^H)-2P_{hst\_r}] \\ &-\mu_1[Tr(\mathbf{Q}_s)-2P_{hst\_s}]+Tr(\mathbf{Z}_1\mathbf{Q}_s) \end{aligned} \tag{A$\cdot$1}$$

where $\mathbf{A} = \mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H\mathbf{h}_{rd}\mathbf{h}_{rd}{}^H\tilde{\mathbf{W}}_r\mathbf{H}_{sr}$, $b = \sigma_d{}^2 + \sigma_r{}^2\mathbf{h}_{rd}{}^H\tilde{\mathbf{W}}_r\tilde{\mathbf{W}}_r^H\mathbf{h}_{rd}$ and $\mu_1, \nu_1, \mathbf{Z}_1$ are the associated dual variables. Besides,

$$\begin{aligned} \frac{\partial l_1}{\partial \mathbf{Q}_s} &= \frac{\mathbf{A}}{b+Tr(\mathbf{Q}_s\mathbf{A})} - \mathbf{H}_{sr}\mathbf{M}_0{}^{-1}\mathbf{H}_{sr}{}^H \\ &\quad - \nu_1\mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H\tilde{\mathbf{W}}_r\mathbf{H}_{sr} - \mu_1\mathbf{I} + \mathbf{Z}_1 \end{aligned} \tag{A$\cdot$2}$$

According to the KKT conditions, it is satisfied that

$$\frac{\partial l_1}{\partial \mathbf{Q}_s{}^*} = 0 \tag{A$\cdot$3a}$$

$$\mathbf{Z}_1\mathbf{Q}_s{}^* = \mathbf{0} \tag{A$\cdot$3b}$$

Hence, it can be obtained

$$\mathbf{Z}_1 = \mathbf{H}_{sr}\mathbf{M}_0{}^{-1}\mathbf{H}_{sr}{}^H + \nu_1\mathbf{H}_{sr}{}^H\tilde{\mathbf{W}}_r^H\tilde{\mathbf{W}}_r\mathbf{H}_{sr} + \mu_1\mathbf{I} - \frac{\mathbf{A}}{b + Tr(\mathbf{Q}_s{}^*\mathbf{A})} \tag{A·4}$$

Due to $rank(\mathbf{A})=1$, we have $rank(\mathbf{Z}_1) \geq N_s-1$. According to (A.3b), it can be obtained $rank(\mathbf{Q}_s{}^*) = N_s - rank(\mathbf{Z}_1)$, which implies $rank(\mathbf{Q}_s{}^*) \leq 1$. Since $rank(\mathbf{Q}_s{}^*) = 0$ is not a feasible solution to (13), we can conclude that $rank(\mathbf{Q}_s{}^*) = 1$. The proof is completed.

Appendix B: Proof of Proposition 2

The Lagrangian function of (20) can be expressed as

$$l_2 = Tr(\bar{\mathbf{Q}}_r\mathbf{F_1}) - \mu_2[1-\sigma_r{}^2 Tr(\bar{\mathbf{Q}}_r\mathbf{F}_2) - t\sigma_d{}^2] - \nu_2[Tr(\bar{\mathbf{Q}}_r\mathbf{F}_3) - 2tP_{hst\_r}] + Tr(\mathbf{Z}_2\bar{\mathbf{Q}}_r) + \lambda t \tag{A·5}$$

where $\mu_2, \nu_2, \mathbf{Z}_2, \lambda$ are associated dual variables. We have

$$\frac{\partial l_2}{\partial \bar{\mathbf{Q}}_r} = \mathbf{F_1} - \mu_2\sigma_r{}^2\mathbf{F}_2 - \nu_2\mathbf{F}_3 + \mathbf{Z}_2 \tag{A·6}$$

According to the KKT conditions, it is satisfied

$$\mathbf{Z}_2 = \mu_2\sigma_r{}^2\mathbf{F}_2 + \nu_2\mathbf{F}_3 - \mathbf{F_1} \tag{A·7}$$

Based on the fact $rank(\mathbf{A}\otimes\mathbf{B}) = rank(\mathbf{A})\cdot rank(\mathbf{B})$ [17], it can be obtained

$$\begin{aligned} &rank(\mathbf{F_1}) = rank(\mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H)\cdot rank(\mathbf{h}_{rd}{}^\dagger\mathbf{h}_{rd}{}^T) = 1 \\ &rank(\mathbf{F}_3) = rank(\mathbf{F}_4)\cdot rank(\mathbf{I}) = N_r{}^2 \end{aligned} \tag{A·8}$$

with $\mathbf{F}_4 = \mathbf{H}_{sr}\tilde{\mathbf{Q}}_s\mathbf{H}_{sr}{}^H + \sigma_r{}^2\mathbf{I} + P_d\mathbf{h}_{dr}\mathbf{h}_{dr}{}^H$. As $\mathbf{F}_2 \geq \mathbf{0}$, it is satisfied $rank(\mathbf{Z}_2) \geq N_r{}^2 - 1$. Using the similar method in Appendix A, it can be verified that $rank(\bar{\mathbf{Q}}_r^*) = 1$. Hence, Proposition 2 is proved.