Physical-Layer Security for Simultaneous Information and Power Transfer in Full-Duplex Multi-User Networks

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Abstract—**While the simultaneous power and information transfer in a multi-user network extends the functionality of a traditional base station (BS) in accordance with the requirements of future communication systems, it gives raise to the problems regarding information security. This stems in the fact that the energy harvesting (EH) nodes can also act as potential eavesdroppers. Hence, in this work we address the network requirements for a full duplex (FD) BS regarding uplink (UL) and downlink (DL) information rate and power transfer to EH nodes, under the constraints regarding the information security. An optimization problem for minimizing the total power consumption is then formulated for a network with multiple antenna BS and multiple antenna EH nodes. Due to the non-convex nature of the resulting problem a semi-definite-relaxation framework is proposed in order to approach an optimal solution. Furthermore, for a simpler setup where the EH nodes are equipped with a single antenna, it is shown that an easier problem formulation is possible. A sub-optimal approach is also provided which reduces the DL beamforming design into a power adjustment problem with a reduced complexity. The numerical results investigate the performance of the proposed methods under different system parameters.**

I. Introduction

The idea of full-duplex operation, as transceiver's capability to transmit and receive at the same time and frequency, is known with the potential to approach various requirements of future communication systems (5G). This includes improving spectral efficiency, physical layer security and reduced end-to-end latency [1], [2]. Nevertheless, such systems have been long considered to be practically infeasible due to the inherent self-interference (SI). In theory, since each node is aware of its own transmitted signal, the interference from the loopback path can be estimated and suppressed. However, in practice this procedure is challenging due to the high strength of the self-interference channel compared to the desired communication path, e.g., up to 100 dB [3]. Recently, specialized cancellation techniques [4]–[8] have provided an adequate level of isolation between Tx and Rx directions to facilitate a FD communication, and motivated wide range of related applications, e.g., [3], [9]–[18]. As a promising use-case, the application of FD capability at the base stations is known with the potential to enhance the spectral efficiency, as the uplink and downlink communications can be accommodated in the same channel [15], [19]–[25]. More specifically, the works in [22]–[25] have studied the achievable gains and design methodologies for a system with a FD-BS, in the presence of an eavesdropper. The common goal is to provide a desired information link quality for the UL and DL, while protecting the information leakage against a potential eavesdropper. In this context, a setup with single antenna users and eavesdropper is studied in [22]. The latter work is then generalized for a setup with multiple antenna nodes, and for a design with energy efficiency considerations in [23]–[25], by minimizing the required network power. In addition to the simultaneous information transfer in different directions, a FD-BS may as well enhance its operational diversity by providing service to the energy harvesting users, via simultaneous wireless information and power transfer (SWIPT). The application of wireless signal as a means of power transfer for EH nodes is been introduced as a controllable mechanism [26], and proved practical for the nodes with relatively low power consumptions, e.g., wireless sensors. Nevertheless, while HD-BSs are commonly studied for various SWIPT applications, e.g., [27], [28], such studies are rarely extended for the scenarios with a FD-BS [29], [30].

In this work we consider a FD-BS which simultaneously provides service to HD UL and HD DL users, and transfers energy to the EH nodes. Note that while the application of a signal both as power and information carrier enhances the efficiency of a SWIPT system, it signifies the issue of security as an EH user may act as a potential eavesdropper. Similar problem has been widely discussed for a setup with a HD-BS, assuming that the BS simultaneously transmit signal and noise, applying different beamforming weights. While a FD-BS, due to the simultaneous control over various signal paths in the same channel, has inherently a better capability to deal with this problem, such study is still missing for a FD-BS.

Contribution: As the first step, we provide a signal model where a FD-BS is applied to simultaneously serve multiple information transmitter, i.e., UL users, multiple information receivers, i.e., DL users, and multiple energy receivers, i.e., EH nodes. Our goal is to design a system which prevents a destructive information leakage to the un-intended users, while providing a required link quality in UL, DL, and transfers power to the EH nodes. Link quality constraints are then formulated in terms of the resulting signal-to-interference+noise-ratio (SINR) and the corresponding optimization is converted into a convex optimization problem. A simpler design procedure is also provided for the case with single antenna EH nodes. Furthermore, a sub-optimal solution for DL beamforming design is proposed which reduces the required computational complexity, at the expense of a slight performance

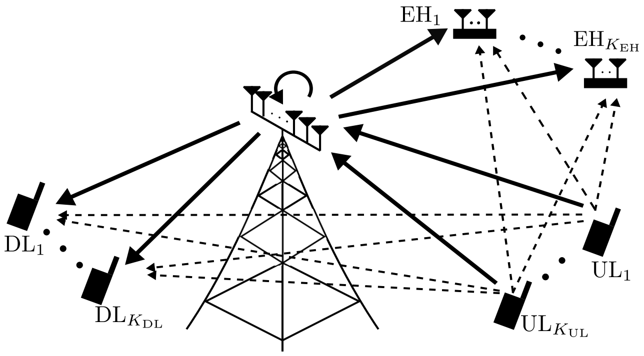

Fig. 1. Schematic of the defined SWIPT system. A FD BS node simultaneously provides communication service to a set of UL and DL users, while transferring power to a set of EH nodes. Solid lines represent the desired signal paths, while dashed lines represent the undesired (interference/information leakage) paths.

degradation. As a result, optimal linear transmit strategies are obtained at the BS, as well as the UL users. The resulting system performance is then studied numerically under different system parameters.

Paper Organization: The remaining parts of the paper is organized as follows. In Section II, the system model is defined. Our design metrics, constraints, and the resulting optimization strategy is then summarized in Section III. In Section IV and V, numerically tractable solutions are provided for the defined optimization problem. The numerical simulations are then discussed in Section VI, and finally Section VII summarizes the main results of this work.

II. System Model

We investigate a system where a FD BS is simultaneously serving K_{UL} number of HD UL users, K_{DL} number of HD DL users, as well as K_{EH} number of EH users, see Fig. 1. The BS is equipped with M_{t} transmit and M_{r} receive antennas, where the EH nodes are equipped with M_{EH} receive antennas. The UL and DL users are equipped with a single antenna. All channels are assumed to follow the block flat-fading model. We denote the channel between the k-th UL user and the BS as $\mathbf{h}_{\text{ul},k} \in \mathbb{C}^{M_{\text{r}}}$, the channel between the k-th UL user and the l-th DL user as $h_{\text{ud},k,l} \in \mathbb{C}$, and the channel between BS and the k-th DL user as $\mathbf{h}_{\text{dl},k}^T \in \mathbb{C}^{M_{\text{t}}}$. The SI channel, i.e., the channel between the transmitter and the receiver ends of the BS is denoted as $\mathbf{H}_{\text{bb}} \in \mathbb{C}^{M_{\text{r}} \times M_{\text{t}}}$. Furthermore, we represent the channel between the BS and the k-th EH mode as $\mathbf{G}_k \in \mathbb{C}^{M_{\text{EH}} \times M_{\text{t}}}$ Where the channel between the k-th UL user and the l-th EH node is denoted by $\mathbf{g}_{k,l} \in \mathbb{C}^{M_{\text{EH}}}$. Furthermore, it is assumed that the channel state information (CSI) regarding all paths are known at the base station. We denote the index set of all UL, DL, and EH nodes as $\mathbb{K}_{\text{UL}}, \mathbb{K}_{\text{DL}}$ and $\mathbb{K}_{\text{EH}}$, respectively. Furthermore, the index set of the UL (DL) nodes whose information needs to be protected against a potential eavesdropping is denoted as $\tilde{\mathbb{K}}_{\text{UL}}$ ($\tilde{\mathbb{K}}_{\text{DL}}$). The index set of the EH nodes which are considered as potential eavesdroppers are presented as $\tilde{\mathbb{K}}_{\text{EH}}$. The following parts define our signal model in more details.

A. UL-BS communication

The transmitted signal from the UL users is written as

$$x_{\text{ul},k} = \sqrt{p_{\text{ul},k}} s_{\text{ul},k}, \quad k \in \mathbb{K}_{\text{UL}}, \tag{1}$$

where $p_{\text{ul},k} \in \mathbb{R}_+$ represents the transmit power of the k-th UL user and $s_{\text{ul},k} \in \mathbb{C}$ is a complex zero-mean data symbol such that $\mathbb{E}\{|s_{\text{ul},k}|^2\} = 1$. The transmitted signal from the UL user is then received by the BS, together with the loopback SI signal from the BS transmitter

$$\mathbf{y}_{\text{bs}} = \mathbf{H}_{\text{bb}} \mathbf{x}_{\text{bs}} + \sum_{k \in \mathbb{K}_{\text{UL}}} \mathbf{h}_{\text{ul},k} x_{\text{ul},k} + \mathbf{n}_{\text{bs}}, \tag{2}$$

where $\mathbf{x}_{\text{bs}} \in \mathbb{C}^{M_{\text{t}}}$ and $\mathbf{y}_{\text{bs}} \in \mathbb{C}^{M_{\text{r}}}$ respectively represent the transmitted and received signals at the BS, and $x_{\text{ul},k} \in \mathbb{C}$ and $\mathbf{n}_{\text{bs}} \sim \mathcal{CN}\left(\mathbf{0}, N_{\text{bs}} \mathbf{I}_{M_{\text{r}}}\right)$ respectively represent the transmit signal from the k-th UL user, and the zero-mean complex Gaussian (ZMCG) noise at the BS.

As it is known for a FD system, the SI signal can not be accurately subtracted due to the high strength of the loopback path, as well as the limited dynamic range of the transceiver. Following the proposed model by [3], [11] we consider a residual SI signal at the BS as

$$\mathbf{e} := \mathbf{H}_{\text{bb}} \mathbf{e}_{\text{t}} + \mathbf{e}_{\text{r}}, \tag{3}$$

where

$$\mathbf{e}_{\text{t}} \sim \mathcal{CN}\Big(\mathbf{0}, \kappa \text{diag}\left(\mathbb{E}\left\{\mathbf{x}_{\text{bs}} \mathbf{x}_{\text{bs}}^H\right\}\right)\Big), \tag{4}$$

$$\mathbf{e}_{\text{r}} \sim \mathcal{CN}\Big(\mathbf{0}, \beta \text{diag}\left(\mathbb{E}\left\{\mathbf{H}_{\text{bb}} \mathbf{x}_{\text{bs}} \mathbf{x}_{\text{bs}}^H \mathbf{H}_{\text{bb}}^H\right\}\right)\Big), \tag{5}$$

respectively represent the transmission, and the reception distortion at the BS, and $\kappa \in \mathbb{R}_+$ ($\beta \in \mathbb{R}_+$) is the distortion coefficient relating the transmit (receive) power to the transmit (receive) distortion intensity at each antenna. Note that the above expression jointly models the usual transceiver imperfections that affect the SI cancellation process corresponding to $\mathbf{e}_{\text{t}}$, e.g., power amplifier non-linearity, oscillator phase noise and digital-to-analog convertor (DAC) error, and also the imperfections of the receiver chains corresponding to $\mathbf{e}_{\text{r}}$, e.g., automatic-gain-control (AGC) noise, analog-to-digital convertor (ADC), and the oscillator phase noise. For more elaboration on the used residual SI signal model please see [3, Section II]. As a result, the SI-reduced received signal at the BS is expressed as

$$\tilde{\mathbf{y}}_{\text{bs}} = \mathbf{H}_{\text{bb}} \mathbf{e}_{\text{t}} + \mathbf{e}_{\text{r}} + \mathbf{n}_{\text{bs}} + \sum_{k \in \mathbb{K}_{\text{UL}}} \mathbf{h}_{\text{ul},k} x_{\text{ul},k}, \tag{6}$$

where the first two terms represent the residual self-interference. A spatial receive filter is then applied at the BS to separate the data streams corresponding to the different UL users

$$\hat{s}_{\text{ul},k} = \mathbf{f}^H \tilde{\mathbf{y}}_{\text{bs}}, \tag{7}$$

where $\hat{s}_{\text{ul},k} \in \mathbb{C}$ is the estimated version of the transmitted data symbol from the k-th UL user at the BS.

B. BS-DL communication

In this work we consider a BS which transmits data together with an artificially generated noise, in order to add robustness to the potential eavesdropping by EH nodes. Note that the transmission of pure data-containing signal, while increasing the efficiency of a SWIPT system, leads to the data leakage to the EH nodes. The transmit signal from the BS is hence written as

$$\mathbf{x}_{\text{bs}} = \mathbf{z} + \sum_{k \in \mathbb{K}_{\text{DL}}} \mathbf{b}_k s_{\text{dl},k}, \tag{8}$$

where $\mathbf{b}_k \in \mathbb{C}^{M_t}$ represents the beamforming vector at the BS for the k-th DL user, $s_{\text{dl},k}$ is the corresponding data symbol with zero mean and $\mathbb{E}\{|s_{\text{dl},k}|^2\} = 1$. The artificially generated noise at the BS is denoted as $\mathbf{z} \in \mathbb{C}^{M_t}$, which is intended to convey energy to the EH nodes. Regarding the generation of $\mathbf{z} \in \mathbb{C}^{M_t}$ we consider two scenarios. In the first (optimistic) scenario, we assume that the information regarding the random sequence $\mathbf{z}$ is distributed in the network, and it is known to the users. Note that this can be achieved by sharing the information regarding the used random sequence and the initial seed with the users, e.g., [30]. Nevertheless, this information is not shared with the EH nodes and hence can be used to degrade the information link to the EH nodes without degrading the information links to DL users. In the second (pessimistic) scenario, we assume that the information regarding the random sequence $\mathbf{z}$ is not distributed in the network. While the second approach is capable of keeping the used sequence from EH nodes with higher certainty, it may degrade the information link to the DL users, specially when the number of antennas at the BS is not large. The received signal at the l-th DL user can be written as

$$y_{\text{dl},l} = \mathbf{h}_{\text{dl},l}^T \mathbf{x}_{\text{bs}} + n_{\text{dl},l} + \sum_{k \in \mathbb{K}_{\text{UL}}} h_{\text{ud},k,l} x_{\text{ul},k}, \tag{9}$$

where $n_{\text{dl},l} \in \mathbb{C}$ is a ZMCG noise with variance $N_{\text{dl},l}$.

C. Received signal at EH nodes

The function of EH nodes is to extract and store energy from the received RF signal, e.g., [31]. The baseband representation of the received signal at the k-th EH node is

$$\mathbf{y}_{\text{eh},k} = \mathbf{G}_k \mathbf{x}_{\text{bs}} + \mathbf{n}_{\text{eh},k} + \sum_{i \in \mathbb{K}_{\text{UL}}} \mathbf{g}_{i,k} x_{\text{ul},i}, \tag{10}$$

where $\mathbf{n}_{\text{eh},k} \sim \mathcal{CN}\left(\mathbf{0}, N_{\text{eh},k}\mathbf{I}_{M_{\text{EH}}}\right)$ is a ZMCG noise at the k-th EH node. In the following sections we provide an overview of our optimization strategy in order to control the network power expenditure, while satisfying the users requirements, as explained in Section I.

III. Network Power Minimization Under Multiple Power and Rate Constraints

In this part we briefly summarize our optimization strategy. Our goal is to provide a required communication rate from the UL users to the BS and from the BS to the DL users, as well as to provide a required power transfer to the EH nodes. Furthermore, the information leakage to the EH nodes should be kept below an acceptable margin to guarantee security for the desired information links. Hence, we address the network power expenditure minimization problem, satisfying the aforementioned rate and power constraints. Similar approaches for a BS with HD operation, or a FD-BS without SWIPT capability, or security considerations are discussed in [23]–[25], [27], [30].

A. Information transfer to the DL users

The signal-to-noise-plus-interference-ratio (SINR) for the k-th DL node can be formulated as

$$\zeta_{\text{dl},k} = \frac{\mathbf{h}_{\text{dl},k}^T \mathbf{b}_k \mathbf{b}_k^H \mathbf{h}_{\text{dl},k}^*}{N_{\text{dl},k} + \sum_{i \in \mathbb{K}_{\text{UL}}} p_{\text{ul},i} |h_{\text{ud},i,k}|^2 + \mathbf{h}_{\text{dl},k}^T \Big(\mu \mathbb{E}\{\mathbf{z}\mathbf{z}^H\} + \sum_{i \in \{\mathbb{K}_{\text{DL}} \backslash k\}} \mathbf{b}_i \mathbf{b}_i^H \Big) \mathbf{h}_{\text{dl},k}^*} \tag{11}$$

where $\zeta_{\text{dl},k} \in \mathbb{R}_+$ represents the corresponding SINR value, and $\mu \in \{0,1\}$ represent the possible scenarios for the random sequence $\mathbf{z}$, i.e., $\mu = 1$ represents the pessimistic, and $\mu = 0$ represents the optimistic scenario where the information regarding the random sequence $\mathbf{z}$ is distributed to the intended users, see Section II. Consequently, the normalized information transfer rate to the k-th DL node is written as

$$R_{\text{dl},k} = \log_2\left(1 + \zeta_{\text{dl},k}\right), \tag{12}$$

assuming a Gaussian distribution for the transmitted signal and all interference sources in the network. Note that $R_{\text{dl},k}$ is normalized to the used bandwidth.

B. Information Reception from the UL users

The desired information link quality in terms of SINR for the k-th UL user is expressed as

$$\zeta_{\text{ul},k} = \frac{p_{\text{ul},k} \mathbf{f}_k^H \mathbf{h}_{\text{ul},k} \mathbf{h}_{\text{ul},k}^H \mathbf{f}_k}{\mathbf{f}_k^H \left(N_{\text{bs}} \mathbf{I}_{M_r} + \mathbb{E}\{\mathbf{e}\mathbf{e}^H\} + \sum_{i \in \{\mathbb{K}_{\text{UL}} \backslash k\}} p_{\text{ul},i} \mathbf{h}_{\text{ul},i} \mathbf{h}_{\text{ul},i}^H \right) \mathbf{f}_k} \tag{13}$$

where $\mathbb{E}\{\mathbf{e}\mathbf{e}^H\}$ represents the covariance matrix of the residual SI signal at the BS, and can be calculated as

$$\mathbb{E}\{\mathbf{e}\mathbf{e}^H\} = \kappa \mathbf{H}_{\text{bb}} \text{diag}\left(\mathbb{E}\{\mathbf{x}_{\text{bs}}\mathbf{x}_{\text{bs}}^H\}\right) \mathbf{H}_{\text{bb}}^H + \beta \text{diag}\left(\mathbf{H}_{\text{bb}} \mathbb{E}\{\mathbf{x}_{\text{bs}}\mathbf{x}_{\text{bs}}^H\} \mathbf{H}_{\text{bb}}^H\right), \tag{14}$$

where the first and second terms respectively correspond to the effect of the transmission and reception distortion at the base station, see [3]. Similar to the arguments in [23], [24], we assume zero-forcing (ZF) spatial filters at the base station to simplify the corresponding multi-user design. Note that the ZF strategy reaches close to optimality for the scenarios where noise is not the dominant factor, and particularly as M_r grows. The corresponding choice of $\mathbf{f}_k^H$ can be hence calculated as k-th row of $\tilde{\mathbf{H}}^\dagger$, where $\tilde{\mathbf{H}} := [\mathbf{h}_{\text{ul},1} \cdots \mathbf{h}_{\text{ul},K_{\text{UL}}}]$ and $\tilde{\mathbf{H}}^\dagger := \left(\tilde{\mathbf{H}}^H \tilde{\mathbf{H}}\right)^{-1} \tilde{\mathbf{H}}^H$, see [23, Equation (12)]. The normalized communication rate can be obtained similar to the DL case as

$$R_{\text{ul},k} = \log_2\left(1 + \zeta_{\text{ul},k}\right). \tag{15}$$

C. Wireless power transfer to EH nodes

As one of the network requirements, the BS node is responsible to transfer wireless power to the EH nodes. The received power at the k-th EH node is expressed as

$$P_k := \mathbb{E}\left\{\|\mathbf{y}_{\text{eh},k}\|_2^2\right\} = \text{tr}\left(N_{\text{eh},k}\mathbf{I}_{M_{\text{EH}}} + \mathbf{G}_k\mathbb{E}\left\{\mathbf{z}\mathbf{z}^H\right\}\mathbf{G}_k^H\right) + \sum_{i\in\mathbb{K}_{\text{UL}}} p_{\text{ul},i}\|\mathbf{g}_{i,k}\|_2^2 + \sum_{i\in\mathbb{K}_{\text{DL}}} \|\mathbf{G}_k\mathbf{b}_i\|_2^2, \quad (16)$$

where $P_k \in \mathbb{R}_+$ represents the received collective power at the k-th EH node.

D. Information leakage to EH nodes

In order to provide security against the potential eavesdropping by the EH nodes, the information rates from the UL nodes to the EH nodes, as well as from BS to the EH nodes should be kept below an acceptable level. The information leakage from the k-th UL user to the l-th EH node is formulated as

$$R_{\text{ul},k,l}^{(\text{Leakage})} = \log_2\left|\mathbf{I}_{M_{\text{EH}}} + p_{\text{ul},k}\mathbf{\Lambda}_{\text{ul},k,l}^{-1}\mathbf{g}_{k,l}\mathbf{g}_{k,l}^H\right|, \quad (17)$$

where

$$\mathbf{\Lambda}_{\text{ul},k,l} := N_{\text{eh},l}\mathbf{I}_{M_{\text{EH}}} + \mathbf{G}_l\mathbb{E}\{\mathbf{x}_{\text{bs}}\mathbf{x}_{\text{bs}}^H\}\mathbf{G}_l^H + \sum_{i\in\{\mathbb{K}_{\text{UL}}\backslash k\}} p_{\text{ul},i}\mathbf{g}_{i,l}\mathbf{g}_{i,l}^H \quad (18)$$

is the covariance of the interference+noise signal at the l-th EH node corresponding to the information leakage from the k-th UL communication. Similarly, the information leakage to the l-th EH node from the BS, corresponding to the k-th DL user is formulated as

$$R_{\text{dl},k,l}^{(\text{Leakage})} = \log_2\left|\mathbf{I}_{M_{\text{EH}}} + \mathbf{\Lambda}_{\text{dl},k,l}^{-1}\mathbf{G}_l\mathbf{b}_k\mathbf{b}_k^H\mathbf{G}_l^H\right|, \quad (19)$$

where

$$\mathbf{\Lambda}_{\text{dl},k,l} := N_{\text{eh},l}\mathbf{I}_{M_{\text{EH}}} + \mathbf{G}_l\Big(\mathbb{E}\{\mathbf{z}\mathbf{z}^H\} + \sum_{i\in\{\mathbb{K}_{\text{DL}}\backslash k\}} \mathbf{b}_i\mathbf{b}_i^H\Big)\mathbf{G}_l^H + \sum_{i\in\mathbb{K}_{\text{UL}}} p_{\text{ul},i}\mathbf{g}_{i,l}\mathbf{g}_{i,l}^H \quad (20)$$

is the covariance of the interference+noise signal at the l-th EH node corresponding to the information leakage from the k-th DL communication.

E. Optimization Problem

In this subsection we define our optimization problem. As explained above, our goal is to minimize the total network power expenditure where the power consumption for each individual node is incorporated in the objective with a known weight. This approach is practical considering the large variety of nodes with different energy storage capability. The corresponding problem can be hence formulated as

$$\min_{\substack{\mathbf{Z}\in\mathcal{H},\\ \mathbf{b}_k,\, k\in\mathbb{K}_{\text{DL}},\\ p_{\text{ul},k},\, k\in\mathbb{K}_{\text{UL}}}} \gamma_{\text{bs}}\text{tr}\Big(\mathbf{Z} + \sum_{k\in\mathbb{K}_{\text{DL}}}\mathbf{b}_k\mathbf{b}_k^H\Big) + \sum_{k\in\mathbb{K}_{\text{UL}}}\gamma_{\text{ul},k}p_{\text{ul},k} \quad (21a)$$

$$\text{s.t.} \quad 0 \le p_{\text{ul},k} \le p_{\max,k}, \quad k\in\mathbb{K}_{\text{UL}}, \quad (21b)$$

$$\text{tr}\Big(\mathbf{Z} + \sum_{k\in\mathbb{K}_{\text{DL}}}\mathbf{b}_k\mathbf{b}_k^H\Big) \le p_{\text{bs-max}}, \quad (21c)$$

$$\xi_k P_k \ge P_{\min,k}, \quad k\in\mathbb{K}_{\text{EH}}, \quad (21d)$$

$$R_{\text{dl},k,l}^{(\text{Leakage})} \le \bar{R}_{\text{dl},k}^{(\text{Leakage})}, \; k\in\tilde{\mathbb{K}}_{\text{DL}}, l\in\tilde{\mathbb{K}}_{\text{EH}}, \quad (21e)$$

$$R_{\text{ul},k,l}^{(\text{Leakage})} \le \bar{R}_{\text{ul},k}^{(\text{Leakage})}, \; k\in\tilde{\mathbb{K}}_{\text{UL}}, l\in\tilde{\mathbb{K}}_{\text{EH}}, \quad (21f)$$

$$R_{\text{ul},k} \ge \bar{R}_{\text{ul},k}, \quad k\in\mathbb{K}_{\text{UL}}, \quad (21g)$$

$$R_{\text{dl},k} \ge \bar{R}_{\text{dl},k}, \quad k\in\mathbb{K}_{\text{DL}}, \quad (21h)$$

where $\mathcal{H}$ denotes the set of positive-semi-definite matrices, $\mathbf{Z} := \mathbb{E}\{\mathbf{z}\mathbf{z}^H\}$, and $\xi_k \in \mathbb{R}_+$ represents the efficiency of the k-th EH node in storing the received wireless energy. In the above problem, $\bar{R}$ represents the tolerable leakage rate for the corresponding links in (21e) and (21f), while representing the minimum required information rate for the corresponding links in (21g) and (21h). The weights $\gamma_{\text{bs}} \in \mathbb{R}_+$ and $\gamma_{\text{ul},k} \in \mathbb{R}_+$ respectively represent the price of the power consumption at the BS and at the k-th UL user. The maximum allowed power consumption at the k-th UL user and at the BS is respectively represented as $p_{\max,k}$ and $p_{\text{bs-max}}$, where the minimum required power at the k-th EH node is denoted by $P_{\min,k}$.

As it is apparent, the defined optimization problem in (21a)-(21h) is not tractable, as it is not convex. It is since the intersection of the sets resulting from the rate constraints (21e)-(21h) does not constitute a convex set. Furthermore, the complexity of the problem does not allow for an analytic approach towards the solution. In the following sections we formulate substitute problems to (21a)-(21h) which hold a convex structure, and hence can be solved in a polynomial time using the state of the art numerical solvers.

IV. Semi-Definite-Relaxation (SDR) for Network Power Minimization

In order to tackle (21a)-(21h), the well-known semi-definite-relaxation (SDR) is applied to obtain a convex optimization framework, see [32]. By defining $\mathbf{B}_k := \mathbf{b}_k\mathbf{b}_k^H$, and additionally imposing the constraints $\mathbf{B}_k \in \mathcal{H}$, $\text{rank}(\mathbf{B}_k) = 1$, we can equivalently formulate (21a)-(21h) as

$$\min_{\substack{\mathbf{Z}\in\mathcal{H},\\ \mathbf{B}_k\in\mathcal{H},\, k\in\mathbb{K}_{\text{DL}},\\ p_{\text{ul},k},\, k\in\mathbb{K}_{\text{UL}}}} \gamma_{\text{bs}}\text{tr}\Big(\tilde{\mathbf{B}}\Big) + \sum_{k\in\mathbb{K}_{\text{UL}}}\gamma_{\text{ul},k}p_{\text{ul},k} \quad (22a)$$

$$\text{s.t.} \quad 0 \le p_{\text{ul},k} \le p_{\max,k}, \quad k\in\mathbb{K}_{\text{UL}}, \quad (22b)$$

$$\text{tr}\Big(\tilde{\mathbf{B}}\Big) \le p_{\text{bs-max}}, \quad (22c)$$

$$\text{tr}\Big(\mathbf{G}_k^H\mathbf{G}_k\tilde{\mathbf{B}}\Big) + \sum_{i\in\mathbb{K}_{\text{UL}}} p_{\text{ul},i}\|\mathbf{g}_{i,k}\|_2^2 \ge P_{\min,k}/\xi_k - M_{\text{EH}}N_{\text{eh},k}, \quad k\in\mathbb{K}_{\text{EH}}, \quad (22d)$$

$$\mathbf{G}_l\mathbf{B}_k\mathbf{G}_l^H \le \bar{\zeta}_{\text{dl},k}\mathbf{\Lambda}_{\text{dl},k,l}, \; k\in\tilde{\mathbb{K}}_{\text{DL}}, l\in\tilde{\mathbb{K}}_{\text{EH}}, \quad (22e)$$

$$p_{\text{ul},k}\mathbf{g}_{k,l}\mathbf{g}_{k,l}^H \le \bar{\zeta}_{\text{ul},k}\mathbf{\Lambda}_{\text{ul},k,l},\ k \in \tilde{\mathbb{K}}_{\text{UL}}, l \in \tilde{\mathbb{K}}_{\text{EH}}, \tag{22f}$$

$$\text{tr}\Big(p_{\text{ul},k}\mathbf{F}_k\mathbf{H}_{\text{ul},k} - \tilde{\zeta}_{\text{ul},k}\mathbf{F}_k\Big(N_{\text{bs}}\mathbf{I}_{M_r} + \mathbf{E} + \sum_{i\in\{\mathbb{K}_{\text{UL}}\setminus k\}} p_{\text{ul},i}\mathbf{H}_{\text{ul},i}\Big)\Big) \ge 0,\ \ k \in \mathbb{K}_{\text{UL}}, \tag{22g}$$

$$\text{tr}\Big(\mathbf{h}_{\text{dl},k}^*\mathbf{h}_{\text{dl},k}^T\tilde{\mathbf{B}}_k\Big) - \tilde{\zeta}_{\text{dl},k}\Big(N_{\text{dl},k} + \sum_{i\in\mathbb{K}_{\text{UL}}} p_{\text{ul},i}|h_{\text{ud},i,k}|^2\Big) \ge 0,\ \ k \in \mathbb{K}_{\text{DL}}, \tag{22h}$$

$$\text{rank}\,(\mathbf{B}_k) = 1,\ \ k \in \mathbb{K}_{\text{DL}}, \tag{22i}$$

where

$$\tilde{\mathbf{B}} := \mathbb{E}\{\mathbf{x}_{\text{bs}}\mathbf{x}_{\text{bs}}^H\} = \mathbf{Z} + \sum_{k\in\mathbb{K}_{\text{DL}}} \mathbf{B}_k, \tag{23}$$

$$\tilde{\mathbf{B}}_k := \mathbf{B}_k - \bar{\zeta}_{\text{dl},k}\Big(\mu\mathbf{Z} + \sum_{i\in\{\mathbb{K}_{\text{DL}}\setminus k\}} \mathbf{B}_i\Big), \tag{24}$$

$$\mathbf{F}_k := \mathbf{f}_k\mathbf{f}_k^H, \tag{25}$$

$$\mathbf{H}_{\text{ul},k} := \mathbf{h}_{\text{ul},k}\mathbf{h}_{\text{ul},k}^H, \tag{26}$$

$$\bar{\zeta}_{\text{dl},k} := 2^{\bar{R}_{\text{dl},k}^{(\text{Leakage})}} - 1,\ \ k \in \mathbb{K}_{\text{DL}}, \tag{27}$$

$$\bar{\zeta}_{\text{ul},k} := 2^{\bar{R}_{\text{ul},k}^{(\text{Leakage})}} - 1,\ \ k \in \mathbb{K}_{\text{UL}}, \tag{28}$$

$$\tilde{\zeta}_{\text{dl},k} := 2^{\bar{R}_{\text{dl},k}} - 1,\ \ k \in \mathbb{K}_{\text{DL}}, \tag{29}$$

$$\tilde{\zeta}_{\text{ul},k} := 2^{\bar{R}_{\text{ul},k}} - 1,\ \ k \in \mathbb{K}_{\text{UL}}, \tag{30}$$

and $\mathbf{E} := \mathbb{E}\{\mathbf{e}\mathbf{e}^H\}$ is obtained by replacing $\tilde{\mathbf{B}}$ in (14). Please note that the interference covariance matrices, i.e., $\mathbf{\Lambda}_{\text{ul},k,l}, \mathbf{\Lambda}_{\text{dl},k,l}$ are expressed as affine combinations of $\mathbf{Z}$, $\mathbf{B}_k, k \in \mathbb{K}_{\text{DL}}$, and $p_{\text{ul},i}, i \in \mathbb{K}_{\text{UL}}$. Nevertheless, the reformulated problem (22a)-(22i) does not hold a convex structure, due to the rank constraint (22i). Hence by temporarily relaxing (22i) we formulate a substitute problem as

$$\min_{\substack{\mathbf{Z}\in\mathcal{H},\\ \mathbf{B}_k\in\mathcal{H}, k\in\mathbb{K}_{\text{DL}},\\ p_{\text{ul},k}, k\in\mathbb{K}_{\text{UL}}}} \quad (22a) \tag{31}$$

$$\text{s.t.} \quad (22b)\text{ - }(22h), \tag{32}$$

which is a convex optimization problem and can be efficiently solved using known numerical solvers, e.g., SDPT3 [32]. If the obtained solutions for $\mathbf{B}_k$, i.e., $\mathbf{B}_k^\star$, satisfy the relaxed constraint (22i), i.e., $\text{rank}\,(\mathbf{B}_k^\star) = 1$, they are also optimal solutions for (22a)-(22i). In this case, an optimal DL transmit beamforming vector is obtained as $\mathbf{b}_k^\star = \lambda_{\max}(\mathbf{B}_k^\star)$, where $\lambda_{\max}(\cdot)$ calculates the eigenvector corresponding to the maximum eigenvalue. Nevertheless a rank-1 optimum solution is not in general guaranteed for (31)-(32). In this context, the well-known randomization technique is applied which obtains a close-to-optimum solution for $\mathbf{b}_k$, using an optimal general-rank solution to $\mathbf{B}_k$, e.g., [33]. It is worth mentioning that a general rank DL covariance matrix can be as well implemented by applying space-time-block coding (STBC) schemes, e.g., see [34]–[36].

V. Simplified Network Power Minimization for Single-Antenna EH Nodes ($M_{\text{EH}} = 1$)

In the variety of the potential scenarios, the EH nodes are small and cheap nodes which does not afford to facilitate multiple antennas in the hardware. In this section we solve the defined optimization problem in (21a)-(21h) assuming $M_{\text{EH}} = 1$. The purpose of this section is to exploit the provided setup simplification to obtain simpler designs. We denote the channel between the BS and the k-th EH node as $\mathbf{g}_k$ and the channel between the k-th UL node and the l-th EH node as $g_{k,l}$. Note that $\mathbf{g}_k \in \mathbb{C}^{1\times M_t}$ and $g_{k,l} \in \mathbb{C}$ respectively represent the vector and scalar notations for the channels $\mathbf{G}_k$ and $\mathbf{g}_{k,l}$, as $M_{\text{EH}} = 1$. Similar to the last section, having $\mathbf{B}_k = \mathbf{b}_k\mathbf{b}_k^H$, $\mathbf{B}_k \in \mathcal{H}$, and relaxing the corresponding rank constraint, our problem is formulated as

$$\min_{\substack{\mathbf{Z}_k\in\mathcal{H}, , k\in\mathbb{K}_{\text{EH}}\\ \mathbf{B}_k\in\mathcal{H}, k\in\mathbb{K}_{\text{DL}},\\ p_{\text{ul},k}, k\in\mathbb{K}_{\text{UL}}}} \quad (22a) \tag{33a}$$

$$\text{s.t.} \quad (22b)\text{-}(22d)\ ,\ (22g)\text{-}(22h), \tag{33b}$$

$$\text{tr}\Big(\mathbf{g}_l^H\mathbf{g}_l\Big(\mathbf{B}_k - \bar{\zeta}_{\text{dl},k}\Big(\tilde{\mathbf{B}} - \mathbf{B}_k\Big)\Big)\Big) - \bar{\zeta}_{\text{dl},k}\Big(N_{\text{eh},l} + \sum_{i\in\mathbb{K}_{\text{UL}}} p_{\text{ul},i}|g_{i,l}|^2\Big) \le 0,\ k \in \tilde{\mathbb{K}}_{\text{DL}}, l \in \tilde{\mathbb{K}}_{\text{EH}}, \tag{33c}$$

$$p_{\text{ul},k}|g_{k,l}|^2 - \bar{\zeta}_{\text{ul},k}\sum_{i\in\{\mathbb{K}_{\text{UL}}\setminus k\}} p_{\text{ul},i}|g_{i,l}|^2 - \bar{\zeta}_{\text{ul},k}\text{tr}\big(\mathbf{g}_k^H\mathbf{g}_k\tilde{\mathbf{B}}\big) \le 0,\ k \in \tilde{\mathbb{K}}_{\text{UL}}, l \in \tilde{\mathbb{K}}_{\text{EH}}, \tag{33d}$$

where the role of $\mathbf{z} = \sum_{k\in\tilde{\mathbb{K}}_{\text{EH}}} \mathbf{z}_k$ is intuitively separated into $|\mathbb{K}_{\text{EH}}|$ mutually independent random noise sequence where each is intended to serve the EH node with the same index (and consequently $\mathbf{Z} = \sum_{k\in\tilde{\mathbb{K}}_{\text{EH}}} \mathbf{Z}_k$). Note that the aforementioned separation does not reduce the optimality of (33a)-(33d) as any optimal random noise covariance $\mathbf{Z}^\star$ from the original problem (22a)-(22h) can be still constructed with a feasible combination of $\mathbf{Z}_k, k \in \tilde{\mathbb{K}}_{\text{EH}}$[1]. Nevertheless, as we see in the following, it may provide further simplification on finding an optimal rank-1 DL beamforming matrices, i.e., $\mathbf{B}_k^\star$. The defined problem (33a)-(33d) holds a complex-valued semi-definite programming structure for which

$$\mathcal{V} = |\mathbb{K}_{\text{UL}}| + |\mathbb{K}_{\text{DL}}| + |\mathbb{K}_{\text{EH}}|, \tag{34}$$

$$\mathcal{C} = 2|\mathbb{K}_{\text{UL}}| + |\mathbb{K}_{\text{EH}}| + |\mathbb{K}_{\text{DL}}| + 1 + |\tilde{\mathbb{K}}_{\text{EH}}|\left(|\tilde{\mathbb{K}}_{\text{UL}}| + |\tilde{\mathbb{K}}_{\text{DL}}|\right), \tag{35}$$

respectively represent the number of the semi-definite complex variables and constraints. The rank-constraint solutions for aforementioned problem structure are studied in the literature, see [37], [38]. Exploiting the results of the [37, Theorem 3.2], an optimal rank-1 set of semi-definite variables for the problem (22a)-(22h) is available and can be constructed if we have

$$|\mathcal{V}| + 3 < |\mathcal{C}| \quad \equiv \quad 2 < |\mathbb{K}_{\text{UL}}| + |\tilde{\mathbb{K}}_{\text{EH}}|\left(|\tilde{\mathbb{K}}_{\text{UL}}| + |\tilde{\mathbb{K}}_{\text{DL}}|\right). \tag{36}$$

Note that the inequality condition (36) does not indicate the existence of a rank-1 solution for a general setup. Nevertheless, it provides an indication for the few setups that the provided

[1] Note that for a practical scenario where the base station is equipped with multiple antennas, higher energy efficiency can be obtained by using more directive beams. Hence unless the EH nodes are tightly co-located, we assume that the power transfer to the EH nodes is done via separated beams, i.e., we have $\mathbf{Z}_k \succ 0,\ \forall k \in \mathbb{K}_{\text{EH}}$.

semi-definite relaxation is tight and can be used interchangeably with the original problem (22a)-(22i). When (36) does not hold for a certain setup, the relaxed problem results in semi-definite general-rank matrices. Hence, similar to the case with multiple antenna EH nodes, a rank-1 approximation on the resulting matrices is applied using the results of the randomization theory [33]. Furthermore, similar to the results of Section IV, the obtained general rank DL covariance matrix can be also implemented by applying space-time-block coding (STBC) schemes, e.g., see [34], [35].

A. Zero-Forcing-Based Transmit DL Beamforming

In the previous part we have provided an optimization framework to approach the optimal performance of the defined SWIPT system, when $M_{\rm EH} = 1$. In this part we provide a suboptimal approach where the design of the transmit strategies is reduced to a power adjustment problem on the fixed (pre-determined) beamforming vectors. We recall that in subsection III-B we justified the use of zero-forcing receive filters at the BS as a simplifying approach, which approaches the optimality as the number of BS antennas grows or as the noise intensity is not significant. In this part, we extend the same idea to the DL beamforming vectors where the data streams are merely transmitted in the null-space of the DL users and the EH nodes. Please note that the aforementioned transmit zero-forcing results in no information leakage from the BS to the EH nodes, while eliminates the DL-to-DL interference. Following the above-mentioned arguments we have

$$\mathbf{b}_k = \frac{p_{{\rm dl},k}}{\|\tilde{\mathbf{b}}_k\|_2}\tilde{\mathbf{b}}_k, \quad k \in \mathbb{K}_{\rm DL}, \tag{37}$$

where $\tilde{\mathbf{b}}_k^T$ is the k-th row of $\bar{\mathbf{H}}^{\dagger} := \left(\bar{\mathbf{H}}^H\bar{\mathbf{H}}\right)^{-1}\bar{\mathbf{H}}^H$ and $\bar{\mathbf{H}} := [\mathbf{h}_{{\rm dl},1}\cdots\mathbf{h}_{{\rm dl},K_{\rm DL}}, \mathbf{g}_1^T\cdots\mathbf{g}_{K_{\rm EH}}^T]$. The resulting power adjustment problem can be hence formulated as

$$\min_{\substack{\mathbf{Z}\in\mathcal{H},\\ p_{{\rm dl},k}\in\mathbb{R}_+,\,k\in\mathbb{K}_{\rm DL},\\ p_{{\rm ul},k}\in\mathbb{R}_+,\,k\in\mathbb{K}_{\rm UL}}} \quad (33a) \tag{38a}$$

$$\text{s.t.} \quad (33d), (33a)\text{-}(33b), \tag{38b}$$

where $\mathbf{B}_k$ is replaced in (38a)-(38b) as $\mathbf{B}_k = \frac{p_{{\rm dl},k}}{\|\tilde{\mathbf{b}}_k\|_2^2}\tilde{\mathbf{b}}_k\tilde{\mathbf{b}}_k^H$, and the constraint regarding the DL information leakage is eliminated due to the ZF in DL beamforming. Note that the above formulation, simplifies the DL beamforming problem into a power optimization problem for UL, DL, as well as finding the corresponding random noise covariance $\mathbf{Z}$. It is worth mentioning that the above problem holds the aforementioned SDP structure and hence can be solved using the known numerical solvers. Moreover, unlike the problems in the previous parts, (38a)-(38b) is defined with no rank-constraints and hence the optimal solution directly defines the transmit strategies from the BS and UL nodes. In the following part, the performance of the proposed methods is evaluated via numerical simulations, and the effect of different system parameters are observed.

VI. Simulation Results

In this part we investigate the performance of the proposed system via Monte-Carlo simulations. We assume that all channels are accurately known and follow the uncorrelated flat-fading model. We average the resulting system performance for 100 channel realizations. Each channel realization is simulated following the 3GPP LTE specifications for a macro-cell deployment [39, Scenario 8]. A single macro BS is hence considered at the center of a cell area, including UL and DL users, as well as energy receivers (EH nodes). The channels between BS and UL (DL) users are assumed to obtain a line-of-sight (LOS) path with the probability

$$P_{\rm LOS}(d) = \min(0.018/d, 1) \times (1 - \exp(-d/0.063)) + \exp(-d/0.063), \tag{39}$$

where d [km] represents the distance between the UL (DL) user and the BS. The EH nodes are assumed to be positioned with a LOS path to the BS, within the 50 meter radius. The flat-fading channel coefficients for the BS-UL, BS-DL, BS-EH, and UL-DL paths are generated as $h = 10^{(-\alpha/20)}\tilde{h}$, where $h \in \mathbb{C}$ represents the complex channel coefficient between two antennas of two different nodes, e.g., BS and DL, and α is representing the large scale fading factor, including shadowing and path loss. The factor $\tilde{h}$ is generated with unit variance and a Rayleigh distribution. Detailed deployment specifications as well as the resulting large-scale fading values are given in Table I. The self-interference channel is generated following [40], and the similar arguments as in [19], as flat-fading matrix with a Rician distribution: $\mathbf{H}_{\rm bb} \sim \mathcal{CN}\left(\sqrt{\frac{\sigma_{\rm SI}^2 K_{\rm R}}{1+K_{\rm R}}}\tilde{\mathbf{H}}_{\rm bb}, \frac{\sigma_{\rm SI}^2}{1+K_{\rm R}}\mathbf{I}_{M_{\rm t}M_{\rm r}}\right)$, where $K_{\rm R}$ is the Rician factor, $\tilde{\mathbf{H}}_{\rm bb}$ is a deterministic matrix, and $\sigma_{\rm SI}^2$ is the passive isolation that is provided by separating the transmit and receive antennas.

TABLE I. Setup Specifications

Parameter	Values
Cell Radius	250m
Carrier Frequency	2GHz
Bandwidth	10MHz
Height	User: 1.5m, BS: 30m
Noise Figure	BS: 5dB, User: 9dB
Thermal Noise Density	-174dBm/Hz
Path Loss (dB) between BS and users (d in km)	LOS: $103.4 + 24.2\log_{10} d$ NLOS: $131.1 + 42.8\log_{10} d$
Path Loss (dB) between users and users (d in km)	LOS: $98.45 + 20\log_{10} d,\ d \leq 50$m NLOS: $175.78 + 40\log_{10} d,\ d > 50$m
Shadowing Standard Deviation	Between UE and BS: 8dB Between UE and UE: 12dB

In Figs. 2-5, we have investigated the total network power consumption, under different values of the information rate requirements in UL and DL, i.e., $R_{{\rm ul},k,l}, R_{{\rm dl},k,l}$, the tolerable information leakage to the undesired destinations, i.e., $R_{{\rm ul},k,l}^{\rm (Leakage)}, R_{{\rm dl},k,l}^{\rm (Leakage)}$, the required successfully stored wireless power at the EH nodes, i.e., $P_{{\rm min},k}$, and the transceiver accuracy in dealing with the self-interference signal, i.e., β, κ. We apply the proposed designs in Section IV regarding the network power minimization. In this context, "ZF, μ=0" and "ZF, μ=1", respectively represent the power adjustment algorithm defined in Subsection V-A, for the optimistic ($\mu = 0$) and the pessimistic scenarios ($\mu = 1$). Similarly, "SDR, μ=0" and "SDR, μ=1" represent the defined SDR algorithm. It is worth mentioning that a similar HD setup leads to infeasibility of the UL information leakage constraints as it is not capable of transmission and reception at the same time. Unless otherwise is stated the following values are used to define our simulated

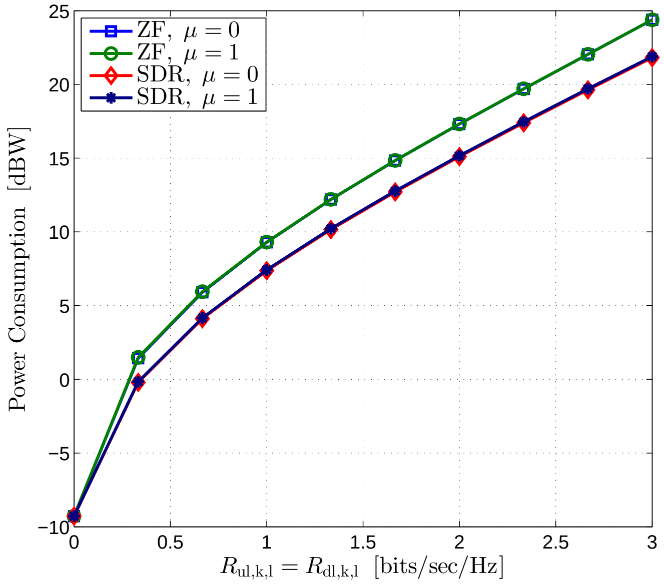

Fig. 2. Network power consumption [dBW] vs. requires information rate [bits/sec/Hz]. Power consumption increases for higher rate demand. The proposed power adjustment method performs close to optimality for different rate values.

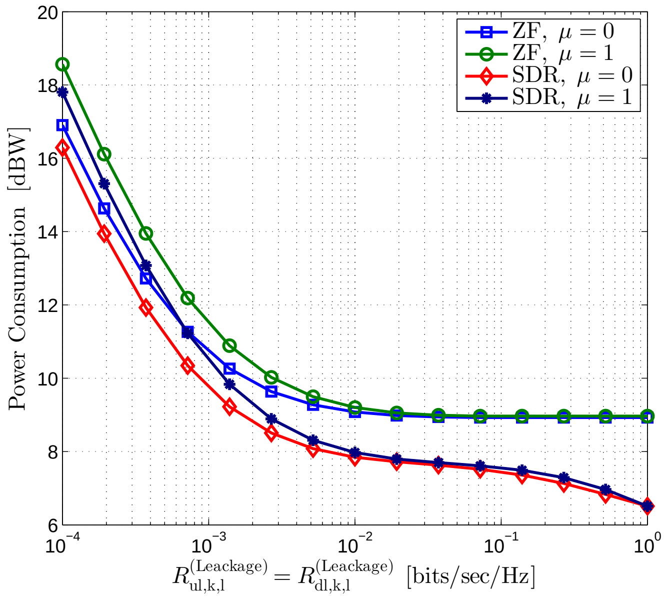

Fig. 3. Network power consumption [dBW] vs. tolerable information leakage rate [bits/sec/Hz]. The optimistic and pessimistic scenarios diverge as the tolerable leakage rate decreases. Smaller tolerable leakage rate results in significantly higher power consumption.

setup: $K_{\text{DL}} = K_{\text{UL}} = K_{\text{EH}} = 2$, $M_{\text{r}} = M_{\text{t}} = 6$, $M_{\text{EH}} = 1$. $\xi_k = 0.1$, $k \in \mathbb{K}_{\text{EH}}$, $P_{\text{min},k} = 0.01$ [μWatt], $k \in \mathbb{K}_{\text{EH}}$. $R^{(\text{Leakage})}_{\text{dl},k,l} = 0.1$ [bits/sec/Hz], $k \in \mathbb{K}_{\text{BS}}, l \in \mathbb{K}_{\text{EH}}$, $R^{(\text{Leakage})}_{\text{ul},k,l} = 0.5$ [bits/sec/Hz], $k \in \mathbb{K}_{\text{UL}}, l \in \mathbb{K}_{\text{EH}}$, $\kappa = \beta = -60$dB. $\bar{R}_{\text{dl},k} = 5$ [bits/sec/Hz], $k \in \mathbb{K}_{\text{BS}}$, $\bar{R}_{\text{ul},k} = 5$ [bits/sec/Hz], $k \in \mathbb{K}_{\text{UL}}$. $\gamma_{\text{bs}} = \gamma_{\text{ul},k} = 1$, $k \in \mathbb{K}_{\text{UL}}$, $K_{\text{R}} = 0.5$, $\sigma^2_{\text{SI}} = -40$ [dB] and $\tilde{\mathbf{H}}_{\text{bb}}$ is chosen to be a matrix of ones.

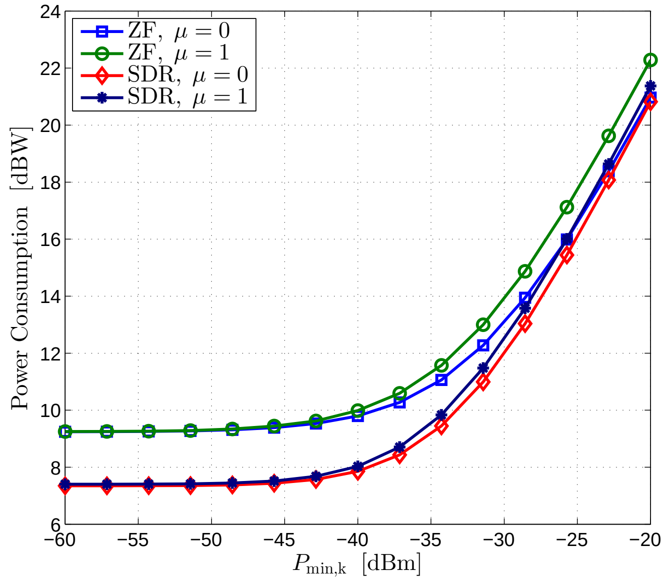

Fig. 4. Network power consumption [dBW] vs. $P_{\text{min},k}$ [dBm]. The optimistic and pessimistic scenarios diverge as the $P_{\text{min},k}$ increases.

VII. CONCLUSION

In this work we have addressed a transmit strategy design, for a multi-user communication network where a FD-BS simultaneously serves a gourp of HD-UL and HD-DL users, while transferring wireless power to a group of EH nodes. Particularly, we recognize that the reception of a power-containing signal at an EH node, may lead to security problems, as EH nodes may also be considered as a potential eavesdroppers. In this context, a physical-layer-security-aware design is proposed in order to minimize the network power consumption, while satisfying the corresponding rate requirements from the users, as well as applying security constraints regarding the information leakage to the EH nodes. Numerical simulations investigate the behavior of the proposed solutions under different system parameters.

REFERENCES

[1] J. I. Choi, S. Hong, M. Jain, S. Katti, P. Levis, and J. Mehlman, “Beyond full duplex wireless,” in *Forty Sixth Asilomar Conference on Signals, Systems and Computers*, Nov 2012.

[2] S. Hong, J. Brand, J. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, “Applications of self-interference cancellation in 5G and beyond,” *IEEE Communications Magazine*, February 2014.

[3] B. Day, A. Margetts, D. Bliss, and P. Schniter, “Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range,” *IEEE Transactions on Signal Processing*, Jul. 2012.

[4] D. Korpi, S. Venkatasubramanian, T. Riihonen, L. Anttila, S. Otewa, C. Icheln, K. Haneda, S. Tretyakov, M. Valkama, and R. Wichman, “Advanced self-interference cancellation and multiantenna techniques for full-duplex radios,” in *Signals, Systems and Computers, 2013 Asilomar Conference on*, Nov 2013.

[5] M. Jain, J. I. Choi, T. Kim, D. Bharadia, K. Srinivasan, S. Seth, P. Levis, S. Katti, and P. Sinha, “Practical, real-time, full duplex wireless,” in *Proceedings of 17th Annual International Conference on Mobile Computing and Networking (MobiCom)*, Las Vegas, NV, Sep. 2011.

[6] Y. Hua, P. Liang, Y. Ma, A. Cirik, and G. Qian, “A method for broadband full-duplex MIMO radio,” *IEEE Signal Processing Letters*, vol. 19, Dec. 2011.

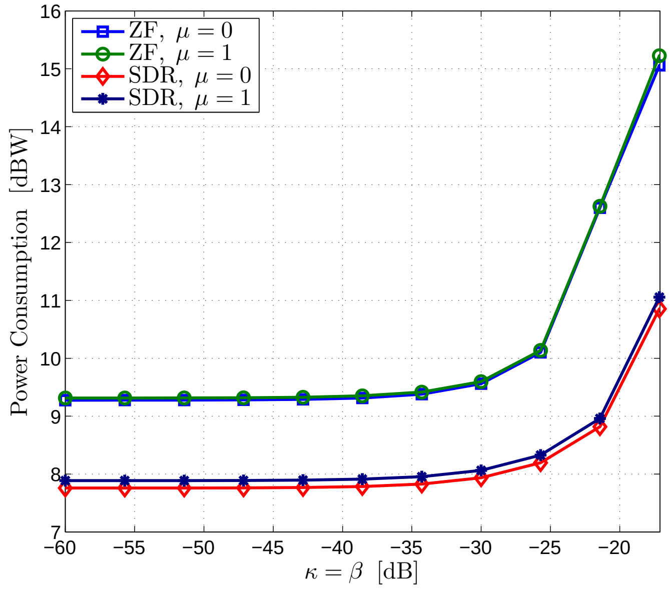

Fig. 5. Network power consumption [dBW] vs. FD transceiver accuracy [dB]. Less hardware accuracy at the FD-BS node results in the significantly higher power consumption, and potential infeasibility. Please note that the hardware accuracy and passive separation of antennas, i.e., $\sigma_{\rm SI}^2 = -40$ [dB], both aim at reducing the self-interference effect.

[7] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *Proceedings of the ACM SIGCOMM*, Aug. 2013.

[8] A. K. Khandani, "Two-way (true full-duplex) wireless," in *13th Canadian Workshop on Information Theory (CWIT, 2013)*.

[9] A. Cirik, R. Wang, Y. Hua, and M. Latva-aho, "Weighted sum-rate maximization for full-duplex mimo interference channels," *Communications, IEEE Transactions on*, vol. 63, March 2015.

[10] A. Cirik, Y. Rong, and Y. Hua, "Achievable rates of full-duplex MIMO radios in fast fading channels with imperfect channel estimation," *Signal Processing, IEEE Transactions on*, vol. 62, no. 15, Aug 2014.

[11] B. Day, A. Margetts, D. Bliss, and P. Schniter, "Full-duplex MIMO relaying: Achievable rates under limited dynamic range," *IEEE Journal on Selected Areas in Communications*, Sep. 2012.

[12] O. Taghizadeh and R. Mathar, "Full-duplex decode-and-forward relaying with limited self-interference cancellation," in *Proceedings of International ITG Workshop on Smart Antennas (WSA), Erlangen, Germany*, March 2014.

[13] T. Riihonen, S. Werner, and R. Wichman, "Transmit power optimization for multiantenna decode-and-forward relays with loopback self-interference from full-duplex operation," *Proc. 45th Annual Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA*, 2010.

[14] G. Zheng, I. Krikidis, J. Li, A. Petropulu, and B. Ottersten, "Improving physical layer secrecy using full-duplex jamming receivers," *IEEE Transactions on Signal Processing*, Oct 2013.

[15] O. Taghizadeh and R. Mathar, "Interference mitigation via power optimization schemes for full-duplex networking," in *19th International ITG Workshop on Smart Antennas*, March 2015.

[16] J. Zhang, O. Taghizadeh, and M. Haardt, "Robust transmit beamforming design for full-duplex point-to-point MIMO systems," *Proceedings of the Tenth International Symposium on Wireless Communication Systems (ISWCS)*, Aug. 2013.

[17] O. Taghizadeh and R. Mathar, "Robust multi-user decode-and-forward relaying with full-duplex operation," in *The Eleventh International Symposium on Wireless Communication Systems (ISWCS 2014)*, Barcelona, Spain, Sep. 2014.

[18] ——, "Cooperative strategies for distributed full-duplex relay networks with limited dynamic range," in *International Conference on Wireless for Space and Extreme Environments (WiSEE), 2014 IEEE*, Noordwijk, Netherlands.

[19] A. Cirik, O. Taghizadeh, R. Mathar, and T. Ratnarajah, "Qos considerations for full duplex multi-user mimo systems," *Wireless Communications Letters, IEEE*, vol. PP, no. 99, pp. 1–1, Oct 2015.

[20] D. Nguyen, L.-N. Tran, P. Pirinen, and M. Latva-aho, "Precoding for full duplex multiuser mimo systems: Spectral and energy efficiency maximization," *Signal Processing, IEEE Transactions on*, 2013.

[21] ——, "On the spectral efficiency of full-duplex small cell wireless systems," *IEEE Transactions on Wireless Communications*, Sept 2014.

[22] F. Zhu, F. Gao, M. Yao, and H. Zou, "Joint information- and jamming-beamforming for physical layer security with full duplex base station," *IEEE Transactions on Signal Processing*, vol. 62, Dec 2014.

[23] D. W. K. Ng, Y. Sun, and R. Schober, "Power efficient and secure full-duplex wireless communication systems," *arXiv preprint arXiv:1506.01853*, 2015.

[24] Y. Sun, D. W. K. Ng, J. Zhu, and R. Schober, "Multi-objective optimization for robust power efficient and secure full-duplex wireless communication systems," *arXiv preprint arXiv:1509.01425*, 2015.

[25] Y. Sun, D. W. K. Ng, and R. Schober, "Multi-objective optimization for power efficient full-duplex wireless communication systems," *arXiv preprint arXiv:1503.06021*, 2015.

[26] K. Huang and X. Zhou, "Cutting the last wires for mobile communications by microwave power transfer," *Communications Magazine, IEEE*, vol. 53, no. 6, pp. 86–93, June 2015.

[27] D. W. K. Ng and R. Schober, "Max-min fair wireless energy transfer for secure multiuser communication systems," in *Information Theory Workshop (ITW), 2014 IEEE*. IEEE, 2014, pp. 326–330.

[28] M. Khandaker and K.-K. Wong, "Robust secrecy beamforming with energy-harvesting eavesdroppers," *Wireless Communications Letters, IEEE*, vol. 4, no. 1, pp. 10–13, Feb 2015.

[29] H. Ju and R. Zhang, "Optimal resource allocation in full-duplex wireless-powered communication network," *Communications, IEEE Transactions on*, vol. 62, no. 10, pp. 3528–3540, 2014.

[30] S. Leng, D. W. K. Ng, N. Zlatanov, and R. Schober, "Multi-objective resource allocation in full-duplex swipt systems," *arXiv preprint arXiv:1510.01434*, 2015.

[31] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *Communications Magazine, IEEE*, vol. 52, no. 11, pp. 104–110, Nov 2014.

[32] S. P. Boyd and L. Vandenberghe, *Convex optimization*. Cambridge University Press, 2004.

[33] Y. Nesterov, "Semidefinite relaxation and nonconvex quadratic optimization," *Optimization methods and software*, vol. 9, 1998.

[34] S. Wu, W.-K. Ma, and A.-C. So, "Physical-layer multicasting by stochastic transmit beamforming and alamouti space-time coding," *Signal Processing, IEEE Transactions on*, vol. 61, no. 17, pp. 4230–4245, Sept 2013.

[35] K. L. Law, X. Wen, and M. Pesavento, "General-rank transmit beamforming for multi-group multicasting networks using ostbc," in *Signal Processing Advances in Wireless Communications (SPAWC), 2013 IEEE 14th Workshop on*, June 2013, pp. 475–479.

[36] Y. Zhao, R. Adve, and T. J. Lim, "Optimal STBC precoding with channel covariance feedback for minimum error probability," *EURASIP Journal on Applied Signal Processing*, vol. 2004, pp. 1257–1265, 2004.

[37] Y. Huang and D. P. Palomar, "Rank-constrained separable semidefinite programming with applications to optimal beamforming," *IEEE Transactions on Signal Processing*, vol. 58, pp. 664–678, Feb. 2010.

[38] G. Pataki, "On the rank of extreme matrices in semidefinite programs and the multiplicity of optimal eigenvalues," *Mathematics of operations research*, vol. 23, no. 2, pp. 339–358, 1998.

[39] T. . 3GPP, "Further enhancements to LTE time division duplex (TDD) for downlink-uplink (DL-UL) interference management and traffic adaptation (release 11)," 2012.

[40] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Transactions on Wireless Communications*, December 2012.