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Artificial Noise Assisted Secure Interference Networks with Wireless Power Transfer

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***Abstract*—Interference alignment (IA) is a remarkable technique to manage interference, and artificial noise (AN) can be utilized to combat one main threat of security, passive eavesdropping. Nevertheless, in the existing schemes AN is only eliminated at each legitimate receiver, which is a waste of energy. In this paper, we propose an AN assisted IA scheme with wireless power transfer (WPT). In the proposed scheme, AN is generated by each transmitter along with data streams, which can disrupt the eavesdropping without introducing any additional interference. Due to the fact that the transmit power of AN should be high enough to ensure the security, energy harvesting (EH) is also performed in the scheme. A power splitter is equipped at each receiver, which can divide the received signal, including desired signal, interference and AN, into two parts: one for information decoding (ID) and the other for EH. To optimize the anti-eavesdropping performance, the total transmit power of AN is maximized by jointly optimizing the information transmit power and the coefficient of power splitting, with the requirements of signal-to-interference-plus-noise ratio (SINR) and harvested power satisfied. Due to the non-convex nature of the problem, a suboptimal solution is also derived to calculate the closed-form solutions with extremely low computational complexity. Extensive simulation results are presented to show the effectiveness of the proposed scheme.**

***Index Terms*—Artificial noise, interference alignment, passive eavesdropping, physical layer security, wireless power transfer.**

I. INTRODUCTION

Recently, *interference alignment* (IA) has been proposed as a revolutionary technique to solve the interference management issue in wireless networks [2], [3]. Since its emergence, IA has drawn wide attention from both academia and industry due to its remarkable performance. In [2], Cadambe and Jafar demonstrated that each user in an interference network is able to obtain nearly one half of the capacity that it could achieve in the absence of interference when the signal-to-noise ratio (SNR) is high, which is superior to the performance of the conventional "cake-cutting" view. The closed-form solutions of IA are extremely difficult to derive as the number of users increases beyond three [4]. Consequently, researchers focused on developing iterative IA algorithms to solve this problem with low computational complexity. In [5], Gomadam *et al.* proposed the MinIL and MAX-SINR algorithms based on a distributed numerical approach, which can calculate the IA solutions iteratively. Although IA has been studied extensively in recent years, there still exist some challenges [6]. For instance, the sum rate of IA networks is far from the theoretical maximum at low or medium SNRs [5], [7], and the overhead of global channel state information (CSI) feedback is too high to achieve [8]–[12].

On the other hand, due to the openness and broadcast nature of wireless transmission, secure information transfer becomes a challenging subject [13], [14]. Thus, the research for physical layer security has attached great importance to combat with malicious attacks in wireless networks [1], [15]–[26]. There are mainly two kinds of malicious attacks that lead to the vulnerability of wireless transmission, passive eavesdropping and active jamming [15], [27].

In this paper, we mainly focus on *eavesdropping*. The eavesdropper can be regarded as an illegal user that attempts to intercept the information transmitted by the authorized users [16], [17]. The traditional approaches towards eavesdroppers depend on cryptographic techniques, which encrypt information with secret keys to prevent information interception [28]. However, the security of cryptographic techniques may be degraded owing to the solvability of secret keys and the unavailability of a trusted key management center [13]. To this end, some new techniques known as physical layer security have emerged, a large group of which were based on artificial noise (AN) [16], [18]–[22]. Besides, Wang *et al.* proposed a new scheme named artificial fast fading (AFF) to combat with eavesdropping, and compared the performance of the AN scheme and the AFF scheme [23]. When IA is involved, AN can also be employed to enhance its security. In [1], [24], an anti-eavesdropping IA scheme was proposed by exploiting AN, and the performance of eavesdropping rate versus transmit power of AN was analyzed.

In the abovementioned research on AN methods, most of the transmit power is allocated to AN to boost the anti-eavesdropping performance, which is really a waste of energy. Fortunately, the emerging technique of *wireless power transfer* (WPT) can be leveraged to collect the redundant energy in

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wireless networks to supply low-power applications, such as ultra-low-power sensors [29], [30]. Thus, AN can also be deemed as a potential source of energy because of its high power. Due to the fact that the radio-frequency (RF) signals can carry information and energy at the same time, simultaneous wireless information and power transfer (SWIPT) becomes a promising technique for energy harvesting and attracts plenty of attention, especially in multi-input multi-output (MIMO) wireless networks [31]–[38].

In our previous works, an AN scheme was proposed to enhance the security of IA networks, and it was shown that the eavesdropping rate will be decreased when the transmit power of AN increases [24]. Nevertheless, the ANs are only eliminated at the legitimate receivers, which could be exploited as a redundant energy source. Thus, in this paper, the WPT is further researched in the AN assisted IA scheme, and the transmit power and the coefficient of power splitting (PS) are jointly optimized to minimize the eavesdropping rate, while satisfying the requirements of information transmission (IT) and EH. The main motivations and contributions of this paper are summarized as follows.

- Interference and jamming signal used to be deemed as harmful to wireless transmission. However, we take a totally different view on this, by turning it from harmful to beneficial. In this paper, the interference among users and AN to combat with eavesdropping are further exploited as a redundant energy source for interference networks.
- In the existing AN assisted IA studies, no power allocation is considered, which seriously limits the improvement of the anti-eavesdropping performance. Thus, in this paper, the power allocation of the AN assisted IA scheme is first researched to maximize the transmit power of AN with the requirement of IT satisfied. Through power allocation, the anti-eavesdropping performance can be significantly improved.
- To further exploit the power of AN, a novel AN assisted IA scheme with WPT is proposed. In the scheme, a power splitter is equipped at each receiver, through which the received signal can be split into two parts, one for ID and the other for EH. To improve the performance of this scheme, the transmit power of AN is maximized to combat with the eavesdropping, through jointly optimizing the transmitted power and the coefficients of PS, with the minimal requirements of IT and EH guaranteed to keep the basic operations of each user.
- Due to the non-convex nature of the optimal problem for the scheme, it is difficult to solve. Thus, a suboptimal algorithm is designed for the proposed scheme with low computational complexity. Through the suboptimal algorithm, the closed-form solutions can be obtained.

The rest of this paper is organized as follows. In Section II, the system model is presented. The power allocation of the previous AN assisted IA scheme is proposed in Section III. In Section IV, a novel AN assisted IA scheme with WPT is proposed, and the suboptimal solutions are derived for the optimal problem of this scheme in Section V. The simulation results are presented in Section VI. Finally, the conclusions are drawn in Section VII.

Notation: $\mathbf{I}_N$ represents the $N \times N$ identity matrix. $\mathbf{A}^\dagger$ is the Hermitian transpose of matrix $\mathbf{A}$. $\mathbf{A}_{*l}$ is the lth column of matrix $\mathbf{A}$. $\|\mathbf{a}\|$ is the Euclidean norm of vector $\mathbf{a}$ and $\|\mathbf{A}\|$ means the Frobenius norm of matrix $\mathbf{A}$. $\mathbb{C}^{M\times N}$ is the space of complex $M \times N$ matrices. $\mathcal{CN}(\mathbf{a},\mathbf{A})$ is the complex Gaussian distribution with mean $\mathbf{a}$ and covariance matrix $\mathbf{A}$. $\mathbf{0}_{M\times N}$ denotes an $M \times N$ zero matrix. $\mathbb{E}(\cdot)$ stands for expectation.

II. SYSTEM MODEL

In this section, the conventional IA network is presented, followed by the model of the AN assisted IA networks.

A. IA Networks

Considering a K-user IA-based wireless network, we assume that $M^{[k]}$ and $N^{[k]}$ antennas are equipped at the kth transmitter and receiver, respectively, and $d^{[k]}$ independent data streams are emitted by the kth transmitter. The recovered signal at the kth receiver can be expressed as

$$\mathbf{y}^{[k]}{=}\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{x}^{[k]}{+}\sum_{j=1,j\neq k}^{K}\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\mathbf{x}^{[j]}{+}\mathbf{U}^{[k]\dagger}\mathbf{n}^{[k]}, \quad (1)$$

where $\mathbf{V}^{[k]} \in \mathbb{C}^{M^{[k]}\times d^{[k]}}$ and $\mathbf{U}^{[k]} \in \mathbb{C}^{N^{[k]}\times d^{[k]}}$ are the unitary precoding and decoding matrices for the transmission of the kth user, respectively. $\mathbf{H}^{[kj]} \in \mathbb{C}^{N^{[k]}\times M^{[j]}}$ denotes the channel coefficient matrix from the jth transmitter to the kth receiver, with independent and identically distributed (i.i.d) entities, following $\mathcal{CN}(0,\alpha_p)$. $0 < \alpha_p < 1$ is the fading power due to path-loss. $\mathbf{n}^{[k]} \in \mathbb{C}^{N^{[k]}\times 1}$ represents the additive white Gaussian noise (AWGN) vector at the kth receiver, $\mathcal{CN}\left(\mathbf{0},\sigma^2\mathbf{I}_{N^{[k]}}\right)$. $\mathbf{x}^{[k]}$ denotes the signal vector including $d^{[k]}$ data streams transmitted by the kth transmitter with power $P_t^{[k]}$, i.e., $\mathbb{E}\left[\left\|\mathbf{x}^{[k]}\right\|^2\right] = P_t^{[k]}$.

To retrieve the desired signal at the kth receiver accurately, the interference from other users should be aligned into the same subspace, and thus can be perfectly eliminated when the following conditions are satisfied.

$$\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{V}^{[j]} = \mathbf{0}_{d^{[k]}\times d^{[j]}},\ \forall j \neq k, \quad (2)$$

$$\text{rank}\left(\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right) = d^{[k]},\ k = 1, 2, \cdots, K. \quad (3)$$

When (2) and (3) are met, the interference of the kth receiver can be aligned and then eliminated completely. Thus, the recovered signal at the kth receiver can be simplified as

$$\mathbf{y}^{[k]} = \mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{x}^{[k]}{+}\mathbf{U}^{[k]\dagger}\mathbf{n}^{[k]}, \quad (4)$$

and the transmission rate of the kth user is expressed as

$$R_t^{[k]} = \log_2\left(\det\left(\mathbf{I}_{d^{[k]}} + \frac{P_t^{[k]}}{d^{[k]}\sigma^2}\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{V}^{[k]\dagger}\mathbf{H}^{[kk]\dagger}\mathbf{U}^{[k]}\right)\right). \quad (5)$$

B. AN Assisted IA Networks

MIMO eavesdropping is a great threat to the secure transmission of IA-based networks, especially when enough antennas are equipped at the eavesdropper. In our previous work [24], an AN assisted IA scheme was proposed to fight against the external eavesdropper of the legitimate network, which can greatly enhance its security. In the AN assisted IA network, AN is generated by each transmitter, and the received signal at the kth receiver can be denoted as

$$\begin{aligned} \mathbf{y}^{[k]} &= \mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{x}^{[k]} + \sum_{j=1, j\neq k}^{K} \mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\mathbf{x}^{[j]} \\ &+ \sum_{j=1}^{K} \mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{W}^{[j]}\mathbf{s}^{[j]} + \mathbf{U}^{[k]\dagger}\mathbf{n}^{[k]}, \end{aligned} \tag{6}$$

where $\mathbf{W}^{[j]} \in \mathbb{C}^{M^{[j]}\times d_{an}^{[j]}}$ is the unitary precoding matrix for AN of the jth user, and $\mathbf{s}^{[j]}$ is the vector that consists of $d_{an}^{[j]}$ streams of AN emitted by the jth transmitter with power $P_{an}^{[j]}$, i.e., $\mathbb{E}\left[\left\|\mathbf{s}^{[j]}\right\|^2\right] = P_{an}^{[j]}$. For simplicity, we assume that all the users have the same parameters in the rest of this paper, i.e., $M^{[k]} = M$, $N^{[k]} = N$, $d^{[k]} = d$ and $d_{an}^{[k]} = d_{an}$, for $k = 1, 2, \ldots, K$.

To guarantee the legitimate transmission of the network, we should eliminate both the interference among users and the AN generated by all the users, and thus the following condition should be satisfied together with (2) as

$$\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{W}^{[j]} = \mathbf{0}_{d\times d_{an}},\ \forall j, k = 1, 2, \cdots, K. \tag{7}$$

When both (2) and (7) can be solved, the generated AN and interference from other users can be eliminated perfectly at each receiver, and the legitimate transmission will not be impacted by the AN. Besides, the feasibility condition for AN assisted IA scheme, was derived in our previous work according to (2) and (7) [24] as

$$dM+dN+d_{an}M\geq d^2+d_{an}^2+d^2K+dd_{an}K, M\geq d, N\geq d. \tag{8}$$

Usually, one stream for AN of each user is enough to disrupt the eavesdropping, and the feasible condition in (8) can be simplified as

$$(d+1)M + dN \geq d^2K + d^2 + dK + 1, M \geq d, N \geq d. \tag{9}$$

When condition (9) is satisfied, both AN and interference can be eliminated at each legitimate receiver through the precoding and decoding matrices, which can be designed by the algorithm in [24]. Specifically, in our previous work [24], an iterative algorithm with necessary modifications based on the MinIL algorithm was proposed for the AN assisted IA scheme to calculate the precoding and decoding matrices. In this algorithm, the reciprocity of wireless networks is exploited. For the forward direction, the interference from other users and the AN from all the IA users are considered together to update the decoding matrix of the kth user, $k = 1, 2, \ldots, K$. Then in the reverse direction, the updated decoding matrices will be utilized cooperatively to obtain the precoding matrices of the legitimate signal and AN for the kth user, respectively, with only interference involved, $k = 1, 2, \ldots, K$. Changing the forward and reverse directions alternatively, the solutions to $\mathbf{V}^{[k]}$, $\mathbf{U}^{[k]}$ and $\mathbf{W}^{[k]}$ will be obtained until it converges, $k = 1, 2, \ldots, K$. More details about the algorithm can be found in [24].

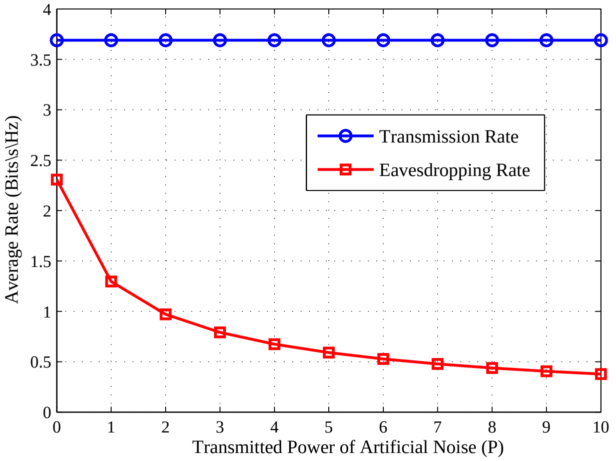

Fig. 1. The transmission rate and eavesdropping rate versus different transmit power of AN [24], where $M = 9$, $N = 5$, $\mathcal{N}_{\varepsilon} = 14$, $d = 2$, $K = 5$ and SNR $= 20$dB. P denotes the transmit power of legitimate signal.

With the precoding and decoding matrices obtained in the iterative algorithm, both AN and interference can be aligned and eliminated at each legitimate receiver, whereas the external eavesdropping will be disrupted by the generated AN. The recovered signal at the kth receiver in the scheme can be expressed as (4) too. Thus, the AN assisted IA scheme can be utilized to disrupt the external eavesdropping without introducing any additional interference to the legitimate transmission.

III. POWER ALLOCATION IN AN ASSISTED IA SCHEME

In the previous work on AN assisted IA scheme [24], the transmit power and the AN power of each user is equally allocated. This can be further improved. The average transmission rate and eavesdropping rate of the AN assisted IA scheme are compared in Fig. 1, when the transmitted power of AN is increased. We can see from Fig. 1 that the eavesdropping rate is decreasing when the transmit power of AN becomes higher, while the transmission rate is unchanged. Thus, it is important to perform power allocation in the AN assisted IA scheme, for the following reasons.

- In Fig. 1, the eavesdropping rate can be obtained when the CSI of the eavesdropper is available. However, in practical systems, we cannot locate the eavesdropper due to its passive mode, and thus we cannot know the eavesdropping rate exactly. Thus, more transmit power should be allocated to AN to degrade the eavesdropping rate, as long as the transmission rate of the legitimate users is guaranteed.
- It is usually assumed that the total transmit power of each user is limited, which contains one part for information transmission and the other part for AN in the AN assisted IA scheme. Thus, we can calculate the minimal transmit power for information transmission of a certain user with its rate requirement satisfied, and all the remaining power

can be allocated to AN to disrupt the eavesdropping as much as possible.

The received SINR of the kth receiver can be derived from (4) as

$$\text{SINR}^{[k]}=\frac{P_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\sigma^2},\tag{10}$$

and the objective function of power allocation in the AN assisted IA scheme can be formulated as

$$\begin{aligned}&\max_{P_t^{[k]}}\ \sum_{k=1}^{K}P_{an}^{[k]}\\&s.t.\ \ \text{SINR}^{[k]}\geq\gamma^{[k]},P_{an}^{[k]}+P_t^{[k]}=P_{sum}^{[k]},P_{an}^{[k]}\geq\bar{P}_{an}^{[k]},\forall k.\end{aligned}\tag{11}$$

In (11), $\gamma^{[k]}$ represents the threshold for the received SINR of the kth user, which can ensure its reliable transmission. $\bar{P}_{an}^{[k]}$ denotes the constraint of AN power at the kth transmitter to guarantee the secure transmission, and $P_{sum}^{[k]}$ is the given total transmit power of the kth user, including the information and AN. Problem (11) can be easily solved, and its solution is derived in Lemma 1.

Lemma 1: The solution to (11) can be expressed as

$$\begin{aligned}P_t^{[k]\star}&=\frac{\gamma^{[k]}\sigma^2}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2},\\P_{an}^{[k]\star}&=P_{sum}^{[k]}-\frac{\gamma^{[k]}\sigma^2}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}.\end{aligned}\tag{12}$$

Proof: Due to the fact that the total transmit power of each user is a known constant, (11) can be simplified as

$$\begin{aligned}&\max_{P_t^{[k]}}\ \sum_{k=1}^{K}\left(P_{sum}^{[k]}-P_t^{[k]}\right)\\&s.t.\ \frac{P_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\sigma^2}\geq\gamma^{[k]},P_{sum}^{[k]}-P_t^{[k]}\geq\bar{P}_{an}^{[k]},\forall k.\end{aligned}\tag{13}$$

Note that (13) is a linear programming over a single variable, and its optimal solution can be obtained when all the SINR constraints hold with equality. Thus, the optimal solution to problem (13) can be derived as

$$P_t^{[k]\star}=\frac{\gamma^{[k]}\sigma^2}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2},P_{an}^{[k]\star}=P_{sum}^{[k]}-\frac{\gamma^{[k]}\sigma^2}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}.$$

■

Problem (11) can be solved according to Lemma 1 as long as the total transmit power limit can meet both of the minimal requirements of the SINR and AN of the kth user, i.e., $\gamma^{[k]}$ and $\bar{P}_{an}^{[k]}$, $k=1,2,\ldots,K$.

When there exists a passive eavesdropper in a K-user AN assisted IA network with $\mathcal{N}_\varepsilon$ antennas, and the AN stream satisfies $d_{an}=1$, the received signal at the eavesdropper can be expressed as

$$\boldsymbol{\upsilon}_\varepsilon=\sum_{j=1}^{K}\mathbf{\Gamma}_\varepsilon^{[j]}\mathbf{V}^{[j]}\mathbf{x}^{[j]}+\sum_{j=1}^{K}\mathbf{\Gamma}_\varepsilon^{[j]}\mathbf{w}^{[j]}s^{[j]}+\mathbf{n}_\varepsilon,\tag{14}$$

where $\mathbf{\Gamma}_\varepsilon^{[j]}\in\mathbb{C}^{\mathcal{N}_\varepsilon\times M}$ denotes the channel matrix from the jth transmitter to the eavesdropper. Similar to $\mathbf{H}^{[kj]}$, each entity of $\mathbf{\Gamma}_\varepsilon^{[j]}$ is i.i.d. and follows $\mathcal{CN}(0,\alpha_p)$. $\mathbf{w}^{[j]}$ represents the unitary transmit beamforming vector of AN at the jth transmitter, $s^{[j]}$ is the AN signal generated by the jth transmitter, and $\mathbf{n}_\varepsilon\in\mathbb{C}^{\mathcal{N}_\varepsilon\times 1}$ is the AWGN vector that satisfies $\mathcal{CN}(\mathbf{0},\sigma^2\mathbf{I}_{\mathcal{N}_\varepsilon})$ at the eavesdropper.

According to the analysis in [24], it is known that, when condition $\mathcal{N}_\varepsilon\geq(d+1)K-d$ is satisfied and a certain legitimate user is targeted to be eavesdropped, the interference and AN from other users can be eliminated at the eavesdropper. Nevertheless, the interference among data streams and AN from this user can't be removed, which will also affect the eavesdropping performance. Thus, the recovered signal can be expressed with decoding performed at the eavesdropper as

$$\upsilon_\varepsilon^{[k]}=\sum_{i=1}^{d}\boldsymbol{\mu}_\varepsilon^{[k]\dagger}\mathbf{\Gamma}_\varepsilon^{[k]}\mathbf{V}_{*i}^{[k]}x_i^{[k]}+\boldsymbol{\mu}_\varepsilon^{[k]\dagger}\mathbf{\Gamma}_\varepsilon^{[k]}\mathbf{w}^{[k]}s^{[k]}+\boldsymbol{\mu}_\varepsilon^{[k]\dagger}\mathbf{n}_\varepsilon,\tag{15}$$

where $\boldsymbol{\mu}_\varepsilon^{[k]}\in\mathbb{C}^{\mathcal{N}_\varepsilon\times 1}$ is the decoding vector of the eavesdropper. In this condition, the eavesdropping rate can be calculated as (16) (on the next page).

From (16), it can be concluded that we should enhance the transmit power of AN and decrease the information transmit power if we want to reduce the eavesdropping rate. This is because the received power of the eavesdropped signal will increase when the information transmit power becomes higher, although the interference among streams of a targeted user can also affect the eavesdropping performance. Thus, based on the power allocation in (11), only the minimal power is allocated to the information streams to ensure reliable transmission, and all the remaining power is devoted to AN to guarantee secure transmission. In addition, the expression of (16) can be obtained only when the CSI of eavesdropper is known. However, in practical systems, the eavesdropping is performed passively, and the CSI of eavesdropper cannot be obtained. The power of AN should be allocated as high as possible to combat with the potential eavesdropping.

Nevertheless, although the eavesdropping is disrupted, the signals of AN are just eliminated at each legitimate receiver along with the interference, which is a waste of energy. Actually, the power of AN and interference can be exploited as a new energy resource, which can be collected to replenish the batteries at the receivers. Thus, a novel AN assisted AN scheme with WPT is presented in the next section.

IV. AN ASSISTED IA SCHEME WITH WPT

In this section, wireless power transfer is first reviewed briefly for wireless networks. Then a novel AN assisted IA scheme with wireless power transfer is proposed to replenish the batteries with secure transmission guaranteed.

A. *Wireless Power Transfer*

Wireless power transfer is a promising technique to collect the power carried by the RF signal to replenish the batteries for low-power applications. Specifically, because RF signal can carry information as well as energy at the same time,

$$\begin{aligned} R_{\varepsilon}^{[k]} &= \sum_{i=1}^{d} \log_2 \left(1 + \frac{P_t^{[k]} \boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{V}_{*i}^{[k]} \mathbf{V}_{*i}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]}}{d\sigma^2 + P_t^{[k]} \sum\limits_{j=1, j\neq i}^{d} \boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{V}_{*j}^{[k]} \mathbf{V}_{*j}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]} + dP_{an}^{[k]} \boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{w}^{[k]} \mathbf{w}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]}} \right) \\ &= \sum_{i=1}^{d} \log_2 \left(1 + \frac{\boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{V}_{*i}^{[k]} \mathbf{V}_{*i}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]}}{\frac{d\sigma^2}{P_t^{[k]}} + \sum\limits_{j=1, j\neq i}^{d} \boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{V}_{*j}^{[k]} \mathbf{V}_{*j}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]} + \frac{P_{an}^{[k]}}{P_t^{[k]}} d\boldsymbol{\mu}_{\varepsilon}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]} \mathbf{w}^{[k]} \mathbf{w}^{[k]\dagger} \boldsymbol{\Gamma}_{\varepsilon}^{[k]\dagger} \boldsymbol{\mu}_{\varepsilon}^{[k]}} \right). \end{aligned} \tag{16}$$

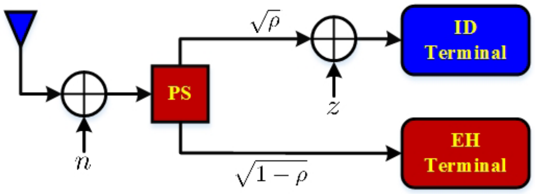

Fig. 2. The power-splitting model of SWIPT with a single antenna [31].

simultaneous wireless information and power transfer is an important kind of WPT. There are two main types of receiver design for SWIPT, i.e., time switching and power splitting [31]. In this paper, we consider the PS technique in our proposed scheme, whose structure with a single antenna is shown in Fig. 2.

As shown in Fig. 2, the received power at the antenna is split into two parts according to the PS coefficient $\rho \in (0, 1)$, i.e., ρ portion of the received power is assigned to the ID terminal and the remaining $(1-\rho)$ portion is devoted to the EH terminal. In addition, n and z denote the noise induced at the antenna and at the baseband, respectively. Providing that the received signal at the antenna is denoted by y, the received signal at the ID terminal can be expressed as

$$y_{\text{ID}} = \sqrt{\rho}\,(y+n) + z. \tag{17}$$

The received signal for EH can be denoted as

$$y_{\text{EH}} = \sqrt{1-\rho}\,(y+n)\,, \tag{18}$$

and thus the harvested power is equal to

$$\mathcal{E} = \zeta \mathbb{E}\left[\left\|y_{\text{EH}}\right\|^2\right] \approx \zeta\,(1-\rho)\,\|y\|^2\,. \tag{19}$$

In (19), $\zeta \in (0,1)$ is the power conversion efficiency of the EH terminal. The power of the antenna noise can be ignored in (19), compared with $\|y\|^2$.

In IA networks, multiple antennas are equipped at each node, and a power splitter is equipped at each receive antenna. Thus, the PS method can be performed at each antenna, and the split ID signals and EH signals of the antennas at a specific receiver are delivered to the ID terminal and EH terminal using the same coefficient of PS, respectively. The detailed SWIPT method for the AN assisted IA scheme will be presented in the next subsection.

B. Wireless Power Transfer in AN Assisted IA Scheme

In Section III, we have mentioned that eliminating both AN and interference directly is really a waste of energy. Thus, we propose a novel AN assisted IA scheme with WPT[1] to maximize the transmit power of AN to improve the anti-eavesdropping performance with WPT performed at each legitimate receiver, when the requirements of transmission can be satisfied.

Consider that an external eavesdropper with $\mathcal{N}_{\varepsilon}$ antennas exists in a K-user IA-based network, as shown in Fig. 3. AN is generated by each transmitter using the method in [24], which can disrupt the external eavesdropping without affecting the legitimate transmission. To further utilize the AN and interference, instead of just eliminating them, energy harvesting is performed at each legitimate receiver to replenish the batteries by collecting wireless energy. Thus, in the proposed scheme, the PS technique is adopted, with ID and EH terminals equipped at each receiver as shown in Fig. 3. Assume that $\rho^{[k]} \in (0,1)$ is the PS coefficient at the kth receiver, and the recovered signal by the ID terminal at the kth receiver can be expressed as (20) (on the next page), where $\mathbf{z}^{[k]} \in \mathbb{C}^{N^{[k]}\times 1} \sim \mathcal{CN}(\mathbf{0}, \delta^2 \mathbf{I}_{N^{[k]}})$ is the ID noise caused by the non-ideal signal recovery and thermal noise. When AN assisted IA scheme is preformed, the AN and interference can be eliminated at each receiver perfectly, and (20) can be simplified as

$$\mathbf{y}_{\text{ID}}^{[k]} = \sqrt{\rho^{[k]}}\left(\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{x}^{[k]} + \mathbf{U}^{[k]\dagger}\mathbf{n}^{[k]}\right) + \mathbf{U}^{[k]\dagger}\mathbf{z}^{[k]}. \tag{21}$$

According to the expression in (21), the received SINR at the ID terminal of the kth receiver can be presented as

$$\text{SINR}^{[k]} = \frac{\rho^{[k]} P_t^{[k]} \left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\rho^{[k]}\sigma^2 + \delta^2}, \tag{22}$$

which measures the quality of service (QoS) of information transmission of the kth user.

On the other hand, the received signal at the EH terminal of the kth receiver can be denoted by

$$\mathbf{y}_{\text{EH}}^{[k]} = \sqrt{1-\rho^{[k]}}\left(\sum_{j=1}^{K}\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\mathbf{x}^{[j]} + \sum_{j=1}^{K}\mathbf{H}^{[kj]}\mathbf{w}^{[j]}s^{[j]} + \mathbf{n}^{[k]}\right). \tag{23}$$

[1] The beamforming optimization strategy can also be adopted to optimize the performance of the AN assisted scheme with WPT for interference networks [39]. In this paper, we exploit IA technique instead, which will not hinder the utilization of the beamforming optimization strategy in the AN assisted scheme with WPT.

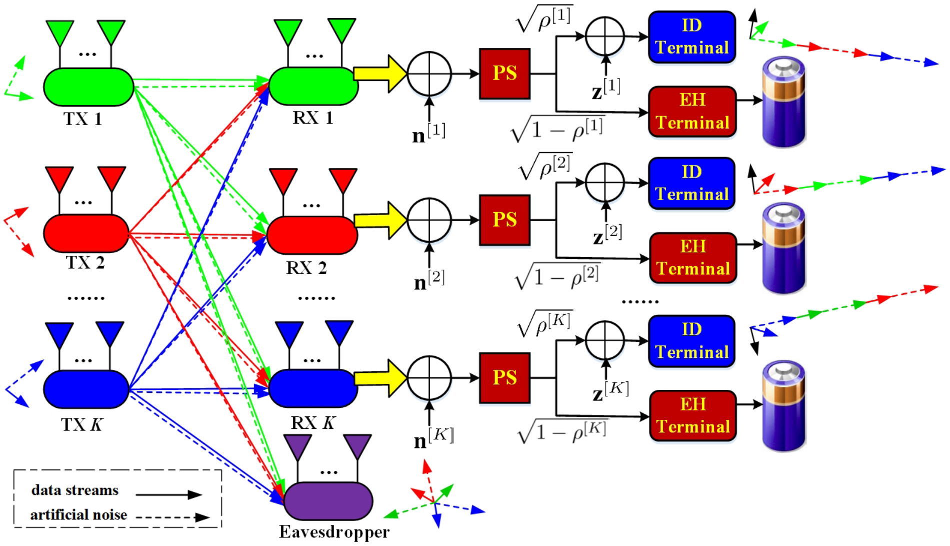

Fig. 3. Demonstration of the K-user AN assisted IA scheme with WPT.

$$\mathbf{y}_{\mathrm{ID}}^{[k]} = \sqrt{\rho^{[k]}}\left(\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\mathbf{x}^{[k]} + \sum_{j=1,j\neq k}^{K}\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\mathbf{x}^{[j]} + \sum_{j=1}^{K}\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kj]}\mathbf{w}^{[j]}s^{[j]} + \mathbf{U}^{[k]\dagger}\mathbf{n}^{[k]}\right) + \mathbf{U}^{[k]\dagger}\mathbf{z}^{[k]}. \tag{20}$$

According to (23), the harvested power by the EH terminal at the kth receiver can be expressed as

$$\mathcal{E}^{[k]}=\zeta\left(1-\rho^{[k]}\right)\sum_{j=1}^{K}\left(P_t^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\right\|^2+P_{an}^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{w}^{[j]}\right\|^2\right), \tag{24}$$

where the power of the antenna noise is ignored compared with the signal power.

In the proposed AN assisted IA scheme with WPT, the transmit power of AN is maximized to combat with the passive eavesdropping, with the requirements of information transmission and energy harvesting satisfied. The objective function can be expressed as

$$\begin{aligned}&\max_{\rho^{[k]},P_t^{[k]}}\ \sum_{k=1}^{K}\left(P_{sum}^{[k]}-P_t^{[k]}\right)\\&\quad s.t.\ \mathrm{SINR}^{[k]}\geq\gamma^{[k]},\mathcal{E}^{[k]}\geq e^{[k]},P_{sum}^{[k]}-P_t^{[k]}\geq\bar{P}_{an}^{[k]},\\&\qquad 0<\rho^{[k]}<1,\ \ \forall k.\end{aligned} \tag{25}$$

In (25), $\bar{P}_{an}^{[k]}$, $\gamma^{[k]}$, and $e^{[k]}$ represent thresholds for transmit power of AN, received SINR for the ID terminal and harvested energy by the EH terminal of the kth user, respectively. $P_{sum}^{[k]}$ is the sum transmit power of the kth user, i.e., $P_{sum}^{[k]}=P_{an}^{[k]}+P_t^{[k]}$, which has been used in (25).

Remark 1: In the objective function of (25), the transmit power of AN is maximized, with the requirements of IT and EH satisfied. This means that only the minimal power is allocated to guarantee the QoS of transmission and energy required for the basic operations of each receiver, and all the remaining power is devoted to AN, by which the potential eavesdropping rate will be minimized according to the analysis of (16).

Remark 2: When the sum of transmit power of each user P_{sum} is fixed, either the SINR constraint $\gamma\to\infty$ or the EH constraint $e\to\infty$ will lead to the infeasibility of problem (25), i.e, the optimal solution to problem (25) cannot be achieved. Thus, for a certain P_{sum}, both SINR and EH thresholds should not be set too large in order to obtain the optimal solution. Without loss of generality, in the rest of this paper we assume that problem (25) is feasible, unless stated otherwise.

In addition, although the objective function of (25) is convex, the constrained conditions of SINR and EH in (25) are non-convex due to the fact that the variables $\rho^{[k]}$ and $P_t^{[k]}$ are coupled, which makes problem in (25) non-convex. Thus, the global optimum of the problem is difficult to obtain directly.

Nevertheless, problem (25) can be converted into a convex problem as follows.

$$\begin{aligned}&\max_{\rho^{[k]},P_t^{[k]}}\ \sum_{k=1}^{K}\left(P_{sum}^{[k]}-P_t^{[k]}\right)\\&s.t.\ \ \frac{P_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\gamma^{[k]}}\geq\sigma^2+\frac{\delta^2}{\rho^{[k]}},\\&\quad\sum_{j=1}^{K}\left(P_t^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\right\|^2+P_{an}^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{w}^{[j]}\right\|^2\right)\geq\frac{e^{[k]}}{\zeta\left(1-\rho^{[k]}\right)},\\&\quad P_{sum}^{[k]}-P_t^{[k]}\geq\bar{P}_{an}^{[k]},0<\rho^{[k]}<1,\ \ \forall k.\end{aligned} \tag{26}$$

Note that the variables $\rho^{[k]}$ and $P_t^{[k]}$ are decoupled through the above conversion, and thus we can obtain the optimal solution to problem (25) by the interior-point algorithm using the existing software, e.g., CVX.

On the other hand, although problem (25) can be converted into a convex expression in (26), it is difficult to derive the closed-formed solutions to (26), and the computational complexity of the interior-point algorithm is very high due to the iterations. Therefore, we proposed an effective suboptimal algorithm to solve problem (25) in the paper with much lower computational complexity in the next section, and a closed-form solution is derived without iterations.

V. SUBOPTIMAL SOLUTIONS OF AN ASSISTED IA SCHEME WITH WPT

To solve the non-convex problem (25), a suboptimal solution is derived in this section.

First assume that $\rho^{[k]}=1$, $k=1,2,\ldots,K$, i.e., the constraint for the minimal harvested power in (25) is relaxed, and problem (25) can be reduced into

$$\begin{aligned}&\max_{P_t^{[k]}} \sum_{k=1}^{K}\left(P_{sum}^{[k]}-P_t^{[k]}\right)\\ &s.t.\ \frac{P_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\sigma^2+\delta^2}\ge\gamma^{[k]}, P_{sum}^{[k]}-P_t^{[k]}\ge\bar{P}_{an}^{[k]},\forall k.\end{aligned}\tag{27}$$

With the help of (27), we can obtain the solution to (25) as $P_t^{[k]}=\beta\widehat{P}_t^{[k]}$, $\beta>1$, which is derived in the following Lemma 2.

Lemma 2: Define $\widehat{P}_t^{[k]}=\dfrac{\gamma^{[k]}(\sigma^2+\delta^2)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}$ and let an auxiliary variable β scale up the $\widehat{P}_t^{[k]}$. The solution of $P_t^{[k]}$ to problem (25) can be expressed as $P_t^{[k]}=\beta\widehat{P}_t^{[k]}$ and $\beta>1$.

Proof: Problem (27) is easy to solve, with its solution denoted as

$$P_t^{[k]}\ge\frac{\gamma^{[k]}(\sigma^2+\delta^2)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}.\tag{28}$$

For the purpose of convenience, we can define

$$\widehat{P}_t^{[k]}=\frac{\gamma^{[k]}(\sigma^2+\delta^2)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}.\tag{29}$$

Make an auxiliary variable β ($\beta\ge1$) scale up the $\widehat{P}_t^{[k]}$, and the solution for $P_t^{[k]}$ can be expressed as

$$P_t^{[k]}=\beta\widehat{P}_t^{[k]}.\tag{30}$$

In addition, note that the SINR constraint in (27) holds with equality when $\beta=1$ and $\rho^{[k]}=1$. Nevertheless, in the original problem (25), we have $0<\rho^{[k]}<1$, which means part of $P_t^{[k]}$ should also be split to the EH terminal to satisfy the additional EH constraint. Thus, $\beta>1$ should be set to meet both the SINR and EH targets in problem (25). In conclusion, Lemma 2 is proved. ■

Based on Lemma 2, problem (25) can be reformulated as

$$\begin{aligned}&\max_{\rho^{[k]},\beta} \sum_{k=1}^{K}\left(P_{sum}^{[k]}-\beta\widehat{P}_t^{[k]}\right)\\ &s.t.\quad \frac{\rho^{[k]}\beta\widehat{P}_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\rho^{[k]}\sigma^2+\delta^2}\ge\gamma^{[k]}\\ &\qquad \widehat{\mathcal{E}}^{[k]}\ge e^{[k]},\ \ P_{sum}^{[k]}-\beta\widehat{P}_t^{[k]}\ge\bar{P}_{an}^{[k]},\\ &\qquad 0<\rho^{[k]}<1,\ \beta>1,\ \ \forall k,\end{aligned}\tag{31}$$

where the expression for $\widehat{\mathcal{E}}^{[k]}$ can be given by (32) (on the next page).

Proposition 1 is presented to calculate the solutions to (31) as follows.

Proposition 1: Define the following variables

$$A^{[k]}=\frac{\widehat{P}_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\gamma^{[k]}},\tag{33}$$

$$B^{[k]}=\sum_{j=1}^{K}P_{sum}^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{w}^{[j]}\right\|^2,\tag{34}$$

$$C^{[k]}=\sum_{j=1}^{K}\widehat{P}_t^{[j]}\left(\left\|\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\right\|^2-\left\|\mathbf{H}^{[kj]}\mathbf{w}^{[j]}\right\|^2\right).\tag{35}$$

Set β_{k2} as the largest real root of the kth equation in the following quadratic equations for β.

$$\frac{e^{[k]}}{\zeta\left(\beta C^{[k]}+B^{[k]}\right)}+\frac{\delta^2}{\beta A^{[k]}-\sigma^2}-1=0,k=1,2,\ldots,K.$$

The optimal solution to problem (31) can be obtained as $\beta^\star=\max\limits_{1\le k\le K}\beta_{k2}$ and $\rho^{[k]\star}=1-\dfrac{e^{[k]}}{\zeta\left(\beta^\star C^{[k]}+B^{[k]}\right)}$, $k=1,2,\ldots,K$.

Proof: It's obvious that the maximum of the transmit power of AN is corresponding to the minimum of the factor β according to (31). With the defined variables $A^{[k]}$, $B^{[k]}$ and $C^{[k]}$, problem (31) can be rewritten as

$$\begin{aligned}&\min_{\rho^{[k]},\beta}\ \beta\\ &s.t.\ \rho^{[k]}\ge\frac{\delta^2}{\beta A^{[k]}-\sigma^2},1-\rho^{[k]}\ge\frac{e^{[k]}}{\zeta(\beta C^{[k]}+B^{[k]})},\\ &\qquad P_{sum}^{[k]}-\beta\widehat{P}_t^{[k]}\ge\bar{P}_{an}^{[k]},0<\rho^{[k]}<1,\ \ \beta>1,\forall k.\end{aligned}\tag{36}$$

Apparently, problem (36) can be equivalently rewritten as (37), when considering the first and second constraints together.

$$\begin{aligned}&\min_{\beta}\quad\beta\\ &s.t.\ f_k(\beta)\le0,\beta>1,P_{sum}^{[k]}-\beta\widehat{P}_t^{[k]}\ge\bar{P}_{an}^{[k]},\end{aligned}\tag{37}$$

where

$$f_k(\beta)=\frac{e^{[k]}}{\zeta\left(\beta C^{[k]}+B^{[k]}\right)}+\frac{\delta^2}{\beta A^{[k]}-\sigma^2}-1.\tag{38}$$

Consider the quadratic equation of $f_k(\beta)=0$ with an unknown variable β, we have equation (39) (on the next page). From (39), we can observe that the second-order coefficient $-\zeta A^{[k]}C^{[k]}<0$, and thus the curve of $F_k(\beta)$ is a downward parabola.

According to (29) and (33), we have

$$\begin{aligned}A^{[k]}=&\frac{\widehat{P}_t^{[k]}\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\gamma^{[k]}}\\ =&\frac{\gamma^{[k]}(\sigma^2+\delta^2)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}\frac{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}{\gamma^{[k]}}=\sigma^2+\delta^2.\end{aligned}\tag{40}$$

$$\widehat{\mathcal{E}}^{[k]} = \zeta\left(1-\rho^{[k]}\right)\left(\sum_{j=1}^{K}\beta\widehat{P_t}^{[j]}\left\|\mathbf{H}^{[kj]}\mathbf{V}^{[j]}\right\|^2+\sum_{j=1}^{K}\left(P_{sum}^{[j]}-\beta\widehat{P_t}^{[j]}\right)\left\|\mathbf{H}^{[kj]}\mathbf{w}^{[j]}\right\|^2\right). \tag{32}$$

$$\begin{aligned} F_k(\beta) &= \delta^2\zeta\left(\beta C^{[k]}+B^{[k]}\right)+e^{[k]}\left(\beta A^{[k]}-\sigma^2\right)-\zeta\left(\beta C^{[k]}+B^{[k]}\right)\left(\beta A^{[k]}-\sigma^2\right)\\ &= -\zeta A^{[k]}C^{[k]}\beta^2+\left(\zeta\delta^2C^{[k]}+e^{[k]}A^{[k]}+\zeta\sigma^2C^{[k]}-\zeta B^{[k]}A^{[k]}\right)\beta+\left(\zeta\delta^2B^{[k]}-\sigma^2e^{[k]}+\zeta\sigma^2B^{[k]}\right)=0. \end{aligned} \tag{39}$$

Based on (40), we have $F_k(1)$ when $\beta = 1$ as follows.

$$F_k(1) = e^{[k]}\delta^2 > 0. \tag{41}$$

Assume that β_{k1} and β_{k2}, where $\beta_{k1} < \beta_{k2}$, are two roots of the equation (38). Since $-\zeta A^{[k]}C^{[k]} < 0$, the solution to the inequality $f_k(\beta) \le 0$ can be achieved by either $\beta \le \beta_{k1}$ or $\beta \ge \beta_{k2}$. In addition, it is worth noting that the curve of the function $f_k(\beta)$ is a downward parabola, and we also know that $f_k(\beta) > 0$ when $\beta = 1$ according to (41). Thus, we have

$$\beta_{k1} < 1 < \beta_{k2}, \tag{42}$$

and then the solution to the inequality $f_k(\beta) \le 0$ can be denoted as $\beta \ge \beta_{k2}$. Besides, consider that the additional condition $\beta \le (P_{sum}^{[k]} - \bar{P}_{an}^{[k]})/\widehat{P_t}^{[k]}$ in problem (37) should be satisfied as well. Hence, problem (37) can be solved only if the term $(P_{sum}^{[k]} - \bar{P}_{an}^{[k]})/\widehat{P_t}^{[k]}$ is larger than 1, i.e., the condition $\bar{P}_{an}^{[k]} < P_{sum}^{[k]} - \widehat{P_t}^{[k]}$ must be met. In the rest of this paper, we assume that the above condition for $\bar{P}_{an}^{[k]}$ is always satisfied, unless stated otherwise. Therefore, problem (37) can be solved in this paper, and its optimal solution can be obtained as (43) to ensure all the inequalities in (37) can be satisfied.

$$\beta^\star = \max_{1\le k\le K}\beta_{k2}. \tag{43}$$

Based on (43) and the second constraint of (36), we can also obtain

$$\rho^{[k]\star} = 1 - \frac{e^{[k]}}{\zeta\left(\beta^\star C^{[k]}+B^{[k]}\right)}. \tag{44}$$

■

Based on (30) and (43), we can calculate the solution to $P_t^{[k]}$ as

$$P_t^{[k]\star} = \beta^\star\widehat{P_t}^{[k]} = \beta^\star\frac{\gamma^{[k]}\left(\sigma^2+\delta^2\right)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}. \tag{45}$$

Accordingly, the solution of the transmit power of AN at the kth transmitter can be expressed as

$$P_{an}^{[k]\star} = P_{sum}^{[k]} - P_t^{[k]\star} = P_{sum}^{[k]} - \beta^\star\frac{\gamma^{[k]}\left(\sigma^2+\delta^2\right)}{\left\|\mathbf{U}^{[k]\dagger}\mathbf{H}^{[kk]}\mathbf{V}^{[k]}\right\|^2}. \tag{46}$$

We summarize the suboptimal algorithm for problem (25) as Algorithm 1.

Through Algorithm 1, the suboptimal solutions to problem (25) can be easily calculated with low computational complexity. In the algorithm, first, the K equations of (39) should be solved for $k = 1, 2, \ldots, K$. Then, the suboptimal solutions to (25) can be calculated according to (43) to (46) directly. Thus, the proposed suboptimal algorithm is very efficient and is suitable to be utilized in practical systems.

Algorithm 1 Suboptimal Algorithm for AN Assisted IA Scheme with Wireless Power Transfer

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1: Set a proper initial value for the threshold of the transmit power of AN $\bar{P}_{an}^{[k]}$.
2: Assume that $\rho^{[k]} = 1$ and obtain the solution to $\widehat{P_t}^{[k]}$ according to (29).
3: Set the parameter $\beta$ to scale up $\widehat{P_t}^{[k]}$, and we can obtain $P_t^{[k]} = \beta\widehat{P}^{[k]}$. Problem (25) can be converted into (31).
4: Define variables $A^{[k]}, B^{[k]}$ and $C^{[k]}$ to simplify problem (31) as problem (37).
5: Calculate the inequality $f_k(\beta) \le 0$ and set $\beta^\star = \max_{1\le k\le K}\beta_{k2}$ as the optimal solution to problem (37). $\beta_{k2}$ is the larger root for the solution to (39).
6: Obtain the suboptimal solutions to $\rho^{[k]}$, $P_t^{[k]}$ and $P_{an}^{[k]}$ as $\rho^{[k]\star} = 1 - \frac{e^{[k]}}{\zeta(\beta^\star C^{[k]}+B^{[k]})}$, $P^{[k]\star} = \beta^\star\widehat{P_t}^{[k]}$ and $P_{an}^{[k]\star} = P_{sum}^{[k]} - P_t^{[k]\star}$, respectively.
```

VI. Numerical Results and Discussion

In this section, extensive simulation results are provided to evaluate the performance of the proposed AN assisted IA scheme with WPT. In the simulation, assume that $K = 5$, $d = 2$, $d_{an} = 1$, $M = 9$, $N = 5$, $\mathcal{N}_\varepsilon = 14$, $\sigma^2 = -70$ dBm, $\delta^2 = -50$ dBm, and $\zeta = 0.25$. Moreover, for simplicity, all the SINR and EH constraints are set to be equal for all the receivers, i.e., $\gamma^{[k]} = \gamma$, $e^{[k]} = e$, $k = 1, 2, \ldots, K$. The targets for the transmit power of AN and the total transmit power of all the users are also assumed to be identical, i.e., $\bar{P}_{an}^{[k]} = \bar{P}_{an} = 5$ mW, $P_{sum}^{[k]} = P_{sum}$, $k = 1, 2, \ldots, K$.

First, the performance of the power allocation in the AN assisted IA scheme without WPT is considered. In Fig. 4, the average transmission rate and eavesdropping rate in the AN assisted IA scheme without WPT are compared, when power allocation and no power allocation are used, respectively. From the results, we can see that, when the requirement of transmission rate is 9bits/s/Hz, the proposed power allocation for the AN assisted IA scheme can minimize the eavesdropping rate to nearly 0 with the requirement of transmission rate satisfied. However, when no power allocation is performed, the transmission rate becomes larger with higher P_{sum}, which is a

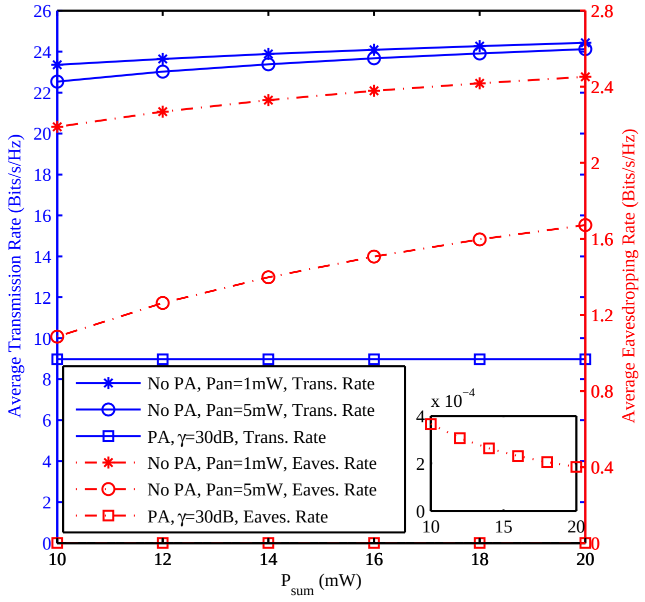

Fig. 4. Comparison of the average transmission rate and eavesdropping rat in the AN assisted IA scheme without WPT, when P_{sum} is varying. Power allocation and no power allocation are considered in the scheme, respectively.

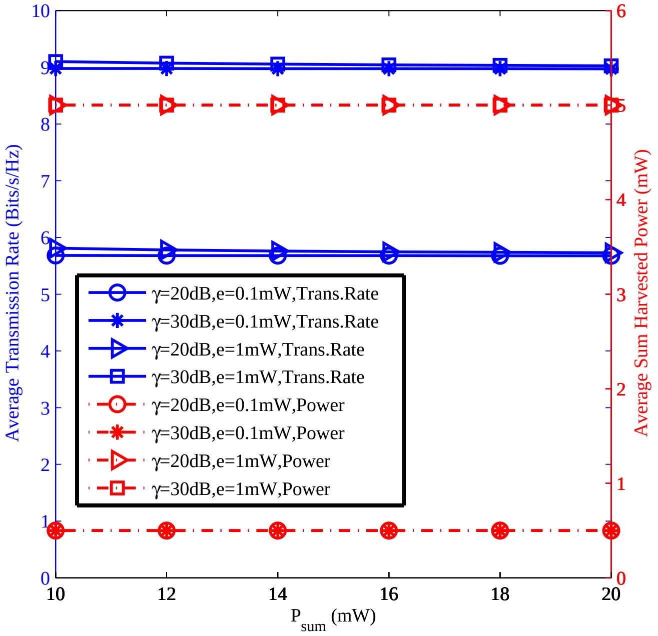

Fig. 5. Comparison of the average transmission rate and average sum harvested power in the AN assisted IA scheme with WPT under different thresholds of γ and e, when P_{sum} is varying.

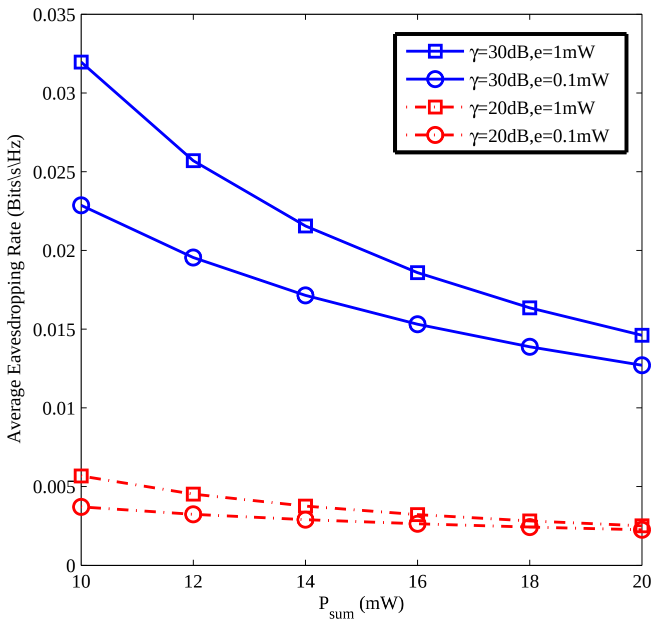

Fig. 6. Comparison of the average eavesdropping in the AN assisted IA scheme with WPT under different thresholds of γ and e, when P_{sum} is varying.

waste of power. This may result in much higher eavesdropping rate, due to the fact that no power allocation is performed with limited power of AN and the transmission rate is much higher than the requirement. Besides, when the transmit power of AN becomes higher, the eavesdropping rate becomes much lower with a lower transmission rate.

Then, the performance of the AN assisted IA scheme with WPT is analyzed, with the suboptimal algorithm adopted to calculate the solutions. In Fig. 5, the average transmission rate of a single user and the average sum harvested power of the network are analyzed when P_{sum} is varying with different thresholds of γ and e. From the results, we can see that the transmission rate and the sum harvested power will be unchanged when P_{sum} becomes higher, which means only the minimal power is allocated to the information transmission and the proper coefficients of PS are chosen to save power to enhance the security performance. Besides, we can also know that when γ becomes larger, the average transmission rate will become higher; when e becomes larger, the average sum harvested power will become higher. In Fig. 6, the average eavesdropping rate of the proposed AN assisted IA scheme with WPT is analyzed, when P_{sum} is varying with different thresholds of γ and e. From this figure, we can see that the eavesdropping rate becomes lower with higher P_{sum}. This is because more power can be allocated to AN when P_{sum} is higher, with the requirements of IT and EH guaranteed. We can also know that the eavesdropping rate becomes lower when γ or e is smaller. This is due to the fact that, when the thresholds of IT and EH is lower, more power can be devoted to AN, which leads to a lower eavesdropping rate.

To compare the performance of the AN assisted IA scheme with WPT and that without WPT when power allocation is performed, the average sum harvested power and the average eavesdropping rate are compared in Fig. 7. In the simulation, P_{sum} is varying with different thresholds of γ and e. The suboptimal algorithm is adopted for the proposed scheme with WPT. From the results, we can see that when no WPT is used in the AN assisted IA scheme, the eavesdropping rate is close to 0, however, the sum harvested power equals to 0 too. Thus, when no WPT is considered, the security performance of the scheme is better. Nevertheless, no power can be reutilized to replenish the batteries. On the other

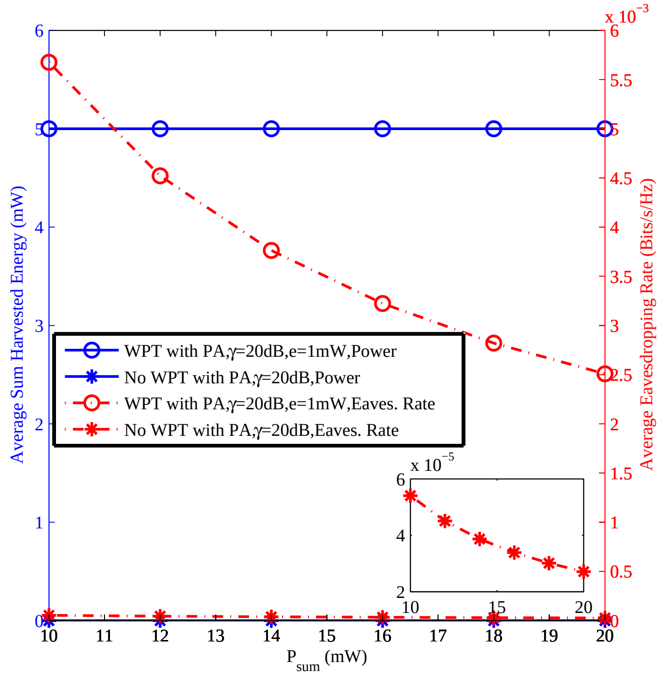

Fig. 7. Performance comparison of the AN assisted IA scheme with WPT and that without WPT when power allocation is performed under different thresholds of γ and e. P_{sum} is varying from 10 dBm to 20dBm.

hand, when WPT is performed in the proposed scheme, the requirement of harvested power can be perfectly satisfied, and the sum power is equal to $K \times e = 5$mW. Although the average eavesdropping rate is a little higher than that of the scheme without WPT, it is lower than 6×10^{-3}bits/s/Hz, which can also guarantee the security of the legitimate network. Besides, when P_{sum} becomes higher, the eavesdropping rate of the proposed scheme with WPT will decrease, due to the fact that more power can be devoted to AN, with the thresholds of IT and EH satisfied.

Finally, the performances of the optimal solutions to (25) and the suboptimal algorithm in Section V are compared. To obtain the optimal solutions to (25), the classical interior-point method is adopted. In Fig. 8, the average transmission rate and sum harvested power of the proposed AN assisted IA scheme with WPT is compared by using the optimal algorithm and suboptimal algorithm, under different thresholds of γ and e; while in Fig. 9, the average eavesdropping rate of the optimal algorithm and suboptimal algorithm is compared, under the above conditions. From the results, we can see that the performance of the proposed suboptimal algorithm for solving (25) is very close to that of the optimal solutions obtained by interior-point method. Thus, we can use the proposed suboptimal algorithm to calculate the solutions of the proposed scheme, with very low computational complexity.

VII. CONCLUSIONS

In this paper, we have studied wireless power transfer for the AN assisted IA scheme. First, the power allocation problem has been studied to improve the existing AN assisted IA scheme without WPT, and the anti-eavesdropping performance has been optimized by allocating all the remaining transmit power to the ANs with the requirement of information transmission satisfied. To fully exploit the benefit from the AN and interference among users, we have presented a novel AN assisted IA scheme with WPT. In the proposed scheme, the transmit power of AN is maximized, with the the minimal requirements of transmission rate and harvested power guaranteed. Nevertheless, the optimal problem is non-convex, which is difficult to solve. To reduce its computational complexity, we have designed a suboptimal algorithm for the proposed scheme, with its closed-form solutions derived. Simulation

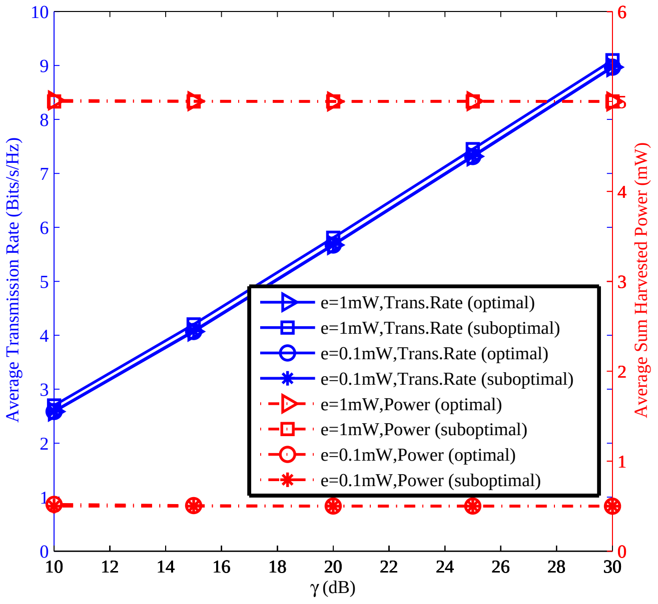

Fig. 8. Comparison of average transmission rate and sum harvested power of the AN assisted IA scheme with WPT by using the optimal algorithm and suboptimal algorithm, under different thresholds of γ and e.

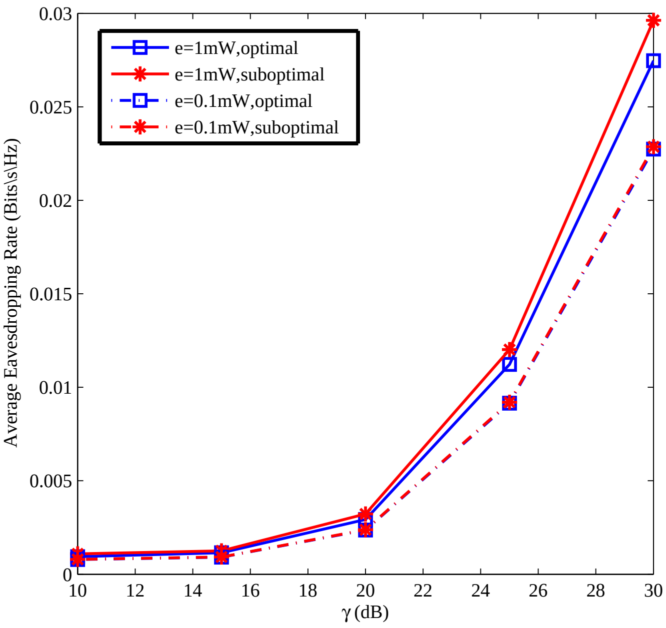

Fig. 9. Comparison of average eavesdropping rate of the AN assisted IA scheme with WPT by using the optimal algorithm and suboptimal algorithm, under different thresholds of γ and e.

results have been presented to show the effectiveness of the proposed AN assisted IA scheme with WPT.

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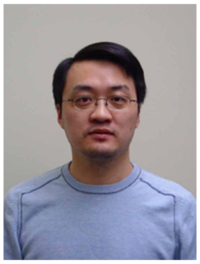

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