IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 15, 2017, accepted March 1, 2017, date of publication March 15, 2017, date of current version April 24, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2682277

Secure Wireless Information and Power Transfer in Heterogeneous Networks

YUAN REN[1], TIEJUN LV[1], (Senior Member, IEEE), HUI GAO[1], (Senior Member, IEEE), AND YINGXIANG LI[2]

[1]School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]School of Communication Engineering, Chengdu University of Information Technology, Chengdu 610225, China

Corresponding author: T. Lv (lvtiejun@bupt.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61401041 and Grant 61671072, in part by the National High Technology Research and Development Program of China (863 Program) under Grant 2015AA01A706, and in part by the Meteorological Information and Signal Processing Key Laboratory of Sichuan Higher Education under Grant QXXCSYS201601.

ABSTRACT In this paper, we investigate secure simultaneous wireless information and power transfer (SWIPT) in a two-tier downlink heterogeneous network (HetNet), wherein the ambient interference signals are exploited for both secure communications and wireless energy harvesting. We assume one macrocell base station (MBS) and several femtocell base stations (FBSs) simultaneously send information to their macrocell users (MUs) and femtocell users, respectively. Meanwhile, the FBSs also transfer energy to some energy receivers, who act as the potential eavesdroppers and are able to wiretap the confidential messages to one MU via the cross-tier interference links. Exploiting interference in the considered HetNet, we jointly optimize the beamforming vectors and artificial noise of the MBS and the FBSs to maximize the secrecy rate of the eavesdropped MU under the quality-of-service, energy harvesting, and transmit power constraints at relevant receivers/transmitters. In particular, we first investigate the ideal case with perfect eavesdropper's channel state information (ECSI) and the optimization problem turns out to be nonconvex. By using the tools of semidefinite relaxation (SDR) and one-dimensional line search, we successfully transfer the original problem into a more tractable two-stage problem to obtain the optimal solution. Furthermore, we extend our study to the imperfect ECSI case, where the worst-case based solution is obtained with the aid of SDR and successive convex approximation. Simulation results demonstrate the effectiveness of the proposed algorithms and also bring useful insights into the design of secure SWIPT in the presence of interference.

INDEX TERMS Beamforming, heterogeneous network, interference, simultaneous wireless information and power transfer (SWIPT), semidefinite programming (SDP).

I. INTRODUCTION

Due to the dramatic increase of the smart phones along with the emerging future applications, the fifth generation (5G) wireless systems will require extremely high data rate, ubiquitous coverage and reliable secrecy performance [1]. The deployment of low cost and plug-and-play devices, such as the femtocell base stations (FBSs) underlaid in the conventional macrocell, can provide better coverage and higher throughput for indoor users [2]. Therefore, heterogeneous networks (HetNets) have been regarded as one of the most promising techniques in the next generation wireless systems [3], [4]. As the densification of various types of heterogeneous transmission nodes and/or antennas, the interference might become severe. Traditional wisdom treats interference as harmful or useless from communications' perspective. Recently, as the emerging of wireless powered communications and the quick development of wireless energy harvesting (EH) devices, interference as a special form of ambient radio-frequency (RF) signal, can be the energy source of low-power energy receivers (ERs) for self-sustained wireless communications [5], [6]. To this regard, densely deployed HetNets bear potentials to enable more efficient wireless power transfer and usage.

By integrating RF power transfer with traditional wireless information transmission, simultaneous wireless information and power transfer (SWIPT) has been considered as one of the major candidate technologies towards green communications [7], [8]. Recently, there are some interesting works integrating SWIPT with HetNet [9], [10]. More specifically, [9] presents a tractable analytical model for K-tier

HetNets with SWIPT, and the outage probability and the average ergodic rate are derived with several typical cell association strategies. In [10], two kinds of beamformers, namely, zero-forcing and mixed beamforming, are proposed to maximize the information transmission efficiency (ITE) and the energy harvesting efficiency (EHE), which reveals the fundamental tradeoff between ITE and EHE. However, in HetNets with SWIPT, the messages intended to the information receivers (IRs) may be at risk of being eavesdropped by the ERs, which brings great challenges to secure SWIPT in HetNets.

Recently, physical-layer security (PLS) [11]–[13] has emerged as a complementary solution to the conventional higher-layer cryptographic methods, and can guarantee the perfect secrecy communication from the information-theoretic perspective. Exploiting the characteristics of wireless channels, such as fading, noise, and interference, PLS can achieve secure transmission to the intended receiver, while defending against the eavesdroppers [14]. Various PLS techniques have been investigated in relay networks [15], [16], interference alignment based networks [17], [18] and HetNets [19], [20], and the developments and applications for SWIPT are more recent works [21].

A. RELATED WORK AND CONTRIBUTIONS

The majority of the secrecy transmission schemes with SWIPT are designed for the broadcasting channel (BC) [22]–[26], where the perfect eavesdropper's channel state information (ECSI) is assumed. However, the transmitter may not obtain the perfect ECSI due to the practical limitations, such as the quantization error, the delay error and the limited capacity of the feedback channel. Assuming imperfect ECSI at the transmitter, there are some valuable works on the robust secrecy beamforming design for the SWIPT BC [27]–[33]. To be more specific, [28] investigates the system with one IR, one ER and one eavesdropper, and the suboptimal Gaussian randomization solutions are proposed based on the semidefinite relaxation (SDR) upper and lower bounds. In [29], multiple ERs act as the potential eavesdroppers, and the information and energy beamforming are jointly designed to maximize the minimum of the harvested energy of the ERs for both perfect and imperfect channel state information (CSI) cases, while guaranteeing the signal-to-interference-plus-noise ratio (SINR) constraints of the IR and the ERs. In [30], taking the power splitting IR into consideration, the authors study the max-min fair EH among multiple multi-antenna ERs with ECSI. In [31], the secure beamforming with and without artificial noise (AN) are designed for the SWIPT system with multiple ERs and eavesdroppers considering both perfect and imperfect CSI at the transmitter, and a novel bisection search based reformation is proposed to transform the secrecy rate maximization problem into a sequence of the associated power minimization problems. In [32], the transmit power minimization problem is studied subject to the outage probability constraints for IRs and ERs, and a low-complexity second-order cone program based iterative algorithm is proposed by applying successive convex approximation (SCA) approach. Recently, with the aid of large-dimensional random matrix theory, [33] designs the optimal transmit covariance matrix to maximize the ergodic secrecy rate for the MIMO SWIPT BC with statistical CSI at the transmitter. Moreover, secrecy SWIPT has also been studied in relay networks [34] and cognitive radio systems [35], respectively.

In summary, the existing research on secure SWIPT mainly focuses on the traditional network architectures, and the research on secrecy communication in HetNet with SWIPT is still largely open. There are various types of co-channel interference (CCI) in the HetNet, which restricts the extension of previous researches to secure SWIPT in HetNets straightforwardly. By properly designing the transmission scheme, the various types of CCI in the HetNet can be utilized to facilitate efficient power transfer and secure communications. Moreover, under the practical consideration of the imperfect ECSI at the transmitters, the problem becomes more complicated and challenging, which motivates this work.

B. CONTRIBUTIONS

In this paper, we consider a two-tier downlink HetNet with SWIPT, in which the macrocell base station (MBS) and the FBSs conduct co-channel information transmission to the corresponding macrocell users (MUs) and femtocell users (FUs), respectively. At the same time, the FBSs transmit energy beams to the ERs for wireless power transfer. Because of the ambient useful and interference signals, the ERs can not only harvest wireless energy but also wiretap the confidential messages of a legitimate MU. Exploiting the interference, an AN-aided secure transmission strategy is applied at the MBS and the FBSs. Moreover, we investigate the joint collaborative information/energy transmit beamforming (TB) and AN design to maximize the secrecy rate of the wiretapped MU subject to the quality-of-service (QoS) constraints of the unclassified MUs and FUs, the EH requirements at ERs and the transmit power constraints at the MBS and the FBSs. To begin with, the scenario of perfect ECSI at the MBS and the FBSs are addressed to serve as the baseline. However, in practice, the channel links connected with the eavesdroppers exist channel uncertainties. Then, to tackle the imperfect ECSI case, we consider the worst-case based robust joint TB and AN design. More explicitly, our contributions are summarized as follows:

1) Assuming perfect ECSI at the MBS and the FBSs, the secrecy rate maximization problem in HetNet with SWIPT is formulated. The problem is nonconvex and difficult to solve. To this end, a two-stage optimization framework is applied to transform the original problem. In particular, with the help of rank relaxation, the inner stage is transformed into a semidefinite programming (SDP) problem. The outer stage turns to be a common one-dimensional line search problem. Therefore, the original secrecy rate maximization problem can be efficiently solved by dealing with a sequence of SDPs. Moreover, we also prove that the relaxed problem always

yields a rank-one solution, which indicates that the relaxation is indeed tight.

2) With only imperfect ECSI at the MBS and the FBSs, we consider a worst-case based optimization framework for secrecy communications in HetNet with SWIPT. Particularly, the TB and AN are jointly designed to maximize the worst-case secrecy rate of the wiretapped MU under the QoS constraints of the unclassified MUs and the FUs, the worst-case EH constraints at the ERs, and the transmit power constraints at the MBS and the FBSs. We first characterize the imperfect ECSI as an ellipsoidal uncertainty model. Then, our design goal is reformulated into solving a nonconvex optimization problem, which can be further transformed into a convex problem with the aid of rank relaxation and SCA. The approximation can be refined at each iteration, which indicates that a local optimum of the original optimization problem can be obtained.

The rest of the paper is organized as follows: Section II describes the two-tier downlink HetNet with SWIPT. In Section III, a joint TB and AN design is proposed with the perfect ECSI at the MBS and the FBSs. In Section IV, the channel uncertainty model is characterized and the robust joint TB and AN design is proposed. In Section V, numerical results are provided to validate the effectiveness of the proposed schemes. Finally, Section VI concludes the paper.

Notations: Vectors and matrices are denoted by bold lower and upper case letters, respectively. $\mathbb{E}\{\cdot\}$ denotes expectation. $(\cdot)^H$ represents the conjugate transpose. $\mathcal{CN}(\mathbf{m}, \Sigma)$ represents a complex Gaussian random vector with mean $\mathbf{m}$ and covariance matrix Σ. $|\cdot|$ and $\|\cdot\|$ represent the mode of a complex number and the Euclidean norm, respectively. $\mathbb{C}^{N\times M}$ and $\mathbf{I}_m$ denote an $N \times M$ complex matrix and an $m \times m$ identity matrix, respectively. $\mathrm{Tr}(\cdot)$ and $\mathrm{rank}(\cdot)$ represent the trace operator and the rank of a matrix. $\mathbf{X} \succeq \mathbf{0}$ and $\mathbf{X} \succ \mathbf{0}$ denote that $\mathbf{X}$ is Hermitian positive semidefinite and Hermitian positive definite, respectively. $[a, b]$ denotes the integer set $\{a, a+1, ..., b\}$. $[x]^+$ denotes $\max\{0, x\}$.

II. SYSTEM MODEL

A two-tier downlink HetNet with SWIPT is considered, which is shown in Fig. 1. The network consists of one N_M-antenna MBS and N N_F-antenna FBSs. The MBS serves M MUs and each FBS serves K FUs, where $N_M > M$ and $N_F > K$. There exists L ERs in the network and they can harvest energy from the N FBSs to recharge their batteries and prolong their work time. The MUs, FUs and ERs each has a single antenna. The ERs can be viewed as the other kind of FUs, which do not receive information from the FBSs. At the same time, the ERs act as the potential eavesdroppers and manage to wiretap the confidential message transmitted to a legitimate MU. We assume that the transmit power of the MBS and each FBS are P_M and P_F, respectively. The relevant variables are summarized in Table 1.

It is assumed that the N FBSs can cooperatively employ the CCI to enhance the secrecy rate and the EH performance of the ERs. Suppose that the AN is transmitted at the MBS and the FBSs. Moreover, we assume the ERs are registered users of the network, and the ECSI is available at the MBS and FBSs to make the joint TB and AN design more tractable. Based on this assumption, the transmit signal at the MBS and the FBS_n can be expressed as

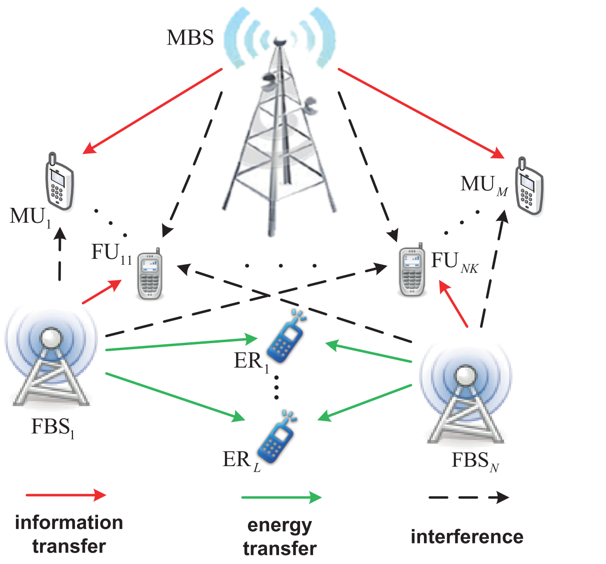

FIGURE 1. Two-tier downlink HetNet with SWIPT, consisting of one MBS and N FBSs. The MBS serves M MUs and each FBS serves K FUs. L ERs harvest energy from the FBSs and manage to wiretap the intended MU.

TABLE 1. List of the Major Variables

Variable	Definition
FBS_n,MU_m, FU_{nk} ,ER_l	the n-th FBS, the m-th MU, the k-th FU of the n-th FBS, and the l-th ER
s_m	the information symbol for the MU_m, with $\mathbb{E}\{\lvert s_m\rvert^2\} = 1$
s_{nk}, $s_{\mathrm{E},ni}$	the information symbol for the FU_{nk} and i-th energy-carrying noise signal of FBS_n, with $\mathbb{E}\{\lvert s_{nk}\rvert^2\} = 1$ and $s_{\mathrm{E},ni} \sim \mathcal{CN}(0,1)$
$\mathbf{h}_m$,$\mathbf{h}_{n,m}$	the channel vectors from the MBS and the FBS_n to MU_m
$\mathbf{h}_{nk}$,$\mathbf{h}_{p,nk}$	the channel vectors from the MBS and the FBS_p to FU_{nk}
$\mathbf{g}_l$,$\mathbf{g}_{n,l}$	the channel vectors from the MBS and the FBS_n to ER_l
$\mathbf{w}_m$,$\mathbf{z}_0$	the information beam for MU_m and the AN vector of the MBS, with $\mathbf{z}_0 \sim \mathcal{CN}(\mathbf{0}, \mathbf{Z}_0)$
$\mathbf{w}_{nk}$, $\mathbf{u}_n$, $\mathbf{z}_n$	the information beam for FU_{nk}, the sum of d energy beams and the AN vector of the FBS_n, with $\mathbf{z}_n \sim \mathcal{CN}(\mathbf{0}, \mathbf{Z}_n)$

$$\mathbf{x}_0 = \sum_{m=1}^{M} \mathbf{w}_m s_m + \mathbf{z}_0, \tag{1}$$

$$\mathbf{x}_n = \sum_{k=1}^{K} \mathbf{w}_{nk} s_{nk} + \mathbf{u}_n + \mathbf{z}_n, \tag{2}$$

where $\mathbf{w}_m \in \mathbb{C}^{N_M\times 1}$ and s_m with $\mathbb{E}\left\{|s_m|^2\right\} = 1$, are the beamforming vector and the information symbol for MU_m, respectively. Similarly, $\mathbf{w}_{nk} \in \mathbb{C}^{N_F\times 1}$ and s_{nk} with $\mathbb{E}\left\{|s_{nk}|^2\right\} = 1$ represent the information beamforming vector and the information symbol for FU_{nk}. $\mathbf{u}_n = \sum_{i=1}^{d} \mathbf{u}_{ni} s_{\mathrm{E},ni}$ is the sum of $d \leq N_F$ energy beams, in which $\mathbf{u}_{ni} \in \mathbb{C}^{N_F \times 1}$ and $s_{\mathrm{E},ni} \sim \mathcal{CN}(0, 1)$ denote the i-th energy beamforming vector and the i-th energy-carrying noise signal, respectively. $\mathbf{U}_n = \sum_{i=1}^{d} \mathbf{u}_{ni}\mathbf{u}_{ni}^H$ denotes the energy covariance matrix of $\mathbf{u}_n$. $\mathbf{z}_i \in \mathbb{C}^{N_F \times 1}$, $i \in [0, N]$, is the AN vector which satisfies $\mathcal{CN}(\mathbf{0}, \mathbf{Z}_i)$, and $\mathbf{Z}_i$ denotes the covariance matrix of $\mathbf{z}_i$. The transmit power constraints of the MBS and FBS_n satisfy $\sum_{m=1}^{M} \|\mathbf{w}_m\|^2 + \mathrm{Tr}(\mathbf{Z}_0) \leq P_M$ and $\sum_{k=1}^{K} \|\mathbf{w}_{nk}\|^2 + \|\mathbf{u}_n\|^2 + \mathrm{Tr}(\mathbf{Z}_n) \leq P_F$, respectively.

The received signal at MU_m is represented as

$$y_m = \mathbf{h}_m^H \mathbf{w}_m s_m + \mathbf{h}_m^H (\sum_{q \neq m}^{M} \mathbf{w}_q s_q + \mathbf{z}_0) + \sum_{n=1}^{N} \mathbf{h}_{n,m}^H (\sum_{k=1}^{K} \mathbf{w}_{nk} s_{nk} + \mathbf{u}_n + \mathbf{z}_n) + n_m, \quad (3)$$

where $\mathbf{h}_m \in \mathbb{C}^{N_M \times 1}$ and $\mathbf{h}_{n,m} \in \mathbb{C}^{N_F \times 1}$ represent the channel vectors from the MBS and the FBS_n to MU_m, respectively. n_m is the additive white Gaussian noise (AWGN) at MU_m obeying independent and identically distributed (i.i.d.) $\mathcal{CN}(0, \sigma_m^2)$. The fading channels are assumed to be i.i.d. Rayleigh block fading channels. Without loss of generality, assume that MU_1 is wiretapped.

Similarly, the received signal at ER_l is expressed as

$$y_{\mathrm{E},l} = \mathbf{g}_l^H \mathbf{w}_1 s_1 + \mathbf{g}_l^H (\sum_{q=2}^{M} \mathbf{w}_q s_q + \mathbf{z}_0) + \sum_{n=1}^{N} \mathbf{g}_{n,l}^H (\sum_{k=1}^{K} \mathbf{w}_{nk} s_{nk} + \mathbf{u}_n + \mathbf{z}_n) + n_{\mathrm{E},l}, \quad (4)$$

where $\mathbf{g}_l \in \mathbb{C}^{N_M \times 1}$ and $\mathbf{g}_{n,l} \in \mathbb{C}^{N_F \times 1}$ denote the channel vectors from the MBS and the FBS_n to ER_l, respectively. $n_{\mathrm{E},l}$ is the AWGN noise at ER_l following i.i.d. $\mathcal{CN}(0, \sigma_{\mathrm{E},l}^2)$. The received signal at FU_{nk} can be represented as

$$y_{nk} = \mathbf{h}_{n,nk}^H \mathbf{w}_{nk} s_{nk} + \mathbf{h}_{n,nk}^H (\sum_{t \neq k}^{K} \mathbf{w}_{nt} s_{nt} + \mathbf{u}_n + \mathbf{z}_n) + \sum_{p \neq n}^{N} \mathbf{h}_{p,nk}^H (\sum_{t=1}^{K} \mathbf{w}_{pt} s_{pt} + \mathbf{u}_p + \mathbf{z}_p) + \mathbf{h}_{nk}^H (\sum_{m=1}^{M} \mathbf{w}_m s_m + \mathbf{z}_0) + n_{nk}, \quad (5)$$

where $\mathbf{h}_{nk} \in \mathbb{C}^{N_M \times 1}$ and $\mathbf{h}_{p,nk} \in \mathbb{C}^{N_F \times 1}$ denote the channel vectors from the MBS and the FBS_p to FU_{nk}, respectively. n_{nk} is the AWGN noise obeying i.i.d. $\mathcal{CN}(0, \sigma_{nk}^2)$. The SINR of MU_m is expressed as

$$\mathrm{SINR}_m = \frac{\left|\mathbf{h}_m^H \mathbf{w}_m\right|^2}{\sum_{q \neq m}^{M} \left|\mathbf{h}_m^H \mathbf{w}_q\right|^2 + \left|\mathbf{h}_m^H \mathbf{z}_0\right|^2 + B_m + \sigma_m^2},$$

where $B_m = \sum_{n=1}^{N} \sum_{k=1}^{K} \left|\mathbf{h}_{n,m}^H \mathbf{w}_{nk}\right|^2 + \sum_{n=1}^{N} (\left|\mathbf{h}_{n,m}^H \mathbf{u}_n\right|^2 + \left|\mathbf{h}_{n,m}^H \mathbf{z}_n\right|^2)$. Similarly, the SINR of ER_l is represented as[1]

$$\mathrm{SINR}_{\mathrm{E},l} = \frac{\left|\mathbf{g}_l^H \mathbf{w}_1\right|^2}{\sum_{q=2}^{M} \left|\mathbf{g}_l^H \mathbf{w}_q\right|^2 + \left|\mathbf{g}_l^H \mathbf{z}_0\right|^2 + B_{\mathrm{E},l} + \sigma_{\mathrm{E},l}^2},$$

where $B_{\mathrm{E},l} = \sum_{n=1}^{N} \sum_{k=1}^{K} \left|\mathbf{g}_{n,l}^H \mathbf{w}_{nk}\right|^2 + \sum_{n=1}^{N} \left|\mathbf{g}_{n,l}^H \mathbf{z}_n\right|^2$. Finally, the SINR of FU_{nk} is expressed as

$$\mathrm{SINR}_{nk} = \frac{\left|\mathbf{h}_{n,nk}^H \mathbf{w}_{nk}\right|^2}{\sum_{m=1}^{M} \left|\mathbf{h}_{nk}^H \mathbf{w}_m\right|^2 + \left|\mathbf{h}_{nk}^H \mathbf{z}_0\right|^2 + B_{nk} + \sigma_{nk}^2},$$

where $B_{nk} = \sum_{t \neq k}^{K} \left|\mathbf{h}_{n,nk}^H \mathbf{w}_{nt}\right|^2 + \sum_{p=1}^{N} (\left|\mathbf{h}_{p,nk}^H \mathbf{u}_p\right|^2 + \left|\mathbf{h}_{p,nk}^H \mathbf{z}_p\right|^2) + \sum_{p \neq n}^{N} \sum_{t=1}^{K} \left|\mathbf{h}_{p,nk}^H \mathbf{w}_{pt}\right|^2$. In the considered scenario, it is assumed that the harvested energy at ERs includes three parts: information beams, energy beams and AN of the FBSs. Therefore, the harvested energy at ER_l can be modeled as[2]

$$Q_{\mathrm{E},l} = \epsilon (\sum_{n=1}^{N} \sum_{k=1}^{K} |\mathbf{g}_{n,l}^H \mathbf{w}_{nk}|^2 + \sum_{n=1}^{N} |\mathbf{g}_{n,l}^H \mathbf{u}_n|^2 + \sum_{n=1}^{N} |\mathbf{g}_{n,l}^H \mathbf{z}_n|^2), \quad (6)$$

where $0 \leq \epsilon \leq 1$ is the energy conversion efficiency. Then, the secrecy rate can be formulated as

$$R_s = [\log(1 + \mathrm{SINR}_1) - \max_{l \in [1,L]} \log(1 + \mathrm{SINR}_{\mathrm{E},l})]^+. \quad (7)$$

III. JOINT TB AND AN DESIGN WITH PERFECT ECSI

In this section, we study the joint TB and AN design with perfect ECSI to secure the transmission of MU_1 in HetNet with SWIPT. In particular, by jointly designing the information beamforming vectors, the energy covariance matrices and the AN covariance matrices of the MBS and FBSs, we aim to maximize the secrecy rate of MU_1 subject to the SINR constraints of the unclassified MUs and FUs, the EH requirements of the ERs, and the transmit power constraints of the MBS and the FBSs. Specifically, each cooperative FBS sends its local CSI to the MBS, and the global CSI is available at the MBS. Then, the beamforming vectors and the AN are jointly optimized at the MBS with the aid of the global CSI. The secrecy rate maximization problem is expressed as

$$\max_{\substack{\mathbf{w}_m, \mathbf{w}_{nk}, \\ \mathbf{U}_n, \mathbf{Z}_i}} \min_{l \in [1,L]} (\log(1 + \mathrm{SINR}_1) - \log(1 + \mathrm{SINR}_{\mathrm{E},l})) \quad (8a)$$

$$\text{s.t.} \quad \mathrm{SINR}_m \geq \gamma_m, m \neq 1, \quad (8b)$$

$$\mathrm{SINR}_{nk} \geq \gamma_{nk}, \forall n, k, \quad (8c)$$

$$Q_{\mathrm{E},l} \geq \phi_l, \forall l, \quad (8d)$$

[1] As shown in [36], for the considered case, the energy beams only serve as the pseudorandom signals and carry no information, and the energy beams can be cancelled at each ER by a cancellation operation.

[2] As mentioned in [35], the harvested energy of the ERs from the MBS and the background noise are ignored as we focus on the worst-case scenario for energy harvesting system design.

$$\sum_{m=1}^{M}\|\mathbf{w}_m\|^2 + \mathrm{Tr}(\mathbf{Z}_0) \le P_M, \tag{8e}$$

$$\sum_{k=1}^{K}\|\mathbf{w}_{nk}\|^2 + \mathrm{Tr}(\mathbf{U}_n + \mathbf{Z}_n) \le P_F, \forall n. \tag{8f}$$

(8b) and (8c) represent the QoS constraints of the unclassified MUs and FUs, respectively. (8d) characterizes the EH requirements of the ERs, which means that the harvested energy should be higher than the given threshold. Finally, (8e) and (8f) constrain the transmit power of the MBS and the FBSs. Without loss of generality, we assume $\sigma_m^2 = \sigma_{\mathrm{E},l}^2 = \sigma_{nk}^2 = 1$.

A. JOINT TB AND AN DESIGN

Define $\mathbf{W}_m = \mathbf{w}_m\mathbf{w}_m^H$ and $\mathbf{W}_{nk} = \mathbf{w}_{nk}\mathbf{w}_{nk}^H$. We further drop the rank-one constraint for $\mathbf{W}_m$ and $\mathbf{W}_{nk}$ due to its nonconvexity, which results in an SDP problem that is convex. Then, we introduce a slack variable t, and the relaxed problem is represented as

$$\max_{\substack{\mathbf{W}_m,\mathbf{W}_{nk},\\ \mathbf{U}_n,\mathbf{Z}_i,t}} \frac{1}{t}\left(1+\frac{\mathrm{Tr}(\mathbf{H}_1\mathbf{W}_1)}{\mathrm{A}_1}\right) \tag{9a}$$

$$\text{s.t. } \frac{\mathrm{Tr}(\mathbf{H}_m\mathbf{W}_m)}{\mathrm{A}_m} \ge \gamma_m, m \neq 1, \tag{9b}$$

$$\frac{\mathrm{Tr}(\mathbf{H}_{n,nk}\mathbf{W}_{nk})}{\mathrm{A}_{nk}} \ge \gamma_{nk}, \forall n,k, \tag{9c}$$

$$\max_{l\in[1,L]} (1+\frac{\mathrm{Tr}(\mathbf{G}_l\mathbf{W}_1)}{\mathrm{A}_{\mathrm{E},l}}) \le t, \tag{9d}$$

$$\epsilon\sum_{n=1}^{N}\mathrm{Tr}(\mathbf{G}_{n,l}\mathbf{D}_n) \ge \phi_l, \forall l, \tag{9e}$$

$$\sum_{m=1}^{M}\mathrm{Tr}(\mathbf{W}_m) + \mathrm{Tr}(\mathbf{Z}_0) \le P_M, \tag{9f}$$

$$\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{W}_{nk}) + \mathrm{Tr}(\mathbf{U}_n + \mathbf{Z}_n) \le P_F, \forall n, \tag{9g}$$

$$\mathbf{W}_m, \mathbf{W}_{nk}, \mathbf{U}_n, \mathbf{Z}_i \succeq \mathbf{0}, \forall m,n,k,i, \tag{9h}$$

where

$$\mathrm{A}_m = \sum_{n=1}^{N}\mathrm{Tr}(\mathbf{H}_{n,m}\mathbf{D}_n) + \mathrm{Tr}(\mathbf{H}_m(\mathbf{D}_0 - \mathbf{W}_m)) + 1, \forall m,$$

$$\mathrm{A}_{nk} = \sum_{p=1}^{N}\mathrm{Tr}(\mathbf{H}_{p,nk}(\mathbf{U}_p + \mathbf{Z}_p)) + \sum_{p\neq n}^{N}\sum_{t=1}^{K}\mathrm{Tr}(\mathbf{H}_{p,nk}\mathbf{W}_{pt}) + \mathrm{Tr}(\mathbf{H}_{nk}\mathbf{D}_0) + \sum_{t\neq k}^{K}\mathrm{Tr}(\mathbf{H}_{n,nk}\mathbf{W}_{nt}) + 1, \forall n,k,$$

$$\mathrm{A}_{\mathrm{E},l} = \mathrm{Tr}(\mathbf{G}_l(\mathbf{D}_0 - \mathbf{W}_1)) + \sum_{n=1}^{N}\mathrm{Tr}(\mathbf{G}_{n,l}(\mathbf{D}_n - \mathbf{U}_n)) + 1, \forall l,$$

and $\mathbf{D}_0 = \sum_{m=1}^{M}\mathbf{W}_m + \mathbf{Z}_0$, $\mathbf{D}_n = \sum_{k=1}^{K}\mathbf{W}_{nk} + \mathbf{U}_n + \mathbf{Z}_n$, $n \in [1,N]$, $\mathbf{H}_m = \mathbf{h}_m\mathbf{h}_m^H$, $\mathbf{G}_l = \mathbf{g}_l\mathbf{g}_l^H$, $\mathbf{H}_{n,nk} = \mathbf{h}_{n,nk}\mathbf{h}_{n,nk}^H$, $\mathbf{H}_{n,m} = \mathbf{h}_{n,m}\mathbf{h}_{n,m}^H$, $\mathbf{H}_{nk} = \mathbf{h}_{nk}\mathbf{h}_{nk}^H$, $\mathbf{G}_{n,l} = \mathbf{g}_{n,l}\mathbf{g}_{n,l}^H$. The logarithm function is monotonically increasing and thus is dropped from the objective function. It is observed that for a given t, the problem (9) can be transformed into an SDP problem by Charnes-Cooper transformation [37]. To deal with the problem, a two-stage optimization framework is employed. To this end, the inner stage part is quasi-convex with fixed t, i.e., a linear fractional function, and the outer stage part is a one-dimensional line search problem with t.

For a fixed t, the inner stage optimization problem of (9) is equivalent to

$$\max_{\mathbf{W}_m,\mathbf{W}_{nk},\mathbf{U}_n,\mathbf{Z}_i} \frac{\mathrm{Tr}(\mathbf{H}_1\mathbf{W}_1)}{\mathrm{A}_1} \tag{10a}$$

$$\text{s.t. } (9\text{b})-(9\text{h}). \tag{10b}$$

Applying Charnes-Cooper transformation [37], the problem (10) can be transformed into a convex problem. We introduce the auxiliary variables $\mathbf{X}_m, \mathbf{X}_{nk}, \mathbf{Q}_n, \mathbf{Y}_i \succeq 0$, $\omega > 0$, i.e., $\mathbf{W}_m = \frac{\mathbf{X}_m}{\omega}$, $\mathbf{W}_{nk} = \frac{\mathbf{X}_{nk}}{\omega}$, $\mathbf{U}_n = \frac{\mathbf{Q}_n}{\omega}$ and $\mathbf{Z}_i = \frac{\mathbf{Y}_i}{\omega}$, and the problem (10) is reformulated as (11), shown at the top of the next page. In (11), we have $\mathbf{C}_0 = \sum_{m=1}^{M}\mathbf{X}_m + \mathbf{Y}_0$, $\mathbf{C}_n = \sum_{k=1}^{K}\mathbf{X}_{nk} + \mathbf{Q}_n + \mathbf{Y}_n$, $n \in [1,N]$. As we can see, the problem (11) becomes a convex SDP and can be solved efficiently by numerical solvers such as `SeDuMi` [38]. Based on the discussion above, the problem (11) and the problem (10) have the same optimal solution, i.e., $(\tilde{\mathbf{X}}_m, \tilde{\mathbf{X}}_{nk}, \tilde{\mathbf{Q}}_n, \tilde{\mathbf{Y}}_i, \tilde{\omega})$, due to the equivalence between them. Therefore, the optimal solution of the problem (9) can be obtained by $(\tilde{\mathbf{W}}_m = \frac{\tilde{\mathbf{X}}_m}{\tilde{\omega}}, \tilde{\mathbf{W}}_{nk} = \frac{\tilde{\mathbf{X}}_{nk}}{\tilde{\omega}}, \tilde{\mathbf{U}}_n = \frac{\tilde{\mathbf{Q}}_n}{\tilde{\omega}}, \tilde{\mathbf{Z}}_i = \frac{\tilde{\mathbf{Y}}_i}{\tilde{\omega}})$.

The outer stage part is a one-dimensional line search problem and can be expressed as

$$\max_t \frac{1+D(t)}{t}$$

$$\text{s.t. } 1 \le t \le 1 + \mathrm{Tr}(\mathbf{H}_1)P_M,$$

where $D(t)$ is the optimal objective value of the problem (11) for a given t. We can obtain the lower bound of t from (9d). Considering the secrecy rate $R_s \ge 0$, the upper bound of t can be obtained by $t \le 1 + \frac{\mathrm{Tr}(\mathbf{H}_1\mathbf{W}_1)}{\mathrm{A}_1} \le 1 + \mathrm{Tr}(\mathbf{H}_1\mathbf{W}_1) \le 1 + \mathrm{Tr}(\mathbf{H}_1)P_M$.

By performing one-dimensional line search, e.g., Golden Section Search, we can get the optimal solution of the problem (9), i.e., $(\mathbf{W}_m^*, \mathbf{W}_{nk}^*, \mathbf{U}_n^*, \mathbf{Z}_i^*, t^*)$. Note that to get the final solution, a sequence of SDP problems are supposed to be solved. As we can see, the only difference between the original problem (8) and the problem (10) is that the relaxed rank-one constraints in the SDR process. If $\mathbf{W}_m^*$ and $\mathbf{W}_{nk}^*$ satisfy the rank-one constraints, the optimal beamforming vectors $(\mathbf{w}_m^*, \mathbf{w}_{nk}^*)$ can be obtained exactly by eigenvalue decomposition. A proposition is proposed in the next subsection to prove that the optimal solution of problem (10) is indeed rank-one.

$$\max_{\substack{\mathbf{X}_m,\mathbf{X}_{nk},\\ \mathbf{Q}_n,\mathbf{Y}_i,\omega}} \quad \mathrm{Tr}(\mathbf{H}_1\mathbf{X}_1) \tag{11a}$$

$$\text{s.t. } \mathrm{Tr}(\mathbf{H}_m\mathbf{X}_m) \geq \gamma_m(\mathrm{Tr}(\mathbf{H}_m(\mathbf{C}_0-\mathbf{X}_m)) + \sum_{n=1}^{N}\mathrm{Tr}(\mathbf{H}_{n,m}\mathbf{C}_n)+\omega),\, m\neq 1, \tag{11b}$$

$$\mathrm{Tr}(\mathbf{H}_{n,nk}\mathbf{X}_{nk}) \geq \gamma_{nk}(\sum_{t\neq k}^{K}\mathrm{Tr}(\mathbf{H}_{n,nk}\mathbf{X}_{nt}) + \sum_{p\neq n}^{N}\sum_{t=1}^{K}\mathrm{Tr}(\mathbf{H}_{p,nk}\mathbf{X}_{pt})$$

$$+\sum_{p=1}^{N}\mathrm{Tr}(\mathbf{H}_{p,nk}(\mathbf{Q}_p+\mathbf{Y}_p)) + \mathrm{Tr}(\mathbf{H}_{nk}\mathbf{C}_0)+\omega),\, \forall n,k, \tag{11c}$$

$$\mathrm{Tr}(\mathbf{G}_l\mathbf{X}_1) \leq (t-1)(\mathrm{Tr}(\mathbf{G}_l(\mathbf{C}_0-\mathbf{X}_1)) + \sum_{n=1}^{N}\mathrm{Tr}(\mathbf{G}_{n,l}(\mathbf{C}_n-\mathbf{Q}_n))+\omega),\, \forall l, \tag{11d}$$

$$\sum_{n=1}^{N}\mathrm{Tr}(\mathbf{G}_{n,l}\mathbf{C}_n) \geq \frac{\omega\phi_l}{\epsilon},\, \forall l, \tag{11e}$$

$$\mathrm{Tr}(\mathbf{H}_1(\mathbf{C}_0-\mathbf{X}_1)) + \sum_{n=1}^{N}\mathrm{Tr}(\mathbf{H}_{n,1}\mathbf{C}_n)+\omega = 1, \tag{11f}$$

$$\mathrm{Tr}(\mathbf{C}_0) \leq P_M\omega,\, \mathrm{Tr}(\mathbf{C}_n) \leq P_F\omega,\, \mathbf{X}_m, \mathbf{X}_{nk}, \mathbf{Q}_n, \mathbf{Y}_i \succeq \mathbf{0},\, \omega > 0,\, \forall m,n,k,i. \tag{11g}$$

B. TIGHTNESS ANALYSES FOR SDR

In this subsection, we analyze the tightness of SDR of the problem (10). The direct analyses on the problem is difficult. To this end, let us turn our concentration into the following power minimization problem

$$\min_{\substack{\mathbf{W}_m,\mathbf{W}_{nk},\\ \mathbf{U}_n,\mathbf{Z}_i}} \quad (\sum_{m=1}^{M}\mathrm{Tr}(\mathbf{W}_m) + \sum_{n=1}^{N}\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{W}_{nk})) \tag{12a}$$

$$\text{s.t.} \quad \mathrm{Tr}(\mathbf{H}_1\mathbf{W}_1) \geq F(t)\mathrm{A}_1, \tag{12b}$$

$$\mathrm{Tr}(\mathbf{H}_m\mathbf{W}_m) \geq \gamma_m\mathrm{A}_m,\, m\neq 1, \tag{12c}$$

$$\mathrm{Tr}(\mathbf{H}_{n,nk}\mathbf{W}_{nk}) \geq \gamma_{nk}\mathrm{A}_{nk},\, \forall n,k, \tag{12d}$$

$$\mathrm{Tr}(\mathbf{G}_l\mathbf{W}_1) \leq (t-1)\mathrm{A}_{\mathrm{E},l},\, \forall l, \tag{12e}$$

$$\sum_{n=1}^{N}\mathrm{Tr}(\mathbf{G}_{n,l}\mathbf{D}_n) \geq \frac{\phi_l}{\epsilon},\, \forall l, \tag{12f}$$

$$(9\text{f})-(9\text{h}), \tag{12g}$$

where $F(t)$ is the optimal objective value of the problem (10) for a fixed t. It can be verified that the optimal solution $(\mathbf{W}_m^o, \mathbf{W}_{nk}^o, \mathbf{U}_n^o, \mathbf{Z}_i^o)$ of the problem (12) is also a feasible solution of the problem (10). Then, the corresponding objective value satisfies $F^o(t) \leq F(t)$, where $F^o(t)$ can be calculated by substituting $(\mathbf{W}_m^o, \mathbf{W}_{nk}^o, \mathbf{U}_n^o, \mathbf{Z}_i^o)$ into (10). On the other hand, by examining the constraints (12b)-(12g), it can be verified that the feasible solution of (12) is the optimal solution of (10), which means $F^o(t) \geq F(t)$ holds as well. Therefore, the optimal solution of (12) has the same quality as the optimal solution of (10). Furthermore, the following proposition is provided to show that the relaxation of $(\mathbf{W}_m^o, \mathbf{W}_{nk}^o)$ is tight.

Proposition 1: The optimal solution $(\mathbf{W}_m^o, \mathbf{W}_{nk}^o)$ of problem (12) is always rank-one.

Proof: Please refer to Appendix. ∎

From Proposition 1, we conclude that there always exists a rank-one solution of problem (10) for all feasible t. Then, for the fixed t^*, the optimal beamforming vectors $(\mathbf{w}_m^*, \mathbf{w}_{nk}^*)$ can be obtained directly from $(\mathbf{W}_m^*, \mathbf{W}_{nk}^*)$ by using eigenvalue decomposition.

Remark 1: By properly designing the transmission scheme, the various types of CCI can be exploited to enhance the secrecy rate of the intended MU as well as the EH efficiency of the ERs. For the proposed scheme, with the limited cross-tier cooperation, the MBS collects the local CSI of the collaborative FBSs and conducts the joint TB and AN design. Then, the MBS delivers the TB and AN to the relevant FBSs. Moreover, no data sharing is required of the proposed scheme and the limited cross-tier cooperation imposes acceptable overhead for the backhaul links.

Remark 2: The proposed scheme is also applicable to the scenario, where a FU is eavesdropped by the ERs, and multiple FBSs work collaboratively to enhance the secrecy performance of the intended FU under the different kinds of constraints at the related receivers and transmitters. The proposed algorithm can be used to solve the problem with a slight modification of the objective function.

IV. ROBUST JOINT TB AND AN DESIGN

In the previous section, we have studied the joint TB and AN design for secure SWIPT in HetNet with perfect ECSI. However, in practical scenarios, it is difficult for the MBS and FBSs to obtain the perfect ECSI. In this section, the

TB and AN are jointly optimized to maximize the worst-case secrecy rate by incorporating ellipsoid-bounded channel uncertainties.

It is assumed that the MBS and FBSs only know the estimation of the ECSI, i.e., $\hat{\mathbf{g}}_l, \hat{\mathbf{g}}_{n,l}, l \in [1, L], n \in [1, N]$. The channel models are represented as

$$\mathbf{g}_l = \hat{\mathbf{g}}_l + \mathbf{e}_l, \quad \mathbf{g}_{n,l} = \hat{\mathbf{g}}_{n,l} + \mathbf{e}_{n,l},$$

where $\mathbf{e}_l$ and $\mathbf{e}_{n,l}$ are the channel errors of the estimated ECSI from the MBS and FBS_n to ER_l, respectively. The ellipsoid-bounded uncertainty models are assumed as

$$\mathbf{e}_l^H \mathbf{C}_l \mathbf{e}_l \le 1, \quad \mathbf{e}_{n,l}^H \mathbf{C}_{n,l} \mathbf{e}_{n,l} \le 1,$$

where $\mathbf{C}_l \succ \mathbf{0}$ and $\mathbf{C}_{n,l} \succ \mathbf{0}$ determine the shape and size of the uncertainty regions.

Next, we investigate the worst-case secrecy rate maximization problem with imperfect ECSI for HetNet with SWIPT. In particular, a robust joint TB and AN design is proposed to maximize the worst-case secrecy rate of MU_1, while guaranteeing the worst-case EH requirements at the ERs, the QoS constraints of the unclassified MUs and FUs, and the transmit power constraints of the MBS and FBSs. To begin with, the worst-case secrecy rate can be represented as

$$R_s^w = \min_{l \in [1,L]} (\log(1 + \text{SINR}_1) - \log(1 + \text{SINR}'_{\text{E},l})),$$

where $\text{SINR}'_{\text{E},l} = \max_{\mathbf{e}_l, \mathbf{e}_{n,l}} \frac{\text{Tr}(\mathbf{G}_l \mathbf{W}_1)}{\text{A}_{\text{E},l}}$. Based on the analyses in the previous section, the worst-case secrecy rate optimization problem is formulated as

$$\max_{\substack{\mathbf{W}_m, \mathbf{W}_{nk} \\ \mathbf{U}_n, \mathbf{Z}_i}} \min_{l \in [1,L]} \min_{\mathbf{e}_l, \mathbf{e}_{n,l}} \frac{1 + \frac{\text{Tr}(\mathbf{H}_1 \mathbf{W}_1)}{\text{A}_1}}{1 + \frac{\text{Tr}(\mathbf{G}_l \mathbf{W}_1)}{\text{A}_{\text{E},l}}} \tag{13a}$$

$$\text{s.t.} \min_{\mathbf{e}_{n,l}} \epsilon \sum_{n=1}^{N} \text{Tr}(\mathbf{G}_{n,l} \mathbf{D}_n) \ge \phi_l, \forall l, \tag{13b}$$

$$\text{Tr}(\mathbf{H}_m \mathbf{W}_m) \ge \gamma_m \text{A}_m, m \ne 1, \tag{13c}$$

$$\text{Tr}(\mathbf{H}_{n,nk} \mathbf{W}_{nk}) \ge \gamma_{nk} \text{A}_{nk}, \forall n, k, \tag{13d}$$

$$(9\text{f}) - (9\text{h}), \tag{13e}$$

where A_m, A_{nk} and $\text{A}_{\text{E},l}$ are defined in the problem (9). For the objective function of the problem (13), the logarithm function is dropped because it is monotonically increasing. (13b) represents the worst-case EH requirements at the ERs. It is noted that (13) is a nonconvex problem due to the complicated objective function and the infinite constraints on the ECSI error, which is difficult to solve. To deal with (13), we first introduce three slack variables r, t_1 and t_2, and the problem is reformulated as

$$\max_{\substack{\mathbf{W}_m, \mathbf{W}_{nk}, \\ \mathbf{U}_n, \mathbf{Z}_i, r, t_1, t_2}} r \tag{14a}$$

$$\text{s.t. } t_1 t_2 \ge r^2, \tag{14b}$$

$$1 + \frac{\text{Tr}(\mathbf{H}_1 \mathbf{W}_1)}{\text{A}_1} \ge t_1, \tag{14c}$$

$$\max_{\mathbf{e}_l, \mathbf{e}_{n,l}} 1 + \frac{\text{Tr}(\mathbf{G}_l \mathbf{W}_1)}{\text{A}_{\text{E},l}} \le \frac{1}{t_2}, \forall l, \tag{14d}$$

$$(13\text{b}) - (13\text{e}). \tag{14e}$$

It is easy to recognize the equivalence of (13) and (14) by noting that the constraints (14b), (14c) and (14d) hold with equalities at the optimal solution. Otherwise, a larger objective value can be obtained by increasing t_1, t_2 or r. To make the problem (14) more tractable, two slack variables u_1 and u_2 are introduced. Then, the optimization problem (14) can be equivalently rewritten as

$$\max_{\substack{\mathbf{W}_m, \mathbf{W}_{nk}, \mathbf{U}_n, \\ \mathbf{Z}_i, r, t_1, t_2, u_1, u_2}} r \tag{15a}$$

$$\text{s.t. Tr}(\mathbf{H}_1 \mathbf{W}_1) \ge (t_1 - 1) u_1, \tag{15b}$$

$$\text{A}_1 \le u_1, \tag{15c}$$

$$\min_{\mathbf{e}_l, \mathbf{e}_{n,l}} \text{A}_{\text{E},l} \ge t_2 u_2, \forall l, \tag{15d}$$

$$\max_{\mathbf{e}_l, \mathbf{e}_{n,l}} \text{A}_{\text{E},l} + \text{Tr}(\mathbf{G}_l \mathbf{W}_1) \le u_2, \forall l, \tag{15e}$$

$$\min_{\mathbf{e}_{n,l}} \sum_{n=1}^{N} \text{Tr}(\mathbf{G}_{n,l} \mathbf{D}_n) \ge \frac{\phi_l}{\epsilon}, \forall l, \tag{15f}$$

$$(13\text{c}) - (13\text{e}), (14\text{b}). \tag{15g}$$

The equivalence of (14) and (15) can be easily recognized, since (15c) and (15e) satisfy equations at the optimum. Otherwise, the objective value can be further increased by decreasing u_1 or u_2. Therefore, we can obtain the fact that the optimization problem (15) is equivalent to the original problem (13). However, as we can see, the constraints (15b), (15d), (15e) and (15f) are not convex. Next, we will try to deal with these problems.

1) TRANSFORMATION OF (15b)

Let $k(x)$ be a convex function and $h(x)$ be a concave function, and thus the constraint $k(x) \le h(x)$ is a convex constraint [39]. It is obvious that (15b) is nonconvex. The main factor causing its nonconvex property is the function on the right-hand side (RHS), i.e., $h(x, y) = xy$, which is quasi-concave. Then, inspired by the idea of SCA [40], [41], we manage to approximate this term with the convex upper estimates. Assuming $\theta > 0$, we consider the following function

$$k_\theta(x, y) = \frac{\theta}{2} x^2 + \frac{1}{2\theta} y^2,$$

which is convex and is always an upper estimate of the function $h(x, y)$ for a fixed θ. Moreover, $k_\theta(x, y)$ also satisfies the following equations

$$k_\theta(x, y) = h(x, y), \nabla k_\theta(x, y) = \nabla h(x, y), \theta = y/x.$$

According to SCA, the RHS of the constraint (15b) can be replaced by $k_\theta(t_1 - 1, u_1)$ with $\theta = \frac{1}{\tilde{t}_1 - 1} \tilde{u}_1$. It is noted that the initial values, i.e., $(\tilde{t}_1^{(1)}, \tilde{u}_1^{(1)})$, are selected randomly, and $(\tilde{t}_1^{(n)}, \tilde{u}_1^{(n)})$ can be updated by the optimal solution of (t_1, u_1) in the $(n-1)$-th iteration when $n \ge 2$.

2) TRANSFORMATION OF (15d), (15e) AND (15f)

Now, we are supposed to focus on the first worst-case constraint (15d). Similarly, we can replace the RHS of the constraint (15d) by $k_\eta(t_2, u_2)$ with $\eta = \frac{1}{t_2}\tilde{u}_2$. It is noted that the left hand side of (15d) contains several ellipsoidal uncertainty regions, which is not known to be tractable [42]. In the following, it can be turned into some exact equivalent convex conditions. By introducing the slack variables p_l and $p_{nl}, l \in [1, L], n \in [1, N]$, the constraint (15d) can be reformulated as

$$\min_{\mathbf{e}_l} \mathrm{Tr}(\mathbf{G}_l(\sum_{m=2}^{M} \mathbf{W}_m + \mathbf{Z}_0)) \geq p_l, \tag{16a}$$

$$\min_{\mathbf{e}_{n,l}} \mathrm{Tr}(\mathbf{G}_{n,l}(\sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{Z}_n)) \geq p_{nl}, \tag{16b}$$

$$p_l + \sum_{n=1}^{N} p_{nl} + 1 \geq k_\eta(t_2, u_2), p_l \geq 0, p_{nl} \geq 0, \forall l. \tag{16c}$$

Recalling the channel uncertainty model introduced in Section IV, the constraints in (16) are equivalent to

$$\mathbf{e}_l^H \mathbf{C}_l \mathbf{e}_l \leq 1$$
$$\Rightarrow (\hat{\mathbf{g}}_l + \mathbf{e}_l)^H \Big(\sum_{m=2}^{M} \mathbf{W}_m + \mathbf{Z}_0\Big)(\hat{\mathbf{g}}_l + \mathbf{e}_l) \geq p_l, \tag{17a}$$

$$\mathbf{e}_{n,l}^H \mathbf{C}_{n,l} \mathbf{e}_{n,l} \leq 1$$
$$\Rightarrow (\hat{\mathbf{g}}_{n,l} + \mathbf{e}_{n,l})^H \Big(\sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{Z}_n\Big)(\hat{\mathbf{g}}_{n,l} + \mathbf{e}_{n,l}) \geq p_{nl}. \tag{17b}$$

Note that the infinite constraints can be solved effectively by the following lemma.

Lemma 1: (S-Procedure [39]) Define $f_k(\mathbf{x}) = \mathbf{x}^H \mathbf{A}_k \mathbf{x} + 2\mathrm{Re}\{\mathbf{b}_k^H \mathbf{x}\} + c_k$, *where* $\mathbf{A}_k = \mathbf{A}_k^H \in \mathbb{C}^{n\times n}$, $\mathbf{b}_k \in \mathbb{C}^{n\times 1}$ *and* $c_k \in \mathbb{R}, k = 1, 2$. *The implication* $f_1(\mathbf{x}) \leq 0 \Rightarrow f_2(\mathbf{x}) \leq 0$ *holds if and only if there exists an* $\alpha \geq 0$ *such that*

$$\alpha \begin{bmatrix} \mathbf{A}_1 & \mathbf{b}_1 \\ \mathbf{b}_1^H & c_1 \end{bmatrix} \succeq \begin{bmatrix} \mathbf{A}_2 & \mathbf{b}_2 \\ \mathbf{b}_2^H & c_2 \end{bmatrix},$$

provided there exists a point $\bar{\mathbf{x}}$ *satisfying* $f_1(\bar{\mathbf{x}}) < 0$.

Based on Lemma 1, we can rewrite (17a) and (17b) as the following equivalent linear matrix inequality's (LMI) form

$$\begin{bmatrix} \alpha_l \mathbf{C}_l + \mathbf{V}_{\mathrm{M1}} & \mathbf{V}_{\mathrm{M1}} \hat{\mathbf{g}}_l \\ \hat{\mathbf{g}}_l^H \mathbf{V}_{\mathrm{M1}} & -\alpha_l + \hat{\mathbf{g}}_l^H \mathbf{V}_{\mathrm{M1}} \hat{\mathbf{g}}_l - p_l \end{bmatrix} \succeq 0, \tag{18a}$$

$$\begin{bmatrix} \alpha_{nl} \mathbf{C}_{n,l} + \mathbf{V}_n & \mathbf{V}_n \hat{\mathbf{g}}_{n,l} \\ \hat{\mathbf{g}}_{n,l}^H \mathbf{V}_n & -\alpha_{nl} + \hat{\mathbf{g}}_{n,l}^H \mathbf{V}_n \hat{\mathbf{g}}_{n,l} - p_{nl} \end{bmatrix} \succeq 0, \tag{18b}$$

$$\alpha_l \geq 0, \alpha_{nl} \geq 0, \forall n, l, \tag{18c}$$

where $\mathbf{V}_{\mathrm{M1}} = \sum_{m=2}^{M} \mathbf{W}_m + \mathbf{Z}_0$, $\mathbf{V}_n = \sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{Z}_n$ and $\alpha_l, \alpha_{nl}, l \in [1, L], n \in [1, N]$, are slack variables.

Next, the second worst-case constraint (15e) can be turned into exact equivalent convex conditions by the similar method above. We introduce the slack variables $q_l, q_{nl}, l \in [1, L], n \in [1, N]$, then (15e) can be recast as

$$\max_{\mathbf{e}_l} \mathrm{Tr}(\mathbf{G}_l(\sum_{m=1}^{M} \mathbf{W}_m + \mathbf{Z}_0)) \leq q_l, \tag{19a}$$

$$\max_{\mathbf{e}_{n,l}} \mathrm{Tr}(\mathbf{G}_{n,l}(\sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{Z}_n)) \leq q_{nl}, \tag{19b}$$

$$q_l + \sum_{n=1}^{N} q_{nl} + 1 \leq u_2, q_l \geq 0, q_{nl} \geq 0, \forall l. \tag{19c}$$

Then, by using S-Procedure [39], (19a) and (19b) are reformulated as the following equivalent LMI's form

$$\begin{bmatrix} \beta_l \mathbf{C}_l - \mathbf{V}_{\mathrm{M2}} & -\mathbf{V}_{\mathrm{M2}} \hat{\mathbf{g}}_l \\ -\hat{\mathbf{g}}_l^H \mathbf{V}_{\mathrm{M2}} & -\beta_l - \hat{\mathbf{g}}_l^H \mathbf{V}_{\mathrm{M2}} \hat{\mathbf{g}}_l + q_l \end{bmatrix} \succeq 0, \tag{20a}$$

$$\begin{bmatrix} \beta_{nl} \mathbf{C}_{n,l} - \mathbf{V}_n & -\mathbf{V}_n \hat{\mathbf{g}}_{n,l} \\ -\hat{\mathbf{g}}_{n,l}^H \mathbf{V}_n & -\beta_{nl} - \hat{\mathbf{g}}_{n,l}^H \mathbf{V}_n \hat{\mathbf{g}}_{n,l} + q_{nl} \end{bmatrix} \succeq 0, \tag{20b}$$

$$\beta_l \geq 0, \beta_{nl} \geq 0, \forall n, l, \tag{20c}$$

where $\mathbf{V}_{\mathrm{M2}} = \sum_{m=1}^{M} \mathbf{W}_m + \mathbf{Z}_0$ and $\beta_l, \beta_{nl}, l \in [1, L]$, $n \in [1, N]$, are slack variables.

Finally, by introducing the slack variables $v_{nl}, n \in [1, N], l \in [1, L]$, the last worst-case constraint (15f) can be equivalently recast as

$$\min_{\mathbf{e}_{n,l}} \mathrm{Tr}(\mathbf{G}_{n,l}(\sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{U}_n + \mathbf{Z}_n)) \geq v_{nl}, \tag{21a}$$

$$\sum_{n=1}^{N} v_{nl} \geq \frac{\phi_l}{\epsilon}, v_{nl} \geq 0, \ \forall l. \tag{21b}$$

Then, with the assistance of S-Procedure [39], (21a) can be rewritten as the following equivalent LMI's form

$$\begin{bmatrix} \lambda_{nl} \mathbf{C}_{n,l} + \overline{\mathbf{V}}_n & \overline{\mathbf{V}}_n \hat{\mathbf{g}}_{n,l} \\ \hat{\mathbf{g}}_{n,l}^H \overline{\mathbf{V}}_n & -\lambda_{nl} + \hat{\mathbf{g}}_{n,l}^H \overline{\mathbf{V}}_n \hat{\mathbf{g}}_{n,l} - v_{nl} \end{bmatrix} \succeq 0, \tag{22a}$$

$$\lambda_{nl} \geq 0, \forall n, l, \tag{22b}$$

where $\overline{\mathbf{V}}_n = \sum_{k=1}^{K} \mathbf{W}_{nk} + \mathbf{U}_n + \mathbf{Z}_n$ and $\lambda_{nl}, n \in [1, N], l \in [1, L]$, are slack variables.

With the transformations above, the problem (15) is equivalently represented as

$$\max_{\substack{\mathbf{W}_m, \mathbf{W}_{nk}, \mathbf{U}_n, \mathbf{Z}_i, r, t_1, \\ t_2, u_1, u_2, p_l, p_{nl}, \alpha_l, \alpha_{nl}, \\ q_l, q_{nl}, \beta_l, \beta_{nl}, v_{nl}, \lambda_{nl}}} \quad r \tag{23a}$$

$$\text{s.t.} \ \|[2r, \ t_1 - t_2]\| \leq t_1 + t_2, \tag{23b}$$

$$\mathrm{Tr}(\mathbf{H}_1 \mathbf{W}_1) \geq k_\theta(t_1 - 1, u_1), \tag{23c}$$

$$(13c) - (13e), (15c), (16c), \tag{23d}$$

$$(18a) - (18c), (19c), (21b), \tag{23e}$$

$$(20a) - (20c), (22a), (22b), \tag{23f}$$

where (23b) is the second-order constraint and it can be obtained from the fact that $z^2 \leq xy$ is equivalent to $\|[2z, x - y]\| \leq x + y$, when $x \geq 0, y \geq 0$. It is observed that

Algorithm 1 The proposed iterative algorithm for solving (23)

1. Initialization: Set $n = 1$, and $(\theta^{(1)}, \eta^{(1)})$ that is feasible to problem (23).
2. Repeat:
   Solve the convex problem (23) with $\left(\frac{1}{\tilde{t}_1^{(n)}-1}\tilde{u}_1^{(n)}, \frac{1}{\tilde{t}_2^{(n)}}\tilde{u}_2^{(n)}\right)$, and obtain the optimal solution as $\left(t_1^*, u_1^*, t_2^*, u_2^*\right)$.
   Update $\left(\theta^{(n+1)}, \eta^{(n+1)}\right) = \left(\frac{1}{t_1^*-1}u_1^*, \frac{1}{t_2^*}u_2^*\right)$,
   n=n+1.
3. Until convergence or reach the maximal number of iterations.

the problem (23) is convex and can be solved efficiently using the numerical solvers such as `SeDuMi` [38]. The proposed iterative algorithm is summarized in Algorithm 1.

Remark 3: Since the problem (23) is convex, we can obtain the optimal solution by solving (23) for a given (θ, η) in the n-th iteration. Based on the optimal solution of the n-th iteration, (θ, η) is updated by $(\tilde{t}_1^{(n)}, \tilde{u}_1^{(n)}, \tilde{t}_2^{(n)}, \tilde{u}_2^{(n)})$ at the $(n+1)$-th iteration. In particular, $(\tilde{t}_1^{(n)}, \tilde{u}_1^{(n)}, \tilde{t}_2^{(n)}, \tilde{u}_2^{(n)})$ is always a feasible solution of the $(n+1)$-th iteration. Then, the optimal value r^*, which is obtained by $(\tilde{t}_1^{(n)}, \tilde{u}_1^{(n)}, \tilde{t}_2^{(n)}, \tilde{u}_2^{(n)})$ in the $(n+1)$-th iteration will become larger than or equal to the optimal value in the n-th iteration. Therefore, the secrecy rate is monotonically increasing or nondecreasing during each iteration. Due to the transmit power constraints at the MBS and the FBSs, there exists an upper bound of the secrecy rate. It reveals that the convergence of the proposed algorithm can be guaranteed, which is shown in Fig. 2.

Up to now, the optimal solution $(\mathbf{W}_m^*, \mathbf{W}_{nk}^*, \mathbf{U}_n^*, \mathbf{Z}_i^*)$ can be obtained by solving the problem (23). Next, we need to extract the beamforming vectors $(\mathbf{w}_m^*, \mathbf{w}_{nk}^*)$ from $(\mathbf{W}_m^*, \mathbf{W}_{nk}^*)$. If $\text{rank}(\mathbf{W}_m^*) = 1$ or $\text{rank}(\mathbf{W}_{nk}^*) = 1$, we can get $\mathbf{w}_m^*$ or $\mathbf{w}_{nk}^*$ by eigenvalue decomposition. Otherwise, we can apply some rank-one approximation procedures, e.g., Gaussian randomization [43], to $\mathbf{W}_m^*$ and $\mathbf{W}_{nk}^*$ to get $\mathbf{w}_m^*$ and $\mathbf{w}_{nk}^*$, respectively.

V. SIMULATIONS

In this section, the simulation results are presented to evaluate the secrecy rate of the intended MU for the proposed schemes. The path loss model is given by $(\frac{d}{d_0})^{-\alpha}$ for all users, i.e., the MUs, FUs and ERs, where d represents the distance between one given user to its connecting base station, the reference distance d_0 is 5 meters, and $\alpha = 3.5$ is the path loss exponent. It is assumed that the small scale fading channels are Rayleigh fading channels. Moreover, we assume that the distance from the MBS to all the users is 80 meters, and the distances from the FBS to the MUs, FUs and the ERs are 35, 25 and 10 meters, respectively. We assume a target harvested power of $\phi_l = \phi, l \in [1, L]$, and the EH efficiency of $\epsilon = 0.5$. The MBS and the FBS are equipped with $N_M = 6$ and $N_F = 4$ antennas, respectively. The number of the FBSs, MUs, ERs, and the FUs served by each FBS are set to be $N = 2, M = 3, L = 2$ and $K = 1$, respectively. Also, sphere-bounded ECSI errors are adopted, i.e., $\mathbf{C}_l = \frac{1}{\tau^2}\mathbf{I}_{N_M}, \mathbf{C}_{n,l} = \frac{1}{\tau^2}\mathbf{I}_{N_F}$.

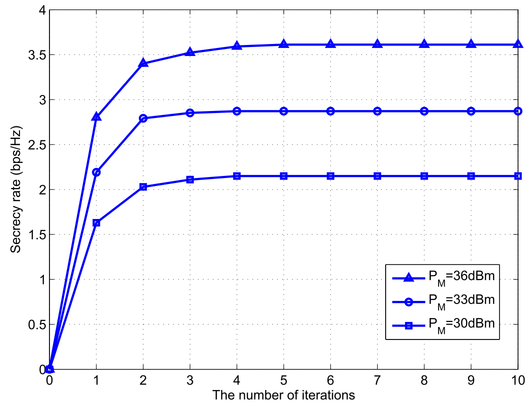

FIGURE 2. Convergence property according to different transmit power of the MBS with $P_F = 15$ dBm and $\tau = 0.1$.

Three benchmarks are considered in the simulations. The non-robust joint TB and AN design is benchmark 1, and the estimated ECSI $(\hat{\mathbf{g}}_l, \hat{\mathbf{g}}_{n,l})$ is treated as the perfect ECSI for benchmark 1. Benchmark 2 is the robust beamforming design without AN, which is denoted as "Robust w/o AN". For benchmark 3, a non-secrecy oriented beamforming scheme is adopted to maximize the information rate of the wire-tapped MU_1 without the consideration of the imperfect ECSI. Therefore, we do not employ the AN at the MBS and the FBSs. In particular, the problem is represented as

$$\max_{\mathbf{W}_m, \mathbf{W}_{nk}, \mathbf{U}_n} \quad \log(1 + \text{SINR}_1) \tag{24a}$$

$$\text{s.t.} \quad (13b) - (13e), \tag{24b}$$

where we set $\mathbf{Z}_i = \mathbf{0}, i \in [0, N]$, in SINR_1 and (13b)-(13e). Following the same method proposed in Section IV, the problem (24) can be reformulated into a convex problem and solved via numerical solvers. The benchmark 3 is denoted as "Benchmark" in the simulation. Moreover, the proposed joint TB and AN design with perfect ECSI and the proposed robust joint TB and AN design are denoted as "Perfect ECSI" and "Robust", respectively.

Fig. 2 presents the convergence of the proposed Algorithm 1, and the convergence behaviors of the worst-case secrecy rate of MU_1 for different sets of the transmit power of the MBS are demonstrated. As can be shown, the secrecy rate of the proposed scheme, as discussed before, increases monotonically in each iteration, and it converges to a stationary value within a few iterations.

In Fig. 3, the secrecy rate of MU_1 is depicted versus the transmit power of the MBS. The secrecy rate of the proposed joint TB and AN design with perfect ECSI serves as the performance upper bound of all the beamforming schemes. We can observe that with the increase of P_M, the worst-case secrecy rate of MU_1 increases monotonically, and the proposed robust joint TB and AN design is able to achieve a better performance gain than the benchmarks. To be more

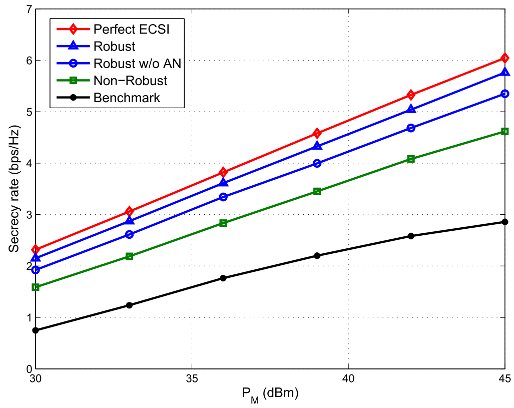

FIGURE 3. The secrecy rate versus the transmit power of the MBS with $P_F = 15$ dBm and $\tau = 0.1$.

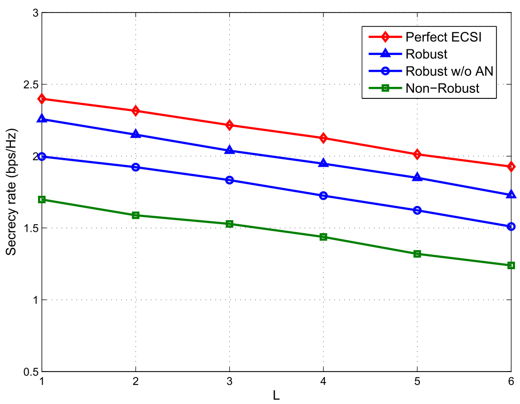

FIGURE 4. The secrecy rate versus the number of ERs with $P_M = 30$ dBm, $P_F = 15$ dBm and $\tau = 0.1$.

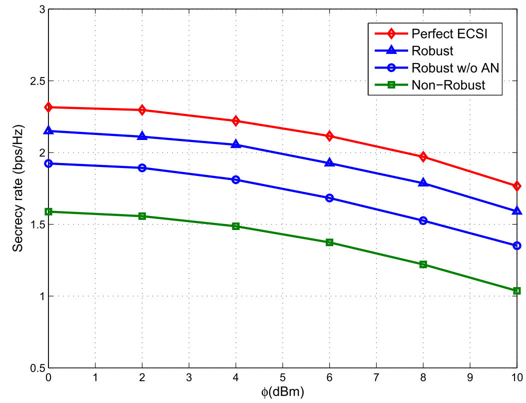

FIGURE 5. The secrecy rate versus the EH requirement at ER with $P_M = 30$ dBm, $P_F = 15$ dBm and $\tau = 0.1$.

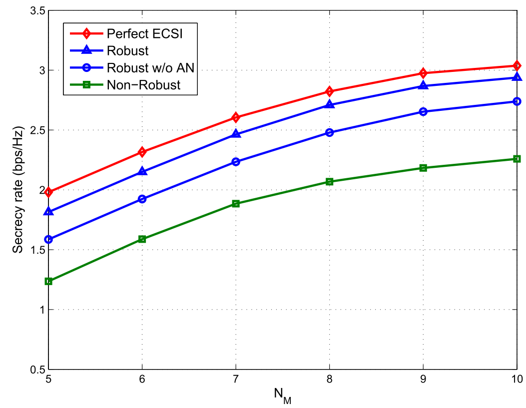

FIGURE 6. The secrecy rate versus the number of transmit antennas of the MBS with $P_M = 30$ dBm, $P_F = 15$ dBm and $\tau = 0.1$.

specific, when P_M increases, the performance gap of the two schemes, i.e., the robust joint TB and AN design and the non-robust scheme, is enlarged. Besides, as we can see, the robust joint TB and AN design has better secrecy performance than the robust beamforming scheme without AN, which indicates that the AN-aided transmission strategy employed at the MBS and FBSs can significantly improve the worst-case secrecy rate. Therefore, considering imperfect ECSI at the MBS and the FBSs, AN is necessary for enhancing the secrecy rate performance of the intended MU in the HetNet with SWIPT.

Fig. 4 shows the secrecy rate of MU_1 versus the number of ERs for different beamforming schemes. It is observed that the secrecy rate decreases with the increase of the number of ERs for two reasons. First, with increasing number of ERs in the network, more devices require EH from the FBSs, even though some of them have poor channel conditions. Therefore, to conduct efficient power transfer, more power of the FBSs should be allocated to the energy beams to guarantee the EH requirements of the increased number of ERs. Second, the increasing number of ERs also indicates that there exist more potential eavesdroppers. Then, the MBS and the FBSs should provide a larger amount of AN for jamming the channels of the potential eavesdroppers, which is difficult to be achieved due to the transmit power constraints of the MBS and the FBSs. Moreover, it can be observed that the secrecy rate performance of the proposed robust joint TB and AN design outperforms that of the benchmark schemes for different number of ERs in the system.

In Fig. 5, we show the secrecy rate of MU_1 versus the EH requirement at ER. It is obtained that the secrecy rate of different beamforming schemes decreases monotonically with increasing ϕ. This is attributed to the fact that for the proposed joint TB and AN design, there exists a trade-off between the EH performance at the ERs and the secrecy performance of the wiretapped MU. Particularly, the excessive harvested power at the ERs comes at the expense of low secrecy rate of MU_1. Besides, the secrecy rate degrades more significantly in the high EH requirement regime due to the limited energy-rate region. Moreover, the robust joint TB and AN design achieves a better secrecy rate performance gain than the robust TB scheme without AN over the whole range of the tested ϕ, which shows that AN is also beneficial for EH.

Fig. 6 shows the secrecy rate of MU_1 versus the number of transmit antennas at the MBS. It is observed that for all schemes the secrecy rate improves with increasing the number of transmit antennas. In fact, increasing the number of transmit antennas at the MBS will increase the degrees-of-freedom for the beamforming design. Thus, the secrecy rate is proportional to the number of transmit antennas at the MBS. Moreover, the secrecy performance of the robust joint TB and AN design approaches that of the proposed scheme with perfect ECSI when N_M is large.

VI. CONCLUSIONS

In this paper, we have investigated the joint TB and AN design for secure SWIPT in a two-tier HetNet with multiple ERs trying to wiretap a legitimate MU. For both perfect and imperfect ECSI cases, we aim to maximize the secrecy rate of the wiretapped MU subject to the QoS constraints of the unclassified MUs and FUs, the EH requirements of the ERs and the transmit power constraints at the MBS and FBSs. To solve the nonconvex problems, we reformulate the problems by using the one-dimensional line search based two-stage framework and SCA. Furthermore, the effectiveness of the proposed schemes is demonstrated by the simulations.

APPENDIX
PROOF OF PROPOSITION 1

The main idea of the proof is based on the Karush-Kuhn-Tucker (KKT) conditions [39]. The parts of KKT conditions relevant to the proof are listed as follows

$$\mathbf{F}_1 = \mathbf{I} - a\mathbf{H}_1 + \sum_{m=2}^{M} a_m\gamma_m\mathbf{H}_m + \sum_{n=1}^{N}\sum_{k=1}^{K} a_{nk}\gamma_{nk}\mathbf{H}_{nk} + \sum_{l=1}^{L} b_l\mathbf{G}_l + d\mathbf{I}, \tag{25}$$

$$\mathbf{F}_1\mathbf{W}_1 = 0, \tag{26}$$

$$\mathbf{D}_0 = aF(t)\mathbf{H}_1 + \sum_{m=2}^{M} a_m\gamma_m\mathbf{H}_m + \sum_{n=1}^{N}\sum_{k=1}^{K} a_{nk}\gamma_{nk}\mathbf{H}_{nk} - (t-1)\sum_{l=1}^{L} b_l\mathbf{G}_l + d\mathbf{I}, \tag{27}$$

$$\mathbf{F}_m = \mathbf{I} + aF(t)\mathbf{H}_1 - a_m\mathbf{H}_m + \sum_{q\neq 1,m}^{M} a_q\gamma_q\mathbf{H}_q + \sum_{n=1}^{N}\sum_{k=1}^{K} a_{nk}\gamma_{nk}\mathbf{H}_{nk} - (t-1)\sum_{l=1}^{L} b_l\mathbf{G}_l + d\mathbf{I},\ m \neq 1, \tag{28}$$

$$\mathbf{F}_m\mathbf{W}_m = 0,\ m \neq 1, \tag{29}$$

$$\mathbf{F}_{nk} = \mathbf{I} + aF(t)\mathbf{H}_{n,1} + \sum_{m=2}^{M} a_m\gamma_m\mathbf{H}_{n,m} - a_{nk}\mathbf{H}_{n,nk} + \sum_{t\neq k}^{K} a_{nt}\gamma_{nt}\mathbf{H}_{n,nt} + \sum_{p\neq n}^{N}\sum_{t=1}^{K} a_{pt}\gamma_{pt}\mathbf{H}_{n,pt} - (t-1)\sum_{l=1}^{L} b_l\mathbf{G}_{n,l} - \sum_{l=1}^{L} c_l\mathbf{G}_{n,l} + d_n\mathbf{I},\ \forall n, k, \tag{30}$$

$$\mathbf{F}_{nk}\mathbf{W}_{nk} = 0,\ \forall n, k, \tag{31}$$

$$\mathbf{D}_n = aF(t)\mathbf{H}_{n,1} + \sum_{m=2}^{M} a_m\gamma_m\mathbf{H}_{n,m} + \sum_{p=1}^{N}\sum_{t=1}^{K} a_{pt}\gamma_{pt}\mathbf{H}_{n,pt} - (t-1)\sum_{l=1}^{L} b_l\mathbf{G}_{n,l} - \sum_{l=1}^{L} c_l\mathbf{G}_{n,l} + d_n\mathbf{I},\ \forall n, \tag{32}$$

where $a \geq 0$, $a_m \geq 0$, $a_{nk} \geq 0$, $b_l \geq 0$, $c_l \geq 0$, $d \geq 0$, $d_n \geq 0$, $\mathbf{F}_s \succeq \mathbf{0}$, $\mathbf{F}_{nk} \succeq \mathbf{0}$ and $\mathbf{D}_i \succeq \mathbf{0}$, $m \in [2, M]$, $n \in [1, N]$, $k \in [1, K]$, $l \in [1, L]$, $s \in [1, M]$, $i \in [0, M]$, are the optimal dual variables associated with the constraints (12b)-(12f), (9f), (9g), $\mathbf{W}_m \succeq \mathbf{0}$, $\mathbf{W}_{nk} \succeq \mathbf{0}$ and $\mathbf{Z}_i \succeq \mathbf{0}$, respectively.

Note that $\mathbf{W}_1 \neq \mathbf{0}$, otherwise the resultant secrecy rate is zero, which is trivial. Based on (26), the rank of $\mathbf{F}_1$ should be less than or equal to $N_M - 1$, i.e.,

$$\text{rank}(\mathbf{F}_1) \leq N_M - 1. \tag{33}$$

By subtracting (27) from (25), we have

$$\mathbf{F}_1 - \mathbf{D}_0 = \mathbf{I} + \sum_{l=1}^{L} tb_l\mathbf{G}_l - a(1 + F(t))\mathbf{H}_1$$
$$\Rightarrow \mathbf{F}_1 = \mathbf{M}_1 - a(1 + F(t))\mathbf{H}_1, \tag{34}$$

where $\mathbf{M}_1 = \mathbf{I} + \mathbf{D}_0 + \sum_{l=1}^{L} tb_l\mathbf{G}_l$. It can be observed that $\mathbf{M}_1$ is positive definite and $\text{rank}(\mathbf{M}_1) = N_M$. From (34), we have

$$\text{rank}(\mathbf{M}_1) = \text{rank}(\mathbf{F}_1 + a(1 + F(t))\mathbf{H}_1) \overset{(a)}{\leq} \text{rank}(\mathbf{F}_1) + \text{rank}(a(1 + F(t))\mathbf{H}_1),$$

where (a) holds true based on the fact that

$$\text{rank}(\mathbf{A} + \mathbf{B}) \leq \text{rank}(\mathbf{A}) + \text{rank}(\mathbf{B}),$$

where $\mathbf{A}, \mathbf{B} \in \mathbb{C}^{m\times n}$. Thus, we have

$$\text{rank}(\mathbf{F}_1) \geq N_M - 1. \tag{35}$$

According to (33) and (35), $\text{rank}(\mathbf{F}_1) = N_M - 1$ always holds. From (26), we can get $\text{rank}(\mathbf{W}_1) \leq \dim(\mathcal{N}(\mathbf{F}_1)) = N_M - \text{rank}(\mathbf{F}_1) = 1$, where $\dim(\mathcal{N}(\mathbf{F}_1))$ represents the dimension of the null space of $\mathbf{F}_1$. Since $\mathbf{W}_1 \neq \mathbf{0}$, thus we have $\text{rank}(\mathbf{W}_1) = 1$.

It is noted that $\text{rank}(\mathbf{W}_m) = 1, m \in [2, M]$, and $\text{rank}(\mathbf{W}_{nk}) = 1, n \in [1, N], k \in [1, K]$, can also be proved following the same procedures. Hence, we have completed the proof.

REFERENCES

[1] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, Feb. 2014.
[2] W. Wang, G. Yu, and A. Huang, "Cognitive radio enhanced interference coordination for femtocell networks," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 37–43, Jun. 2013.
[3] A. Damnjanovic *et al.*, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Commun.*, vol. 18, no. 3, pp. 10–21, Jun. 2011.
[4] A. Ghosh *et al.*, "Heterogeneous cellular networks: From theory to practice," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 54–64, Jun. 2012.

[5] N. Zhao, F. R. Yu, and V. C. M. Leung, "Opportunistic communications in interference alignment networks with wireless power transfer," *IEEE Wireless Commun.*, vol. 22, no. 1, pp. 88–95, Feb. 2015.

[6] N. Zhao, F. R. Yu, and V. C. M. Leung, "Wireless energy harvesting in interference alignment networks," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 72–78, Jun. 2015.

[7] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[8] Z. Chang *et al.*, "Energy efficient resource allocation for wireless power transfer enabled collaborative mobile clouds," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3438–3450, Dec. 2016.

[9] S. Akbar, Y. Deng, A. Nallanathan, M. Elkashlan, and A.-H. Aghvami, "Simultaneous wireless information and power transfer in K-tier heterogeneous cellular networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5804–5818, Aug. 2016.

[10] M. Sheng, L. Wang, X. Wang, Y. Zhang, C. Xu, and J. Li, "Energy efficient beamforming in MISO heterogeneous cellular networks with wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 954–968, Apr. 2016.

[11] A. D. Wyner, "The wire-tap channel," *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, 1975.

[12] N. Zhao, F. R. Yu, M. Li, Q. Yan, and V. C. M. Leung, "Physical layer security issues in interference-alignment-based wireless networks," *IEEE Commun. Mag.*, vol. 54, no. 8, pp. 162–168, Aug. 2016.

[13] H.-M. Wang and X.-G. Xia, "Enhancing wireless secrecy via cooperation: Signal design and optimization," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 47–53, Dec. 2015.

[14] L. J. Rodríguez, N. H. Tran, T. Q. Duong, T. Le-Ngoc, M. Elkashlan, and S. Shetty, "Physical layer security in wireless cooperative relay networks: State of the art and beyond," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 32–39, Dec. 2015.

[15] C. Wang, H.-M. Wang, D. W. K. Ng, X.-G. Xia, and C. Liu, "Joint beamforming and power allocation for secrecy in peer-to-peer relay networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3280–3293, Jun. 2015.

[16] C. Wang and H.-M. Wang, "Robust joint beamforming and jamming for secure AF networks: Low-complexity design," *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 2192–2198, May 2015.

[17] N. Zhao, F. R. Yu, M. Li, and V. C. M. Leung, "Anti-eavesdropping schemes for interference alignment (IA)-based wireless networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 8, pp. 5719–5732, Aug. 2016.

[18] N. Zhao, J. Guo, F. Yu, M. Li, and V. C. M. Leung, "Antijamming schemes for interference-alignment-based wireless networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1271–1283, Feb. 2017.

[19] T. Lv, H. Gao, and S. Yang, "Secrecy transmit beamforming for heterogeneous networks," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1154–1170, Jun. 2015.

[20] H.-M. Wang, T.-X. Zheng, J. Yuan, D. Towsley, and M. H. Lee, "Physical layer security in heterogeneous cellular networks," *IEEE Trans. Commun.*, vol. 64, no. 3, pp. 1204–1219, Mar. 2016.

[21] X. Chen, D. W. K. Ng, and H.-H. Chen, "Secrecy wireless information and power transfer: Challenges and opportunities," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 54–61, Apr. 2016.

[22] L. Liu, R. Zhang, and K.-C. Chua, "Secrecy wireless information and power transfer with MISO beamforming," *IEEE Trans. Signal Process.*, vol. 62, no. 7, pp. 1850–1863, Apr. 2014.

[23] H. Xing, L. Liu, and R. Zhang, "Secrecy wireless information and power transfer in fading wiretap channel," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 5402–5407.

[24] D. W. K. Ng, R. Schober, and H. Alnuweiri, "Secure layered transmission in multicast systems with wireless information and power transfer," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 5389–5395.

[25] B. Zhu, J. Ge, Y. Huang, Y. Yang, and M. Lin, "Rank-two beamformed secure multicasting for wireless information and power transfer," *IEEE Signal Process. Lett.*, vol. 21, no. 2, pp. 199–204, Feb. 2014.

[26] Q. Shi, W. Xu, J. Wu, E. Song, and Y. Wang, "Secure beamforming for MIMO broadcasting with wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2841–2853, May 2015.

[27] D. W. K. Ng, E. S. Lo, and R. Schober, "Robust beamforming for secure communication in systems with wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4599–4615, Aug. 2014.

[28] R. Feng, Q. Li, Q. Zhang, and J. Qin, "Robust secure transmission in MISO simultaneous wireless information and power transfer system," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 400–405, Jan. 2015.

[29] M. R. A. Khandaker and K.-K. Wong, "Robust secrecy beamforming with energy-harvesting eavesdroppers," *IEEE Wireless Commun. Lett.*, vol. 4, no. 1, pp. 10–13, Feb. 2015.

[30] W. Wu and B. Wang, "Robust secrecy beamforming for wireless information and power transfer in multiuser MISO communication system," *EURASIP J. Wireless Commun. Netw.*, vol. 2015, no. 1, pp. 1–11, Dec. 2015.

[31] Z. Chu, Z. Zhu, M. Johnston, and S. Y. L. Goff, "Simultaneous wireless information power transfer for MISO secrecy channel," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 6913–6925, Sep. 2016.

[32] Z. Zhu, Z. Chu, Z. Wang, and I. Lee, "Outage constrained robust beamforming for secure broadcasting systems with energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7610–7620, Nov. 2016.

[33] J. Zhang, C. Yuen, C.-K. Wen, S. Jin, K.-K. Wong, and H. Zhu, "Large system secrecy rate analysis for SWIPT MIMO wiretap channels," *IEEE Trans. Inf. Forensics Security*, vol. 11, no. 1, pp. 74–85, Jan. 2016.

[34] Q. Li, Q. Zhang, and J. Qin, "Secure relay beamforming for simultaneous wireless information and power transfer in nonregenerative relay networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2462–2467, Jun. 2014.

[35] D. W. K. Ng, E. S. Lo, and R. Schober, "Multiobjective resource allocation for secure communication in cognitive radio networks with wireless information and power transfer," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3166–3184, May 2016.

[36] J. Xu, L. Liu, and R. Zhang, "Multiuser MISO beamforming for simultaneous wireless information and power transfer," *IEEE Trans. Signal Process.*, vol. 62, no. 18, pp. 4798–4810, Sep. 2014.

[37] K. T. K. Cheung, S. Yang, and L. Hanzo, "Spectral and energy spectral efficiency optimization of joint transmit and receive beamforming based multi-relay MIMO-OFDMA cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6147–6165, Nov. 2014.

[38] M. Grant and S. Boyd. (2010). *CVX: MATLAB Software for Disciplined Convex Programming, Version 1.21 (2011)*. [Online]. Available: http://cvxr.com/cvx/

[39] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[40] A. Beck, A. Ben-Tal, and L. Tetruashvili, "A sequential parametric convex approximation method with applications to nonconvex truss topology design problems," *J. Global Optim.*, vol. 47, no. 1, pp. 29–51, May 2010.

[41] L.-N. Tran, M. F. Hanif, A. Tolli, and M. Juntti, "Fast converging algorithm for weighted sum rate maximization in multicell MISO downlink," *IEEE Signal Process. Lett.*, vol. 19, no. 12, pp. 872–875, Dec. 2012.

[42] G. Zheng, K.-K. Wong, and B. Ottersten, "Robust cognitive beamforming with bounded channel uncertainties," *IEEE Trans. Signal Process.*, vol. 57, no. 12, pp. 4871–4881, Dec. 2009.

[43] Z.-Q. Luo, W.-K. Ma, A. M.-C. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Process. Mag.*, vol. 27, no. 3, pp. 20–34, May 2010.

YUAN REN received the B.E. degree from the Beijing University of Posts and Telecommunications, Beijing, China, in 2010, where he is currently pursuing the Ph.D. degree with the School of Information and Communication Engineering. His current research interests include energy harvesting, physical-layer security, and interference alignment.

TIEJUN LV (M'08–SM'12) received the M.S. and Ph.D. degrees in electronic engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 1997 and 2000, respectively.

From 2001 to 2003, he was a Post-Doctoral Fellow with Tsinghua University, Beijing, China. In 2005, he was a Full Professor with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing. From 2008 to 2009, he was a Visiting Professor with the Department of Electrical Engineering, Stanford University, Stanford, CA, USA. He has authored or co-authored over 200 published technical papers on the physical layer of wireless mobile communications. His current research interests include signal processing, communications theory, and networking.

Dr. Lv is a senior member of the Chinese Electronics Association. He was a recipient of the Program for New Century Excellent Talents in University Award from the Ministry of Education, China, in 2006.

HUI GAO (S'10–M'13–SM'16) received the B.Eng. degree in information engineering and the Ph.D. degree in signal and information processing from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2007 and 2012, respectively.

From 2009 to 2012, he was a Research Assistant with the Wireless and Mobile Communications Technology Research and Development Center, Tsinghua University, Beijing. In 2012, he was also a Research Assistant with the Singapore University of Technology and Design, Singapore, where he was later a Post-Doctoral Researcher from 2012 to 2014. He is currently an Assistant Professor with the School of Information and Communication Engineering, BUPT. His research interests include massive multiple-input–multiple-output systems, cooperative communications, and ultrawideband wireless communications.

YINGXIANG LI received the B.S degree in physical education from Sichuan Normal University, Chengdu, China, in 1995, and the M.S. and Ph.D. degrees in communication and electronic systems from the University of Electronic Science and Technology of China, Chengdu, China, in 2000 and 2003, respectively.

He is currently a Professor with the School of Communication Engineering, Chengdu University of Information Technology, Chengdu. His research interests include weak signal processing, communication signal processing, embedded system design, and artificial intelligence.