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 rises 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 energy harvesting (EH) nodes, under the constraints regarding 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 to 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, 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]–[16]. 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], [17]–[23]. More specifically, the works in [20]–[23] 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 studies in [20]. The latter work is then generalized for a setup with multiple antennas, and for a design with energy efficiency considerations in [21]–[23], 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 power as a source of energy for EH users is been introduced as an efficient and controllable source for EH [24], 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., [25], [26], such studies are only rarely extended for the scenarios with a FD-BS [27], [28].

In this work we consider a FD-BS which provides service simultaneously to HD UL and HD DL users, and provide energy transfer 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 hence to design a system which prevents a destructive information leakage to the un-intended users, while providing a required link quality in UL, DL, as well as the required power transfer to the ERs. 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 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 concludes the main results of this work. Please note that the current document is in the form of an extended abstract, and a more extensive simulation results will be provided in the final version of this paper.

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 $\mathbf{h}_{\text{dl},k} \in \mathbb{C}^{M_{\text{t}}}$. 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 with 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 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 $\mathbf{n}_{\text{bs}} \sim \mathcal{CN}(\mathbf{0}, N_{\text{bs}} \mathbf{I}_{M_{\text{r}}})$ respectively represent the transmit
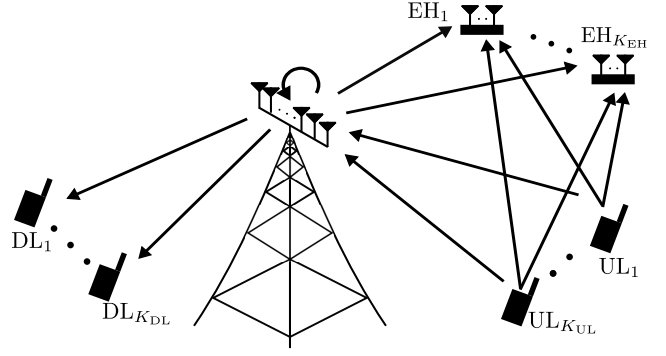

Fig. 1. Schematic of the defined SWIPT system. A FD BS node simultaneously provide communication service to a set of UL and DL users, while transferring power to a set of EH nodes.

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

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

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

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

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

where $\mathbf{b}_k \in \mathbb{C}^{M_{\mathrm{t}}}$ represents the beamforming vector at the BS for the k-th DL user, $s_{\mathrm{dl},k}$ is the corresponding data symbol with zero mean and $\mathbb{E}\{|s_{\mathrm{dl},k}|^2\} = 1$. The artificially generated noise at the BS is denoted as $\mathbf{z} \in \mathbb{C}^{M_{\mathrm{t}}}$, which is intended to convey energy to the EH nodes. Regarding the generation of $\mathbf{z} \in \mathbb{C}^{M_{\mathrm{t}}}$ 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., [28]. 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 k-th DL user can be written as

$$y_{\mathrm{dl},k} = \mathbf{h}_{\mathrm{dl},k}^T \mathbf{x}_{\mathrm{bs}} + n_{\mathrm{dl},k}, \tag{9}$$

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

C. Received signal at EH nodes

The function of EH nodes is to extract and store energy from the received RF signal, e.g., [29]. The baseband representation of the received signal at the k-th EH node is

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

where $\mathbf{n}_{\mathrm{eh},k} \sim \mathcal{CN}\left(\mathbf{0}, N_{\mathrm{eh},k} \mathbf{I}_{M_{\mathrm{EH}}}\right)$ 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, 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 [21]–[23], [25], [28].

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

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

where $\zeta_{\mathrm{dl},k} \in \mathbb{R}_+$ 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

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

assuming Gaussian distribution for the transmitted signal and all interference sources in the network. Note that $R_{\mathrm{dl},k}$ 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

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

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

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

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 [21], [22], 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 $\tilde{\mathbf{H}} := [\mathbf{h}_{\mathrm{ul},1} \cdots \mathbf{h}_{\mathrm{ul},K_{\mathrm{UL}}}]$ and $\tilde{\mathbf{H}}^\dagger := \left(\tilde{\mathbf{H}}^H \tilde{\mathbf{H}}\right)^{-1} \tilde{\mathbf{H}}^H$, see [21, Equation (12)]. The normalized communication rate can be obtained similar to the DL case as

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

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

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

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

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

where

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

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

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

where

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

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

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

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

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

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

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

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

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

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

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 $p_{\text{max},k}$ and $p_{\text{bs-max}}$, where the minimum required power at the k-th EH node is denoted by $P_{\text{min},k}$.

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 equivalent 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 [30]. 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

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

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

$$\text{tr}\left(\tilde{\mathbf{B}}\right) \leq p_{\text{bs-max}}, \tag{22c}$$

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

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

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

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

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

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

where

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

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

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

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

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

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

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

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

and $\mathbf{E} := \mathbb{E}\{\mathbf{e} \mathbf{e}^H\}$ is obtained by replacing $\tilde{\mathbf{B}}$ in (14). Nevertheless, the reformulated problem (22a)-(22i) does not hold a convex structure, due to the rank constraint (22i). Hence by temporarily ignoring (22i) the corresponding rank-relaxed problem is formulated as

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

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

which is a convex optimization problem and can be efficiently solved using known numerical solvers, e.g., SDPT3 [30]. If the obtained solutions for $\mathbf{B}_k$, i.e., $\mathbf{B}_k^\star, k \in \mathbb{K}_{\text{DL}}$ satisfy the relaxed constraint (22i), i.e., rank$\left(\mathbf{B}_k^\star\right) = 1$, they are also an optimal solution for (22a)-(22i). In this case, an optimal DL transmit beamforming vector is obtained as $\mathbf{b}_k^\star = \lambda_{\text{max}}\left(\mathbf{B}_k^\star\right)$, where $\lambda_{\text{max}}(\cdot)$ 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., [31]. It is worth mentioning that a general rank DL covariance matrix can be as well obtained by applying a space-time-block coding (STBC) schemes, e.g., see [32]. Further explanations will be included in this regard in the final version of this paper.

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 $\mathbf{g}_k \in \mathbb{C}^{1 \times M_r}$ 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

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

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

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

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

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 $\mathbf{Z}_k, k \in \tilde{\mathbb{K}}_{\text{EH}}$. Nevertheless, as we see later on, it provides further simplifications on finding an optimal rank-1 DL beamforming matrices, i.e., $\mathbf{B}_k^\star$. It is worth mentioning that the above problem holds a simpler structure compared to Note that 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 [33], [34]. Exploiting the results of the [33, Theorem 3.2], an optimal rank-1 set of semi-definite variables for the problem (22a)-(22h) is available and can be calculated if we have

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

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 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 [31]. Further explanations will be included in this regard in the final version of this paper.

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 $M_{\text{EH}} = 1$. 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 reaches close optimality as the number of BS antennas are very high 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 to the EH nodes, while eliminates the UL-to-UL and DL-to-DL interference. Following the above-mentioned arguments we have

$$\mathbf{b}_k = p_{\text{dl},k} \tilde{\mathbf{b}}_k, \quad k \in \mathbb{K}_{\text{DL}}, \qquad (37)$$

where $\tilde{\mathbf{b}}_k$ 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 $\bar{\mathbf{H}} := [\mathbf{h}_{\text{dl},1} \cdots \mathbf{h}_{\text{dl},K_{\text{DL}}}, \mathbf{g}_1^T \cdots \mathbf{g}_{K_{\text{EH}}}^T]$. The resulting power adjustment problem can be hence formulated as

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

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

where $\mathbf{B}_k$ is replaced in (38a)-(38b) as $\mathbf{B}_k = p_{\text{dl},k} \tilde{\mathbf{b}}_k \tilde{\mathbf{b}}_k^H$, 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 Rayleigh flat-fading model. We apply the proposed designs in Section IV regarding the network power minimization, under explicit information rate constraints for UL and DL, the information leakage constraints. Unless otherwise is stated the following values are used to define our simulated setup: $K_{\text{DL}} = K_{\text{UL}} = K_{\text{EH}} = 2$, $M_{\text{r}} = M_{\text{t}} = 6$, $M_{\text{EH}} = 1$, $N_{\text{eh}} = N_{\text{eh},k} = 0.1$, $k \in \mathbb{K}_{\text{EH}}$, $N_{\text{dl}} = N_{\text{dl},k} = 0.1$, $k \in \mathbb{K}_{\text{DL}}$, $N_{\text{bs}} = N_{\text{bs},k} = 0.1$, $k \in \mathbb{K}_{\text{BS}}$. $\xi_k = 0.1$, $k \in \mathbb{K}_{\text{EH}}$, $P_{\text{min},k} = 1$, $k \in \mathbb{K}_{\text{EH}}$. $R_{\text{dl},k,l}^{(\text{Leakage})} = 0.5$, $k \in \mathbb{K}_{\text{BS}}, l \in \mathbb{K}_{\text{EH}}$, $R_{\text{ul},k,l}^{(\text{Leakage})} = 0.5$, $k \in \mathbb{K}_{\text{UL}}, l \in \mathbb{K}_{\text{EH}}$, $\kappa = \beta = 0.001$. $\bar{R}_{\text{dl},k} = 5, k \in \mathbb{K}_{\text{BS}}$, $\bar{R}_{\text{ul},k} = 5, k \in \mathbb{K}_{\text{UL}}$. $\gamma_{\text{bs}} = \gamma_{\text{ul},k} = 1$, $k \in \mathbb{K}_{\text{UL}}$. The variance of the channel coefficients regarding all paths are assumed to be 1, except for the self-interference path which is assumed to be 10^4 times bigger than the other paths. In Fig. 2, the impact of different noise levels are observed on the network power consumption. It is observed that a higher resource is required to satisfy a fixed requirements as the noise level increases. Other than the total network power consumption, the consumed power in the UL and BS are plotted with separated curves. Furthermore, $\mu = 0$ represents an optimistic scenario in which the generated noise sequence is known in the intended DL users. On the other hand, $\mu = 1$ represents the case that the information regarding the noise sequence $\mathbf{z}$ is not distributed in the network. In Fig. 3, the network power consumption is studied for different required power values at the EH nodes. Note that as the required power in the EH node increases, the intensity of the generated random sequence $\mathbf{z}$ also increases at the BS. This leads to a larger performance gap between the two studied scenarios, i.e., $\mu = 0$ and $\mu = 1$. **A more extensive simulation results will be provided in the final version of this paper, under the 3GPP LTE specifications for small cell deployments [35], in order to observe the impact of the proposed methods under a realistic scenario.**

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 the 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 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.

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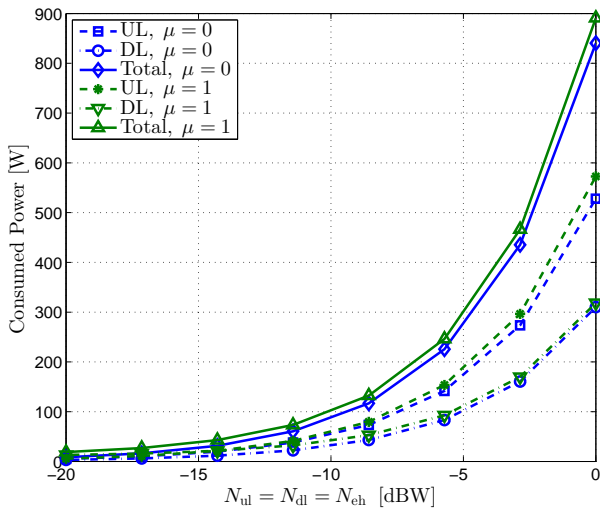
Fig. 2. Network power consumption vs. Noise intensity. Power consumption increases significantly as noise level increases.
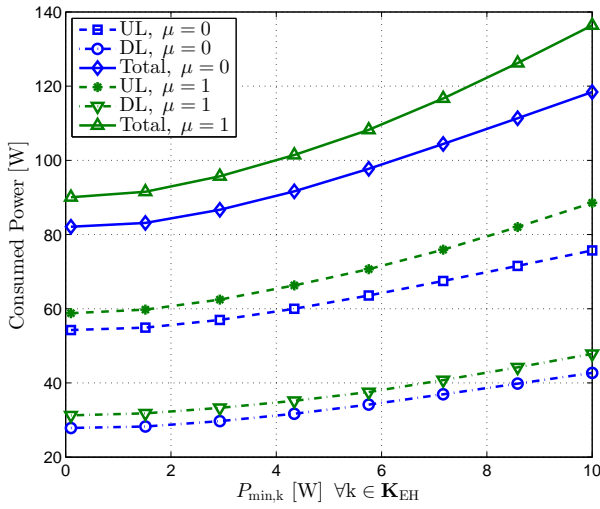

Fig. 3. Network power consumption vs. required power at EH nodes. More UL and DL power is required as the required harvesting power increases.

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