Multigroup Multicast Beamforming and Antenna Selection with Rate-Splitting in Multicell Systems

Oskari Tervo*, Le-Nam Tran†, Symeon Chatzinotas‡, Björn Ottersten‡, and Markku Juntti*
*Centre for Wireless Communications, University of Oulu, Oulu, Finland
†The School of Electrical and Electronic Engineering, University College Dublin, Dublin 4, Ireland
‡the Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, Luxembourg
Email: {oskari,tervo,markku.juntti}@oulu.fi, nam.tran@ucd.ie, {symeon.chatzinotas, bjorn.ottersten}@uni.lu

***Abstract*—This paper studies energy-efficient joint coordinated beamforming and antenna selection in multi-cell multi-user multigroup multicast multiple-input single-output systems. We focus on interference-limited scenarios, e.g., when the number of radio frequency (RF) chains is of the same order as the number of multicasting groups. To tackle the interference, we exploit rate-splitting to divide the group messages into common and group-specific sub-messages. We propose a per-cell rate-splitting approach, where the common message is locally designed to be decoded by the in-cell users, while treated as noise by the out-cell users. We consider the case where the number of RF chains is smaller than that of antennas, and consider a switching architecture, that is, the antenna selection is employed to choose the best antennas for transmission. Numerical results illustrate the potential of the proposed approach to significantly improve the energy efficiency in the interference-limited regime.**

***Index Terms*—Coordinated beamforming, antenna selection, energy efficiency, rate splitting, multicasting.**

I. Introduction

The increasing popularity of smart mobile handsets and the associated applications have created a special type of data traffic in wireless communications. In particular, much requested data can be highly correlated. A typical reason is the case wherein many users request or share the same information simultaneously. Multicasting transmission [1]–[3], where a common beamformer is designed for a group of users, is highly efficient for such a scenario. Multicast beamforming (BF) has been investigated for different performance metrics, e.g., transmit power minimization [1], [2], max-min fairness [2], sum rate maximization (SRmax) [3], and energy efficiency (EE) maximization [4], [5].

The above works adopted the conventional BF approach, wherein all the interference is simply treated as noise. When the number of degrees of freedom (DoF) in the network is small, e.g., in ultra-dense networks where the numbers of base station (BS) radio frequency (RF) chains and users are comparable, the interference coordination capability of the conventional approach is relatively limited, leading to a significant performance degradation. For such situations, Joudeh *et al.* [6], [7] proposed to use rate-splitting (RS), and illustrated significant performance gains over the conventional BF in terms of max-min fairness. Specifically, they considered a single-cell multigroup system, where each group message is divided into the lower-rate private (group-specific) and common sub-messages (SMs). All the common SMs are then packed and encoded into a single common stream (using a public codebook), while the private SMs are encoded to independent streams. All the private signals are then superposed on top of the common signal and transmitted simultaneously using a separate beamformer for each stream. Since the desired information for the users is contained in two different streams, each user first decodes the common message, and then their own desired group-specific SM using successive interference cancellation (SIC). The strategy is based on partial decoding of interference, i.e., the users decode the common SMs of the other groups only for interference mitigation. However, in a practical multi-cell scenario, encoding all the common SMs into a single transmission as in [6] is challenging to realize, because different groups are served by different BSs.

RS has been considered in other works as well. Dai *et al.* [8] considered hybrid precoding for multiuser mmWave system with analog phase shifters. It has been also studied in the context of massive MIMO [9], multiantenna interference channels [10], [11] and under different performance metrics, such as SRmax [8], [12] and max-min fairness [8], [13]. However, it has not been studied for EE maximization or for multi-cell joint coordinated multigroup multicast beamforming and antenna selection (JBAS) to the best of our knowledge.

In this paper, we study energy-efficient coordinated beamforming (CB) for multi-cell multigroup multi-user multicast multiple-input single-output (MISO) systems. We assume a limited number of RF chains at each BS, which are connected to the larger antenna array via a switching circuit.[1] We consider a standard network EE as a performance metric [4], [5], [15], [16]. All the BS antennas are individually constrained by maximum power and the users have minimum rate targets. The scenario of interest is the interference limited case so that treating interference as noise is highly suboptimal. Based on [6], we propose the per-cell RS approach, which is motivated by the fact that it does not require any data sharing between the BSs. That is, each BS splits each group message of its own groups to a common (BS-specific) and private (group-specific) SMs. At each BS, the common SMs are then packed and encoded into a single stream, while the private SMs are

[1]Another option would be to use analog phase shifters, or combination of both, which, however, consume more power compared to the switches [14]. This is an interesting topic for future work.

encoded to independent streams. Thereby, each user served by the same cell decodes first the common stream while treating all the private streams and common streams of the neighboring cells as interference, and then use SIC to decode its desired private stream.

The problem at hand is inherently nonconvex and not easy to solve in general. We propose an iterative algorithm to find a high-quality suboptimal solution using the continuous relaxation and successive convex approximation (SCA) framework. Several reformulations are introduced to exploit the hidden convexity of the problem. The numerical results show that the proposed per-cell RS approach provides significant performance gains over the conventional multi-cell JBAS scheme.

The rest of the paper is organized as follows. Section II presents the system model and reviews the conventional multigroup multicast BF. The proposed approach and the solution are provided in Sections III and IV. The simulations and conclusions are presented in Section V and VI, respectively.

The following notations are used. $|x|$ denotes the absolute value of x if x is scalar, and length of x, otherwise. $||\mathbf{x}||_2$ is the Euclidean norm of $\mathbf{x}$ and boldcase letters are vectors. $[\mathbf{x}]_i$ denotes the ith component of $\mathbf{x}$. $\mathbf{x}^H, \mathrm{Re}(\mathbf{x})$ mean Hermitian transpose and real part of $\mathbf{x}$, respectively. For a positive integer K, $\mathcal{K}$ is defined as the set $\{1,\ldots,K\}$.

II. System Model and Conventional Beamforming

A. System Model

We consider a network of B BSs, where BS $b \in \mathcal{B}$ has N_b antennas, transmitting messages $W_g, g \in \mathcal{G}_b \subset \mathcal{G}$ to its multicasting groups, where $\mathcal{G}_b$ is the set of groups served by BS b and $\mathcal{G}$ is the set of groups in the network.[2] Each BS b has only $L_b \leq N_b$ RF chains, i.e., fully digital beamforming is not possible. Instead, analog switching circuit is employed to select the best antenna to be connected to each RF chain. The serving BS of user group g is denoted as b_g. The set of single-antenna users in group g and cell b is denoted by $\mathcal{K}_g \subset \mathcal{K}$ and $\mathcal{U}_b \subset \mathcal{K}$, respectively, where $\mathcal{K}$ is the set of users in the network. We assume that each user belongs to only one group, i.e., $\mathcal{K}_i \cap \mathcal{K}_j = \emptyset$, $\forall i,j \in \mathcal{G}, i \neq j$.

Conventional Multigroup Multicasting Scheme: To appreciate the method proposed in the next section, we briefly review the conventional multigroup multicasting scheme. Conventionally, the messages are encoded into independent data symbols $s_g \in \mathbb{C}, g \in \mathcal{G}$ and transmitted using linear beamforming. The received signal at user k in group g is given by

$$y_k = \overbrace{\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_g s_g}^{\text{desired signal}} + \overbrace{\sum\nolimits_{i\in\mathcal{G}\setminus\{g\}} \mathbf{h}_{b_i,k}\mathbf{F}_{b_i}\mathbf{w}_i s_i}^{\text{inter-group interference}} + n_k \quad (1)$$

where $\mathbf{h}_{b,k} \in \mathbb{C}^{1\times N_b}$ is the channel (row) vector from BS b to user k, $\mathbf{w}_g \in \mathbb{C}^{L_b\times 1}$ is the transmit BF vector for group g, $\mathbf{F}_b \in \mathbb{C}^{N_b\times L_b}$ is the analog switching matrix which involves only a single 1 at each column, while other elements are zero, $n_k \sim \mathcal{CN}(0,\sigma_k^2)$ is the complex white Gaussian noise sample with zero mean and variance σ_k^2. Conventional multicasting treats all the interference as noise, and, thus, the SINR of user k can be written as $\Gamma_k(\mathbf{w}) = |\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_g|^2/(N_0 + \sum_{u\in\mathcal{G}\setminus\{g\}}|\mathbf{h}_{b_u,k}\mathbf{F}_{b_u}\mathbf{w}_u|^2)$, where $N_0 = W\sigma_k^2$ is the total noise power over the transmission bandwidth W.[3]

III. Per-Cell Rate-Splitting

Treating all interference as noise is simple, but the resulting performance is very poor with low DoF, because the inter-group interference becomes a limiting performance factor. It is certainly better to decode part of the interference instead. These approaches can be combined with the RS method, which was originally proposed for the two-user interference channel in [17], [18]. Joudeh *et al.* [6] proposed RS for max-min fairness in a single-cell multigroup multicasting system, where each group message is split into two different SMs, one of which is broadcast to all the user groups (i.e., transmitted as a single-group multicasting manner) and one group designated SM. Each receiver decodes its desired message contained in two separate streams but also the common SMs of other users for the sake of interference mitigation.

The RS approach as described above is more challenging for a multi-cell system with CB, because the splitting can only be possible for the in-cell users due to the constraint that data sharing is not allowed among the BSs. For CB, we propose a per-cell RS that works as follows. The message W_g for group g is split into two SMs as $W_g = \{W_g^{\mathrm{C}}, W_g^{\mathrm{G}}\}$, where W_g^{C} and W_g^{G} is the common and group designated SM, respectively. Under the assumption of CB, all the user groups inside the same cell (i.e., served by BS b_g) can decode all the common SMs $W_{g'}^{\mathrm{C}}, \forall g' \in \mathcal{G}_b$. All the common SMs from BS b_g are packed into a single concatenated message $W_{\mathrm{C}b_g} = \{W_i^{\mathrm{C}}\}_{i\in\mathcal{G}_b}$ and encoded into an independent data symbol $d_{\mathrm{C}b_g}$. The group designated parts $W_i^{\mathrm{G}}, i \in \mathcal{G}_b$ are then separately encoded in a conventional way to independent symbols $d_i, i \in \mathcal{G}_b$. As a result, the transmitted signal vector from BS b can be written as $\mathbf{x}_b = \mathbf{F}_b\mathbf{w}_{\mathrm{C}b}d_{\mathrm{C}b} + \sum_{g\in\mathcal{G}_b}\mathbf{F}_b\mathbf{w}_g d_g$, and the received signal at user k is

$$\begin{aligned} y_k &= \overbrace{\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_{\mathrm{C}b_g}d_{\mathrm{C}b_g}}^{\text{desired common stream}} + \overbrace{\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_g d_g}^{\text{desired private stream}} \\ &+ \underbrace{\sum_{u\in\mathcal{G}\setminus\{g\}} \mathbf{h}_{b_u,k}\mathbf{F}_{b_u}\mathbf{w}_u d_u}_{\text{private stream interference}} + \underbrace{\sum_{j\in\mathcal{B}\setminus\{b_g\}} \mathbf{h}_{j,k}\mathbf{F}_j\mathbf{w}_{\mathrm{C}j}d_{\mathrm{C}j}}_{\text{common stream interference}} + n_k. \quad (2) \end{aligned}$$

The common stream $d_{\mathrm{C}b_g}$ is first decoded by all the users served by BS b_g. The private and common streams of the other cells are treated as Gaussian noise. Thus, the SINR expression for the common stream at user k belonging to group g reads

$$\Gamma_{\mathrm{C}k}(\mathbf{w},\mathbf{F}) = \frac{|\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_{\mathrm{C}b_g}|^2}{N_0 + I_{\mathrm{C}k}(\mathbf{w}_{\mathrm{C}},\mathbf{F}) + I_k(\mathbf{w}_{\mathrm{G}},\mathbf{F})} \quad (3)$$

where $I_{\mathrm{C}k}(\mathbf{w}_{\mathrm{C}},\mathbf{F}) \triangleq \sum_{j\in\mathcal{B}\setminus\{b_g\}}|\mathbf{h}_{j,k}\mathbf{F}_j\mathbf{w}_{\mathrm{C}j}|^2$ and $I_k(\mathbf{w}_{\mathrm{G}},\mathbf{F}) \triangleq \sum_{i\in\mathcal{G}}|\mathbf{h}_{b_i,k}\mathbf{F}_{b_i}\mathbf{w}_i|^2$ are functions denoting the interference caused by the common streams of other cells and all the private streams, respectively, and $\mathbf{w}_{\mathrm{C}} \triangleq \{\mathbf{w}_{\mathrm{C}b}\}_{b\in\mathcal{B}}$,

[2] Each group is served by a single BS without any data sharing.

[3] The bandwidth is dropped from the equations for notational simplicity.

$\mathbf{w}_{\mathrm{G}} \triangleq \{\mathbf{w}_g\}_{g\in\mathcal{G}}, \mathbf{w} \triangleq \{\{\mathbf{w}_{\mathrm{C}}\},\{\mathbf{w}_{\mathrm{G}}\}\}$. We have to guarantee that the common message $W_{\mathrm{C}b}$ can be decoded by all the users in cell b, i.e., the rate for the common stream is defined as $R_b^{\mathrm{C}}(\mathbf{w}) \triangleq \min_{k\in\mathcal{U}_b}(R_{\mathrm{C}k}(\mathbf{w}))$, where $R_{\mathrm{C}k}(\mathbf{w}) \triangleq W\log(1+\Gamma_{\mathrm{C}k}(\mathbf{w},\mathbf{F}))$. Note that, since message $W_{\mathrm{C}b}$ consists of $|\mathcal{G}_b|$ common SMs, the rate of the gth common stream is $C_g \triangleq (|W_g^{\mathrm{C}}|/\sum_{u\in\mathcal{G}_b}|W_u^{\mathrm{C}}|)R_b^{\mathrm{C}}(\mathbf{w})$. In other words, $\sum_{g\in\mathcal{G}_b} C_g = R_b^{\mathrm{C}}(\mathbf{w},\mathbf{F})$. After the common stream has been decoded, the users remove it from the private streams by means of SIC. Thus, the SINR expression for the private stream becomes

$$\Gamma_k(\mathbf{w},\mathbf{F}) = \frac{|\mathbf{h}_{b_g,k}\mathbf{F}_{b_g}\mathbf{w}_g|^2}{N_0 + I_{\mathrm{C}k}(\mathbf{w}_{\mathrm{C}},\mathbf{F}) + \hat{I}_k(\mathbf{w}_{\mathrm{G}},\mathbf{F})} \tag{4}$$

where $\hat{I}_k(\mathbf{w}_{\mathrm{G}},\mathbf{F}) \triangleq \sum_{u\in\mathcal{G}\setminus\{g\}}|\mathbf{h}_{b_u,k}\mathbf{F}_{b_u}\mathbf{w}_u|^2$. The total rate for group g is $R_g(\mathbf{w}) \triangleq C_g + \min_{k\in\mathcal{K}_g}\log(1+\Gamma_k(\mathbf{w},\mathbf{F}))$.

Power Consumption Model: To formulate the EE optimization we consider the power consumption model

$$P_{\text{tot}} = \frac{1}{\eta}\Big(\sum_{g\in\mathcal{G}}||\mathbf{F}_{b_g}\mathbf{w}_g||_2^2 + \sum_{b\in\mathcal{B}}||\mathbf{F}_b\mathbf{w}_{\mathrm{C}b}||_2^2\Big) + P_0 \tag{5}$$

where $\eta \in [0,1]$ describes the efficiency of the power amplifiers, and $P_0 \triangleq P_{\text{RF}}\sum_{b\in\mathcal{B}}L_b + P_{\text{SW}}\sum_{b\in\mathcal{B}}L_b + P_{\text{sta}} + |\mathcal{K}|P_{\text{UE}}$. Here, P_{SW} is the power consumed by each switch, P_{RF} is the power consumption of an RF chain, P_{sta} is the power consumed by cooling systems, power supplies, local oscillators, etc., and P_{UE} is the power consumption of each user [4], [15].

Problem Formulation: We consider the problem of network EE maximization. Note that we can equivalently think analog switching as fully digital beamforming involving N_b RF chains, but only L_b elements of those are chosen. That is, let us introduce $\mathbf{u}_g = \mathbf{F}_{b_g}\mathbf{w}_g \in \mathbb{C}^{N_b\times 1}$ as extended digital beamformer for private stream of group g and $\mathbf{u}_{\mathrm{C}b} \in \mathbb{C}^{N_b\times 1}$ for common stream of BS b. Then, we collect all the beamformers related to a single antenna to a vector $\hat{\mathbf{w}}_{b,i} \triangleq [\mathbf{u}_{\mathcal{G}_b(1)}[i], \mathbf{u}_{\mathcal{G}_b(2)}[i], \ldots, \mathbf{u}_{\mathcal{G}_b(G_b)}[i], \mathbf{u}_{\mathrm{C}b}[i]]^T$ which includes the beamforming coefficients related to antenna i of BS b. Then introduce binary variables $a_{b,i} \in \{0,1\}$, which is 1 if antenna i is selected for transmission and zero otherwise. As a result, the JBAS problem is expressed as

$$\max \quad \frac{\sum_{g\in\mathcal{G}} R_g(\mathbf{u})}{\frac{1}{\eta}\sum\limits_{b\in\mathcal{B}}\sum\limits_{i\in\mathcal{N}_b} v_{b,i} + (P_{\text{RF}}+P_{\text{SW}})\sum\limits_{b\in\mathcal{B}}\sum\limits_{i\in\mathcal{N}_b} a_{b,i} + \bar{P}_0} \tag{6a}$$

$$\text{s.t.} \quad \log(1+\Gamma_k(\mathbf{u})) + C_g \geq \bar{R}_k, \forall g\in\mathcal{G}, k\in\mathcal{K}_g, \tag{6b}$$

$$\log(1+\Gamma_{\mathrm{C}k}(\mathbf{u})) \geq \sum_{g\in\mathcal{G}_b} C_g, \forall b\in\mathcal{B}, k\in\mathcal{U}_b \tag{6c}$$

$$\sum_{i\in\mathcal{N}_b} a_{b,i} \leq L_b, \forall b\in\mathcal{B} \tag{6d}$$

$$||\hat{\mathbf{w}}_{b,i}||_2^2 \leq a_{b,i}^2 v_{b,i}, \forall b\in\mathcal{B}, i\in\mathcal{N}_b \tag{6e}$$

$$v_{b,i} \leq P_{b,i}, \forall b\in\mathcal{B}, i\in\mathcal{N}_b \tag{6f}$$

$$a_{b,i} \in \{0,1\}, \forall b\in\mathcal{B}, i\in\mathcal{N}_b \tag{6g}$$

where the variables are $\mathbf{u}, \mathbf{a}, \mathbf{v}$ and $\mathbf{C} \geq 0$, and we denote $\bar{P}_0 \triangleq P_{\text{sta}} + |\mathcal{K}|P_{\text{UE}}$. Compared to the conventional multigroup multicast JBAS [4], we have additional variables $\{\mathbf{u}_{\mathrm{C}b}\}_{b\in\mathcal{B}}$ and $C_g, \forall g\in\mathcal{G}$ for optimizing the rate of common streams. The first constraints make sure that the user k's rate is at least the predefined value $\bar{R}_k$, the second constraints guarantee that the common stream of cell b is decodable by all the users in its cell. Constraint (6d) guarantees that no more than L_b antennas are selected. In the above formulation, we have used the formulation as in [15], [4] to introduce constraints (6e) and (6f), where $v_{b,i}$ is a soft power level for antenna i of BS b. That is, constraint (6e) guarantees that beamformers related to antenna i of BS b are zero if $a_{b,i}$ is zero, and $v_{b,i} = ||\hat{\mathbf{w}}_{b,i}||_2^2$ if $a_{b,i}$ is binary, and finally (6f) restricts the antenna-specific output powers to $P_{b,i}$. Note that this formulation is used to tighten the feasible set of the relaxation and improve the algorithm as in [15], [4]. Even when continuous relaxation of the binary variables is used, the difficulty of the above problem lies in the non-convexity of (6a), (6b), (6c), (6e).

IV. Proposed Solution

The aim is to use continuous relaxation and SCA to solve (6). That is, as a first step, (6g) is replaced by $a_{b,i} \in [0,1]$. Then, to tackle the non-convexity of (6), we use the approach from [4] to equivalently transform it as

$$\max \quad \frac{\sum_{g\in\mathcal{G}}\big(\min\limits_{k\in\mathcal{K}_g}\log(1+\gamma_k) + C_g\big)}{\frac{1}{\eta}\sum_{b\in\mathcal{B}}\sum_{i\in\mathcal{N}_b} v_{b,i} + \sum_{b\in\mathcal{B}}\sum_{i\in\mathcal{N}_b} a_{b,i} + \bar{P}_0} \tag{7a}$$

$$\text{s.t.} \quad \min_{k\in\mathcal{K}_g}\log(1+\gamma_k) + C_g \geq \max_{k\in\mathcal{K}_g}(\bar{R}_k), \forall g\in\mathcal{G} \tag{7b}$$

$$\log(1+\gamma_{\mathrm{C}k}) \geq \sum_{g\in\mathcal{G}_b} C_g, \forall b\in\mathcal{B}, k\in\mathcal{U}_b, \tag{7c}$$

$$\gamma_k \leq \frac{|\mathbf{h}_{b_g,k}\mathbf{u}_g|^2}{N_0 + I_{\mathrm{C}k}(\mathbf{u}_{\mathrm{C}}) + \hat{I}_k(\mathbf{u}_{\mathrm{G}})}, \forall k\in\mathcal{K} \tag{7d}$$

$$\gamma_{\mathrm{C}k} \leq \frac{|\mathbf{h}_{b,k}\mathbf{u}_{\mathrm{C}b}|^2}{N_0 + I_{\mathrm{C}k}(\mathbf{u}_{\mathrm{C}}) + I_k(\mathbf{u}_{\mathrm{G}})}, \forall k\in\mathcal{K} \tag{7e}$$

$$||\hat{\mathbf{w}}_{b,i}||_2^2/v_{b,i} \leq a_{b,i}^2, \forall b\in\mathcal{B}, i\in\mathcal{N}_b \tag{7f}$$

$$0 \leq a_{b,i} \leq 1, \forall b\in\mathcal{B}, i\in\mathcal{N}_b, \text{(6d)}, \text{(6f)} \tag{7g}$$

where $\boldsymbol{\gamma} \triangleq \{\gamma_k, \gamma_{\mathrm{C}k}\}_{k\in\mathcal{K}}$ are new slack variables to optimize the SINR of the private and common streams at each user k, respectively. Note that (7b) is the compact form of (6b).

Looking at (7), we observe that the objective is a concave-convex fractional function and the remaining challenge in solving (7) is in the nonconvex constraints (7d), (7e) and (7f). To handle (7d), (7e), we use the same idea as in [4], [16] to replace them equivalently as

$$\gamma_k \leq |\mathbf{h}_{b_g,k}\mathbf{u}_g|^2/\beta_k, \gamma_{\mathrm{C}k} \leq |\mathbf{h}_{b,k}\mathbf{u}_{\mathrm{C}b}|^2/\beta_{\mathrm{C}k}, \forall k\in\mathcal{K} \tag{8a}$$

$$\beta_k \geq N_0 + I_{\mathrm{C}k}(\mathbf{u}_{\mathrm{C}}) + \hat{I}_k(\mathbf{u}_{\mathrm{G}}), \forall k\in\mathcal{K} \tag{8b}$$

$$\beta_{\mathrm{C}k} \geq N_0 + I_{\mathrm{C}k}(\mathbf{u}_{\mathrm{C}}) + I_k(\mathbf{u}_{\mathrm{G}}), \forall k\in\mathcal{K} \tag{8c}$$

where $\boldsymbol{\beta}_{\mathrm{G}} \triangleq \{\beta_k\}_{k\in\mathcal{K}}$ and $\boldsymbol{\beta}_{\mathrm{C}} \triangleq \{\beta_{\mathrm{C}k}\}_{k\in\mathcal{K}}$ are new variables representing total interference-plus-noise for the private and common stream at user k, respectively. We remark that (8b) and (8c) are convex while (8a) are in difference-of-convex forms. We now recall the following inequality regarding convex quadratic-over-linear term $|\mathbf{h}_{b_g,k}\mathbf{u}_g|^2/\beta_k$

$$|\mathbf{h}_{b_g,k}\mathbf{u}_g|^2/\beta_k \geq 2\mathrm{Re}((\mathbf{u}_g^{(n)})^H\mathbf{h}_{b_g,k}^H\mathbf{h}_{b_g,k}\mathbf{u}_g)/\beta_k^{(n)} - (|\mathbf{h}_{b_g,k}\mathbf{u}_g^{(n)}|/\beta_k^{(n)})^2\beta_k \triangleq \Psi_k^{(n)}(\mathbf{u}_g,\beta_k) \tag{9}$$

Algorithm 1 Proposed JBAS Design with Per-Cell RS.

Initialization: Set $n = 0$, find feasible $(\mathbf{u}_{\mathrm{G}}^{(n)}, \boldsymbol{\beta}_{\mathrm{G}}^{(n)}, \mathbf{u}_{\mathrm{C}}^{(n)}, \boldsymbol{\beta}_{\mathrm{C}}^{(n)}, \mathbf{a}^{(n)})$.

1: **repeat**

2: Solve (11) with $(\mathbf{u}_{\mathrm{G}}^{(n)}, \boldsymbol{\beta}_{\mathrm{G}}^{(n)}, \mathbf{u}_{\mathrm{C}}^{(n)}, \boldsymbol{\beta}_{\mathrm{C}}^{(n)}), \mathbf{a}^{(n)}$ and get optimal solutions $(\mathbf{u}_{\mathrm{G}}^{*}, \boldsymbol{\beta}_{\mathrm{G}}^{*}, \mathbf{u}_{\mathrm{C}}^{*}, \boldsymbol{\beta}_{\mathrm{C}}^{*}, \mathbf{a}^{*})$.

3: Update $\mathbf{u}_{\mathrm{G}}^{(n+1)} = \mathbf{u}_{\mathrm{G}}^{*}, \boldsymbol{\beta}_{\mathrm{G}}^{(n+1)} = \boldsymbol{\beta}_{\mathrm{G}}^{*}, \mathbf{u}_{\mathrm{C}}^{(n+1)} = \mathbf{u}_{\mathrm{C}}^{*}, \boldsymbol{\beta}_{\mathrm{C}}^{(n+1)} = \boldsymbol{\beta}_{\mathrm{C}}^{*}, \mathbf{a}^{(n+1)} = \mathbf{a}^{*}$ and $\Psi_k^{(n+1)}(\mathbf{w}_g, \beta_k), \Psi_{\mathrm{C}k}^{(n+1)}(\mathbf{w}_{\mathrm{C}b}, \beta_{\mathrm{C}k}), \Upsilon_{b,i}^{(n+1)}(a_{b,i})$. Set $n := n + 1$.

4: **until** specified accuracy level

Output: $a_{b,i}^{*}, \forall b \in \mathcal{B}, i \in \mathcal{N}_b$

5: At each BS b, choose L_b antennas i with the largest $a_{b,i}$.

6: Run steps 1 – 4 again with fixed $\mathbf{a}$ to find beamformers with reduced dimensions.

Output: $\mathbf{w}_g^{*}, \mathbf{w}_{\mathrm{C}b}^{*}, \forall g \in \mathcal{G}, b \in \mathcal{B}$

where $\Psi_k^{(n)}(\mathbf{u}_g, \beta_k)$ is a linear lower bound approximation. A similar approximation applies to $|\mathbf{h}_{b_g,k}\mathbf{u}_{\mathrm{C}b}|^2/\beta_{\mathrm{C}k}$, denoted as $\Psi_{\mathrm{C}k}^{(n)}(\mathbf{u}_{\mathrm{C}b}, \beta_{\mathrm{C}k})$. Moreover, (7f) is also in a form where both sides are convex. Thus, we can approximate it as [4]

$$a_{b,i}^2 \geq (a_{b,i}^{(n)})^2 + 2a_{b,i}^{(n)}(a_{b,i} - a_{b,i}^{(n)}) \triangleq \Upsilon_{b,i}^{(n)}(a_{b,i}). \tag{10}$$

Based on the SCA framework, we obtain the following concave-convex fractional program at fixed point $(\mathbf{u}_{\mathrm{G}}^{(n)}, \boldsymbol{\beta}_{\mathrm{G}}^{(n)}, \mathbf{u}_{\mathrm{C}}^{(n)}, \boldsymbol{\beta}_{\mathrm{C}}^{(n)}, \mathbf{a}^{(n)})$

$$\max \quad \frac{\sum_{g\in\mathcal{G}}\left(\min\limits_{k\in\mathcal{K}_g} \log(1+\gamma_k) + C_g\right)}{\frac{1}{\eta}\sum_{b\in\mathcal{B}}\sum_{i\in\mathcal{N}_b} v_{b,i} + \sum_{b\in\mathcal{B}}\sum_{i\in\mathcal{N}_b} a_{b,i} + \bar{P}_0} \tag{11a}$$

$$\mathrm{s.t.}\, \gamma_k \leq \Psi_k^{(n)}(\mathbf{w}_g, \beta_k), \gamma_{\mathrm{C}k} \leq \Psi_{\mathrm{C}k}^{(n)}(\mathbf{w}_{\mathrm{C}b}, \beta_{\mathrm{C}k}), \forall k \in \mathcal{K} \tag{11b}$$

$$||\hat{\mathbf{w}}_{b,i}||_2^2/v_{b,i} \leq \Upsilon_{b,i}^{(n)}(a_{b,i}), \forall b \in \mathcal{B}, i \in \mathcal{N}_b \tag{11c}$$

$$\text{(8b), (8c), (7b), (7c), (7g)} \tag{11d}$$

where the variables are $\mathbf{u}, \mathbf{v}, \mathbf{a}, \boldsymbol{\gamma}, \boldsymbol{\beta}, \mathbf{C} \geq 0$ with $\boldsymbol{\beta} \triangleq \{\{\boldsymbol{\beta}_{\mathrm{C}}\}, \{\boldsymbol{\beta}_{\mathrm{G}}\}\}$. Though (11) is not convex at hand, it can be solved optimally using the Dinkelbach's method [19] or reformulated as a convex program using the Charnes-Cooper transformation [20] as in [4], [16]. After convergence, the L_b antennas at each BS having the largest $a_{b,i}$ are chosen, and the algorithm is rerun without antenna selection for the fixed antenna set (i.e., a low-dimensional problem). The whole method is outlined in Algorithm 1.

V. Numerical Results

The performance is studied for a quasistatic frequency flat Rayleigh fading channels by considering $B = 2$ BSs. The path loss is calculated as $35\log_{10}(d_{b,k}) + 30$ dB, where $d_{b,k}[m]$ is the distance from BS b to user k. In order to consider the worst-case interference scenario, we set $d_{b,k} = 150m, \forall b, k$. Each BS serves $G_b = \bar{G}$ groups of users with U users per group, i.e., the total number of users in the network is $K = 2\bar{G}U$. We assume a bandwidth of 20 MHz and noise power $N_0 = -125$ dBW. We set $N_b = N$ for all b, i.e., N is the number of antennas at each BS, and $L_b = L, \forall b \in \mathcal{B}$. The other parameters are set as $\eta = 0.35$, $P_{\mathrm{SW}} = 5$ mW, $P_{b,i} = 0$ dBW, $P_{\mathrm{RF}} = 0.4$ Watts, $P_{\mathrm{sta}} = 6$ Watts, $P_{\mathrm{UE}} = 0.1$ Watts, $\bar{R}_k = \bar{R} = 4$ Mbits/s, $\forall k \in \mathcal{K}$. The results are averaged over 100 channel realizations.

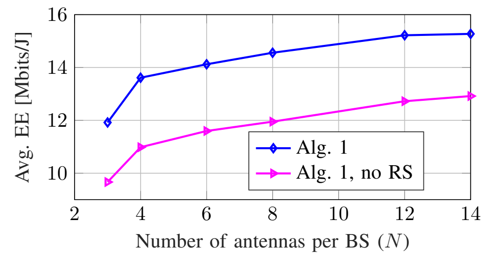

Fig. 1. Average EE versus N with $\bar{G} = 3, U = 2, L = 3$.

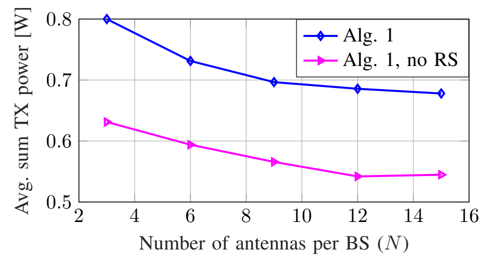

Fig. 2. Average TX power versus N with $\bar{G} = 3, U = 2, L = 3$.

Fig. 1 plots the average EE versus N. We compare the proposed method with the conventional energy-efficient multi-group multicast JBAS strategy which was proposed in [4]. We can see that in both cases the EE increases with N (up to a saturation point) because there are more independent antenna paths, providing more diversity in the selection. It is observed that the additional DoF in the RS approach provide significant EE gains over the conventional method.

Fig. 2 compares the transmit power of the strategies versus N. Specifically, since only part of the available power is used for energy-efficient transmission, it is interesting to see how the RS approach uses the power. It is observed that it is actually energy-efficient to use a lot more power than in the conventional method. This is because the RS enables 'bad' groups to be served with common streams (using rate close to minimum target), which then makes it possible to transmit some of the private streams with high rate (with lower interference or interference-free). It is also observed that increasing the number of antennas (by keeping the number of RF chains fixed) decreases the transmit power in the energy-efficient transmission, because the same rate can be achieved with lower power consumption.

Fig. 3 shows how increasing the number of RF chains for fixed N impacts on the performance. It is observed that significant gains are achieved in the RF chain limited case and the gap naturally decreases when L increases (and also when N increases), because it increases the DoF and RS provides performance improvements only when DoF is limited.

Fig. 4 illustrates the effect of the number of groups. First, when $\bar{G} = 1$, the proposed approach does not provide benefit compared to the conventional method since only per-cell rate splitting is applied. When the number of groups increases,

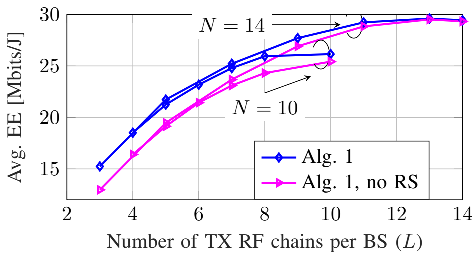

Fig. 3. Average EE versus L with $\bar{G} = 3, U = 2$.

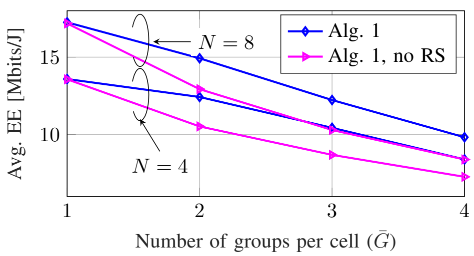

Fig. 4. Average EE versus $\bar{G}$ with $U = 3, L = 4$.

clear improvements are obtained over the conventional method. The EE decreases with the increasing number of groups both due to the extra power consumption of additional users and the increased interference (more users have to be served with the target rate). However, the rate splitting approach can handle the interference significantly better and take a clear advantage of it both in fully digital beamforming ($N = 4$) and joint beamforming and antenna selection ($N = 8$).

Fig. 5 illustrates the effect of multicasting group size on the performance. The EE decreases with the group size because the group rate is determined by the worst user, and also the power consumption increases with the number of users. However, it is observed that RS scheme is able to provide significant improvements with different group sizes both in the fully digital case ($N = 3$) and the JBAS scheme ($N = 9$).

VI. Conclusions

This paper has studied energy-efficient multi-cell joint multigroup coordinated beamforming and antenna selection using a rate-splitting approach. We proposed a per-cell rate-splitting method, where the common message was locally designed to be decoded by all the users belonging to the same cell, while treated as interference in the neighboring cells. The simulations have illustrated significant performance gains over the conventional beamforming in terms of the EE.

VII. Acknowledgment

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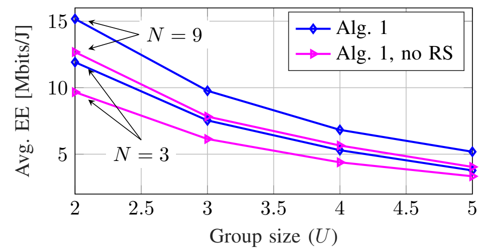

Fig. 5. Average EE versus U with $\bar{G} = 3, L = 3$.

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