Uplink Ad Hoc Cooperation by Distributed Equalization Under a Constrained Backhaul

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***Abstract*—Theoretical analysis of base station cooperation methods have proven their potential for solving interference limitation in today's cellular networks by showing immense capacity and fairness gains. However, a major downside of base station cooperation is the additional information exchanged amongst base stations which has been the motivation for recent work on backhaul efficient cooperation schemes. In this paper, we introduce a method that is based on distributed equalization and joint decoding, which has several benefits when compared to other kinds of distributed antenna systems. On the one hand, no additional exchange of channel information is required and on the other, distributed equalization provides an elegant solution for backhaul efficient cooperation with outdated channel knowledge at the scheduler.**

I. INTRODUCTION

A primary motivation for technical innovations in the field of cellular communications are the high costs and the scarcity of licensed spectrum, which lead to the wish of reusing frequency bands in every cell. A drawback of this approach is the occurring inter-cell interference, which is the capacity limiting factor of today's mobile communication systems. A promising means to overcome this limitation is to introduce cooperation among base stations, allowing them to actively exploit signal propagation across cell borders rather than treating it as noise. In the cellular uplink, several authors have shown that joint detection of multiple mobile terminals (MTs) by cooperating base stations (BSs) provides significant gains in terms of spectral efficiency (e.g. [1]–[3]).

From a system operator's point of view, a major drawback of the base station cooperation (BSC) concept is the additional backhaul infrastructure required for the information exchange among BSs. In this work, we hence consider the uplink of a cooperative cellular network for a system with a backhaul infrastructure that is constrained in terms of capacity.

An outstanding approach to base station cooperation in the cellular uplink is a distributed antenna system, where compressed signals received at the base stations are forwarded to a common decoder. The best known compression strategy for this setup is distributed Wyner-Ziv coding with conditional Karhunen-Loeve transformations at the forwarding base stations [4]. On the downside, this approach requires full channel knowledge at the decoder. In this paper, we introduce a different approach that consists of three steps: distributed equalization, exchange of compressed equalized symbols, and joint decoding at a central decoder. As we will show, the distributed equalization approach is suboptimal in terms of the backhaul deployment, but allows users to be decoded with only local channel information.

In Section IV, we investigate another important advantage of the distributed equalization scheme, which comes into play when scheduling delay is considered to account for imperfect channel knowledge. In this case, it was shown in [5] that, in order to achieve an improved throughput-backhaul rate trade-off, the decision on the compression rate should be made after transmission, considering the possibility of a changed channel state. However, it was also shown that the performance of this ad-hoc CoMP method decreases with the number of MTs that are decoded jointly as long as single antenna BSs are used. In this paper, we extend previous research by observing systems with multi-antenna BSs. In this case, we have additional degrees of freedom for distributing the available backhaul rate on the dimensions of the receive signal space. As we shall show, distributed equalization greatly reduces the complexity of the associated optimization problem, because user signals are spatially separate prior to the information exchange. Thus, we are able to provide each user with the appropriate compression accuracy that is required for successful decoding.

II. SYSTEM MODEL

The system that is investigated is depicted in Figure 1. It consists of K MTs with one transmit antenna each and M BSs, each equipped with N_{bs} receive antennas, where we assume $N_{\text{bs}} \geq K$. Here, $\mathcal{K} = \{1, \ldots, K\}$ refers to the set of MTs and $\mathcal{M} = \{0, \ldots, M\}$ to the set of BSs. The BSs can exchange information via an error-free backhaul channel with limited sum capacity. We assume a block fading channel which is invariant during the transmission of a codeword of N_{c} symbols. The transmission is disturbed by additive i.i.d. Gaussian noise. The MTs transmit independent messages mapped onto codewords that are drawn i.i.d. from Gaussian random vectors with variance p. Furthermore, all BSs and MTs are assumed to be fully synchronized in time and frequency, and the channel is assumed to be perfectly estimated for each transmission block. Hence, the received signal $\mathbf{y}_m \in \mathbb{C}^{N_{\text{bs}}}$ at BS m is given by

$$\mathbf{y}_m = \sum_{k=1}^{K} \mathbf{h}_{m,k} x_k + \mathbf{v}_m, \; m \in \mathcal{M}, \tag{1}$$

where $x_k \in \mathbb{C}$ is the transmit signal, $\mathbf{h}_{m,k} \in \mathbb{C}^{N_{\text{bs}}}$ is the vector of channel gains from MT k to BS m, and $\mathbf{v}_m \in \mathbb{C}^{N_{\text{bs}}}$ is i.i.d. noise of distribution $\mathcal{NC}\left(\mathbf{0}, \sigma_v^2 \mathbf{I}\right)$.

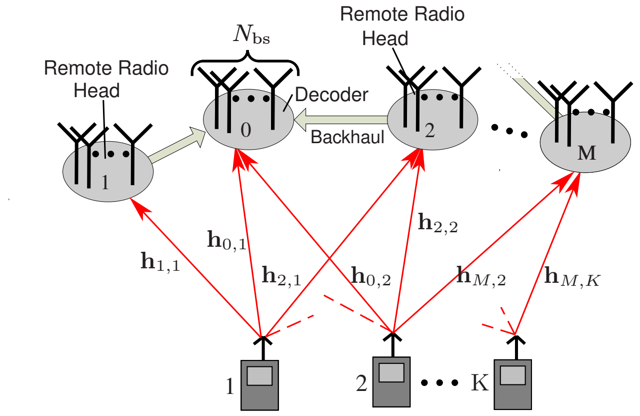

Fig. 1: Model of a distributed antenna system

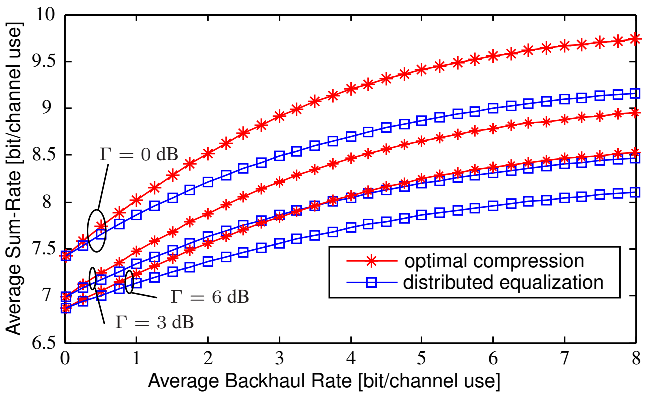

Fig. 2: Comparison of the average sum rates

Since the backhaul network is limited in its capacity, achievable data rates depend on the BSC scheme that is employed. For example, it is shown in [6] that the relative performance of these BSC schemes depends on the channel realization, which suggests that we should consider a channel dependent use of different BSC schemes. In this paper, however, we only consider a setup that functions as a distributed antenna system, where BSs $1, \ldots, M$ function as remote radio heads (RRHs) and BS 0 as the decoder.

III. DISTRIBUTED EQUALIZATION AND JOINT DECODING

The problem of finding the optimal codebook for a system as depicted above with sum backhaul constraint $c_{\max}$ is approached in [4]. The best known method for the exchange of receive signals is distributed Wyner-Ziv compression with prior use of conditional Karhunen-Loeve transformation of the received signal at all RRHs, which is invertible at the decoding BS without loss of mutual information. However, this approach requires that BS 0 has full knowledge of the compound channel, and hence requires that additional channel information be forwarded over the backhaul, resulting in an additional backhaul load. In this paper, we propose an alternate approach of using MMSE-equalization filters and forwarding compressed versions of local estimates $\tilde{x}_k \in \mathbb{C}$. Due to the absence of full channel knowledge at the decoder, the exploitation of side-information by Wyner-Ziv coding is not possible. Since the use of Wyner-Ziv coding is questionable from a practical perspective and for a better comparability of both schemes, we do not make use of this option in the Karhunen-Loeve approach as well.

At BS m, MMSE-equalization results in estimates for the transmitted signal of MT k, which can be modeled as

$$\tilde{x}_k^{[m]} = x_k + \tilde{v}_k^{[m]}. \tag{2}$$

The remaining distortion is $\tilde{v}_k^{[m]} \sim \mathcal{NC}\left(0, \sigma^2_{\tilde{v}_k^{[m]}}\right)$, where

$$\sigma^2_{\tilde{v}_k^{[m]}} = 1 - \mathbf{h}_{m,k}^H \mathbf{\Phi}_{\mathbf{y}_m\mathbf{y}_m}^{-1} \mathbf{h}_{m,k}, \tag{3}$$

and $\mathbf{\Phi}_{\mathbf{y}_m\mathbf{y}_m}$ is the covariance matrix of the received signal.

For solving the problem of finding the codebooks that maximize the sum-rate, the algorithms as described in [4, Sec. IV] can be applied. Each $\tilde{x}_k^{[m]}$ is interpreted as being forwarded by a separate virtual BS that receives only one MT under i.d.d. Gaussian noise of variance σ_v^2. The channel of this virtual BS is thus

$$\mathbf{H}_{\tilde{x}_k^{[m]}} = \kappa_k^{[m]} \mathbf{e}_k \mathbf{e}_k^H, \text{ where } \mathbf{H}_{\tilde{x}_k^{[m]}} \in \mathbb{C}^{[K \times K]}, \tag{4}$$

and where $\mathbf{e}_k$ is the unit vector with a one in the kth position, and $\kappa_k^{[m]}$ is introduced in order to normalize the noise, given by:

$$\kappa_k^{[m]} = \sqrt{\frac{\sigma_v^2}{\sigma^2_{\tilde{v}_k^{[m]}}}}. \tag{5}$$

The problem for finding the optimal set of codebooks $\mathbf{\Phi}^{[1:MK]} = \left\{\mathbf{\Phi}^{[1,1]}, \ldots, \mathbf{\Phi}^{[M,K]}\right\}$ that maximize the sum-rate can be readily formulated as:

$$\text{max. ld}\left|\mathbf{I} + \mathbf{P}\mathbf{H}_0^H \mathbf{\Phi}_{nn}^{-1} \mathbf{H}_0 + \sum_{m,k=1}^{M,K} \mathbf{P}\mathbf{H}_{\tilde{x}_k^{[m]}}^H \left(\mathbf{\Phi}^{[m,k]} + \sigma_v^2 \mathbf{I}\right)^{-1} \mathbf{H}_{\tilde{x}_k^{[m]}}\right| \tag{6a}$$

$$\text{s.t. ld}\left|\mathbf{I} + \text{diag}^{-1}\left(\mathbf{\Phi}^{[1,1]}, \ldots, \mathbf{\Phi}^{[M,K]}\right) \mathbf{\Phi}_{\tilde{\mathbf{x}}}\right| \leq c_{\max}. \tag{6b}$$

The conditional covariance of the equalized symbols given the received signal at BS 0 is given by [4]:

$$\mathbf{\Phi}_{\tilde{\mathbf{x}}} = \begin{bmatrix} \mathbf{H}_{\tilde{x}_1^{[1]}} \\ \vdots \\ \mathbf{H}_{\tilde{x}_K^{[M]}} \end{bmatrix} \mathbf{P} \begin{bmatrix} \mathbf{H}_{\tilde{x}_1^{[1]}} \\ \vdots \\ \mathbf{H}_{\tilde{x}_K^{[M]}} \end{bmatrix}^H + \sigma_v^2 \mathbf{I} \tag{7}$$

Figure 2 compares the performance of both schemes in system with two double antenna BSs and two MTs. The curves show the average sum-rate as a function of the backhaul rate constraint for a Rayleigh distributed fading channel. Since, the MTs are located at different distances to the BSs, we introduced the isolation factor Γ that determines the power gain ratio of cross links $(\mathbf{h}_{1,1}, \mathbf{h}_{0,2})$ to that of direct links

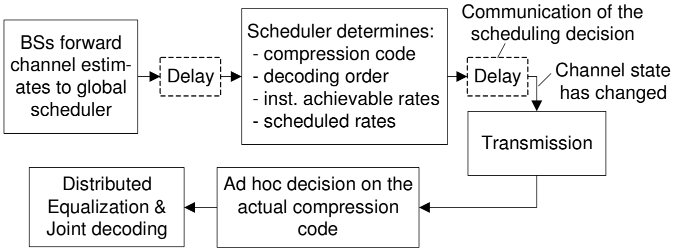

Fig. 3: Scheduling and ad hoc decoding process

$(\mathbf{h}_{0,1}, \mathbf{h}_{1,2})$. Note that the applied distributed equalization scheme achieves lower rates compared to the optimal scheme proposed by del Coso and Simoens, because we lost the advantage of successive interference cancellation of the forwarded signals due to distributed equalization of both the MTs at the RRHs. This is a direct consequence of the fact that we only have local channel information at the decoder and that we separate the MT signals at the RRHs. For a fair comparison of both scheme, we have to trade-off this loss of sum-rate performance and the benefit that only local channel information is required for distributed equalization.

IV. Scheduling and Ad Hoc Compression

In the previous section, we pointed out that the distributed equalization approach, as an important benefit, requires only local channel information at the decoder. We will point out another important benefit of distributed equalization, which is easier adaptation of compression codebooks for multi-antenna BS systems. However, the ad hoc cooperation method that shall be proposed in this section requires full knowledge of the channel, which is assumed to be available for the remainder of this paper.

A. Scheduling

The scheduling, transmission, and decoding process is depicted in Figure 3. Based on the available channel information, the scheduler assigns scheduled transmission rates $r_{\text{s},k}$ $(k \in \mathcal{K})$. However, as achievable rates depend on the compression accuracy, the scheduler has to find a trade-off between throughput and the required backhaul capacity.

B. Ad Hoc Compression for Time Variant Channels

Subsequent to the transmission, the BSs decide which rate is used for compression. As pointed out in [5], in this decision, the BSs are not bound to use a codebook with the same rate that was assumed by the scheduler. As depicted in Figure 3, in a real system the scheduled transmission is carried out with a certain delay, the amount of time it takes to forward the channel estimates to the scheduler and then to compute and communicate the scheduling decision. Because the channel information after transmission is more precise, it is beneficial to adapt the compression accordingly. We compare two strategies:

1) Fixed compression: the compression codebooks that were determined by the scheduler $\mathbf{\Phi}_{\text{s}}^{[1:MK]}$ are also used for the exchange of compressed signals.
2) Adaptive ad hoc compression: the updated channel state information after transmission is taken into account to decide in an ad hoc manner which compression codebooks $\mathbf{\Phi}_{\text{adapt}}^{[1:MK]}$ have the lowest rate while achieving successful decoding.

For the following examination of these schemes, we define four rates:

r_k	Rate of MT k
$r_{\text{s},k}$	Scheduled Rate
$r_{\text{fix},k}$	Rate for the fixed compression scheme
$r_{\text{adapt},k}$	Rate for adaptive ad hoc compression

In order to find $r_k[n,c]$, we determine codebooks by solving (6) for a sum backhaul constraint of c. The rates $r_k[n,c]$ are then determined using the well known rate expressions of the MAC channel (e.g. [7]), where the compression distortion has to be considered as an additional i.i.d. Gaussian noise termn, as stated in (6).

For simplicity, we assume that $r_{\text{s},k}[n]$ is solely a function of the rates that were observed n_{d} codewords earlier:

$$r_{\text{s},k} = f(r_k[n - n_{\text{d}}, c]). \tag{8}$$

In particular, we assume that the scheduler makes its decision based on the fixed backhaul rate c_{fix} and determines codebooks that maximize the sum-rate by solving (6) and then chooses

$$r_{\text{s},k}[n, c_{\text{fix}}, \Gamma] = (1-\Gamma) r_{\text{fix},k}[n - n_{\text{d}}],\ 0 \le \Gamma \le 1, \tag{9}$$

where Γ is a backoff-factor similar to an SINR margin that is often used in practical systems.

If the adaptive scheme is employed, we exploit the fact that the BSs have full knowledge of the current channel state after the transmission. The RRHs are therefore able to appropriately adapt the compression to enable successful decoding at BS 0 with as little information exchange as possible. In any case, a backhaul usage above a certain threshold is uneconomical. Hence, we limit the maximum backhaul rate that can be used for the exchange to a value of c_{lim}.

C. Performance Measures

The transmission rate of MT k for any transmission block n is always $r_{\text{s},k}[n]$, and a transmission is successful as long as the rate that is supported by the channel is not smaller than the scheduled rate, i.e. $r_{\text{s},k}[n, c_{\text{fix}}, \Gamma] \le r_{\text{k}}[n, c]$. These facts are relevant for the computation of the average throughput, which for the fixed scheme is defined as

$$\begin{aligned} &T_{\text{fix},k}(c_{\text{fix}}, \Gamma) = \\ &E_n\left[\mathbf{1}\Big(r_{\text{s},k}[n, c_{\text{fix}}, \Gamma] \le r_{\text{fix},k}[n]\Big) r_{\text{s},k}[n, c_{\text{fix}}, \Gamma]\right], \end{aligned} \tag{10}$$

where $\mathbf{1}(\cdot)$ is the indicator function, and $E_n[\cdot]$ determines the expected value over all transmitted blocks. Accordingly, the average throughput for the adaptive scheme is defined as

$$\begin{aligned} &T_{\text{adapt},k}(c_{\text{fix}}, c_{\text{lim}}, \Gamma) = \\ &E_n\left[\mathbf{1}\Big(r_{\text{s},k}[n, c_{\text{fix}}, \Gamma] \le r_{\text{adapt},k}[n, c_{\text{lim}}]\Big) r_{\text{s},k}[n, c_{\text{fix}}, \Gamma]\right]. \end{aligned} \tag{11}$$

Furthermore, we are interested in the average backhaul rate, which is

$$\bar{c}_{\text{adapt}} = E_n\left[c_{\text{adapt}}[n]\right] \tag{12}$$

for the adaptive scheme, and $\bar{c}_{\text{fix}} = c_{\text{fix}}$ for the fixed scheme.

The average throughput for a certain channel model depends on the scheduling parameters c_{fix}, Γ, and the ad hoc decoding parameter c_{lim}. Thus, for a fair comparison, we choose the maximum throughput, which is defined as

$$T^*_{\text{fix},k}(c = c_{\text{fix}}) = \max_{\Gamma: 0 \leq \Gamma \leq 1}, T_{\text{fix},k}(c_{\text{fix}}, \Gamma), \tag{13}$$

for the fixed backhaul scheme and as

$$T^*_{\text{adapt},k}(c) = \max_{c_{\text{fix}}, c_{\text{lim}}, \Gamma, \bar{c}_{\text{adapt}} \leq c} T_{\text{adapt},k}(c_{\text{fix}}, c_{\text{lim}}, \Gamma), \tag{14}$$

for the adaptive scheme.

V. ADAPTIVE AD HOC COMPRESSION

A. Achievable Data Rates and Optimal Compression

The problem of optimal ad hoc compression is basically the inverse of the problem stated in (6). Each MT transmits with a scheduled rate $r_{\text{s},k}$, and we are looking for the compression codebooks $\mathbf{\Phi}^{[1:MK]}_{\text{adapt}}$ with the minimum rate that supports this rate. Hence, the problem can be defined as

$$\text{min.} \quad \text{ld}\left|\mathbf{I} + \text{diag}^{-1}\left(\mathbf{\Phi}^{[1,1]}, \ldots, \mathbf{\Phi}^{[M,K]}\right) \mathbf{\Phi}_{\tilde{\mathbf{x}}|\mathbf{y}_0}\right| \tag{15a}$$

$$\text{s.t.} \quad r_k[n, c] \geq r_{\text{s},k}[n, c_{\text{fix}}, \Gamma]. \tag{15b}$$

The solution for this problem is found by a simple bisection method. When this method is applied, the adaptive rates $r_{\text{adapt},k}$ follow the scheduled rates $r_{\text{s},k}$ for all channels which are not in outage $c_{\text{adapt},k}[n] \leq c_{\text{lim}}$. Due to the use of successive interference cancellation, at the decoding BS error propagation has to be taken into account. When a MT which should be decoded first is in outage, the interference for all other users increases, which increases their outage probabilities as well.

B. Simulation Results

The following results were obtained by Monte Carlo simulations for a rich scattering environment, leading to complex Gaussian channel realizations (Rayleigh channel). The MT is assumed to be located at the cell edge. Hence, without loss of generality, we assume the channel gains of all links to be $\mathcal{NC}(0, 1)$. We employ Jakes' spectrum to model the effects of the Doppler spread [8], which occur due to movements of the MTs with speed v. Furthermore, we assume Gaussian coding over a complete transmission block of duration $T_\text{s} = \frac{1}{15\text{kHz}}$ and a scheduling delay of 3 ms which corresponds to $n_\text{d} = 45$.

In Figure 4, we compare the average backhaul that is required for a certain maximum throughput with different degrees of time variance of the channel. The optimal parameters $(c_{\text{fix}}, c_{\text{lim}}, \Gamma)$ of the maximum throughput problems (13) and (14) stated in Section IV-C were found by an exhaustive search over the parameter space. As a major result, compared to [5], we do not see a strong degradation of ad hoc cooperation gains with the number of users.

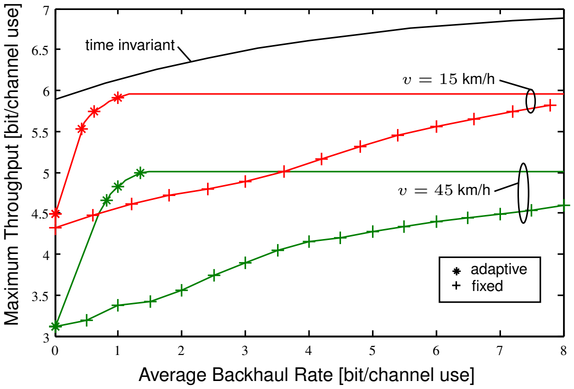

Fig. 4: Maximum sum throughput over backhaul for distributed equalization for different time varying Rayleigh channels ($f_\text{c} = 2.68$ GHz, $\sigma_v^2 = 0.1$, $P = 1$)

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced the concept of distributed equalization for distributed antenna systems that exchange information through a rate constrained backhaul. The proposed scheme has the advantage that only local channel information is required at the decoder. As we have shown for an illustrative scenario, the downside, distributed equalization does not allow us to achieve the same sum-rates as schemes for distributed antenna systems that require full channel knowledge. However, we explored further benefits of distributed equalization, by finding a low complexity adaptation of the compression rate according to the channel state after transmission, which is very beneficial when a scheduling delay is considered.

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