A Framework for Optimizing the Downlink Performance of Distributed Antenna Systems under a Constrained Backhaul

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***Abstract*— Recent work has shown that multi-cell co-operations in cellular networks, enabling distributed antenna systems and joint transmission or joint detection across cell boundaries, can significantly increase system capacity and user fairness. Most publications in this field assume that an infinite amount of information can be exchanged between the co-operating base stations, neglecting the main downside of such systems, namely the need for an additional network backhaul. In a recent publication [1], we have proposed an optimization framework and algorithm that applies joint detection to a subset of users for scenarios of constrained backhaul. In this paper, we will now observe joint transmission in the downlink, which can be described in a similar way, but allows for an additional degree of freedom in the way the backhaul infrastructure is used. Different schemes are compared, yielding that linear multi-user beamforming to selected users can significantly improve the downlink performance of cellular systems under a strongly limited backhaul.**

I. Introduction

It is well known that inter-cell interference poses the main capacity limitation in future cellular systems. To overcome this problem, multi-user detection or transmission across cell borders, often observed in the context of so-called *distributed antenna systems* (DAS) has been proposed by various authors. Optimistic capacity bounds for large clusters of co-operating cells have been determined for the uplink [2] and downlink [3], [4], and corresponding detection and transmission schemes investigated in e.g. [3], [5], [6].

The main downside of inter-cell co-operation is the vast amount of backhaul required for information exchange between involved base stations. Recently, we have thus introduced a framework [1] to improve both the sum capacity and, more significantly, the fairness of a cellular system by applying joint detection only to selected users, while limited by a pre-defined backhaul infrastructure. We will now show that the developed framework can be applied analoguously to the downlink. Here, we have the additional degree of freedom to either exchange pre-processed and quantized signal values over the backhaul, or the uncoded, binary data of jointly pre-processed users, which we will observe in detail. For simplicity, we generally assume that perfect transmitter-side channel knowledge is available at the base stations, though the framework could easily be extended to model performance degradation due to incomplete channel information.

In section II, we will summarize basic aspects about linear joint transmission. In sections III and IV, we will adapt our framework from [1] to the downlink and show that the proposed optimization algorithm can also be similarly applied here. We will then discuss simulation results in section V and conclude the paper in section VI.

II. Basics

A. Notation

The notation we use throughout the paper is as follows. In general, if $\mathbf{X}$ is a matrix, then we refer to the jth *column vector* as $\mathbf{x}_j$, and refer to the matrix elements as $x_{i,j}$, *except* for channel matrices $\mathbf{H}$, where $\mathbf{h}_k$ refers to the *row vector* corresponding to user k. The operator $\odot$ denotes element-wise multiplication, $\preceq$ denotes element-wise inequality, and operator Δ yields a square matrix with non-zero elements only on the diagonal, either extracted from a given square matrix or generated from a vector. The operator $\mathbf{Y} = \lfloor \mathbf{X} \rfloor$ yields $y_{i,j} = 1$ if $x_{i,j} > 0$, otherwise zero. The expressions $\mathbf{0}_{[i\times j]}$ and $\mathbf{1}_{[i\times j]}$ denote matrices with i rows and j columns, filled with zeros and ones, respectively. $\mathbf{I}_{[i]}$ denotes a size i identity matrix, operators $(\cdot)^T$ and $(\cdot)^H$ denote matrix transpose and Hermitian transpose, respectively, and $E\{\cdot\}$ denotes expectation value.

B. Joint transmission in Distributed Antenna Systems

We observe linear joint transmission schemes, enabling an easy derivation of lower achievable rate bounds which can then be exceeded by non-linear schemes, e.g. Costa precoding, proven to approach channel capacity in [7]. A joint transmission from M base stations with a total of N_T transmit antennas to K users with one receive antenna each can be stated as

$$\mathbf{y} = \mathbf{H}\mathbf{W}\Delta(\mathbf{p})^{\frac{1}{2}}\mathbf{s} + \mathbf{n}, \quad \text{where } \Delta(\mathbf{W}^H\mathbf{W}) = \mathbf{I}_{[K]} \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{[K\times N_T]}$ is the matrix of a frequency-flat channel, and $\mathbf{W} \in \mathbb{C}^{[N_T\times K]}$ is the beamforming matrix. Vectors $\mathbf{p} \in \mathbb{R}^{+[K\times 1]}$, $\mathbf{s} \in \mathbb{C}^{[K\times 1]}$, and $\mathbf{n} \in \mathbb{C}^{[K\times 1]}$ are the transmit powers, transmitted signals and zero-mean white Gaussian noise at the receivers of the mobile terminals, respectively. The resulting achievable rate of a user k is known to be

$$c_k = \log_2\left(1 + \frac{p_k \mathbf{h}_k \mathbf{w}_k \mathbf{w}_k^H \mathbf{h}_k^H}{\mathbf{h}_k\left(\sum_{i=1,i\neq k}^{K} p_i \mathbf{w}_i \mathbf{w}_i^H\right)\mathbf{h}_k^H + \sigma_k^2}\right) \tag{2}$$

where $\sigma_k^2 = E\{n_k^H n_k\}$. We will from now on use the term *capacity* for the achievable rate of a user under a given beamforming matrix $\mathbf{W}$ and power allocation $\mathbf{p}$. Major research has been done on the joint choice of these two parameters, e.g. for maximizing sum capacity [3] or balancing user SINRs [6]. In large systems with many users per cell and selective joint transmission, however, power allocation is yet uninvestigated. We thus want to decouple the problems and determine the achievable capacity if for a given power allocation $\mathbf{p}$, an optimal beamforming matrix $\mathbf{W}$ is chosen. We derive from [6] and [8] that such vectors are obtained for all users k as

$$\mathbf{w}_k = \frac{\mathbf{A}_k^{-1}\mathbf{h}_k^H}{\mathbf{h}_k \mathbf{A}_k^{-2}\mathbf{h}_k^H},\ \mathbf{A}_k = \sum_{i=1, i\neq k}^{K} p_i \mathbf{h}_i^H \mathbf{h}_i + \bar{\sigma}^2 \mathbf{I}_{[N_T]} \quad (3)$$

where $\bar{\sigma}^2$ is the average noise over all users. This corresponds to the transmit Wiener filter solution [9], succeeded by a unit column power constraint on $\mathbf{W}$. Within a cellular network, however, we have to constrain the transmit power contributed by *each base station*. Assuming that sets of users chosen for joint transmission will usually be close to cell borders, s.t. the average path gain from all transmit antennas to a user is similar, we suggest to let the involved base stations equally share the sum transmit power, hence the additional constraint

$$\mathbf{M}_B \Delta\left(\mathbf{W}\Delta(\mathbf{p})\mathbf{W}^H\right)\mathbf{1}_{[N_T\times 1]} = \frac{1}{K}\mathbf{p}^T \mathbf{1}_{[K\times 1]}\mathbf{1}_{[M\times 1]} \quad (4)$$

where $\mathbf{M}_B \in \{0,1\}^{[M\times N_T]}$ maps transmit antennas to base stations. Though downlink beamforming with per-antenna power constraints [10] could possibly be extended to *per-base-station* constraints, we propose to simply compute the beamforming matrix for all involved users jointly as

$$\mathbf{W} = \Delta\begin{pmatrix} \beta_1 \\ \vdots \\ \beta_{N_T}\end{pmatrix}\left(\mathbf{H}^H\Delta(\mathbf{p})\mathbf{H} + \bar{\sigma}^2\mathbf{I}\right)^{-1}\mathbf{H}^H\Delta\begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_K\end{pmatrix} \quad (5)$$

where factors α_k are initially chosen to ensure the constraint in (1), and β_t are subsequently chosen to fulfill (4). Though the resulting $\mathbf{W}$ does not fulfill (1), and thus the beamforming vectors are not optimal w.r.t. (3), our simulations have shown only a marginal degradation in performance.

III. Optimization Framework

We will now adapt the framework from [1] to the downlink, allowing us to describe user capacity as a function of a set of input parameters. Note that all variables (M, K, N_T, $\mathbf{p}$ etc.) are now used to describe a large cellular system, where S refers to the number of *sites*, typically grouping three base stations into one location. We assume uncorrelated signal propagation paths due to cross-polarization antennas at base stations and large distances between antennas otherwise, perfect transmitter-side channel information at one central point, and errorless backhaul links (e.g. fixed wire) with limited capacity between certain sites, as specified later.

In [1], we stated the concept of *groups*, i.e. a set of users in different cells sharing the same resources (e.g. sub-carriers, codes etc.). These users will observe mutual interference, but can be selected for joint transmission to combat exactly this interference. User grouping is described through matrix

$$\mathbf{G} \in \{0,1\}^{[K\times K]} \text{ e.g. } \mathbf{G} = \begin{bmatrix} \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \mathbf{1} & \mathbf{1} \\ 0 & 0 & 0 & \cdots & \mathbf{1} & \mathbf{1} \end{bmatrix}, \quad (6)$$

in this example grouping the first three and last two users onto the same resources, respectively. Grouping follows the law of transcivity and reflexivity, hence $\mathbf{G}^T = \mathbf{G}$ and $\forall i,j : \mathbf{g}_i^T\mathbf{g}_j \in \{0, \mathbf{g}_i^T\mathbf{g}_i\}$. For a given user grouping, we can state channel matrices $\mathbf{H}_l \in \mathbb{C}^{[K\times N_T]}$, where index $1 \leq l \leq L$ allows to observe L channel coefficients on each spatial link, if desired, e.g. representing different sub-carriers. We further define the so-called *joint transmission configuration* matrix as

$$\mathbf{V} \in \mathbb{N}_0^{+[N_T\times K]} \text{ e.g. } \mathbf{V} = \begin{bmatrix} 16 & 0 & 16 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 8 & 8 \\ 0 & 0 & 0 & \cdots & 8 & 8 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 10 & 0 & 10 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 16 & 16 \end{bmatrix} \quad (7)$$

where each entry $v_{t,u} > 0$ determines that transmit antenna t is involved in the transmission to user u, the actual value stating the quantization bits used if the transmit signals are pre-processed in a central location and then relayed via the backhaul. For all users involved in a common joint transmission operation, the set of transmit antennas and the quantization level per antenna must be equal, fulfilling $\forall i,j : \mathbf{g}_i^T\mathbf{g}_j > 0 \rightarrow \mathbf{v}_i^T\mathbf{v}_j \in \{0, \mathbf{v}_i^T\mathbf{v}_i\}$. From (2), we can now derive the per-user capacity as stated in equation (10), where (11) fulfills the constraints discussed in (5), and $\mathbf{u}_k$ refers to matrix

$$\mathbf{U} \in \{0,1\}^{[K\times K]} = \lfloor \mathbf{G} \odot \left(\mathbf{V}^T\mathbf{V}\right)\rfloor \quad (8)$$

stating which users are involved in the same joint transmission operation. ξ_k is the relative quantization noise power (w.r.t. the average transmit power at each antenna), given by

$$\xi_k \in \mathbb{R}^{+[N_T\times 1]} = \left[\frac{1}{2^{v_{1,k}-2}}, \frac{1}{2^{v_{2,k}-2}}, \ldots, \frac{1}{2^{v_{N_T,k}-2}}\right]^T \quad (9)$$

In (10), the expectation value over multiple channel matrices $\mathbf{H}_l, 1 \leq l \leq L$ is observed, where index l is omitted for notational brevity. Perspectively, we could extend the quantization noise term in (10) to incorporate the effect of chosing beamforming vectors under incomplete channel knowledge.

A. Calculating Backhaul

We now derive the backhaul required for the selective joint transmission specified through $\mathbf{V}$, expressed as a matrix $\mathbf{B} \in \mathbb{N}_0^{+[S\times S]}$, where $b_{i,j}$ states the required backhaul from site i to site j. We will now discuss the two mentioned scenarios how to use the backhaul infrastructure in the downlink

$$c_k = E_{\mathbf{H}} \left\{ \log_2 \left(1 + \frac{\overbrace{p_k \cdot \left|\mathbf{h}_k [\mathbf{W}_{(k)}]_k\right|^2}^{\text{Desired signal power}}}{\underbrace{\mathbf{h}_k \mathbf{W}_{(k)} \Delta([\mathbf{U}-\mathbf{I}]_k \mathbf{p}^T) \mathbf{W}_{(k)}^H \mathbf{h}_k^H}_{\text{Interference from users within joint transmission}} + \underbrace{\mathbf{h}_k \check{\mathbf{V}} \Delta(\check{\mathbf{V}}^T \check{\mathbf{V}})^{-1} \Delta([\mathbf{G}-\mathbf{U}]_k \mathbf{p}^T) \mathbf{h}_k^H}_{\text{Interference from other users within group}} + \underbrace{\frac{\mathbf{p}^T \mathbf{u}_k}{\mathbf{1}^T \check{\mathbf{v}}_k} \mathbf{h}_k \Delta(\xi_k \check{\mathbf{v}}_k^T) \mathbf{h}_k^H}_{\text{Quantization noise}} + \sigma_k^2} \right) \right\} \quad (10)$$

$$\text{where } \check{\mathbf{V}} = \lfloor \mathbf{V} \rfloor \text{ and } \mathbf{W}_{(k)} = \Delta(\beta_1 ... \beta_{N_t}) \left(\Delta(\mathbf{v}_k) \mathbf{H}^H \Delta(\mathbf{p}) \mathbf{H} \Delta(\mathbf{v}_k) + \frac{\mathbf{n}^T \mathbf{u}_k}{\mathbf{1}_{[1\times K]} \mathbf{u}_k} \cdot \mathbf{I}_{[N_T]} \right)^{-1} \Delta(\mathbf{v}_k) \mathbf{H}^H \Delta(\alpha_1 ... \alpha_K) \quad (11)$$

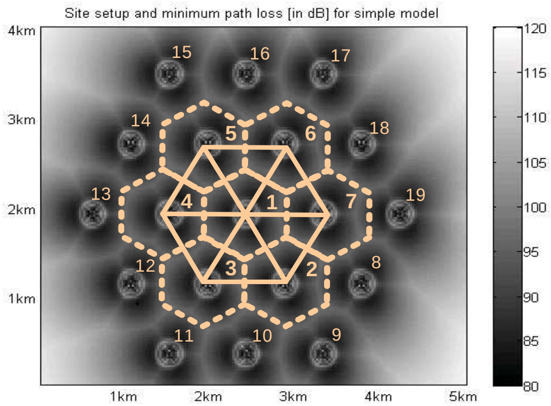

Fig. 1. Site setup for simulations, containing a co-operating cluster of 7 sites surrounded by a tier of 12 sites additionally introducing interference

1) Relaying pre-processed, quantized signals: For each joint transmission operation, one central site having complete channel information could pre-process all transmit signals, quantize and distribute them to all other involved sites. Then,

$$\mathbf{B} = \rho \cdot \sum_{k=1}^{K} \frac{\left[\mathbf{0}_{[S\times s_k-1]} \quad \mathbf{M}_S \mathbf{v}_k \quad \mathbf{0}_{[S\times S-s_k]}\right]^T}{\mathbf{1}_{[1\times K]} \mathbf{u}_k} \quad (12)$$

where ρ is the per-user bandwidth, i.e. the number of quantized signal values per user, antenna and second. $\mathbf{M}_S \in \{0,1\}^{[S\times N_T]}$ maps transmit antennas to sites. $\mathbf{s} = [s_1 ... s_K]$ states each user's *master site*, i.e. the site performing the pre-processing, constrained by the backhaul infrastructure to

$$s_k \in \left\{ 1 \le s \le S : \lfloor \mathbf{M}_S \mathbf{v}_k \rfloor^T \lfloor \mathbf{D}^T + \mathbf{I} \rfloor_s = \mathbf{1}_{[1\times S]} \lfloor \mathbf{M}_S \mathbf{v}_k \rfloor \right\} \quad (13)$$

where $\mathbf{D} \in \mathbb{N}_0^{+[S\times S]}$ is the available backhaul between sites.

2) Relaying uncoded, binary user data: Alternatively, uncoded user data could be distributed from a master site to all involved base stations, where coding and computation of beamforming matrices is performed redundantly, assuming distributed channel knowledge. Then, quantization noise is avoided, and the required backhaul depends on the actual user throughput, leading to an upper bound for the backhaul as

$$\mathbf{B} \preceq \rho \cdot \sum_{k=1}^{K} c_k \left[\mathbf{0}_{[S\times s_k-1]} \quad \lfloor \mathbf{M}_S \mathbf{v}_k \rfloor \quad \mathbf{0}_{[S\times S-s_k]}\right]^T \quad (14)$$

with s_k as in (13). Regardless of the backhaul scenario, any choice of $(\mathbf{V}, \mathbf{s})$ finally has to fulfill the backhaul constraint

$$\mathbf{B} \preceq \mathbf{D} \quad (15)$$

B. Overall Optimization Problem

We now have the same optimization problem as in the uplink [1], i.e. we can compute user capacities and backhaul as a function of user grouping $\mathbf{G}$, joint transmission configuration $(\mathbf{V}, \mathbf{s})$ and power allocation $\mathbf{p}$, and have to solve

$$[\hat{\mathbf{G}}, \hat{\mathbf{V}}, \hat{\mathbf{s}}, \hat{\mathbf{p}}] = \underset{\mathbf{G},\mathbf{V},\mathbf{s},\mathbf{p}}{\text{argmax}} W \left[\mathbf{c}(\mathbf{G}, \mathbf{V}, \mathbf{s}, \mathbf{p})\right] \Big|_{\mathbf{D}} \quad (16)$$

for a given backhaul infrastructure $\mathbf{D}$ and power constraint

$$\mathbf{M}_U \Delta(\mathbf{U}\mathbf{1}_{[K\times 1]})^{-1} \mathbf{U}\mathbf{p} \preceq P_{max} \cdot \mathbf{1}_{[M\times 1]} \quad (17)$$

where $\mathbf{M}_U \in \{0,1\}^{[M\times K]}$ maps users onto base stations, P_{max} is the total transmit power per base station, and W a function that takes the user capacities and yields an overall performance metric. In our case, W is designed to maximize the average capacity of the 5 percent of weakest users.

IV. An Optimization Algorithm

As the dimensionality of the optimization problem and the discreteness of input parameters $\mathbf{G}, \mathbf{V}, \mathbf{s}$ prohibits any brute force search or convex optimization approach, we stated an algorithm in [1] that serializes the problem in order to yield a good result at low complexity. We will now see that this algorithm can also be applied to the downlink. As a first simplification, we set $\mathbf{p}$ to an equal power per user.

A. Isolation-based User Grouping

In [1], we have shown that a non-random user grouping onto resources (i.e. design of $\mathbf{G}$), can improve both average capacity and system fairness. Intuitively, it should also be beneficial for the downlink if we rank the users in each cell according to their *isolation*, i.e. a value close to one for cell-center users, and lower for cell-edge users, defined as

$$\gamma_k = \sum_{\phi\in\Phi_k} E\{|h_{k,\phi}|^2\} \Bigg/ \sum_{1\le\phi\le N_T} E\{|h_{k,\phi}|^2\} \quad (18)$$

where Φ_k are the antennas of the home base station of user k. We then group the users according to their isolation, i.e. such that users with a similar isolation share the same resources.

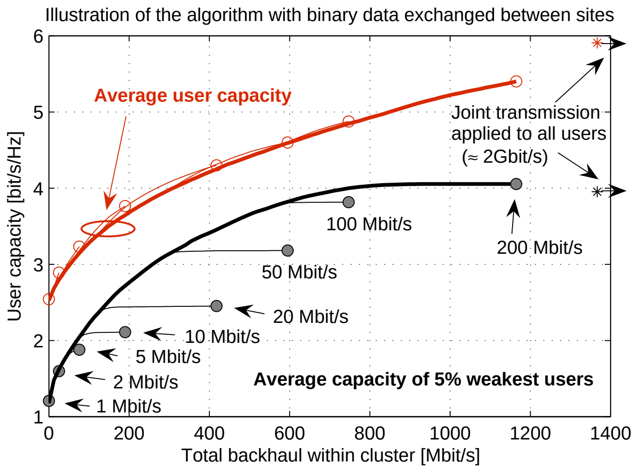

Fig. 2. Illustration of the optimization algorithm throughout iterations, using backhaul scenario 2 and isolation-based user grouping

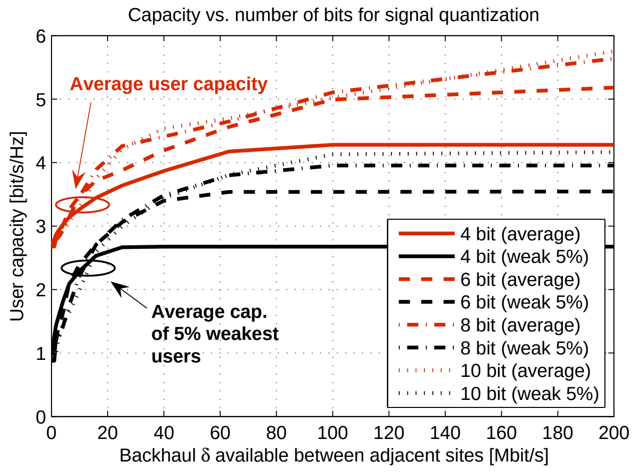

Fig. 3. Simulation results for different numbers of quantization bits q, if backhaul scenario 1 is employed with random user grouping

B. Joint Transmission Optimization

Now that $\mathbf{p}$ and $\mathbf{G}$ are fixed, we propose to determine $(\mathbf{V}, \mathbf{s})$ through the same algorithm as in [1]:

1) Choose a number of quantization bits q for all relayed signals in backhaul scenario 1 (see section V)
2) Initialize $\mathbf{V}$, so that each terminal is linked to only the N_t transmit antennas of its home base station
3) Calculate capacities $\mathbf{c} = [c_1, c_2, ..., c_K]^T$, according to equation (10), and the performance measure $w = W(\mathbf{c})$
4) Calculate total backhaul $\beta = \sum_{i,j} b_{i,j}$ from (12) or (14)
5) Loop through users, starting with low-capacity users
   a) For a user k, determine set Ψ of tupels (ϕ, s) of additional transmit antennas and feasible master sites, based on the underlying infrastructure, i.e.

$$\Psi = \{(\phi, s) | 1 \leq \phi \leq N_T, 1 \leq s \leq S, v_{\phi,k} = 0 \\ \wedge \quad [\lfloor \mathbf{D} + \mathbf{I} \rfloor^T]_s^T \chi(k, \phi) = \mathbf{1}_{[1 \times S]} \chi(k, \phi)$$

   where $\chi(k, \phi) \in \{0, 1\}^{[S \times 1]}$ states the sites involved into the joint transmission operation determined by $\mathbf{v}_k$ and ϕ, i.e.

$$\chi(k, \phi) = \lfloor \mathbf{M}_S \mathbf{V}(\mathbf{g}_k \odot (\mathbf{V}^T(\mathbf{v}_k[v_{\phi,k} = 1]))) \rfloor$$

   b) For all $(\phi, s) \in \Psi$, determine the corresponding system parameters $\mathbf{V}'(\phi, s, q)$ and $\mathbf{s}'(s)$ and calculate the resulting performance metrics $\tilde{w}(\mathbf{G}, \mathbf{V}', \mathbf{s}', \mathbf{p})$, and total backhaul $\tilde{\beta}(\mathbf{V}', \mathbf{s}')$
   c) Choose $(\phi, s) \in \Psi$ that fulfills the backhaul constraint (15), fulfills $\tilde{w}(\mathbf{G}, \mathbf{V}'(\phi, s, q), \mathbf{s}'(s), \mathbf{p}) \geq w$, and maximizes the improvement gradient

$$\widehat{(\phi, s)} = \underset{(\phi,s) \in \Psi}{\operatorname{argmax}} \frac{\tilde{w}(\mathbf{G}, \mathbf{V}'(\phi, s, q), \mathbf{s}'(s), \mathbf{p}) - w}{\tilde{\beta}(\mathbf{V}'(\phi, s, q), \mathbf{s}'(s)) - \beta},$$

   d) Update $(\mathbf{V}, \mathbf{s})$ according to $\widehat{(\phi, s)}$ and the initial choice of the number of quantization bits q
6) Stop when no more improvements are possible within the backhaul constraint $\mathbf{D}$

As in the uplink, convergence is guaranteed as $(\mathbf{V}, \mathbf{s})$ are only updated if metric w can be improved, until all base station antennas transmit to all users or the backhaul limit is reached.

V. Simulation Results

We observe a co-operating cluster of 7 sites with 3 base stations each, surrounded by another tier of sites causing interference, as shown in figure 1. We assume 2 transmit antennas per base station, and that each site within the cluster is connected to its partners via bi-directional, errorless links of a common capacity δ. We can then state

$$\mathbf{D} = \begin{bmatrix} \begin{bmatrix} 0 & \delta & \delta & \delta & \delta & \delta & \delta \\ \delta & 0 & \delta & 0 & 0 & 0 & \delta \\ \delta & \delta & 0 & \delta & 0 & 0 & 0 \\ \delta & 0 & \delta & 0 & \delta & 0 & 0 \\ \delta & 0 & 0 & \delta & 0 & \delta & 0 \\ \delta & 0 & 0 & 0 & \delta & 0 & \delta \\ \delta & \delta & 0 & 0 & 0 & \delta & 0 \end{bmatrix} & \mathbf{0}_{[7 \times 12]} \\ \mathbf{0}_{[12 \times 7]} & \mathbf{0}_{[12 \times 12]} \end{bmatrix} \quad (19)$$

We constrain $\mathbf{V}$ to $v_{\phi,k} \in \{0, q, 16\}$, where the same quantization level q is used throughout the system for backhaul scenario 1, and basically noise-less 16-bit quantization is assumed within master sites for scenario 1, and in general for scenario 2. We observe a fully loaded 5MHz OFDMA system where 50 users per cell occupy $L = 6$ maximally spaced sub-carriers each, leading to a per-user bandwidth $\rho = 84$kHz, and assume that the coherence bandwidth is so small that each user's sub-carriers are fairly uncorrelated. We observe the ergodic behavior of Rayleigh fading channels with an average gain obtained from an Okumura Hata pathloss model as in [2]. Only the performance of the central site is plotted.

Figure 2 shows the average and 5th percentile user capacity improvements throughout the iterations of the algorithm for

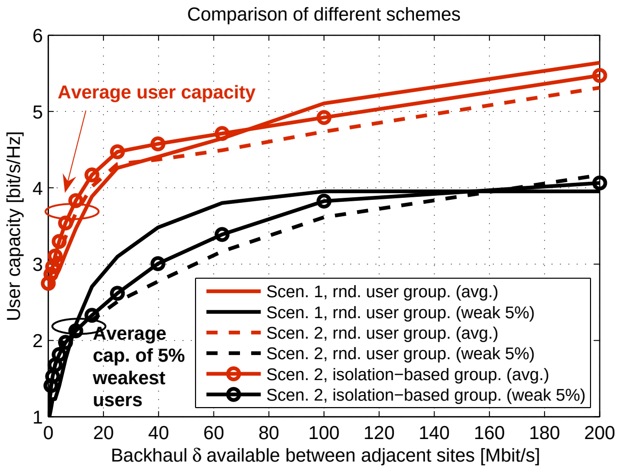

Fig. 4. User capacity vs. backhaul per link for backhaul scenarios 1 and 2, i.e. exchange of pre-processed signals or uncoded data bits between sites

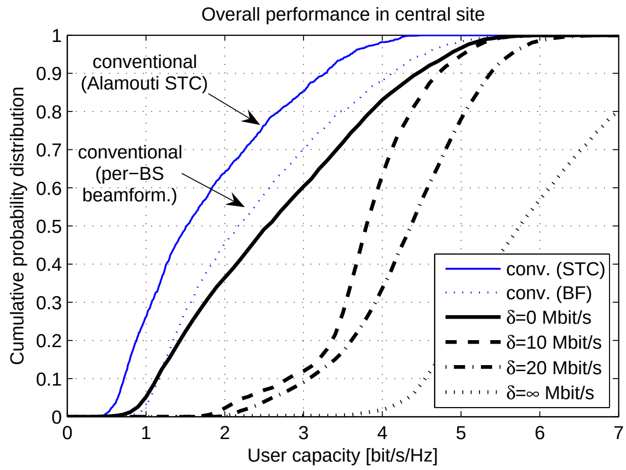

Fig. 5. Cumulative distribution of user capacity for a conventional and the novel scheme using backhaul scenario 2 and isolation-based user grouping

backhaul scenario 2 and isolation-based user grouping. The 5th percentile capacity achieved by the algorithm is larger than that obtained by complete joint transmission to all users, as joint transmission is not always beneficial to all users involved, as opposed to joint detection in the uplink. Thus, even for unlimited backhaul, the complete joint transmission performance indicated through stars will not be reached by the algorithm, if w is defined to optimize fairness. In figure 3, we can see that for backhaul scenario 1, $q = 8$ is a suitable number of quantization bits for a strongly constrained backhaul.

Figure 4 compares backhaul scenarios 1 and 2. The impact of isolation-based user grouping as opposed to random user grouping (only plotted for scenario 2) is similar, but stronger than in the uplink, as the capacity of certain users can even be degraded especially if joint transmission is applied to heterogeneous groups of cell-center and cell-edge users. Scenario 2 yields a superior average and 5th percentile performance for $\delta \leq 10$Mbit/s. This is because the backhaul needed for the distribution of uncoded data among sites is initially lower, but increases quadratically in the number of users involved, while for scenario 1, it increases linearly in the number of transmit antennas involved. The slight superiority of scenario 2 for $\delta \geq 160$Mbit/s is due to the missing quantization noise. It has to be noted that the backhaul for scenario 2 is a pessimistic estimate due to the inequality in (14), and in practical systems where joint transmission will most likely only be applied to small sets of users, scenario 2 should generally show a better ratio of capacity over backhaul, if the distribution of transmitter-side channel knowledge can somehow be realized.

Figure 5 shows the user capacities within the central site. We compare backhaul scenario 2 with isolation-based user grouping to a conventional system employing transmit diversity (Alamouti) or beamforming from the two transmit antennas of each base station. As in the uplink, we observe large capacity and fairness improvements achievable through selective joint transmission, even for a strongly constrained backhaul.

VI. Conclusions and Future Outlook

In this paper, we have adapted a framework for optimizing the uplink of distributed antenna systems to the downlink. After having derived user capacity expressions for linear joint transmission with per-base-station power constraints, we have shown that the same algorithmical approach from [1] can be used to achieve major capacity and fairness improvements under a constrained backhaul in the downlink. We have compared two scenarios of how the backhaul can be used, and seen that the previously proposed isolation-based user grouping is also beneficial in the downlink.

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