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

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***Abstract*—It has recently been shown that multi-cell cooperations in cellular networks, enabling distributed antenna systems and joint transmission or joint detection across cell boundaries, can significantly increase capacity, especially that of users at cell borders. Such concepts, typically implicitly assuming unlimited information exchange between base stations, can also be used to increase the network fairness. In practical implementations, however, the large amounts of received signals that need to be quantized and transmitted via an additional backhaul between the involved cells to central processing points, will be a non-negligible issue. In this paper, we thus introduce an analytical framework to observe the uplink performance of cellular networks in which joint detection is only applied to a subset of selected users, aiming at achieving best possible capacity and fairness improvements under a strongly constrained backhaul between sites. This reveals a multi-dimensional optimization problem, where we propose a simple, heuristic algorithm that strongly narrows down and serializes the problem while still yielding a significant performance improvement.**

I. INTRODUCTION

It is well known that current and future cellular systems, aimed at providing high data rates for a large number of users, are mainly interference limited. Multi-user detection or transmission across cell borders, often mentioned in the context of *distributed antenna systems* (DAS) has proven suitable to combat such interference, offering excellent link quality and improving cell coverage [1]. Optimistic capacity bounds that can be achieved by using large clusters of cooperating cells have been determined both for the uplink [2] and the downlink [3], where the actual joint detection or joint transmission algorithms have for example been investigated in detail in [4] and [5], respectively.

The main problem connected to distributed antenna systems is the large amount of information that has to be gathered from or conveyed to involved receive or transmit antennas, requiring a large backhaul infrastructure between the cells. In this paper, we want to constrain ourselves to linear MMSE detection in the uplink, and extend our previous work in [2] to develop a mathematical framework for observing both capacity and fairness improvements, as well as the required backhaul, if only a subset of users is selected for joint detection. Based on the framework, we will then propose a simple algorithm that can significantly increase cellular network performance under a strongly constrained backhaul.

In section II, we will define certain notations and state the basics for linear MMSE detection. In sections III and IV, we will then introduce our framework, state the optimization problem and describe our proposed algorithm, respectively. We will then provide and 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 $x_{i,j}$. The operator $\odot$ denotes element-wise multiplication, and the operator Δ yields a square matrix with non-zero elements only on the diagonal, either extracted from a 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. Operators $(\cdot)^T$ and $(\cdot)^H$ denote matrix transpose and Hermitian transpose, respectively. $\mathbf{I}_{[N]}$ denotes an $N \times N$ identity matrix, and $E\{\cdot\}$ an expectation value.

B. Joint Detection in Distributed Antenna Systems

As mentioned, we want to focus on joint linear MMSE detection across cell borders in the uplink. In [2], [6], it has been shown that the maximum achievable rate of each user k involved in such a joint detection can be stated as

$$c_k = \log_2 \left[\left(\left[(\Phi_{ss}^{\frac{1}{2}} \mathbf{H}^H \Phi_{nn}^{-1} \mathbf{H} \Phi_{ss}^{\frac{1}{2}} + \mathbf{I})^{-1} \right]_{[k,k]} \right)^{-1} \right], \quad (1)$$

assuming transmission over a frequency-flat channel given by matrix $\mathbf{H}$, where Φ_{ss} and Φ_{nn} are transmit and noise covariance, respectively, assuming white Gaussian, zero-mean noise. In this paper, we will use the term *user capacity* for the maximum rate a user can achieve under a given channel, transmit and noise covariance.

III. OPTIMIZATION FRAMEWORK

In this section, we will introduce a mathematical framework to describe the user capacity as a function of a clearly defined set of input parameters, in order to structure the optimization problem and later aim at solving sub-problems.

We observe a cellular network with M base stations (i.e. M cells) and a total of K mobile users distributed within this network. In current cellular networks, typically 3 base stations are grouped into one location, leading to a total of S *sites*. We assume that each base station has N_r receive antennas, whereas each mobile has only one transmit antenna, and that the usage of cross-polarization antennas at base stations and large distances between users and between base stations lead to uncorrelated signal propagation paths. We further assume that complete receiver-side channel information of the whole network is available at one central point, and that errorless backhaul links (e.g. fixed wire) with limited capacity are given between certain sites, as specified later in detail.

We first introduce the concept of *groups*. A group is a set of users across cells who are sharing the same resources, i.e. the same set of sub-carriers, codes etc., leading to interference between these users, but also offering the possibility of jointly detecting these users to gain diversity and combat mutual interference. User grouping is described through matrix

$$\mathbf{G} \in \{0,1\}^{[K\times K]} \text{ e.g. } \mathbf{G} = \begin{bmatrix} \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \mathbf{1} & \mathbf{1} & \mathbf{1} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \mathbf{1} & \mathbf{1} \\ 0 & 0 & 0 & \cdots & \mathbf{1} & \mathbf{1} \end{bmatrix}, \tag{2}$$

in this example indicating that the first three and last two users are grouped, respectively. As the grouping of users follows the law of transcivity and reflexivity, $\mathbf{G}$ is constrained to a subset of cases that fulfill $\mathbf{G}^T = \mathbf{G}$ and $\forall i,j : \mathbf{g}_i^T\mathbf{g}_j \in \{0, \mathbf{g}_i^T\mathbf{g}_i\}$. Based on a given user grouping, we can now state multiple channel matrices between all base stations and users as $\mathbf{H}_l \in \mathbb{R}^{[N_R\times K]}$, where $N_R = M \cdot N_r$ is the total number of receive antennas. The index $1 \leq l \leq L$ allows us to observe L different channel coefficients on each spatial link, if desired, e.g. representing different sub-carriers or channel representations over time. The main optimization task in distributed antenna systems is to determine the set of receive antennas by which each user is detected (referred to as the *joint detection configuration*), expressed through matrix

$$\mathbf{V} \in \mathbb{N}_0^{+[N_R\times K]} \text{ e.g. } \mathbf{V} = \begin{bmatrix} 16 & 0 & 16 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 8 & 8 \\ 0 & 0 & 0 & \cdots & 8 & 8 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 10 & 0 & 10 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 16 & 16 \end{bmatrix}, \tag{3}$$

where each entry determines with how many quantization bits a certain user is actively detected by which antenna, i.e., a zero states no active detection at all. We assume here that all users within a group who are involved in a common joint detection operation are detected by the same set of antennas with the same extents of quantization. Hence, for all users i,j with $\mathbf{g}_i^T\mathbf{g}_j > 0$ it follows that $\mathbf{v}_i^T\mathbf{v}_j \in \{0, \mathbf{v}_i^T\mathbf{v}_i\}$. Based on (1), we can now derive the per-user capacity $\mathbf{c}_k$ of each user $1 \leq k \leq K$ as stated in equation (6), where $\mathbf{u}_k$ is the kth column (i.e. the column corresponding to user k) of matrix

$$\mathbf{U} \in \{0,1\}^{[K\times K]} = \left\lfloor \mathbf{G} \odot \left(\mathbf{V}^T\mathbf{V}\right) \right\rfloor \tag{4}$$

indicating which users are involved in the same joint detection operation. Vector $\mathbf{n} = [\sigma_1^2, \sigma_2^2, ..., \sigma_{N_R}^2]^T$ contains the thermal noise variance plus any noise power from outside the modelled system at each receive antenna, which we assume to be white Gaussian with zero mean. Vector $\mathbf{p} = [p_1, p_2, ..., p_K]^T$ denotes the mean transmit power of each user, and ξ_k states the relative quantization noise power (with respect to the average received power at each antenna), calculated as

$$\xi_k \in \mathbb{R}^{+[N_R\times 1]} = \left[\frac{1}{2^{v_{1,k}-2}}, \frac{1}{2^{v_{2,k}-2}}, ..., \frac{1}{2^{v_{N_R,k}-2}}\right]^T \tag{5}$$

A. Calculating Backhaul

We will now derive the backhaul required for jointly detecting selected users. Here, not only the total amount of backhaul needed in the observed system is interesting, but also the backhaul on each link between two sites, as in a practical system this will usually be strongly constrained. When users assigned to different sites are jointly detected, there exists the degree of freedom to determine which of the involved sites is the *master*, i.e. the instance that collects and processes the received signals, having an impact on backhaul and capacity. For this, we introduce the variable $\mathbf{s} = [s_1, s_2, ..., s_K]$, determining each user's master site. The backhaul can then be expressed as a matrix $\mathbf{B} \in \mathbb{N}_0^{+[S\times S]}$, where $b_{i,j}$ states the backhaul (in *bit/s*) required from site i to site j, as

$$\mathbf{B} = \rho \cdot \sum_{k=1}^{K} \frac{\left[\mathbf{0}_{[S\times s_k-1]} \quad \mathbf{M}\mathbf{v}_k \quad \mathbf{0}_{[S\times S-s_k]}\right]}{\mathbf{u}_k^T\mathbf{1}_{[K\times 1]}}, \tag{7}$$

where matrix $\mathbf{M} \in \{0,1\}^{[S\times N_R]}$ maps receive antennas to sites and ρ is the number of quantized values per user, antenna and second. For each joint detection operation, the set of sites that can act as joint detection masters according to the underlying backhaul infrastructure can be determined as

$$s_k \in \left\{1 \leq s \leq S : \lfloor \mathbf{d}_s \rfloor^T \lfloor \mathbf{M}\mathbf{v}_k \rfloor = \mathbf{1}_{[1\times S]} \lfloor \mathbf{M}\mathbf{v}_k \rfloor - 1\right\}, \tag{8}$$

where $\mathbf{D} \in \mathbb{N}_0^{+[S\times S]}$ determines the total backhaul capacity available between tuples of sites. Any joint detection configuration $(\mathbf{V}, \mathbf{s})$ finally has to fulfill the backhaul constraint

$$\forall i,j \quad : \quad b_{i,j} \leq d_{i,j} \tag{9}$$

B. Overall Optimization Problem

We have now derived the analytical framework to calculate the per-user uplink capacity and the required backhaul as a function of a chosen user grouping $\mathbf{G}$, a joint detection configuration $(\mathbf{V}, \mathbf{s})$ and a power allocation $\mathbf{p}$. The optimization problem can now be stated as

$$[\hat{\mathbf{G}}, \hat{\mathbf{V}}, \hat{\mathbf{s}}, \hat{\mathbf{p}}] = \underset{\mathbf{G},\mathbf{V},\mathbf{s},\mathbf{p}}{\operatorname{argmax}} \quad W\left[\mathbf{c}(\mathbf{G}, \mathbf{V}, \mathbf{s}, \mathbf{p})\right]\Big|_{\mathbf{D}}, \tag{10}$$

$$c_k = \underset{1\le l\le L}{E}\left\{\log_2\left(\left[\left(\Delta\left(\mathbf{p}\mathbf{u}_k^T\right)^{\frac{1}{2}}\mathbf{H}_l^H[\underbrace{\Delta\left(\mathbf{H}_l\Delta(\mathbf{p}[\mathbf{g}_k^T-\mathbf{u}_k^T])\mathbf{H}_l^H\right)}_{\text{Interference from other users in group}}+\dots\right.\right.\right.\right.$$

$$\left.\left.\left.\left.+\ \underbrace{\Delta(\mathbf{H}_l\Delta(\mathbf{p}\mathbf{g}_k^T)\mathbf{H}_l^H+\Delta(\mathbf{n}))\Delta(\xi_k)}_{\text{Quantization noise}}+\Delta(\mathbf{n})]^{-1}\mathbf{H}_l\Delta\left(\mathbf{p}\mathbf{u}_k^T\right)^{\frac{1}{2}}+\mathbf{I}_{[K]}\right)^{-1}\right]_{k,k}\right)\right\} \qquad (6)$$

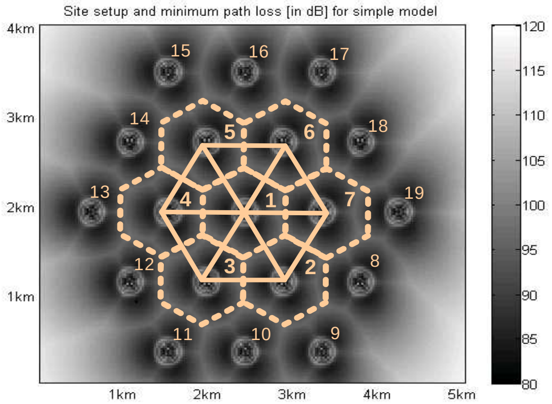

Fig. 1. Site setup for simulations, containing a co-operating cluster of 7 sites surrounded by a tier of 12 sites additionally introducing interference

where W is any kind of function that takes the user capacities and yields an overall performance metric. An operator might for example be interested in maximizing the sum capacity or the capacity of the weakest user, i.e. he might choose

$$W(\mathbf{c}) = \mathbf{c}^T\mathbf{1}_{[K\times 1]} \quad \text{or} \quad W(\mathbf{c}) = \min_{1\le k\le K} c_k \qquad (11)$$

Obviously, this is a high-dimensional optimization problem appearing not to be solvable through e.g. convex optimization theory, due to the discreteness of parameters $\mathbf{G}, \mathbf{V}, \mathbf{s}$. Also, the dimensionality of the parameter space prohibits any brute force approach, even in a moderately sized system. In the next section, we will thus fix certain parameters, serialize the optimization problem and suggest an algorithm that shows good performance at a feasible complexity.

IV. AN OPTIMIZATION ALGORITHM

We suggest to initially narrow down the optimization problem by using a standard power control policy. Here, each mobile terminal adjusts its transmit power such that it is received with a power level P_{rx} at its assigned base station, constrained by a maximum transmit power P_{max}, e.g.

$$p_k = min\left(\frac{N_r\cdot P_{rx}}{\sum\limits_{\phi\in\Phi_k} E\{|h_{\phi,k}|^2\}}, P_{max}\right), \qquad (12)$$

where Φ_k is the set of the indices of the receive antennas belonging to the base station assigned to user k.

A. Isolation-based User Grouping

We now propose a simple scheme to group the users of different cells onto blocks of resources, i.e. to determine matrix $\mathbf{G}$. The idea is to rank the users in each cell according to their *isolation*, i.e. a value close to one if the user is in the cell center, and lower if the user is close to a cell border and thus causing interference towards adjacent cells, defined as

$$\gamma_k = \sum_{\phi\in\Phi_k} E\{|h_{\phi,k}|^2\} \Big/ \sum_{1\le\phi\le N_R} E\{|h_{\phi,k}|^2\} \qquad (13)$$

We then group users with a strong or weak isolation onto the same resources, respectively. When determining an optimal joint detection configuration, we can then focus on (and invest backhaul into) those groups of users that have a weak isolation, and where joint detection yields the highest performance gains.

B. Joint detection Optimization

After having fixed power allocation $\mathbf{p}$ and user grouping $\mathbf{G}$, we propose the following algorithm to optimize $(\mathbf{V}, \mathbf{s})$:

1) Choose a number of quantization bits q for all signals that are to be relayed via backhaul (see section V)
2) Set $\mathbf{V}$ to a default value, so that each terminal is detected by the N_r receive antennas of its home base station
3) Calculate capacities $\mathbf{c} = [c_1, c_2, ..., c_k]^T$, according to equation (6), and the performance measure $w = W(\mathbf{c})$
4) Calculate the total backhaul $\beta = \sum_{i,j} b_{i,j}$ from (7)
5) Loop through users, starting with low-capacity users
    a) For a user k, determine set Ψ of tupels (ϕ, s) of additional receive antennas and feasible master sites, based on the underlying infrastructure, i.e.

$$\begin{aligned}\Psi = \{(\phi, s)|&1\le\phi\le N_R, 1\le s\le S, v_{\phi,k} = 0\\ \wedge\quad &\lfloor\mathbf{d}_s\rfloor^T\chi(k,\phi) = \mathbf{1}_{[1\times S]}\chi(k,\phi) - 1\end{aligned} \qquad (14)$$

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

$$\chi(k,\phi) = \lfloor\mathbf{M}\mathbf{V}(\mathbf{g}_k\odot(\mathbf{V}^T(\mathbf{v}_k[v_{\phi,k}=1])))\rfloor \qquad (15)$$

    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 $\tilde{\beta}(\mathbf{V}', \mathbf{s}')$

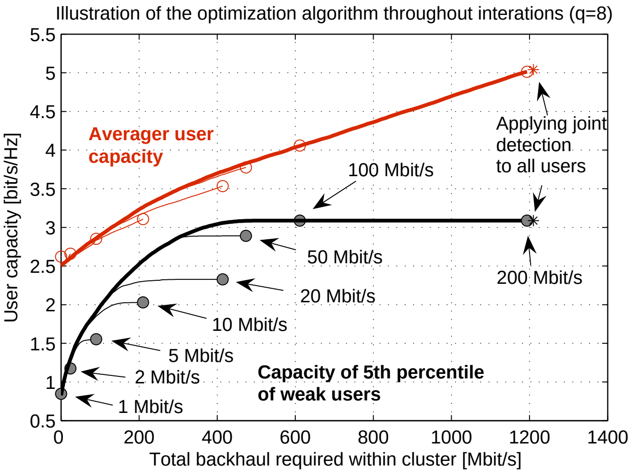

Fig. 2. Illustration of the optimization algorithm throughout iterations, showing the convergence under different per-link backhaul constraints δ

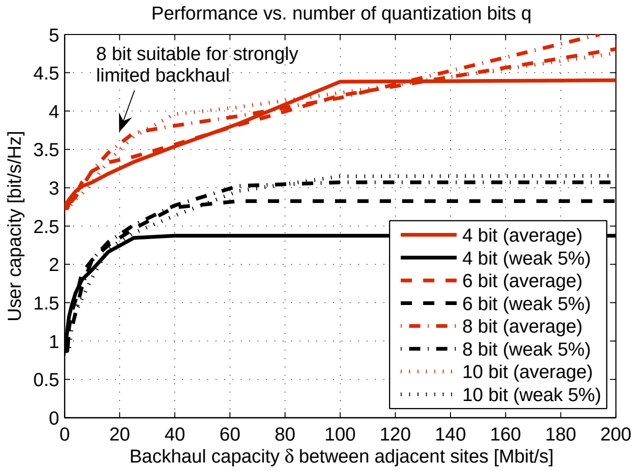

Fig. 3. Simulation results for different numbers of quantization bits q

c) Choose $\widehat{(\phi, s)} \in \Psi$ that fulfills the backhaul constraint (9), fulfills $\tilde{w}(\mathbf{G}, \mathbf{V}'(\phi, s, q), \mathbf{s}'(s), \mathbf{p}) \geq w$, and maximizes the improvement gradient

$$\widehat{(\phi, s)} = \underset{(\phi,s)\in\Psi}{\text{argmax}} \frac{\tilde{w}(\mathbf{G}, \mathbf{V}'(\phi, s, q), \mathbf{s}'(s), \mathbf{p}) - w}{\tilde{\beta}(\mathbf{V}'(\phi, s, q), \mathbf{s}'(s)) - \beta}, \tag{16}$$

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 more complex joint detection operations are only added to the system if they yield an improvement, it is clear that the algorithm will converge to the point where either all users are detected by all base station antennas in the system, or no more improvements are possible due to the backhaul constraint.

V. SIMULATION RESULTS

Our simulations are based on the site and cell setup shown in figure 1, where 7 sites form a co-operating cluster of cells, surrounded by another tier of sites causing interference. Within the cluster, we assume that each site is connected to its adjacent sites through errorless, bi-directional links with a common capacity δ. The infrastructure is thus defined through

$$\mathbf{D} = \left[\begin{array}{cc} \left[\begin{array}{ccccccc} 0 & \delta & \delta & \delta & \delta & \delta & \delta \\ \delta & 0 & \delta & 0 & 0 & 0 & \delta \\ \delta & \delta & 0 & \delta & 0 & 0 & 0 \\ \delta & 0 & \delta & 0 & \delta & 0 & 0 \\ \delta & 0 & 0 & \delta & 0 & \delta & 0 \\ \delta & 0 & 0 & 0 & \delta & 0 & \delta \\ \delta & \delta & 0 & 0 & 0 & \delta & 0 \end{array} \right] & \mathbf{0}_{[7\times12]} \\ \mathbf{0}_{[12\times7]} & 0 \end{array} \right] \tag{17}$$

Our optimization metric according to (10) is defined to optimize the average performance of the 5th percentile of weakest users in the central site, succeeded by an optimization of the average performance of all users. We constrain matrix $\mathbf{V}$ such that $v_{\phi,k} \in \{0, q, 16\}$, i.e. if a certain receive antenna is used to actively detect a certain user, the corresponding matrix entry is set to 16 bits, if the receive antenna is located at the chosen master site, or to a value of q, if the quantized signal has to be relayed to a master site via backhaul.

We simulate an OFDMA system with an uplink bandwidth of 5 MHz, 300 data sub-carriers, FFT size 512, and 14000 OFDMA-symbols per second, taken from [7]. We assume that 50 users per cell obtain an equal, maximally distributed share of 6 sub-carriers each (i.e. $L = 6$ and $\rho = 6 \cdot 14000$ samples/antenna/s), and that the coherence bandwidth is small enough to ensure that each user's sub-carriers are fairly uncorrelated. We observe Rayleigh fading channels with an average gain obtained from an Okumura Hata pathloss model as described in [2]. We only observe the performance in the central site, whereas the optimization algorithm is applied to all 21 cells of the observed cluster.

Figure 2 shows how the 5th percentile and average user capacity are improved during the iterations of the algorithm. Here, the x-axis indicates the sum backhaul required over all links. For each execution of the algorithm, here shown with different backhaul constraints, it is visible that the algorithm initially strongly improves the performance of the weak users at a low cost, until a saturation is reached and further backhaul is invested in improving the average user capacity. We can see that for a large given backhaul, the algorithm reaches the solution where all users are detected by all base station antennas, as in the uplink - given a sufficiently dimensioned q - adding more receive antennas can only increase capacity.

In figure 3, user capacity is plotted as a function of the maximum backhaul per link for different q, applying the isolation-based user grouping. We see that even a strongly limited backhaul between adjacent sites can shift the weak users' capacity to the performance obtained when all users are jointly detected. Note that even for zero backhaul, a slight

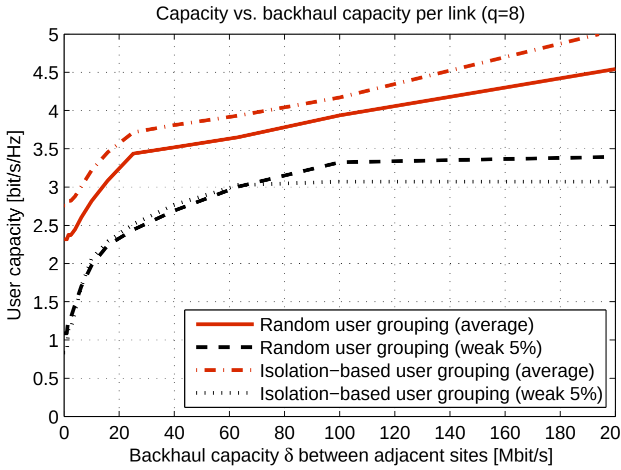

Fig. 4. Simulation results showing the impact of isolation-based user grouping vs. random user grouping

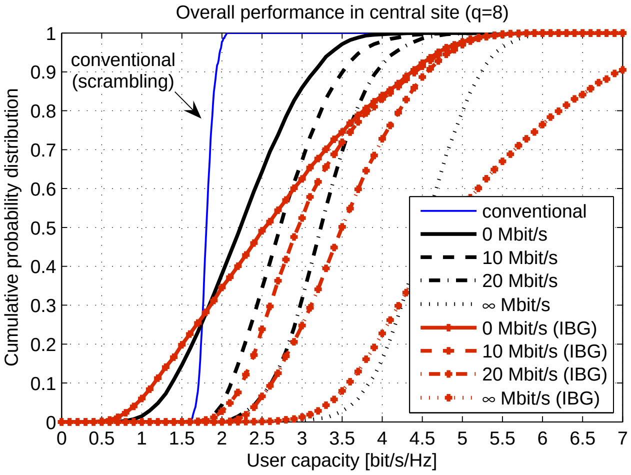

Fig. 5. Cumulative distribution function of user capacity for different backhaul constraints and with random or isolation-based user grouping (IBG)

improvement compared to a conventional system is achieved, as joint detection between cells of the same site can be applied. Whereas a higher q is beneficial in large-backhaul scenarios, we have determined $q = 8$ to be optimal for $\delta \leq 20$ Mbit/s.

Figure 4 shows the impact of the proposed isolation-based user grouping. When users are ranked and grouped according to their isolation, the average capacity is improved by about 0.3 bit/s/Hz as opposed to random user grouping - even if no joint detection is applied. The capacity of the 5th percentile of weak users, however, drops if the users are ranked, if either no joint detection at all, or a large extent of joint detection is performed. This is expectable, as a few users will be facing exceptionally strong interference after isolation-based user grouping, which cannot be completely cancelled through linear MMSE joint detection. For the performance of the weak users, the proposed user grouping is only beneficial if a small extent of per-link backhaul capacity is available, i.e. 10 Mbit/s $\leq \delta \leq$ 60 Mbit/s, as then this limited backhaul can be focussed especially on the users with a bad cell isolation.

Figure 5 finally shows the overall performance of the users within the central site. As a benchmark, we use the performance of a conventional system without joint detection, but using scrambling to average out the interference between cells. Corresponding to the previous plots, we can see that already a limited backhaul infrastructure enables a significant increase in average and 5th percentile user capacity. Also, the benefit of isolation-based user grouping is clearly visible.

VI. CONCLUSIONS AND FUTURE OUTLOOK

In this paper, we have introduced a mathematical framework to observe distributed antenna systems in which only a subset of users are selected for joint detection, due to a constrained backhaul. The system performance depends on the grouping of users, the joint detection configuration, transmit power allocation, and the choice of the number of quantization bits, yielding a multi-dimensional optimization problem being difficult to solve analytically due to the discreteness of most input parameters. We have thus suggested a simple optimization algorithm that fixes the power allocation, uses a simple, heuristic, but effective grouping of users onto resources, and serializes the remaining optimization problem.

Simulation results have shown that a strongly limited backhaul can already significantly increase the average and 5th percentile user capacity. Our additionally proposed scheme of grouping users with a similar degree of isolation onto the same resources strongly increases the average user capacity, and slightly improves the capacity of the 5th percentile of weak users in scenarios with a limited backhaul.

Our research has been based on the assumption that complete receiver-side channel information is available at one central point in a pre-defined cluster of cells. Our future research will thus focus on how the proposed optimization algorithm can be distributed over a large network, requiring only local channel knowledge in small sub-systems.

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