Energy Efficient Hybrid Duplexing and Resource Allocation for Distributed Antenna Systems

Zhongxiang Wei*, Sumei Sun†, Xu Zhu* , Yi Huang* and Jingjing Wang‡
*Department of Electrical Engineering and Electronics, The University of Liverpool, Liverpool, U.K.
Email: {hszwei,xuzhu,yihuang}@liverpool.ac.uk
†Institute for Infocomm Research, A*STAR, Singapore. Email: sunsm@i2r.a-star.edu.sg
‡Department of Electric Engineering, Tsinghua University, Beijing, China.
chinaeephd@gmail.com

***Abstract*—Motivated by the high data rate requirement, full-duplex (FD) multiple-input multiple-output (MIMO) has attracted much attention in both academia and industry. However, FD and MIMO techniques require high power consumption. To strike the balance between the data rate and power consumption, we propose a novel hybrid duplexing strategy, in which antennas are distributed across the service areas and are capable of working in hybrid modes of FD, half-duplex (HD) and sleeping mode, leading to higher energy efficiency (EE) than FD mode only due to enhanced degree of freedom. Based on the hybrid duplexing strategy, we maximize system EE by jointly designing transmitting/receiving chains' activation/deactivation at DAs, downlink beamformer, and uplink transmission power. Novel optimization algorithms are developed. Simulation results confirm that the hybrid duplexing distributed antenna (DA) system provides significant EE improvement over the conventional centralized FD MIMO system, showing its green evolution and applicability to future network deployment.**

***Index Terms*—Hybrid duplexing, distributed antennas, energy efficiency, nonconvex optimization**

I. Introduction

To meet the exponential data rate increase in future wireless communications, multiple-input multiple-output (MIMO) [1] technique is regarded as a promising solution. The early stage of MIMO adopts half-duplex (HD) mode, where uplink and downlink transmission are decoupled into orthogonal time slots or frequencies [2]. In an effort to further improve the spectral efficiency (SE), full-duplex (FD) MIMO communication has been proposed, where uplink and downlink transmission are operated simultaneously over the same frequency [3] [4], subject to effective self-interference cancellation (SIC). The authors in [5] utilize transmitting/receiving diversities in MIMO system to suppress the self-interference. In [6], a FD MIMO precoding transceiver structure applicable for orthogonal frequency division multiplexing (OFDM) systems is presented to maximize SE, while the authors in [7] consider a small cell FD system, where a FD base station (BS) communicates with multiple single-antenna users in downlink and uplink simultaneously. The authors in [8] study the power adaptation in a co-located FD MIMO deployment, which are limited in reducing path loss (PL) and blockage effect.

FD and MIMO techniques, however, both require higher power consumption, which is against the green evolution requirement for future communication systems [9]. This is because MIMO increases the number of active transmitting/receiving chains, leading to much higher power consumption than single-input single-output (SISO) configuration. For FD systems, additional power is consumed by SIC [3] in FD systems. As a result, how to ensure high energy efficiency (EE) transmission becomes a fundamental challenge in the conventional centralized FD MIMO systems [10].

Motivated by the aforementioned outstanding issues, in this paper, we investigate hybrid duplexing and resource allocation to maximize EE performance of bi-directional distributed antenna (DA) systems. Our work is different in the following aspects.

1) We first propose a hybrid duplexing strategy for DA system. Compared to the co-located FD MIMO system in [7] and FD SISO in our previous work [3] [10], the advantages of hybrid duplexing DA system are threefold: a) The hybrid duplexing strategy allows DA to work in HD mode (transmitting or receiving), which has only one active transmitting or receiving chain and does not require SIC by HD DAs. As a result, lower power consumption and higher EE is endorsed by the hybrid duplexing. b) Because of the distributed deployment of antennas and the reduced PL, the self-interference among different DAs can be effectively mitigated in the propagation domain, and active SIC (analog/digital cancellation) is only needed within FD DAs, which becomes as easy as that in SISO case. c) High PL and blockage can be significantly alleviated by the geometrically located DAs.

2) We take EE maximization as optimization target, which is essentially different from the existing optimization design on SE maximization [1] or total power consumption minimization [11]. To solve the problem with low complexity, a DA clustering algorithm is first proposed to perform transmitting/receiving chains activation/deactivation at DAs, and then a distributed hybrid duplexing based EE maximization (DHD-EE) algorithm is developed to concurrently allocate beamformer at transmitting-chain-active DAs and transmission power at uplink users.

3) To rationalize the system model, residual self-interference at DAs, co-channel interference from uplink users to downlink users and multiuser interference in both uplink and downlink are taken into account. The power amplifier (PA) dissipated

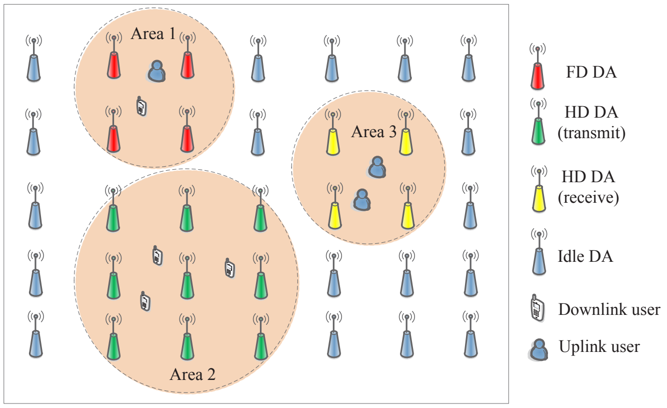

Fig. 1. The illustration of bidirectional hybrid duplexing DA system, where DAs are capable of working in FD, HD and sleeping modes.

consumption, circuit power consumption and power consumed by SIC operation are included into the power consumption model, which is more accurate than existing power model formulated for FD systems in [11] [12].

Notation: Matrices and vectors are represented by boldface capital and lower case letters, respectively. $|\cdot|$ denotes the absolute value of a complex scalar. $||\cdot||$ denotes the Euclidean vector norm. $\boldsymbol{A}^H$ and tr($\boldsymbol{A}$) denote the Hermitian transpose and trace of matrix $\boldsymbol{A}$. Rank($\boldsymbol{A}$) denote the rank of matrix $\boldsymbol{A}$. diag ($\boldsymbol{A}$) returns a diagonal matrix with diagonal elements from matrix $\boldsymbol{A}$. $\boldsymbol{A} \succeq 0$ means $\boldsymbol{A}$ is a positive semi-definite matrix. Superscript k or u denotes the downlink/uplink user's index.

II. System Model and Problem Formulation

A. System Model

We consider a bi-directional DA system with one central signal processing unit. All L DAs ports are connected to the central unit through a noise-free wired front-haul for cooperative communications. The DAs can work in FD, HD (transmitting or receiving) or sleeping mode, while the users employ single-antenna HD for low hardware complexity. In particular, there are U uplink users and K downlink users. We assume that the channel state information is available, obtained by the pilot assisted reciprocal channel estimation.

Define a receiving chain activation vector $\boldsymbol{r} \in \mathbb{C}^{L\times 1}$, whose $l-th$ element r_l is equal to 1 if the $l-th$ DA's receiving chain is activated, otherwise r_l is equal to 0. Similarly, define a transmitting chain activation vector $\boldsymbol{t} \in \mathbb{C}^{L\times 1}$, whose $l-th$ element t_l is equal to 1 if the $l-th$ DA's transmitting chain is activated, otherwise t_l is equal to 0. Define $\boldsymbol{w_k} \in \mathbb{C}^{L\times 1}$, as beamformer at DAs for downlink user k, $\forall k \in K$. For each vector $\boldsymbol{w_k}$, its element w_k^l denotes the beamforming weight of antenna l for user k. Denote p_u as transmission power allocation at uplink users, for $\forall u \in U$.

To maximize the system EE, we jointly optimize vectors $\boldsymbol{r}, \boldsymbol{t}$, beamformer $\boldsymbol{w_k}$, for $\forall k \in K$, and transmission power p_u, for $u \in U$. Define $\omega(\boldsymbol{r}, \boldsymbol{t}, \boldsymbol{w_k}, p_u)$ as the EE (in bits/Joule/Hz), which is the ratio of the system total throughput T_{total} to the incurred total power consumption P_{total}. Since the EE maximization involves with throughput and power consumption in both downlink and uplink. In this section, we analyze the downlink and uplink throughput in Subsection II-B and II-C, respectively. Then the power consumption is presented in Subsection II-D.

B. Downlink Throughput

In each time slot, the received signal at downlink user $k \in \{1, ..., K\}$ is given by

$$y_k^{DL} = \boldsymbol{h_k}(\boldsymbol{t} \circ \boldsymbol{w_k})d_k^{DL} + \sum_{k'\neq k}^{K} \boldsymbol{h_k}(\boldsymbol{t} \circ \boldsymbol{w_{k'}})d_{k'}^{DL} + \sum_{u=1}^{U} \sqrt{p_u} e_{u,k} d_u^{UL} + z_k, \quad (1)$$

where the operator $\circ$ denotes the pair-wise product of two elements of vectors or matrices. Vector $\boldsymbol{h_k} \in \mathbb{C}^{1\times L}$ is downlink channel between L DAs and downlink user k, which captures the PL and small scale fading. $d_k^{DL} \in \mathbb{C}$ is the transmitted data for downlink user k. $e_{u,k} \in \mathbb{C}$ denotes the channel from uplink user u to downlink user k. $d_u^{UL} \in \mathbb{C}$ is the transmitted data from uplink user u. $z_k \sim CN(0, \sigma_k^2)$ is the complex Additive While Gaussian Noise (AGWN) at downlink user k. Without loss of generality, we assume the transmitted data has unit power, that $\mathbb{E}\{|d_k^{DL}|^2\} = \mathbb{E}\{|d_u^{UL}|^2\} = 1$, for $\forall k \in K$ and $\forall u \in U$.

For simplicity, we introduce the auxiliary matrices $\boldsymbol{F_l} = diag\{\underbrace{0, ..., 0}_{l\text{-}1}, 1, \underbrace{0, ..., 0}_{L\text{-}l}\}$ to transform the pair-wise product $\boldsymbol{t} \circ \boldsymbol{w_k}$ into a simple form $\boldsymbol{t} \circ \boldsymbol{w_k} = \sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k}$, $\forall l \in L$. Therefore, the received signal at downlink user k can be re-expressed as

$$y_k^{DL} = \boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k})d_k^{DL} + \sum_{k'\neq k}^{K} \boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_{k'}})d_{k'}^{DL} + \sum_{u=1}^{U} \sqrt{p_u} e_{u,k} d_u^{UL} + z_k. \quad (2)$$

According to (2), the signal-to-interference-and-noise ratio (SINR) of downlink user k is calculated as

$$\Gamma_k^{DL} = \frac{\left|\boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k})\right|^2}{\sum_{k'\neq k}^{K} \left|\boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_{k'}})\right|^2 + \sum_{u=1}^{U} p_u \left|e_{u,k}\right|^2 + \sigma_k^2}. \quad (3)$$

Therefore, the overall downlink throughput can be calculated by (4). To further simplify the mathematical expression, we define matrices $\boldsymbol{H_k} = \boldsymbol{h_k}^H \boldsymbol{h_k}$ and $\boldsymbol{W_k} = \boldsymbol{w_k} \boldsymbol{w_k}^H$, and transform the total downlink throughput into the structure $\log(1 + \frac{A}{B}) = \log(A + B) - \log B$. Now the overall downlink throughput is re-written as

$$T_{DL} = \sum_{k=1}^{K} \log_2\Big(1 + \frac{\left|\boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k})\right|^2}{\sum_{k' \neq k}^{K} \left|\boldsymbol{h_k}(\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_{k'}})\right|^2 + \sum_{u=1}^{U} p_u \left|e_{u,k}\right|^2 + \sigma_k^2}\Big). \tag{4}$$

$$\begin{aligned} T_{DL} = & \sum_{k=1}^{K} \log_2\big(\sum_{k'=1}^{K} \mathrm{Tr}(\sum_{m=1}^{L}\sum_{n=1}^{L} t_m t_n \boldsymbol{F_m} \boldsymbol{W_{k'}} \boldsymbol{F_n}^H \boldsymbol{H_k}) \\ & + \sum_{u=1}^{U} p_u |e_{u,k}|^2 + \sigma_k^2\big) \\ & - \sum_{k=1}^{K} \log_2\big(\sum_{k' \neq k}^{K} \mathrm{Tr}(\sum_{m=1}^{L}\sum_{n=1}^{L} t_m t_n \boldsymbol{F_m} \boldsymbol{W_{k'}} \boldsymbol{F_n}^H \boldsymbol{H_k}) \\ & + \sum_{u=1}^{U} p_u |e_{u,k}|^2 + \sigma_k^2\big). \end{aligned} \tag{5}$$

C. Uplink Throughput

In uplink, define self-interference channel matrix $\boldsymbol{H_{SI}} \in \mathbb{C}^{L\times L}$, and an SIC amount α, denoting the post-SIC self-interference power over the pre-SIC self-interference power. As a result, the residual self-interference vector after SIC is given by $\frac{1}{\sqrt{\alpha}} \boldsymbol{H_{SI}} \sum_{k=1}^{K}\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k} d_k^{DL}$, and the uplink received signal at the DAs is given by

$$\boldsymbol{y}^{UL} = \sum_{u=1}^{U} \sqrt{p_u} \boldsymbol{g_u} d_u^{UL} + \frac{1}{\sqrt{\alpha}} \boldsymbol{H_{SI}} \sum_{k=1}^{K}\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k} d_k^{DL} + \boldsymbol{z}, \tag{6}$$

where vector $\boldsymbol{g_u} \in \mathbb{C}^{L\times 1}$ is the uplink channel from user u to L DAs. Vector $\boldsymbol{z} \in \mathbb{C}^{L\times 1}, \sim CN(0, \sigma^2 \boldsymbol{I_L})$ is the AWGN noise at DAs.

We assume that the central unit employs a linear maximum ratio combining receiver [11], $\boldsymbol{v_u} \in \mathbb{C}^{L\times 1}$, for decoding of the received $u-th$ uplink user information, which is given by $\boldsymbol{v_u} = \sum_{i=1}^{L} r_i \boldsymbol{F_i} \boldsymbol{g_u}$. It is obvious that $r_i = 0$ means the receiving chain of the $i-th$ DA is deactivated. As a result, the equivalent SINR for uplink user u is given by

$$\Gamma_u^{UL} = \frac{p_u |\boldsymbol{v_u}^H \boldsymbol{g_u}|^2}{\sum_{u' \neq u}^{U} p_{u'} |\boldsymbol{v_u}^H \boldsymbol{g_{u'}}|^2 + \frac{\left|\boldsymbol{v_u}^H \boldsymbol{H_{SI}} \sum_{k=1}^{K}\sum_{l=1}^{L} t_l \boldsymbol{F_l} \boldsymbol{w_k}\right|^2}{\alpha} + \sigma'^2}, \tag{7}$$

where $\sigma'^2 = ||\boldsymbol{v_u}||^2 \sigma^2$. Define $\boldsymbol{G_u} = \boldsymbol{g_u} \boldsymbol{g_u}^H$ and substitute $\boldsymbol{v_u} = \sum_{i=1}^{L} r_i \boldsymbol{F_i} \boldsymbol{g_u}$ into (7), the overall uplink throughput is finally given by (8).

D. Power Consumption

The power consumption model consists two main parts [10] [12]: PA power and circuit power. In particular, the circuit power can be further divided into a static power and a dynamic part.

a) PA dissipated power is given by $\frac{1}{\eta}\big(\mathrm{Tr}(\sum_{k=1}^{K} \boldsymbol{W_k}) + \sum_{u=1}^{U} p_u\big)$ [11], where η is the drain efficiency (DE) of PAs. Without loss of generality, we assume that all PAs (of DAs and users) have the same DE performance.

b) Dynamic circuit power is proportional to the number of active transmitting and receiving chains, including the power consumed by digital/analogue (D/A) converter, filter, synthesizer, electrical to optical (E/O) converter, *etc*. Dynamic circuit power is given by $\sum_{l=1}^{L} \big((1-r_l)(1-t_l)\big) p_{idle} + \sum_{l=1}^{L} r_l p_{c,r} + \sum_{l=1}^{L} t_l p_{c,t}$, where $p_{c,t}$ and $p_{r,t}$ denote the circuit power consumed by active receiving and transmitting chain, respectively. p_{idle} denotes the circuit power consumption of each sleeping DA. On the other hand, static circuit power p_{fix} includes the power consumed by power supply, cooling, *etc.,* which is independent of the state of transmitting/receiving chains.

For the DAs working in FD mode, *i.e.,* $r_l = 1$ and $t_l = 1$, for $\forall l \in L$, additional power is required for SIC operation. The power consumed by SIC is related to the specific operation, and can be considered as a constant value [10]. Define p_{can} as the power required by SIC at each DA, and the overall power consumed by SIC is given as $\sum_{l=1}^{L} r_l t_l p_{can}$. At last, the total power is given as

$$\begin{aligned} P_{\text{total}} = & \frac{1}{\eta}\big(\mathrm{Tr}(\sum_{k=1}^{K} \boldsymbol{W_k}) + \sum_{u=1}^{U} p_u\big) + \sum_{l=1}^{L} t_l r_l p_{can} \\ & + \sum_{l=1}^{L} \big((1-r_l)(1-t_l)\big) p_{idle} + \sum_{l=1}^{L} r_l p_{c,r} + \sum_{l=1}^{L} t_l p_{c,t} + p_{fix}. \end{aligned} \tag{9}$$

III. Energy Efficiency Maximization Design

According to the throughput and power consumption analysis in Section II, the optimization problem is expressed as

$$\begin{aligned} P1: & \underset{\boldsymbol{r},\boldsymbol{t},\boldsymbol{W_k},p_u}{\mathrm{argmax}} \ \frac{T_{DL}(\boldsymbol{r},\boldsymbol{t},\boldsymbol{W_k},p_u) + T_{UL}(\boldsymbol{r},\boldsymbol{t},\boldsymbol{W_k},p_u)}{P_{\text{total}}(\boldsymbol{r},\boldsymbol{t},\boldsymbol{W_k},p_u)}, \\ s.t. \ & (C1): \sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W_k}\boldsymbol{F_l}) \le p_{DA}, \forall l \in L, \\ & (C2): 0 \le p_u \le p_{u,max}, \forall u \in U, \\ & (C3): r_l = \{0,1\}, \forall l \in L, \\ & (C4): t_l = \{0,1\}, \forall l \in L, \\ & (C5): \boldsymbol{W_k} \succeq 0, \forall k \in K, \\ & (C6): \mathrm{Rank}(\boldsymbol{W_k}) = 1, \forall k \in K, \end{aligned} \tag{10}$$

where constraint $(C1)$ denotes the transmission power at each DA is upper bounded by p_{DA}, for $\forall l \in L$. $(C2)$ denotes that

$$
\begin{aligned}
T_{UL} = &\sum_{u=1}^{U} \log_2 \Big(\sum_{u'=1}^{U} p_{u'} \mathrm{Tr}(\boldsymbol{G_{u'}} \sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \boldsymbol{F_i G_u F_j^H}) + \\
&\frac{1}{\alpha}\mathrm{Tr}\big(\mathrm{diag}(\boldsymbol{H_{SI}}(\sum_{k=1}^{K}\sum_{m=1}^{L}\sum_{n=1}^{L} t_m t_n \boldsymbol{F_m W_k F_n^H})\boldsymbol{H_{SI}^H})(\sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \boldsymbol{F_i G_u F_j^H})\big) + \sigma^2 \mathrm{Tr}(\sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \mathbf{F}_i \mathbf{G}_u \mathbf{F}_j^H)\Big) \\
&- \sum_{u=1}^{U} \log_2 \Big(\sum_{u' \neq u}^{U} p_{u'} \mathrm{Tr}(\boldsymbol{G_{u'}} \sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \boldsymbol{F_i G_u F_j^H}) + \\
&\frac{1}{\alpha}\mathrm{Tr}\big(\mathrm{diag}(\boldsymbol{H_{SI}}(\sum_{k=1}^{K}\sum_{m=1}^{L}\sum_{n=1}^{L} t_m t_n \boldsymbol{F_m W_k F_n^H})\boldsymbol{H_{SI}^H})(\sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \boldsymbol{F_i G_u F_j^H})\big) + \sigma^2 \mathrm{Tr}(\sum_{i=1}^{L}\sum_{j=1}^{L} r_i r_j \boldsymbol{F_i G_u F_j^H})\Big).
\end{aligned} \tag{8}
$$

the transmission power allocated at each uplink user u is non-negative and upper bounded by $p_{u,max}$, for $\forall u \in U$. $(C3)$ and $(C4)$ denote the status of the receiving and transmitting chains of DA l, for $\forall l \in L$. $(C5)$ and $(C6)$ are imposed to guarantee that $\boldsymbol{W_k} = \boldsymbol{w_k w_k^H}$ holds after optimization.

The problem in $P1$ is generally very difficult to solve. It involves a) vectors $\boldsymbol{r}, \boldsymbol{t}$ with binary elements in the objective function and constraints. b) product of binary variables t_m, t_n, r_i, r_j with continuous variables $\boldsymbol{W_k}, p_u$, for $\forall k \in K, u \in U$, $\forall m, n, i, j \in L$. c) rank constraint in $(C6)$. Besides, with L DAs, there are 4^L possibilities of DA configurations. It is prohibitive to find the global optimum in terms of computational complexity and thus a low-complexity suboptimal algorithm is desirable. Therefore, in the Subsection III-A, we first propose a DA clustering algorithm to reduce the complexity significantly, which effectively removes the binary variables in the objective function as well as in constraints $(C3)$ and $(C4)$. Then a novel DHD-EE algorithm is proposed to optimize beamformer $\boldsymbol{W_k}$, for $\forall k \in K$ and transmission power p_u, for $\forall u \in U$, in Subsection III-B.

A. Transmitting/Receiving Chain Activation/Deactivation

Intuitively, if the channel condition between the $l-th$ DA and uplink users is good, while the channel condition between the DA and downlink users is poor, the DA should work in HD receiving mode. Since if the DA works in FD mode, its downlink throughput contribution is poor for all downlink users, while more power consumption is required. Also, the downlink transmission corrupts its uplink reception due to the introduced self-interference. Conversely, the DA should work in HD transmitting mode, if the channel condition between the DA and uplink users is poor while the channel condition between the DA and downlink users is strong. Also, one DA can work in FD mode if it has good channel condition from uplink and downlink users, which contributes affordable throughput in both uplink and downlink with additional power consumption. At last, if one DA has poor channel condition from all users, the DA can be turned-off to save power consumption.

To implement the DA cluster algorithm, a threshold, *i.e.*, ψ, is needed for judgment. The threshold can be adjusted according to different requirements and DA density. For example, one can increase ψ if power consumption requirement is stringent. It means less antennas will be activated and therefore power consumption is decreased. If users' quality of service requirement is stringent, one can decrease the value of ψ, it means more antennas will be activated. Also, for a dense DA deployment, the value of ψ could be higher than a sparse deployment. Then beamformer at DAs and transmission power allocation at uplink users are ready to perform.

B. Design of Beamformer and Uplink Transmission Power

After the transmitting/receiving chains deactivation/activation, we define a super matrix $\boldsymbol{W} = \{\boldsymbol{W_1}, \boldsymbol{W_2}, ..., \boldsymbol{W_K}\}$, including all beamformer variables $\boldsymbol{W_k}, \forall k \in K$, and a vector $\boldsymbol{p} = \{p_1, p_2, ..., p_U\}$, including all uplink transmission power variables $p_u, \forall u \in U$. The feasible domain confined by the constraints is expressed as $\boldsymbol{\Theta}$. For the rank constraint in $(C6)$, rank relaxation can be applied [7]. In particular, with the condition that the downlink channel vectors $\boldsymbol{h_k}, k \in K$, and the uplink channel vector $\boldsymbol{g_u}, u \in U$, can be modeled as i.i.d variables, the solution of original problem is rank-one [11]. In DA systems, the channel can be modeled by independent and uncorrelated [13], which is different from the co-located antennas systems. Accordingly, we drop the rank-1 constraint $(C6)$ benefiting from the DA deployment.

Then for total throughput $T_{DL}(\boldsymbol{W}, \boldsymbol{p}) + T_{UL}(\boldsymbol{W}, \boldsymbol{p})$, as expressed by (5) and (8), we collect the positive parts into $f_1(\boldsymbol{W}, \boldsymbol{p})$, and the negative parts into $f_2(\boldsymbol{W}, \boldsymbol{p})$. Then the total throughput can be expressed as $f_1(\boldsymbol{W}, \boldsymbol{p}) - f_2(\boldsymbol{W}, \boldsymbol{p})$. Obviously, $f_1(\boldsymbol{W}, \boldsymbol{p})$ and $f_2(\boldsymbol{W}, \boldsymbol{p})$ are both jointly-concave with respect to the variables $\boldsymbol{W}, \boldsymbol{p}$ in the considered domain. To find the maximum value of the difference of two concave functions, FW method is adopted. The FW method considers the first order majorazation of the minus concave part $-f_2(\boldsymbol{W}, \boldsymbol{p})$ by its Taylor series, and updates the variables at each iteration along the direction that improves the objective value [7]. Suppose the value of $(\boldsymbol{W}, \boldsymbol{p})$ at the $n-th$ iteration is denoted by $(\boldsymbol{W^{(n)}}, \boldsymbol{p^{(n)}})$, and $f_2(\boldsymbol{W}, \boldsymbol{p})$ is approximated by $f_2^{(n)}(\boldsymbol{W}, \boldsymbol{p})$ at the $n-th$ iteration, which is given by (11), where $(a_k^{(n)}) = \sum_{k' \neq k}^{K} \mathrm{Tr}(\sum_{i=1}^{L}\sum_{j=1}^{L} t_m t_n \boldsymbol{F_m W_{k'}^{(n)} F_n^H H_k}) +$

$$
\begin{aligned}
f_2^{(n)}(\boldsymbol{W},\boldsymbol{p}) = {} & f_2(\boldsymbol{W^{(n)}},\boldsymbol{p^{(n)}})+ \\
& \sum_{k=1}^{K}(a_k^{(n)})^{-1}\sum_{k'\neq k}^{K}\mathrm{Tr}\big(\sum_{m=1}^{L}\sum_{n=1}^{L}t_m t_n \boldsymbol{F_m}(\boldsymbol{W_{k'}}-\boldsymbol{W_{k'}^{(n)}})\boldsymbol{F_n^H}\boldsymbol{H_k}\big)+\sum_{k=1}^{K}(a_k^{(n)})^{-1}\sum_{u=1}^{U}(p_u-p_u^{(n)})|e_{u,k}|^2+ \\
& \sum_{u=1}^{U}(b_u^{(n)})^{-1}\frac{1}{\alpha}\mathrm{Tr}\big(\mathrm{diag}(\boldsymbol{H_{SI}}(\sum_{k=1}^{K}\sum_{m=1}^{L}\sum_{n=1}^{L}t_m t_n\boldsymbol{F_m}(\boldsymbol{W_k}-\boldsymbol{W_k^{(n)}})\boldsymbol{F_n^H})\boldsymbol{H_{SI}^H})(\sum_{i=1}^{L}\sum_{j=1}^{L}r_i r_j\boldsymbol{F_i}\boldsymbol{G_u}\boldsymbol{F_j^H})\big)+ \\
& \sum_{u=1}^{U}(b_u^{(n)})^{-1}\sum_{u'\neq u}^{U}(p_{u'}-p_{u'}^{(n)})\mathrm{Tr}\big(\boldsymbol{G_{u'}}\sum_{i=1}^{L}\sum_{j=1}^{L}r_i r_j\boldsymbol{F_i}\boldsymbol{G_u}\boldsymbol{F_j^H}\big),
\end{aligned}
\tag{11}
$$

$\sum_{u=1}^{U}p_u^{(n)}|e_{u,k}|^2+\sigma_k^2$, and $(b_u^{(n)}) = \sigma^2\mathrm{Tr}(\sum_{i=1}^{L}\sum_{j=1}^{L}r_i r_j\boldsymbol{F_i}\boldsymbol{G_u}\boldsymbol{F_j^H}) + \sum_{u'\neq u}^{U}(p_{u'}^{(n)})\mathrm{Tr}(\sum_{i=1}^{L}\sum_{j=1}^{L}r_i r_j\boldsymbol{F_i}\boldsymbol{G_u}\boldsymbol{F_j^H}) + \frac{1}{\alpha}\mathrm{Tr}\big(\mathrm{diag}(\boldsymbol{H_{SI}}(\sum_{k=1}^{K}\sum_{m=1}^{L}\sum_{n=1}^{L}t_m t_n\boldsymbol{F_m}\boldsymbol{W_k^{(n)}}\boldsymbol{F_n^H})\boldsymbol{H_{SI}^H})(\sum_{i=1}^{L}\sum_{j=1}^{L}r_i r_j\boldsymbol{F_i}\boldsymbol{G_u}\boldsymbol{F_j^H})\big)$. Since the re-formulated total throughput $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})$ is the lower bound of the original one $f_1(\boldsymbol{W},\boldsymbol{p})-f_2(\boldsymbol{W},\boldsymbol{p})$. In this way, the variables $\boldsymbol{W^{(n)}},\boldsymbol{p^{(n)}}$ are iteratively updated and the lower bound of throughput increases after every iterations. Because of the power consumption constraints, the iterative procedure is guaranteed to converge. Now, the total throughput is re-expressed as $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})$, which is jointly-concave with respect to the variables. It is because that $f_1(\boldsymbol{W},\boldsymbol{p})$ is jointly-concave, and $f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})$ is affine with respect to all variables $\boldsymbol{W},\boldsymbol{p}\in\{\boldsymbol{\Theta}\}$. The optimization problem can be re-expressed as

$$
\begin{aligned}
& P2:\underset{\boldsymbol{W},\boldsymbol{p}\in\boldsymbol{\Theta}.}{\mathrm{argmax}}\,\frac{f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})}{P_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})}, \\
& s.t.\ (C1),(C2),(C5).
\end{aligned}
\tag{12}
$$

Now we introduce Theorem 1 to solve the problem.

Theorem 1: The reformulated EE, as shown in (12), is jointly quasi-concave with respect to the variables $\boldsymbol{W},\boldsymbol{p}$.

Proof: The reformulated EE is the ratio of a concave function over an affine function, and hence it is jointly quasi-concave with respect to the variables [10]. $\square$

For the quasi-concavity maximization problem in (12), the fractional programming $\beta=\frac{f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})}{p_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})}$ can be associated with a subtract programming $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})-\beta p_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})$ [1]. Assume that β^* is the optimal value of (11), it is obvious that maximizing (11) is equivalent to finding the root of $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})-\beta^* P_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})$. With the fixed value of β, the equivalent optimization problem is maximizing $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})-\beta P_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})$, subject to $(C1),(C2),(C5)$. With a fixed β, maximizing $f_1(\boldsymbol{W},\boldsymbol{p})-f_2^{(n)}(\boldsymbol{W},\boldsymbol{p})-\beta P_{\mathrm{total}}(\boldsymbol{W},\boldsymbol{p})$ is a standard semi-definite programming (SDP). Therefore, we can adopt the CVX solver to solve the problem [1]. Finally, a distributed hybrid duplexing maximizing EE (DHD-EE) algorithm is proposed to concurrently optimize $\boldsymbol{W},\boldsymbol{p}$.

[1]The CVX contains multiples solvers for SDP optimization, *e.g.,* SEDuMi, SDPT3 and MOSEK. By claiming variables, objective function and constraints, the SDP optimization can be readily solved.

Algorithm 1 DHD-EE algorithm

Input: Antenna configuration vectors $\boldsymbol{r},\boldsymbol{t}$, left/right bounds β_l and β_r, channel conditions and power consumption parameters.

Output: Optimal beamforming weight $\boldsymbol{W_k^*}$, for $\forall k\in k$, and optimal uplink transmission power p_u^*, $\forall u\in U$.

```
Set accuracy factor ϵ > 0, and suppose F(β) is the optimal value of f_1(W,p)+f_2^(n)(W,p)−βP_total(W,p). Initialize left bound β_l and right bound β_r that ensure the F(β_l)·F(β_r) < 0.
while β_r − β_l > ϵ do
    β = (β_r+β_l)/2.
    Solve the problem P5 with the FW method until convergence.
    if F(β_l)·F(β) < 0 then
        β_r = β.
    else
        β_l = β.
    end if
end while
```

IV. Simulation Results

We present the simulated performance in this Section. The central frequency is set to 2 GHz with 1 MHz bandwidth. The AWGN power spectral density is -174 dBm/Hz. A 30×30 m^2 square grid cell model is considered with 16 DAs. For illustration purpose, the users are randomly positioned. DE of all PAs is set to 25%. Power consumption parameters are set to $p_{idle}=10$ mW, $p_{c,r}=100$ mW, $p_{c,t}=100$ mW, $p_{can}=50$ mW, $p_{fix}=500$ mW, $p_{DA}=100$ mW and $p_{u,max}=40$ mW, respectively. The PL model in [7] is adopted, as $\mathrm{PL}=145.4+37.5\log_{10}(d/1000)$, where d is the distance between two nodes. The threshold ψ is set to 5×10^{-8}. Besides, the co-located FD MIMO (CFD-SE) in [7] and distributed FD only system (DFD-SE) in [11] are selected as benchmarks.

Fig. 2(a) demonstrates the EE performance among three systems. The centralized antennas of CFD-SE are located in the center of the map. It is seen that the proposed DHD-EE algorithm outperforms others in EE at all SIC levels. It is because the proposed hybrid duplexing system enjoys higher

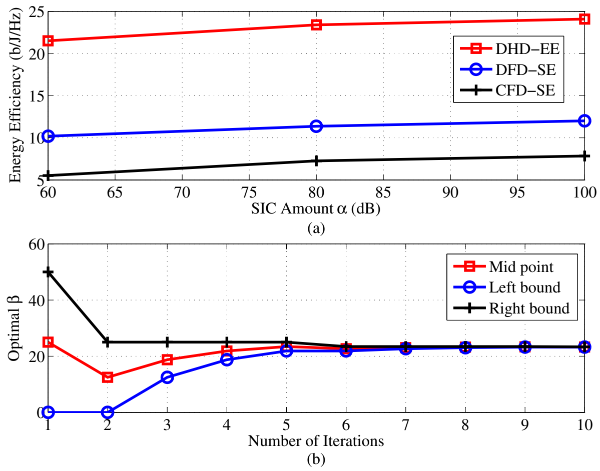

Fig. 2. (a) Average EE performance vs. different SIC amount. (b) An example to show the convergence behavior, with initial left/right bound $\beta_l = 0$, $\beta_r = 100$.

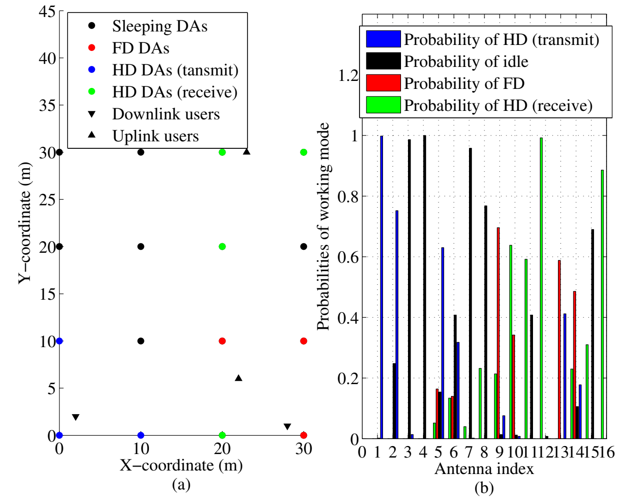

Fig. 3. (a) An illustration of DAs' configuration by the DA clustering algorithm. (b) The probabilities of DAs' working modes.

degree of freedom, allowing DAs to work in hybrid modes and reducing the power consumption significantly. Besides, the distributed deployment of antenna suffers lower PL than the centralized MIMO system. In addition, in CFD-SE system, all antennas are activated and only work in FD mode, leading to much higher power consumption. Its throughput performance is poor due to the high PL. Second, higher EE can be achieved with a higher SIC amount for all the three systems due to the reduced residual self-interference. Fig. 2(b) demonstrates the convergence behavior of the DHD-EE algorithm. It is seen that at most 10 iterations are required to confirm the convergence, showing the low complexity of the algorithm.

Fig. 3(a) shows an illustration of DAs' configuration by the DA clustering algorithm. The DAs far from users are turned-off to save power. The DA close to uplink users whereas far from downlink users work in HD (receiving) mode, and vice versa. Only the DAs close to both uplink and downlink users work in FD mode. Fig. 3(b) shows the probabilities of DAs' working modes. Benefiting from DA deployment, the proposed hybrid duplexing strategy has higher degree of freedom compared to the conventional FD MIMO system [7] and FD only DA system [11].

V. Conclusion

In the paper, a novel hybrid-duplexing distributed antenna (DA) system has been proposed, where the antennas are geographically distributed and capable of working in half duplex, full duplex or sleeping modes. Based on the developed system, we have investigated energy efficiency (EE)-oriented resource allocation by jointly designing transmitting/receiving chain activation/deactivation, downlink beamformer and uplink transmission power. We first present a DA clustering algorithm to activate/deactivate the DAs, which significantly reduces the total power consumption. Then a distributed hybrid duplexing maximizing EE (DHD-EE) algorithm is proposed to further perform downlink beamformer and uplink transmission power concurrently. Simulation results show that the proposed algorithms achieve twice as high EE as the benchmarking systems, showing the advantages in cutting carbon footprint in the future communication systems.

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