Improved Rate-Energy Tradeoff for Energy Harvesting Interference Alignment Networks

Rishabh Gupta, Ajit K. Chaturvedi, *Senior Member, IEEE*, and Rohit Budhiraja

***Abstract*—Energy harvesting (EH) from RF signals is being investigated to ensure the perpetual operation of energy-constrained wireless devices. Interference alignment (IA) achieves maximum degrees of freedom (DoF) in a K-user interference channel. In this letter, we propose a novel transceiver to improve rate-energy tradeoff for EH in IA networks, the design of which is a non-convex problem. The proposed transceiver, designed using an iterative algorithm and semidefinite relaxation approach, relaxes the perfect IA condition to improve the rate-energy trade-off. We also analyze the performance of the proposed transceiver for different antennas configurations and show the existence of a diversity-energy tradeoff for the large EH constraint when there are excess antennas. In this antenna regime, this letter shows that the potential diversity gains can be sacrificed to allow the additional DoF provided by excess antennas to be utilized for EH (to satisfy the large EH constraint) without compromising IA.**

***Index Terms*—Energy harvesting, interference alignment.**

I. Introduction

Most of the existing works on wireless networks assume availability of unlimited energy at the receivers. However, practical wireless receivers have pre-installed batteries with limited energy storage capability. Energy Harvesting (EH) from RF signals is an emerging technique to enable perpetual communications in energy-constrained wireless networks [1].

Interference is a major barrier for successful communications in wireless networks. Interference Alignment (IA) is a cooperative interference management technique that achieves maximum degrees of freedom (DoF) in a K-user interference channel [2]–[4]. IA uses multiple signaling dimensions to align multiple interfering signals in a reduced dimensional subspace at each receiver. The receivers can then decode their desired signals by zero forcing the aligned interference, which is good for sum-rate but also a great waste of energy [5]. In an energy constrained network, this aligned interference could be used for harvesting energy [5]. Therefore, IA and energy harvesting can complement each other if implemented in conjunction.

There are some existing studies on energy harvesting in IA networks [5]–[7]. References [5] and [6] assume IA precoders and decoders as fixed, and focus on the receiver design. Reference [7] studies optimal transceiver design problem for simultaneous wireless information and power transfer in a K-user MIMO interference channel (IFC) to minimize the total transmit power. In the current work, we address the following question - how to achieve the best rate-energy (R-E) trade off in a MIMO IA network? To simplify this problem, which requires joint optimization of transceiver and power splitting/ time switching variables, we assume "ideal" receivers that can simultaneously harvest energy and decode information [1].

Since optimal transmit strategies for wireless information transfer and wireless power transfer are different [1], the IA strategy, which achieves the maximum DoF, may not achieve the best R-E trade in a MIMO IFC. To achieve this objective, sum-rate of an IFC should be maximized subject to a given EH constraint. Since sum-rate maximization in MIMO IFCs is analytically intractable [8], we use leakage minimization, similar to [3] and [4], as a surrogate objective to maximize the EH-constrained sum-rate. The problem is still non-convex and we use semidefinite relaxation (SDR) and alternating minimization to design precoders and decoders for EH-constrained IA. We will show that the proposed transceiver varies its transmit strategy to yield improved R-E trade off. We also analyze the performance of the proposed algorithm in three different antennas regimes and show that with excess antennas, the system can satisfy even large EH constraint (i.e., the total harvested energy is high) without compromising IA. To explain this result, we show the existence of a diversity-energy trade off wherein the additional DoF provided by excess antennas are used to satisfy the large EH constraint instead of realizing receive diversity gains in an IA system.

The main contributions of this letter are: 1) we design an iterative transceiver with improved R-E trade off for EH-constrained IA network; 2) we show that additional antennas in an IA network, which conventionally are used for receive diversity, can also be used for satisfying the EH constraint without violating the IA condition; and 3) we demonstrate a diversity-energy trade off for the large EH constraint.

II. System Model

We consider downlink MIMO IFC with $K > 2$ users where each of the K transmitter transmits data to its intended receiver on a common channel. We assume that each transmitter and receiver is equipped with N_t and N_r antennas, respectively. Each user transmits single information stream – transmit signal of the kth transmitter is $\mathbf{x}_k = \mathbf{v}_k s_k$, where $\mathbf{v}_k$ is the normalized transmit precoder such that $\mathrm{Tr}(\mathbf{v}_k \mathbf{v}_k^H) = P_t$ and $s_k \sim \mathcal{CN}(0, 1)$. The signal received by the kth receiver is

Manuscript received February 16, 2017; revised April 3, 2017; accepted April 23, 2017. Date of publication April 27, 2017; date of current version June 19, 2017. The associate editor coordinating the review of this paper and approving it for publication was S. Zhou. *(Corresponding author: Rohit Budhiraja.)*

R. Gupta was with the Department of Electrical Engineering, IIT Kanpur, Kanpur 208016, India. He is now with the Samsung Research and Development Institute, Bengaluru 560037, India (e-mail: rishabh.gupta1694@gmail.com).

A. K. Chaturvedi is with the Department of Electrical Engineering, IIT Kanpur, Kanpur 208016, India, and also with the Department of Electronics and Communication Engineering, IIT Roorkee, Roorkee 247667, India (e-mail: akc@iitk.ac.in).

R. Budhiraja is with the Department of Electrical Engineering, IIT Kanpur, Kanpur 208016, India (e-mail: rohitbr@iitk.ac.in).

Digital Object Identifier 10.1109/LWC.2017.2698462

$\mathbf{y}_k = \mathbf{H}_{kk}\mathbf{x}_k + \sum_{i\neq k}\mathbf{H}_{ki}\mathbf{x}_i + \mathbf{w}_k$, where $\mathbf{H}_{ki} \in \mathbb{C}^{N_r\times N_t}$ is the channel matrix between the kth receiver and the ith transmitter. The vector $\mathbf{w}_k \in \mathbb{C}^{N_r\times 1}$ denotes additive white Gaussian noise with $\mathbb{E}(\mathbf{w}_k\mathbf{w}_k^H) = \sigma^2\mathbf{I}_{N_r}$. We assume that perfect CSI is available at all the nodes and all receivers are ideal. We note that obtaining CSI requires spectral resources and the CSI accuracy needs to be carefully decided. It is, however, still important to characterize the performance with the assumption that network channel information is available at all the nodes. Insight from such a study is valuable for practical scenarios where only coarse or partial CSI can be obtained in practice. The kth receiver uses vector $\mathbf{u}_k$ to detect data as $\mathbf{u}_k^H\mathbf{y}_k = \mathbf{u}_k^H\mathbf{H}_{kk}\mathbf{v}_k s_k + \sum_{i\neq k}\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{v}_i s_i + \mathbf{u}_k^H\mathbf{w}_k$. In this letter, we minimize the interference leakage at the receivers and relax the assumption that the interference has to be necessarily aligned. The sum-rate of the network consequently is [3] $R_{sum} = \sum_{k=1}^{K}\log(1 + \frac{|\mathbf{u}_k^H\mathbf{H}_{kk}\mathbf{v}_k|^2}{L_k+\sigma^2})$. The term L_k denotes the leaked interference at the kth receiver and is given as $L_k = \mathbb{E}[|\mathbf{u}_k^H\sum_{i\neq k}\mathbf{H}_{ki}\mathbf{v}_i s_i|^2] = \sum_{i\neq k}|\mathbf{u}_k^H\mathbf{H}_{ki}\ \mathbf{v}_i|^2$. The "ideal" kth receiver also simultaneously harvests which, assuming perfect energy conversion efficiency, is $Q_k = \mathbb{E}[\|\mathbf{y}_k\|^2] = \mathrm{Tr}(E[\mathbf{y}_k\mathbf{y}_k^H]) = \mathrm{Tr}(\sum_{i=1}^{K}\mathbf{H}_{ki}\mathbf{v}_i\mathbf{v}_i^H\mathbf{H}_{ki}^H)$. We note that the perfect conversion efficiency provides an upper-bound on the harvested energy. To assess the effect of imperfect conversion efficiency, total energy harvested, as in [1] and [7], can be scaled by a constant.

III. Problem Formulation and Proposed Algorithm

The objective is to maximize the sum-rate of the network subject to the sum EH constraint which needs to be satisfied at the receivers. The sum-rate maximization for MIMO IFC is a difficult problem to solve and is still open. We therefore, similar to [3] and [4], maximize the sum-rate by minimizing the total leaked interference $\sum_{k=1}^{K}L_k = \sum_{k=1}^{K}\sum_{i\neq k}|\mathbf{u}_k^H\ \mathbf{H}_{ki}\mathbf{v}_i|^2$ as

$$\begin{aligned}\mathbf{P}_1:\ \underset{\mathbf{v}_i,\mathbf{u}_k}{\text{Minimize}}\ & \sum_{k=1}^{K}\sum_{i\neq k}\left|\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{v}_i\right|^2\\ \text{subject to}\ & \sum_{k=1}^{K}\sum_{i=1}^{K}\mathrm{Tr}\left(\mathbf{H}_{ki}\mathbf{v}_i\mathbf{v}_i^H\mathbf{H}_{ki}^H\right) \geq P_{EH}\\ & \mathbf{v}_i^H\mathbf{v}_i = P_t\ \forall i,\quad \text{and}\quad \mathbf{u}_k^H\mathbf{u}_k = 1\ \forall k \qquad (1)\end{aligned}$$

The first constraint ensures that the total harvested energy is above a specified value P_{EH}. Problem $\mathbf{P}_1$ is non-convex due to interdependence of the objective function on variable vectors $\mathbf{v}_i$ and $\mathbf{u}_k$. We therefore alternately optimize vectors $\mathbf{v}_i$ and $\mathbf{u}_k$.

A. Alternating Minimization

We first fix $\mathbf{u}_k$ vectors and optimize $\mathbf{v}_i$ vectors. The problem $\mathbf{P}_1$ then reduces to

$$\begin{aligned}\mathbf{P}_2:\ \underset{\mathbf{v}_i}{\text{Minimize}}\ & \sum_{k=1}^{K}\sum_{i\neq k}\left|\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{v}_i\right|^2\\ \text{subject to}\ & \sum_{k=1}^{K}\sum_{i=1}^{K}\mathrm{Tr}\left(\mathbf{H}_{ki}\mathbf{v}_i\mathbf{v}_i^H\mathbf{H}_{ki}^H\right) \geq P_{EH}\\ & \mathbf{v}_i^H\mathbf{v}_i = P_t\ \forall i \qquad (2)\end{aligned}$$

Algorithm 1 Improved Rate-Energy Trade Off IA Transceiver

1: Choose $\mathbf{u}_k\forall\ k$ randomly such that $\mathbf{u}_k^H\mathbf{u}_k = 1$.
2: With fixed $\mathbf{u}_k$, solve $\mathbf{P}_3$ to calculate optimal $\mathbf{S}_i^*\ \forall\ i$. Calculate optimal $\mathbf{v}_i^*$ by SVD of $\mathbf{S}_i^*$ and by picking the first singular vector.
3: Using $\mathbf{v}_i$ vectors obtained in the above step, the receive vectors $\mathbf{u}_k$'s $\forall\ k$ are updated, using (6), as $\mathbf{u}_k^* = \nu_{min}(\mathbf{C}_k)$ where $\mathbf{C}_k = \sum_{i\neq k}\mathbf{H}_{ki}\mathbf{s}_i\mathbf{s}_i^H\mathbf{H}_{ki}^H$.
4: Iterate until convergence.

The EH expression $\mathrm{Tr}(\mathbf{H}_{ki}\mathbf{v}_i\mathbf{v}_i^H\mathbf{H}_{ki}^H)$, by using circular property of the trace operator $\mathrm{Tr}(\mathbf{AB}) = \mathrm{Tr}(\mathbf{BA})$ can be expressed as $\mathrm{Tr}(\mathbf{v}_i^H\mathbf{H}_{ki}^H\mathbf{H}_{ki}\mathbf{v}_i)$. The EH expression is therefore a convex quadratic function of $\mathbf{v}_i$ as $\mathbf{H}_{ki}^H\mathbf{H}_{ki}$ is a positive semidefinite matrix. The EH constraint is non-convex as it is bounded from below. The optimization problem $\mathbf{P}_2$ is therefore non-convex.

B. Semidefinite Relaxation

We use semidefinite relaxation to cast the above non-convex optimization as a convex semidefinite program (SDP). Let $\mathbf{S}_i = \mathbf{v}_i\mathbf{v}_i^H$. Then the problem $\mathbf{P}_2$ can be equivalently cast as

$$\begin{aligned}\underset{\mathbf{S}_i\succeq\mathbf{0}}{\text{Minimize}}\ & \sum_{k=1}^{K}\sum_{i\neq k}\mathrm{Tr}\left(\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{S}_i\mathbf{H}_{ki}^H\mathbf{u}_k\right)\\ \text{subject to}\ & \sum_{k=1}^{K}\sum_{i=1}^{K}\mathrm{Tr}(\mathbf{H}_{ki}\mathbf{S}_i\mathbf{H}_{ki}^H) \geq P_{EH}\\ & \mathrm{Tr}(\mathbf{S}_i) = P_t,\ \ \mathrm{rank}(\mathbf{S}_i) = 1\ \forall i \qquad (3)\end{aligned}$$

We drop the non-convex rank-one constraint to cast (3) as the following SDP.

$$\begin{aligned}\mathbf{P}_3:\ \underset{\mathbf{S}_i\succeq\mathbf{0}}{\text{Minimize}}\ & \sum_{k=1}^{K}\sum_{i\neq k}\mathrm{Tr}\left(\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{S}_i\mathbf{H}_{ki}^H\mathbf{u}_k\right)\\ \text{subject to}\ & \sum_{k=1}^{K}\sum_{i=1}^{K}\mathrm{Tr}(\mathbf{H}_{ki}\mathbf{S}_i\mathbf{H}_{ki}^H) \geq P_{EH}\\ & \mathrm{Tr}(\mathbf{S}_i) = P_t\ \forall i \qquad (4)\end{aligned}$$

The above relaxation is in fact tight and optimal $\mathbf{S}_i^*$ is rank-one. This can be proved by forming Lagrangian dual of (4), by using Cholesky Decomposition, and by showing the fact, as in [7], that *any optimal* $\mathbf{S}_i^*$ *with rank* > 1 *will only increase the dual objective when compared with a rank-1 solution.*

For fixed $\mathbf{v}_i$ vectors, the optimization problem $\mathbf{P}_1$ in (1) is

$$\begin{aligned}\underset{\mathbf{u}_k}{\text{Minimize}}\ & \sum_{k=1}^{K}\sum_{i\neq k}\left|\mathbf{u}_k^H\mathbf{H}_{ki}\mathbf{v}_i\right|^2\\ \text{subject to}\ & \mathbf{u}_k^H\mathbf{u}_k = 1\quad \forall k \qquad (5)\end{aligned}$$

The optimal $\mathbf{u}_k\forall k$ are given by the eigenvector corresponding to the smallest eigenvalue of the interference covariance matrix $\mathbf{C}_k = \sum_{i\neq k}\mathbf{H}_{ki}\mathbf{v}_i\mathbf{v}_i^H\mathbf{H}_{ki}^H$ [3], i.e.,

$$\mathbf{u}_k^* = \nu_{min}(\mathbf{C}_k). \qquad (6)$$

We then iterate until convergence between the designs of $\mathbf{v}_i$ and $\mathbf{u}_k$ as stated in Algorithm 1.

Remark 1 (Algorithm Convergence): Since the same global objective is minimized in Step-2 and Step-3 of the algorithm, its value can never increase during an iteration. Moreover, the objective is a non-negative function, the algorithm is bound to converge to a solution. The solution can either be locally or globally optimal depending on the initial vector.

Further, for a given channel, fairly large number of IA solutions exist, which yield same leakage power but significantly different sum-rates [3], [4]. We therefore run this algorithm for large number of random initializations and choose the solution with the maximum sum-rate [4].

Remark 2 For multi-stream transmission, the precoders and decoders will be matrices. It is not clear whether their optimization can be cast as a SDP, as in the current work. Investigation of precoder and decoder design for multi-stream transmission can be taken up as future work.

IV. Three Regimes

The feasibility of IA is closely related to its properness, i.e., the number of variables should be $\geq$ than the number of equations and it is shown in [2] that IA conditions are proper if

$$N_t + N_r \geq (K+1)d. \qquad (7)$$

For single-stream IA systems with $d = 1$, reference [9] shows that (7) is necessary and sufficient for feasibility. Since we consider only $d = 1$, we use (7) to check the feasibility of IA for a given system configuration. When system has additional antennas than required by (7), the spatial DoF provided by additional antennas can be used to achieve receive diversity gains simultaneously with IA. For this scenario, the feasibility conditions are more strict [7], [10] and are given as

$$d(N_t - d) + d^{'}\left(N_r - d^{'}\right) \geq dd^{'}(K-1), \qquad (8)$$

where d and $d^{'}$ are the number of columns of precoders and decoders, respectively. We will compare R-E performance of the proposed algorithm in three different regimes.

1)Regime I: IA is not feasible, i.e., Eq. (7) is not satisfied.

2)Regime II: IA is feasible but receive diversity cannot be realized, i.e., Eq. (7) is satisfied but (8) is not.

3)Regime III: Receive diversity can be realized simultaneously with IA, i.e., both (7) and (8) are satisfied. We will show in this regime the diversity-energy trade off for the large EH constraint (i.e., the large P_{EH} value in (1)).

V. Simulation Results

For this study, we assume that the entries of the channel matrices are independent and identically distributed with circularly symmetric complex Gaussian distribution with unity variance. We also set $P_t/\sigma^2 = 20$ dB.

A. Improved Rate-Energy Trade Off

We consider a 4-user MIMO IFC and compare in Fig. 1 the R-E trade off of proposed design with three baseline schemes.

i) *IA with Time Switching (TS)* (referred to as IA-TS) where receiver periodically switches between information detection (ID) and EH. For IA-TS, the bottom corner point in Fig. 1 is obtained when receiver performs EH all the time. Similarly top corner point in Fig. 1 is obtained when receiver performs ID all the time. The intermediate points are obtained by varying between 0 and 1, the fraction of time allocated for ID and EH.

ii) *IA with EH* (referred to as IA-EH). This scheme designs precoder and decoder to minimize leakage as in Algorithm 1 without considering the EH constraint, which is the algorithm proposed in [4]. As we assume ideal receivers, this scheme simultaneously harvests energy while performing ID. Recall that the proposed transceiver with ideal receivers, in contrast, incorporates the EH constraint while minimizing leakage.

iii) *IA with Antenna Selection [11]* (referred to as IA-AS). This scheme optimally partitions antennas into two groups – one for ID with IA and other for EH – to maximize linear combination of IA rate and the harvested energy.

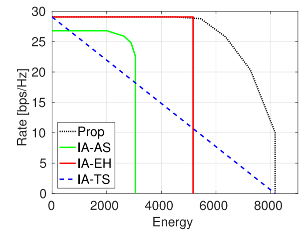


Fig. 1. Rate-Energy trade off for a 4-user MIMO IFC with $(N_t, N_r, d) = (3, 3, 1)$.

We see that for EH $<$ 5100, the IA-EH scheme outperforms the IA-TS scheme as it can satisfy the EH constraint while performing IA. In the IA-TS scheme, in contrast, due to time switching, separate time is allocated to harvest energy which reduces its sum-rate. For large EH constraints with EH $>$ 5100, the IA-TS scheme outperforms the IA-EH scheme because it fixes the transmit strategy as IA. We also see that the proposed design outperforms these two designs for all EH constraints because it alters the transmit strategy depending on the EH constraint. For example, the proposed design, for a large EH constraint, chooses a solution that has non-zero leakage but satisfies the EH constraint. We also see that the proposed scheme outperforms the IA-AS scheme as it uses all the antennas for both EH and ID, whereas IA-AS scheme uses only a subset of antennas for EH and ID. We note that the joint design of IA transceiver and practical EH schemes like antenna selection and power splitting is challenging and is a future direction to pursue. The proposed scheme with ideal receivers only gives a better upper bound on practical schemes.

B. Performance in Different Antenna Regimes

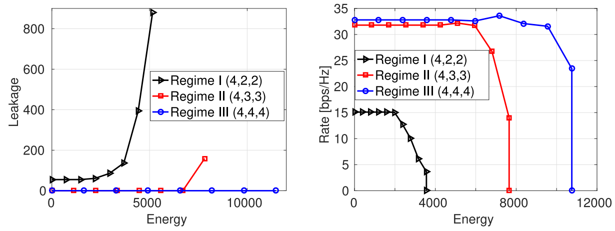
We next analyze the performance of the proposed algorithm in the three different antenna regimes for a 4-user MIMO IFC.

1) Effect of EH Constraints on Leakage (Leakage vs Energy) in Fig. 2a: i) Regime I: Since IA is not feasible, leakage is non-zero even for zero EH constraint, and increases as the EH constraint increases.

ii) Regime II: Since IA is feasible, leakage is zero till IA can satisfy the EH constraint. With a large EH constraint with EH $>$ 6600, IA is relaxed and therefore leakage increases.

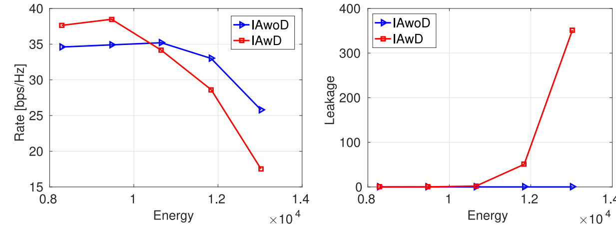
iii) Regime III: With additional antennas both diversity gains and IA can be simultaneously realized [7], [10]. For this letter, we use additional antennas for harvesting energy with IA instead of realizing diversity with IA. We will later justify this approach in Section V-C where we show a diversity-energy trade off. We observe from Fig. 2a that a) additional antennas increase the harvestable energy; and b) importantly the energy is harvested without any leakage. The DoF provided by additional antennas, which could be utilized for diversity gains, can thus be used for harvesting more energy, and that too without compromising IA.

2) Rate vs Energy Trade Off: Fig. 2b plots the network sum-rate subject to different EH constraints. As mentioned



(a) (b)

Fig. 2. a) Leakage vs Energy; and b) Rate-Energy trade offs for different (K, N_t, N_r) regimes of MIMO IFC.



(a) (b)

Fig. 3. a) Rate vs Energy; and b) Leakage vs Energy trade offs for regime III with $(K, N_t, N_r) = (4, 4, 4)$.

before, multiple initializations are required to find maximum sum-rate solutions. We use 500 initializations to get R-E trade offs.

i) Regime I: Due to non-zero leakage, sum-rate Fig. 2b is small even for zero EH constraint. As we increase the EH constraint, rate decreases sharply due to further increase in leakage.

ii) Regime II: Since IA is feasible, sum-rate improves. We also observe Fig. 2b that 75% of maximum available energy can be harvested without sacrificing the sum-rate. With a large EH constraint with EH > 6600, leakage becomes non-zero and sum-rate consequently degrades.

iii) Regime III: Here also we use additional antennas for harvesting energy and not for exploiting diversity. We observe Fig. 2b that 90% of the maximum available energy can be harvested without sacrificing the sum-rate. With a large EH constraint with EH > 8000, sum-rate decreases marginally. This is because maximum sum-rate solution cannot satisfy the EH constraint, and the proposed design chooses an IA solution with lesser sum-rate but still satisfies the EH constraint; this solution, we see from Fig. 2a, still has zero leakage.

C. Diversity-Energy Trade Off in Regime III

We begin by briefly explaining IA with diversity (IAwD) scenario. Here N_t and N_r not only satisfy (7) with strict inequality but also satisfy (8). These additional antennas can be used for exploiting diversity by designing precoders and decoders with extra columns [7], [10]. For example in Fig. 3, with $(K, N_t, N_r) = (4, 4, 4)$, we exploit receive diversity by designing decoder with $d' = 2$ columns and precoder with $d = 1$ column. The IA precoders and decoders, designed according to Algorithm 1, now realize diversity gains. Recall that we also harvest energy as we assume ideal receivers. With this information, we now justify the use of additional antennas for EH and not for realizing diversity gains. To this end, we study R-E trade off. We compare it with the scenario considered earlier in this letter wherein $d = d' = 1$ and we used additional antennas for EH and not for realizing diversity. We refer to this scenario now as IA without diversity (IAwoD).

We observe from Fig. 3a that for a small EH constraint with EH $< 1.04 \times 10^4$, IAwD has higher sum-rate than IAwoD. This is because both IAwD and IAwoD satisfy the EH constraint and diversity gains realized in IAwD scheme increase its sum-rate. For a large EH constraint, in contrast, IAwD has lower sum-rate than IAwoD. This is because of a diversity-energy trade off wherein the system cannot simultaneously satisfy EH constraint and realize diversity gains. The system therefore sacrifices IA to satisfy EH constraint, which degrades its sum-rate. This is also shown in Fig. 3b where leakage increases in IAwD scheme for large EH constraints with EH $> 1.04 \times 10^4$. The IAwoD scheme, on the other hand for a large EH constraint, achieves higher sum-rate as it sacrifices the diversity gain and uses additional DoF offered by excess antennas to satisfy EH requirements without compromising IA.

VI. CONCLUSION

We proposed a novel IA transceiver with which provides a better upper bound for the existing designs. The proposed transceiver minimizes interference leakage subject to an EH constraint and finds optimal precoder and decoder using an iterative algorithm. We also analyzed the performance of the proposed transceiver for three different antenna regimes and showed that excess antennas in an IA network, which are conventionally used for realizing diversity gains, can also be used for energy harvesting without compromising IA.

REFERENCES

[1] 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.

[2] C. M. Yetis, T. Gou, S. A. Jafar, and A. H. Kayran, "On feasibility of interference alignment in MIMO interference networks," *IEEE Trans. Signal Process.*, vol. 58, no. 9, pp. 4771–4782, Sep. 2010.

[3] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "A distributed numerical approach to interference alignment and applications to wireless interference networks," *IEEE Trans. Inf. Theory*, vol. 57, no. 6, pp. 3309–3322, Jun. 2011.

[4] S. W. Peters and R. W. Heath, "Cooperative algorithms for MIMO interference channels," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 206–218, Jan. 2011.

[5] 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.

[6] X. Li, Y. Sun, F. R. Yu, and N. Zhao, "Antenna selection and power splitting for simultaneous wireless information and power transfer in interference alignment networks," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Austin, TX, USA, Dec. 2014, pp. 2667–2672.

[7] Z. Zong *et al.*, "Optimal transceiver design for SWIPT in *K*-user MIMO interference channels," *IEEE Trans. Wireless Commun.*, vol. 15, no. 1, pp. 430–445, Jan. 2016.

[8] J. Park and B. Clerckx, "Joint wireless information and energy transfer in a two-user MIMO interference channel," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4210–4221, Aug. 2013.

[9] H. Ning, C. Ling, and K. K. Leung, "Feasibility condition for interference alignment with diversity," *IEEE Trans. Inf. Theory*, vol. 57, no. 5, pp. 2902–2912, May 2011.

[10] M. Guillaud, "Receive diversity and ergodic performance of interference alignment on the MIMO Gaussian interference channel," in *Proc. 48th Annu. Allerton Conf. Commun. Control Comput. (Allerton)*, Monticello, IL, USA, Sep. 2010, pp. 208–214.

[11] B. Koo and D. Park, "Interference alignment and wireless energy transfer via antenna selection," *IEEE Commun. Lett.*, vol. 18, no. 4, pp. 548–551, Apr. 2014.