Secure Information Transmission and Power Transfer in Cellular Networks

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***Abstract*—This letter studies simultaneous data transmission and power transfer for multiple information receivers (IRs) and energy-harvesting receivers (ERs) in cellular networks. We formulate an optimization problem to minimize the total transmit power across the network subject to the following three sets of constraints: i) *data reliability* by maintaining the required level of signal to interference plus noise ratio (SINR) for all IRs; ii) *information security* by keeping all SINR levels of the intended IRs measured at each ER below a predefined value, which helps prevent possible eavesdroppers, i.e., ERs, from detecting information aimed for the IRs; and iii) *energy harvesting* by guaranteeing the required level of received power at each ER. Using semidefinite relaxation technique, the proposed problem is then transformed into a convex form which is proved to always yield rank-one optimal solution.**

I. Introduction

Recently, simultaneous information and power transfers via radio-frequency (RF) signals have attracted increasing research interests [1]–[4]. The idea is based on the possibility that mobile receivers can directly harvest energy from electromagnetic waves in RF signals. The authors of [2] and [3] considered a scenario that a transmitter sends information to multiple information receivers (IRs) while transferring power to a set of ERs. They then proposed beamforming approaches that maximize the total harvested energy at all ERs [2] or the weighted sum-power transferred to all ERs [3] subject to the signal to interference plus noise ratio (SINR) constraint at each IR and the transmit power constraint at the transmitter. However, the approaches in [2] and [3] do not protect the information sent to any IR from being detected by the ERs, which can potentially be eavesdroppers.

To tackle the security problem, the authors of [1], [4]–[6] simplified the scenario studied in [2] and [3] to only one IR. Khandaker and Wong [1] and Liu *et. al.* [6] proposed schemes to maximize the secrecy rate of the IR subject to individual harvested energy constraints of the ERs and the transmit power constraint. In [5], one more set of constraints is introduced to a similar optimization problem considered in [3] to keep the IR message secured from the detections of ERs by suppressing their SINRs. Liu *et. al.* [6] also introduced another scheme that replaces the SINR constraint set in the optimization problem in [3] by another set of constraints to guarantee the secrecy rate above the required level. Ng *et. al.* [4] tried to minimize the transmit power while satisfying the minimum requirements of IR's SINR and ERs' received power as well as forcing IR's SINR levels at all ERs and passive eavesdroppers below required thresholds. Furthermore, the effect of channel estimation errors has been taken into account in [4] and [5].

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To the best of the authors' knowledge, the works in the area of wireless information and power transfer have so far been considered as single-cell designs where outer-cell interferences are treated as background noise. Adopting the single-cell design in a multi-cell scenario under the frequency reuse of one significantly degrades the performance of the network due to the coupling effect of inter-cell interference [7], [8]. Moreover, none of those existing works protects the information sent to multiple IRs from overhearing by multiple ERs.

This letter is the first attempt to develop a beamforming approach to simultaneously transfer secured information and power to multiple IRs and ERs in a multi-cell network. We propose an optimization problem to design information-beamforming and jamming vectors such that the total transmit power across all base stations (BSs) is minimized. The minimization is subject to: i) maintaining required levels of SINR for all IRs; ii) forcing all SINR levels of the intended IRs measured at each ER below a predefined value; and iii) guaranteeing the required level of received power at each ER. We then transform the proposed problem into a convex form using the semidefinite relaxation (SDR) technique. Furthermore, we analytically prove that the transformed problem always yields rank-one optimal solutions. Therefore, the proposed algorithm does not require any additional randomization procedure which would be computationally expensive in achieving rank-one solutions with a sufficiently practical accuracy, as in a typical SDR approach.

II. System Model

Consider a cellular network with N BSs where each BS sends information to its U local receivers, i.e., IRs. There are D ERs within the network. We assume that each BS has M antennas and each IR or ER has a single antenna. Let $\mathbf{h}^{\mathrm{H}}_{i,q,p} \in \mathbb{C}^{1\times M}$ be the channel between the ith IR of the qth cell and the pth BS, while $\mathbf{g}^{\mathrm{H}}_{t,p} \in \mathbb{C}^{1\times M}$ be the channel between the tth ER and the pth BS. Let $\mathbf{w}_{j,q} \in \mathbb{C}^{M\times 1}$ be the information-beamforming vector for the jth IR of the q cell, $s^{(I)}_{j,q} \sim \mathcal{CN}(0,1)$ represent the data symbol to be sent to the jth IR of the qth cell, $\mathbf{v}_p \in \mathbb{C}^{M\times 1}$ be the jamming vector of the pth BS and $s^{(E)}_p \sim \mathcal{CN}(0,1)$ denote the jamming signal of the pth BS. Hereafter, if otherwise stated, $\{i,j\} \in \{1,\cdots,U\}$, $\{p,q\} \in \{1,\cdots,N\}$ and $t \in \{1,\cdots,D\}$. The overall signal received by the ith IR of the qth cell and the tth ER are

$$y^{(I)}_{i,q} = \sum_{p=1}^{N}\sum_{j=1}^{U} \mathbf{h}^{\mathrm{H}}_{i,q,p}\mathbf{w}_{j,p}s^{(I)}_{j,p} + \sum_{p=1}^{N}\mathbf{v}_p s^{(E)}_p + n^{(I)}_{i,q}, \qquad (1)$$

$$y^{(E)}_{t} = \sum_{p=1}^{N}\sum_{j=1}^{U} \mathbf{g}^{\mathrm{H}}_{t,p}\mathbf{w}_{j,p}s^{(I)}_{j,p} + \sum_{p=1}^{N}\mathbf{v}_p s^{(E)}_p + n^{(E)}_{t}. \qquad (2)$$

$$\Gamma_{i,q}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)=\frac{\mathbf{w}_{i,q}^{\mathrm{H}}\mathbf{H}_{i,q,q}\mathbf{w}_{i,q}}{\sum_{j=1,j\neq i}^{U}\mathbf{w}_{j,q}^{\mathrm{H}}\mathbf{H}_{i,q,q}\mathbf{w}_{j,q}+\sum_{p=1,p\neq q}^{U}\sum_{j=1}^{U}\mathbf{w}_{j,p}^{\mathrm{H}}\mathbf{H}_{i,q,p}\mathbf{w}_{j,p}+\sum_{p=1}^{N}\mathbf{v}_p^{\mathrm{H}}\mathbf{H}_{i,q,p}\mathbf{v}_p+\sigma^2}. \tag{3}$$

$$\Gamma_{i,q}^{(t)}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)=\frac{\mathbf{w}_{i,q}^{\mathrm{H}}\mathbf{G}_{t,q}\mathbf{w}_{i,q}}{\sum_{j=1,j\neq i}^{U}\mathbf{w}_{j,q}^{\mathrm{H}}\mathbf{G}_{t,q}\mathbf{w}_{j,q}+\sum_{p=1,p\neq q}^{U}\sum_{j=1}^{U}\mathbf{w}_{j,p}^{\mathrm{H}}\mathbf{G}_{t,p}\mathbf{w}_{j,p}+\sum_{p=1}^{N}\mathbf{v}_p^{\mathrm{H}}\mathbf{G}_{t,p}\mathbf{v}_p+\sigma^2}. \tag{4}$$

Here, $n_{j,q}^{(I)}$ and $n_t^{(E)}$ are zero mean circularly symmetric complex Gaussian noise with variance σ^2, i.e., $n_{j,q}^{(I)}, n_t^{(E)} \sim \mathcal{CN}(0,\sigma^2)$, at the jth IR of the qth cell and the tth ER, respectively. Let $\mathbf{H}_{j,q,p} = \mathbf{h}_{j,q,p}\mathbf{h}_{j,q,p}^{\mathrm{H}}$ and $\mathbf{G}_{t,p} = \mathbf{g}_{t,p}\mathbf{g}_{t,p}^{\mathrm{H}}$ for the instantaneous channel state information (CSI) or $\mathbf{H}_{j,q,p} = \mathbb{E}\left(\mathbf{h}_{j,q,p}\mathbf{h}_{j,q,p}^{\mathrm{H}}\right)$ and $\mathbf{G}_{t,p} = \mathbb{E}\left(\mathbf{g}_{t,p}\mathbf{g}_{t,p}^{\mathrm{H}}\right)$ for the statistical CSI, $\{\mathbf{w}_{i,q}\} = \{\mathbf{w}_{1,1},\mathbf{w}_{2,1},\cdots,\mathbf{w}_{U,1},\cdots,\mathbf{w}_{1,N},\mathbf{w}_{2,N},\cdots,\mathbf{w}_{U,N}\}$ be the set of candidate information-beamforming vectors for all IRs and $\{\mathbf{v}_t\}=\{\mathbf{v}_1,\mathbf{v}_2,\cdots,\mathbf{v}_N\}$ be the set of candidate energy-beamforming vectors. The SINR at the ith IR of the qth cell, denoted by $\Gamma_{i,q}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)$, is given in (3) at the top of this page. The *leakage SINR* of the ith IR of the qth cell measured at the tth ER, denoted by $\Gamma_{i,q}^{(t)}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)$, is given in (4) at the top of this page.

III. Beamforming Scheme for Secure Information Transmission and Power Transfer

In order to prevent information leakage, the IRs' signals power toward each ER should be reduced. This however contradicts a higher power level required to compensate for low conversion efficiency at the ER. The jamming signal is therefore introduced to achieve both goals, i.e., reducing the leakage SINR levels at ERs while increasing energy levels toward them. We design two sets of beamforming vectors $\{\mathbf{w}_{i,q}\}$ and jamming vectors $\{\mathbf{v}_t\}$ such that the total transmit power of the network is minimized. This is subject to the constraint such that each ith IR of the qth cell obtains the required SINR level of $\gamma_{i,q}$ while each tth ER receives the target power level of P_t. Here we assume that P_t already takes into account the conversion efficiency at the tth ER. To protect the information of all IRs from the potentially eavesdropping ERs, we design to limit the leakage SINR level of any ith IR of the qth cell at any tth ER below a given *secure level* $\gamma_{i,q}^{(t)}$. Hence we proposed the following optimization problem:

$$\begin{aligned}
\min_{\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}} \quad & \sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{w}_{i,q}^{\mathrm{H}}\mathbf{w}_{i,q}+\sum_{p=1}^{N}\mathbf{v}_p^{\mathrm{H}}\mathbf{v}_p,\\
\text{s. t.} \quad & \Gamma_{i,q}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)\geq\gamma_{i,q},\quad\forall i,q\\
& \Gamma_{i,q}^{(t)}\left(\{\mathbf{w}_{i,q}\},\{\mathbf{v}_t\}\right)\leq\gamma_{i,q}^{(t)},\quad\forall i,q,t,\\
& \sum_{p=1}^{N}\left(\sum_{i=1}^{U}\mathbf{w}_{i,p}^{\mathrm{H}}\mathbf{G}_{t,p}\mathbf{w}_{i,p}+\mathbf{v}_p^{\mathrm{H}}\mathbf{G}_{t,p}\mathbf{v}_p\right)\geq P_t,\forall t.
\end{aligned} \tag{5}$$

We proceed by defining beamforming matrix $\mathbf{W}_{i,q}=\mathbf{w}_{i,q}\mathbf{w}_{i,q}^{\mathrm{H}}$ and jamming matrix $\mathbf{V}_t=\mathbf{v}_t\mathbf{v}_t^{\mathrm{H}}$ where $\mathbf{W}_{i,q}\succeq 0$, $\mathbf{V}_t\succeq 0$, $\mathbf{W}_{i,q}$ and $\mathbf{V}_t$ are rank-one matrices[1]. Here, notation $\mathbf{Y}\succeq 0$ indicates that $\mathbf{Y}$ is a positive semi definite matrix. Then, by rearranging the constraints, using $\mathbf{x}^{\mathrm{H}}\mathbf{Y}\mathbf{x}=\mathrm{Tr}\left(\mathbf{Y}\mathbf{x}\mathbf{x}^{\mathrm{H}}\right)$, and relaxing the rank-one conditions on $\mathbf{W}_{i,q}$ and $\mathbf{V}_t$, (5) is converted to the following semidefinite programming (SDP) form:

$$\begin{aligned}
\min_{\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}} \quad & \mathrm{Tr}\left(\sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{W}_{i,q}+\sum_{p=1}^{N}\mathbf{V}_p\right),\\
\text{s. t.} \quad & k_{i,q}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)\geq 0,\ \forall i,q\\
& d_{i,q}^{(t)}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)\geq 0,\ \forall i,q,t\\
& \mathrm{Tr}\left(\sum_{p=1}^{N}\mathbf{G}_{t,p}\left(\sum_{i=1}^{U}\mathbf{W}_{i,p}+\mathbf{V}_p\right)\right)-P_t\geq 0,\forall t\\
& \mathbf{W}_{i,q}\succeq 0,\ \mathbf{V}_t\succeq 0,\ \forall i,q,t
\end{aligned} \tag{6}$$

where $\{\mathbf{W}_{i,q}\}=\{\mathbf{W}_{1,1},\cdots,\mathbf{W}_{U,1},\cdots,\mathbf{W}_{1,N},\cdots,\mathbf{W}_{U,N}\}$ and $\{\mathbf{V}_t\}=\{\mathbf{V}_1,\mathbf{V}_2,\cdots\mathbf{V}_N\}$ are two sets of beamforming matrices,

$$\begin{aligned}
k_{i,q}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)=&\left(1+\frac{1}{\gamma_{i,q}}\right)\mathrm{Tr}\left(\mathbf{H}_{i,q,q}\mathbf{W}_{i,q}\right)\\
&-\sum_{j=1}^{U}\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{H}_{i,q,p}\mathbf{W}_{j,p}\right)-\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{H}_{i,q,p}\mathbf{V}_p\right)-\sigma^2,
\end{aligned} \tag{7}$$

$$\begin{aligned}
d_{i,q}^{(t)}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)=&-\left(1+\frac{1}{\gamma_{i,q}^{(t)}}\right)\mathrm{Tr}\left(\mathbf{G}_{t,q}\mathbf{W}_{i,q}\right)\\
&+\sum_{j=1}^{U}\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{G}_{t,p}\mathbf{W}_{j,p}\right)+\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{G}_{t,p}\mathbf{V}_p\right)+\sigma^2.
\end{aligned} \tag{8}$$

The optimization problem in (6) can be solved by the SeDuMi solver, provided by CVX optimization package [9], to obtain the sets of optimal beamforming matrices $\mathbf{W}_{i,q}^{\star}$ and $\mathbf{V}_t^{\star}$. In the sequel, we show that (5) and (6) are in fact equivalent. To show this we need the following proposition.

Proposition: If an $M\times M$ Hermitian matrix $\mathbf{W}_{i,q}$ has a rank of $K\leq M$, then it can be expressed as $\mathbf{W}_{i,q}=\sum_{j=1}^{K}\epsilon_{i,q,k}\mathbf{a}_{i,q,k}\mathbf{a}_{i,q,k}^{\mathrm{H}}$, where $\epsilon_{i,q,k}$ and $\mathbf{a}_{i,q,k}$ are the kth eigenvalue and the corresponding eigenvector of $\mathbf{W}_{i,q}$, respectively[2].

In the following theorem we prove that the optimal solutions to problem (6) are rank one. Therefore, relaxing the rank-one conditions does not affect the optimality of the transformation.

[1] A matrix is rank one if its largest number of linearly independent columns/rows is one.

[2] This can be simply shown using the facts that the Hermitian matrix $\mathbf{W}_{i,q}$ has K real eigenvalues and K orthogonal eigenvectors.

Theorem: If there are optimal solutions to (6), i.e., $\{\mathbf{W}_{i,q}^\star\}$ and $\{\mathbf{V}_t^\star\}$, then they always have rank one.

Proof: Problem (6) is convex. Hence, the optimal solution to (6) can be obtained through its corresponding dual problem with zero duality gap. The Lagrangian of (6) is:

$$L\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\},\overrightarrow{\alpha},\overrightarrow{\beta},\overrightarrow{\mu},\{\mathbf{Y}_{i,q}\},\{\mathbf{Z}_t\}\right)=\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{V}_p\right)$$
$$\sum_{q=1}^{N}\sum_{i=1}^{U}\mathrm{Tr}\left(\mathbf{W}_{i,q}\right)-\sum_{q=1}^{N}\sum_{i=1}^{U}\alpha_{i,q}k_{i,q}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)$$
$$-\sum_{t=1}^{D}\sum_{q=1}^{N}\sum_{i=1}^{U}\beta_{i,q}^{(t)}d_{i,q}^{(t)}\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}\right)$$
$$-\sum_{t=1}^{D}\mu_t\left(\sum_{p=1}^{N}\sum_{i=1}^{U}\mathrm{Tr}\left(\mathbf{G}_{t,p}\mathbf{W}_{i,p}\right)+\sum_{p=1}^{N}\mathrm{Tr}\left(\mathbf{G}_{t,p}\mathbf{V}_p\right)-P_t\right)$$
$$-\sum_{q=1}^{N}\sum_{i=1}^{U}\mathrm{Tr}\left(\mathbf{W}_{i,q}\mathbf{Y}_{i,q}\right)-\sum_{t=1}^{D}\mathrm{Tr}\left(\mathbf{V}_t\mathbf{Z}_t\right) \quad (9)$$

where $\alpha_{i,q}$, $\beta_{i,q}^{(t)}$, μ_t, $\mathbf{Y}_{i,q}$ and $\mathbf{Z}_t$ are Lagrangian multipliers associated with (6), $\overrightarrow{\alpha}=\left[\alpha_{1,1},\cdots,\alpha_{U,1},\cdots,\alpha_{1,N}\cdots,\alpha_{U,N}\right]^T$, $\overrightarrow{\beta}=\left[\beta_{1,1}^{(1)},\cdots,\beta_{U,1}^{(1)},\cdots\beta_{1,N}^{(N)},\cdots,\beta_{U,N}^{(N)}\right]^T$, $\overrightarrow{\mu}=\left[\mu_1,\cdots,\mu_N\right]^T$, $\{\mathbf{Y}_{i,q}\}=\{\mathbf{Y}_{1,1},\cdots,\mathbf{Y}_{U,1},\cdots,\mathbf{Y}_{1,N},\cdots,\mathbf{Y}_{U,N}\}$ and $\{\mathbf{Z}_t\}=\{\mathbf{Z}_1,\cdots,\mathbf{Z}_N\}$. Hence, the dual function is $g\left(\overrightarrow{\alpha},\overrightarrow{\beta},\overrightarrow{\mu},\{\mathbf{Y}_{i,q}\},\{\mathbf{Z}_t\}\right)=\min_{\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}}L\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\},\overrightarrow{\alpha},\overrightarrow{\beta},\overrightarrow{\mu},\{\mathbf{Y}_{i,q}\},\{\mathbf{Z}_t\}\right)$ and the corresponding dual problem is as follows

$$\begin{aligned}&\max_{\overrightarrow{\alpha},\overrightarrow{\beta},\overrightarrow{\mu},\{\mathbf{Y}_{i,q}\},\{\mathbf{Z}_t\}} && g\left(\overrightarrow{\alpha},\overrightarrow{\beta},\overrightarrow{\mu},\{\mathbf{Y}_{i,q}\},\{\mathbf{Z}_t\}\right),\\ &\text{s. t.} && \overrightarrow{\alpha}\succcurlyeq 0,\ \overrightarrow{\beta}\succcurlyeq 0,\ \overrightarrow{\mu}\succcurlyeq 0,\\ &&& \mathbf{Y}_{i,q}\succeq 0,\mathbf{Z}_t\succeq 0,\ \forall i,q,t,\end{aligned} \quad (10)$$

where the notation $\mathbf{a}\succcurlyeq 0$ is used to indicate that all elements of vector $\mathbf{a}$ are non-negative. Let $\overrightarrow{\alpha^\star},\overrightarrow{\beta^\star},\overrightarrow{\mu^\star},\{\mathbf{Y}_{i,q}^\star\},\{\mathbf{Z}_t^\star\}$ be the optimal solutions to the dual problem (10). The corresponding optimal solution $\left(\{\mathbf{W}_{i,q}^\star\},\{\mathbf{V}_t^\star\}\right)$ to problem (6) can be obtained through

$$\min_{\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\}}L\left(\{\mathbf{W}_{i,q}\},\{\mathbf{V}_t\},\overrightarrow{\alpha^\star},\overrightarrow{\beta^\star},\overrightarrow{\mu^\star},\{\mathbf{Y}_{i,q}^\star\},\{\mathbf{Z}_t^\star\}\right)$$
$$=\min_{\{\mathbf{W}_{i,q}\}}\mathrm{Tr}\sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{A}_{i,q}\mathbf{W}_{i,q}+\min_{\{\mathbf{V}_t\}}\mathrm{Tr}\sum_{t=1}^{N}\mathbf{B}_t\mathbf{V}_t \quad (11)$$

where $\mathbf{A}_{i,q}=\mathbf{I}-\alpha_{i,q}^\star\left(1+\frac{1}{\gamma_{i,q}}\right)\mathbf{H}_{i,q,q}+\sum_{p=1}^{N}\mathbf{H}_{i,p,q}\sum_{j=1}^{U}\alpha_{j,p}^\star+\mathbf{H}_{i,q,q}\sum_{t=1}^{D}\beta_{i,q}^{(t)\star}\left(1+\frac{1}{\gamma_{i,q}^{(t)}}\right)-\sum_{p=1}^{N}\sum_{j=1}^{U}\sum_{t=1}^{D}\beta_{j,p}^{(t)\star}\mathbf{G}_{t,q}-\sum_{t=1}^{D}\mu_t^\star\mathbf{G}_{t,q}-\mathbf{Y}_{i,q}^\star$ and $\mathbf{B}_t=\mathbf{I}+\sum_{q=1}^{N}\sum_{i=1}^{U}\alpha_{i,q}^\star\mathbf{H}_{i,q,p}-\sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{H}_{i,q,p}\sum_{t=1}^{D}\beta_{i,q}^{(t)\star}-\sum_{t=1}^{D}\mu_t^\star\mathbf{G}_{t,q}-\mathbf{Z}_p^\star$. Here $\mathbf{I}$ represents an identity matrix of suitable dimensions.

In obtaining the right hand side of (11), we substitute (7) and (8) into (9) followed by some mathematical manipulations. We also note that $\mathbf{A}_{i,q}$ and $\mathbf{B}_t$ must be positive semi-definite, i.e., $\mathbf{A}_{i,q}\succeq 0$ and $\mathbf{B}_t\succeq 0$, for all i,q,t, to bound the Lagrangian dual below on $\mathbf{W}_{i,q}$ and $\mathbf{V}_t$, i.e., avoiding the Lagrangian dual function goes to -∞. Here, we assume that $\mathbf{W}_{i,q}^\star$, with rank $K>1$, $\forall i,q$ is the optimal solution to (6). Adopting the aforementioned Proposition, $\mathbf{W}_{i,q}^\star=\sum_{k=1}^{K}\epsilon_{i,q,k}\mathbf{a}_{i,q,k}\mathbf{a}_{i,q,k}^{\mathrm{H}}$. Hence, one can find $\overline{\mathbf{W}}_{i,q}^\star=\epsilon_{i,q,p}\mathbf{a}_{iq,p}\mathbf{a}_{iq,p}^{\mathrm{H}}$, where $p=\arg\min_{k\in\{1,\cdots,K\}}\left(\epsilon_{i,q,k}\mathbf{a}_{iq,k}^{\mathrm{H}}\mathbf{A}_{i,q}\mathbf{a}_{i,q,k}\right)$. This leads to the conclusion that $\mathrm{Tr}\sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{A}_{i,q}\overline{\mathbf{W}}_{i,q}^\star<\mathrm{Tr}\sum_{q=1}^{N}\sum_{i=1}^{U}\mathbf{A}_{i,q}\mathbf{W}_{i,q}^\star$ which is in contradiction to the optimality assumption of $\mathbf{W}_{i,q}^\star$. Therefore, $\mathbf{W}_{i,q}^\star$ must be rank-one for all i,q. Following similar arguments, one can show that $\mathbf{V}_t^\star$ must be rank-one for all t. ■

IV. Simulation Results

A. Simulation setup

We adopt the far-field electromagnetic radiation [10] in the form of beamforming for cellular networks. Each BS is equipped with six antennas, i.e., $M=6$. The (u,v)th entry of the 6×6 channel matrice $\mathbf{H}_{j,q,p}$ or $\mathbf{G}_{t,p}$ is obtained using [11]:

$$Kl^{-3.5}e^{-0.5\frac{(\sigma_s\ln 10)^2}{100}}e^{\frac{j2\pi\Delta}{\lambda}[(v-u)\sin\phi]}e^{-2\left[\frac{\pi\Delta\sigma_a}{\lambda}\{(v-u)\cos\phi\}\right]^2}, \quad (12)$$

where $K=10^{-3.45}$ is the path-loss constant factor, $l\geq 35$m is the distance, σ_s represents the standard deviation of the log-normal shadow fading coefficient in dB, i.e., $10^{-\frac{x}{10}}$, $x\sim\mathcal{N}(0,\sigma_s^2)$, Δ is the antenna spacing at the BS, λ is the carrier wavelength, σ_a is the angular spread and ϕ is the angle of departure. In (12), we set $\Delta=\lambda/2$, $\sigma_a=2°$, and $\sigma_s=8$. The noise power, noise figure at each IR or ER, and the transmit antenna gain are assumed to be -132dBm, 5dB, and 15dBi, respectively. The cell radius is 1.5km.

B. Comparison with a coordinate beamforming scheme

We first investigate the performance of our proposed approach and compare it against a coordinate beamforming (CBF) scheme [7] in which the objective is to minimize the total transmit power across the BSs subject to maintaining a certain level of SINR for each IR. Similar to [7], we consider a two-cell configuration where each cell supports two IRs. There are two ERs in the cell border area. Monte-Carlo simulations are carried out over user distributions where four IRs and two ERs are randomly located in one user distribution.

Figure 1 (a) indicates that the proposed approach guarantees the minimum required received power for all ERs. On the other hand, the received power levels at all ERs of the CBF method are significantly lower than that of our approach for most of the observed cases. Fig. 1 (a) also reveals that the proposed approach provides a higher received power level at ERs with a higher secure level. This result can be explained as follows. At a higher secure level, BSs need to increase their jamming levels, i.e., Tr$(\mathbf{V}_p)$ $\forall p$, in order to further reduce the leakage SINRs of all IRs at every ER. This, in turn, raises the power levels at ERs. It can be seen from Fig. 1 (b) that the

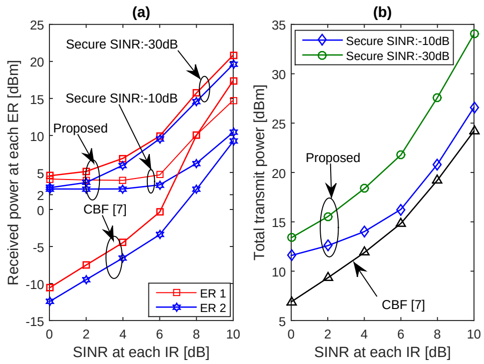

Fig. 1. Performance comparison of the proposed approach, with different secure levels and the minimum required power level at each ER of 2dBm, against the coordinated beamforming (CBF) method [7]. (a): Total received power at each ER *vs.* various SINR levels at each IR. (b): The total transmit power of all BSs *vs.* various SINR levels at each IR.

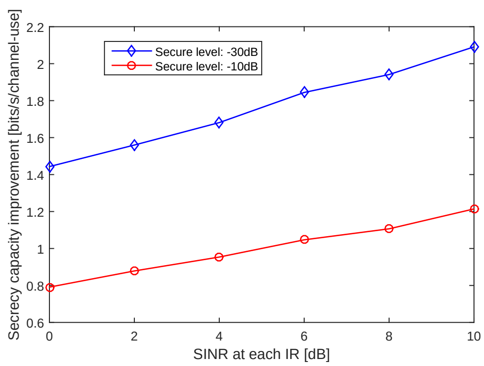

Fig. 2. Total achievable IRs' secrecy capacity improvement of our approach compared with the CBF method [7] *vs.* various SINR levels at each IR. The proposed approach is tested with the minimum required power level at each ER of 2dBm and the secure levels of -10dB and -30dB.

proposed approach consumes higher transmit power than the CBF scheme due to its energy-transfer and secure tasks.

We proceed by observing the security performances of the proposed approach and the CBF scheme. The achievable secrecy rate of ith user of qth cell is defined as $r_{i,q} = \min_t \left(\log_2(1+\Gamma_{i,q}) - \log_2(1+\Gamma^{(t)}_{i,q})\right)$ [6]. The total achievable secrecy capacity is then calculated as $R = \sum_{i,q} r_{i,q}$. Fig. 2 shows the total achievable secrecy capacity improvement of our approach compared with the CBF method, i.e. $R_{\text{Prop.}} - R_{\text{CBF}}$ where $R_{\text{Prop.}}$ and R_{CBF} are the total achievable IRs' secrecy rate of the proposed and CBF schemes, respectively. It is clear that the proposed approach offers higher achievable IRs' secrecy capacity than the CBF. Furthermore, the stricter the secure level is, the higher level of the improvement. For instance, at the IR's SINR of 10dB, the improvements are 1.21bits/s/channel-use and 2.09bits/s/channel-use when the secure levels are at -10dB and -30dB, respectively.

C. Comparison with other energy harvesting scheme

Finally, we compare the performance of the proposed approach against an energy harvesting scheme introduced in [4]. Since, the method [4] only supports single IR, we randomly locate one IR and two ERs for each BS in one user distribution

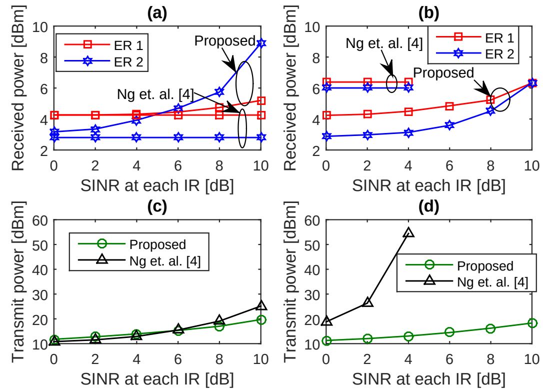

Fig. 3. Performance comparison of the proposed approach against the method introduced in [4], i.e., shown as Ng et. al., in (a) and (c): single-cell setup, (b) and (d): two-cell setup. The minimum required power level at each ER is 2dBm and the secure SINR level is -30dB.

in this experiment. Monte-Carlo simulations are carried out over user distributions. Fig. 3 (a) and (c) show the comparison for a single-cell setup. In such setup, the two schemes consume comparable amount of power, however the proposed scheme provide higher power for ERs in the IRs' SINR range from 8 to 10dB. Figs. 3 (b) and (d) illustrate the results for a two-cell setup. In this setup, method [4], designed for single-cell transmission, requires significantly higher transmit power than the proposed approach to cope with inter-cell interference. As a result, the former provides higher power levels for ERs than the latter in the IRs' SINR range from 0dB to 4dB. However, beyond 4dB, method [4] fails to operate while the proposed approach still works efficiently. The result shown in Fig. 3 indicates the efficiently-working capability of the proposed approach in multi-cell environments.

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