Power Control and Scheduling for Joint Detection Cooperative Cellular Systems

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Abstract—Cooperative joint detection in the uplink of cellular systems is a promising means to combat inter-cell interference. In fact, interference from other users in the same cooperation cluster is turned into useful signal energy in such systems. While cooperation is generally beneficial, the system behavior largely depends on the power control and scheduling strategies employed, as demonstrated in this paper. We investigate different combinations of these two mechanisms and provide insights into the system behavior considering spectral efficiency, fairness and energy efficiency.

Index Terms—Joint Detection, CoMP, Scheduling, User Grouping, Power Control

I. INTRODUCTION

Inter-cell interference is a major limiting factor for the performance of cellular communication systems. Coordinated Multi-Point (CoMP) techniques in which neighboring base stations (BSs) cooperate by exchanging information are promising candidates to fight inter-cell interference in future wireless systems. Through the exchange of received signals in the uplink, a cluster of cooperating BSs is transformed into a distributed antenna system (DAS). This allows user signals to be jointly detected at a central processing unit. Through the additional spatial degrees of freedom, users can be spatially separated and thus interference from within the cluster is effectively transformed into useful signal energy. Examples of the benefits of joint detection are presented in [1].

To utilize the extra degrees of freedom to their fullest potential, a centralized scheduler that is aware of the interference situation in all participating cells is required. By opportunistically assigning transmission resources to user terminals based on their instantaneous channel realizations (e.g., users that can be well separated spatially), schedulers can greatly enhance the transmission efficiency (multi-user diversity). In a CoMP system, the scheduling task is (in principle) similar to that in a multi-user MIMO system: several users are assigned to the same transmission resources. This process is often referred to as user grouping or pairing. Many algorithms for user grouping have been proposed and analyzed, [2]–[6]. An overview of resource allocation for systems with spatial multiplexing is provided in [8].

For user transmissions in the uplink, different power control schemes can be implemented. In practical systems, these schemes commonly adjust the transmit powers based on long-term channel statistics. In this way, pathloss variation can for example be compensated. In fact, different power controls have a large impact on the system behavior and performance indicators such as fairness and spectral efficiency. Thus it is important for system designers to get a good intuition about the behavior of different combinations. To the best of our knowledge, the impacts of power control algorithms have not been investigated together with different scheduling algorithms for joint detection CoMP in the literature yet. Instead, scheduling algorithms are often evaluated for multi-user MIMO systems, where power control mechanisms are sometimes considered (e.g., [6]). In this case, the localization of antennas leads to channel statistics that differ strongly from the ones that are observed in distributed antenna systems.

In this paper, we provide insights into the performance of different combinations of scheduling algorithms and power control schemes for a cooperative system with multiple BSs. In our evaluation, we focus on the metrics spectral efficiency, fairness, and energy efficiency.

The paper is structured as follows: In Section II, we describe the scenario considered, and present our system model. In Sections III and IV respectively, we detail the power control schemes and scheduling algorithms considered. Section V is used to present numerical results, before the paper is concluded in Section VI.

Notation: We use bold lower case letters to denote vectors and bold upper case letters to denote matrices. With \( \text{diag}(x, y) \) we denote a \( 2 \times 2 \) diagonal matrix with \( x \) and \( y \) on the diagonal. Furthermore, we use \( E[\cdot] \) to denote expectation and \( \mathbf{I} \) to denote an identity matrix.

II. SYSTEM MODEL

We consider a small toy-scenario with two neighboring BSs as depicted in Figure 1. We have also investigated larger cooperation clusters. However, since the basic observations remain the same, we concentrate on the smallest cooperation size for simplicity. In the case depicted, the \( K \) user equipments (UEs) considered are placed on a straight line between the two access points with a minimum distance \( d_0 \) to the BSs. The BSs are separated by \( d_{BS} \) meters and, both BSs and UEs are equipped with a single receive and transmit antenna.

For simplicity, we consider that the scheduled terminals transmit on one flat channel (this could, for example, be an OFDM subcarrier). We assume that the central scheduler...
knows all channel states of the UEs perfectly. Thus, it knows the matrix
\[
H = [h_1, \ldots, h_K],
\]
where \( h_k = [h_{1k}, h_{2k}]^T \) is the channel vector of user \( k \), which contains the complex channel states to each of the two BSs. The channel coefficient of user \( k \) to BS \( m \), \( h_{mk} \) is modeled as a zero mean complex Gaussian random variable with a distance dependent variance
\[
\sigma_{mk}^2 = E[|h_{mk}|^2] = \mu \cdot \left( \frac{d_0}{d} \right)^r,
\]
where \( d \) is the distance between user \( k \) and BS \( m \), \( r \) is the pathloss exponent and the constant \( \mu = \lambda^2/(4d_0^2\pi)^2 \) relates the distance dependent attenuation to the wavelength \( \lambda \) and thus carrier frequency of the transmission.

As the received signals from both BSs are forwarded to a central decoder where they are jointly decoded, the two terminals can be spatially separated in the scenario considered. Thus, we assume that the central scheduler assigns two UEs \( i, j \) for transmission in each transmit time interval (TTI).

Once the two terminals are selected by the scheduling algorithm, the transmission can occur. The delay between the scheduling decision and the actual transmission will, in practice, lead to scheduling decisions that are slightly outdated. Here, we assume that the channel states do not change between scheduling decision and transmission. The combined received signal at the two BSs can then be denoted as
\[
y = H_{ij}P^{1/2}x + n,
\]
where \( P = \text{diag}(p_i, p_j) \) holds the transmit powers, \( H_{ij} = [h_i, h_j] \) is the channel matrix containing the channel vectors of the two selected users and \( x \) contains the transmit symbols of the two terminals. We assume that the transmit symbols are drawn independently from a Gaussian distribution with unit variance so that \( E[xx^H] = I \). The vector \( n \) contains the thermal noise at the two BSs. We model the noise as white complex Gaussian circular symmetric with variance \( \sigma_n^2 \), so that \( E[nn^H] = \sigma_n^2 I \).

Assuming a capacity achieving MMSE-SIC receiver (Minimum Mean Square Error - Successive Interference Cancellation), the maximum achievable sum rate for the above transmission can be denoted as
\[
R_{i,j} = \log_2 \left( 1 + \frac{p_i h_i h_j^H}{p_j h_j h_j^H + \sigma_n^2 I} \right),
\]
where the norm \( ||h||^2 \) is equal to the scalar product \( h^H h \). In the following, we assume that the decoding order is chosen such that the difference between the two user rates is minimized.

### III. Power Control

We consider three different power control schemes that adjust the transmission power of the UEs. We do not consider schemes that make use of instantaneous fading conditions, as they have only limited practical relevance. In the following, we describe the three different power control mechanisms in detail.

1) **Constant Transmit Power:** The simplest considered power control sets the transmit power of all UEs in the service area to the same constant power level, \( p_{\text{const}} \).

2) **Single-Cell Power Control:** In this power control strategy, the user power is adjusted to compensate the pathloss and to ensure an average SNR at the nearest BS. Thus, the power allocation solely depends on the position of the UEs in the service area. Let \( d \) be the distance between the user and its nearest BS. With a target average SNR of \( \gamma_s \), the transmit power is then chosen as
\[
p_{\text{single}}(d) = \frac{\gamma_s \sigma_n^2}{E[||h||^2]} = \frac{\gamma_s \sigma_n^2}{\mu \cdot \left( \frac{d_0}{d} \right)^r}.
\]

Here \( h \) represents the channel to the closest BS. This power control strategy is used in 3GPP LTE with the difference that LTE also offers the possibility to compensate the pathloss only partially in order to reduce inter-cell interference (ICI) in the uplink. As ICI does not exist within the cooperation cluster that we consider here, we do not consider partial pathloss compensation.

3) **Multi-Cell Power Control:** As the received signals from both BSs are used for joint detection, we can define another SNR that considers the received power at both BSs. In case the grouped users can be perfectly separated by the MMSE receive filter (the channel vectors are orthogonal, i.e. there is no remaining inter-user interference), this SNR would directly relate to the achieved user rates. We refer to it as **multi-cell SNR**, which can be denoted as
\[
\gamma_m = \frac{p \cdot E[||h_1|^2 + E[||h_2|^2]]}{\sigma_n^2}.
\]

Given a target average multi-cell SNR \( \gamma_m \), we can set the transmit power of users based on their distance \( d \) to the nearest BS as
\[
p_{\text{multi}}(d) = \frac{\gamma_m \sigma_n^2}{E[||h_1|^2 + E[||h_2|^2]]} = \frac{\gamma_m \sigma_n^2}{\mu \cdot \left( \frac{d_0}{d} \right)^r + \left( \frac{d_0}{d_{BS} - d} \right)^r}.
\]
A. Normalization

One of our evaluation metrics for the performance of different scheduling schemes combined with the above power controls, will be the distribution of throughput over the service area. In order to have a somewhat fair comparison, we normalize the above power controls in the following way: For a given single-cell SNR $\gamma_s$, we calculate the average power over the service area as

$$p_{\text{single}} = \frac{1}{d_{BS}/2 - d_0} \int_{d_0}^{d_{BS}/2} \tilde{p}_{\text{single}}(\delta) \, d\delta. \quad (10)$$

Then we set $p_{\text{const}} := p_{\text{single}}$ and calculate the mean transmit power over the service area $p_{\text{multi}}$ as in (10) using an arbitrary multi-cell SNR $\gamma_m$. Finally, we scale the power for Multi-Cell Power Control with the scaling factor $F = \tilde{p}_{\text{single}} / \tilde{p}_{\text{const}}$ (i.e., we set $p_{\text{multi}}(d) := F \cdot p_{\text{multi}}(d)$). In this way, we ensure that the average power (averaged over the service area) is the same for all three power control schemes. Hence, the selection of $\gamma_s$ defines the behavior of all power controls. Figure 2 depicts the transmit power for the three schemes depending on the user position. The values depicted are based on the assumptions given in Table I and are used throughout the remainder of this paper. In the same figure, we also depict the resulting multi-cell SNR (8) for all schemes. By definition, the multi-cell SNR is constant for the Multi-Cell Power Control. For the Single-Cell Power Control, it has its peak at the cell-edge as the single-cell control does not consider that the user signal is received at both BSs. We have chosen a very high edge as the single-cell control does not consider that the user target SNR $\gamma_s$ the average power (averaged over the service area) is the same for all three power control schemes. Hence, the selection of $\gamma_s$ defines the behavior of all power controls. Figure 2 depicts the transmit power for the three schemes depending on the user position. The values depicted are based on the assumptions given in Table I and are used throughout the remainder of this paper. In the same figure, we also depict the resulting multi-cell SNR (8) for all schemes. By definition, the multi-cell SNR is constant for the Multi-Cell Power Control. For the Single-Cell Power Control, it has its peak at the cell-edge as the single-cell control does not consider that the user signal is received at both BSs. We have chosen a very high edge as the single-cell control does not consider that the user target SNR $\gamma_s$, as we want the system to operate exclusively in an interference limited regime, which is most interesting for cooperative detection.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-site distance</td>
<td>$d_{BS} = 500$ m</td>
</tr>
<tr>
<td>Minimum distance</td>
<td>$d_0 = 50$ m</td>
</tr>
<tr>
<td>Pathloss exponent</td>
<td>$r = 4$</td>
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<tr>
<td>Target SNR</td>
<td>$\gamma_s = 30$ dB</td>
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<tr>
<td>Carrier frequency</td>
<td>$f_c = 2$ GHz</td>
</tr>
<tr>
<td>Noise density</td>
<td>$-179$ dBm/Hz</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>$180$ kHz</td>
</tr>
</tbody>
</table>

IV. SCHEDULING ALGORITHMS

We consider three different scheduling algorithms that try to achieve different scheduling goals in terms of spectral efficiency, and fairness. In general, channel aware schedulers try to maximize an objective function that depends on the current channel states of the users. Thus, the users $i,j$ are selected by trying to solve the following optimization problem

$$\arg \max_{i,j \in \{1, \ldots, K\}, i \neq j} O(\mathbf{H}_{ij}), \quad (11)$$

where $O(.)$ is an objective function (e.g., sum rate). However, finding the optimal user grouping involves an exhaustive search over all possible combinations that can easily become prohibitively large as the number of users increases. Greedy algorithms reduce this complexity by iteratively constructing user groups. This reduces the number of required evaluations of the scheduling metric from $(K)^2$ to $\sum_{s=0}^{G-1} (K-s)$, where $G$ is the group size. In this work, we restrain ourselves to greedy algorithms. It has been shown, e.g., in [7] that the performance of greedy grouping algorithms can be very close to the solution of the optimization problem above. For comparison, we also consider a scheduler that is not channel aware.

1) Greedy Max Rate Scheduling: The Greedy Max Rate scheduler [7] first selects the user $i$ with the best instantaneous receive power $p_i||\mathbf{h}_i||^2$ for transmission. In the following iterations, users are added to the group iteratively by selecting the users that maximize the achievable sum rate. As we are considering user groups of size two, $K - 1$ users are tested for compatibility with user $i$ using equation (4). Finally, the combination with the highest sum rate is selected. Thus, the scheduler tries to maximize the sum rate.

2) Greedy Proportional Fair Scheduling: Here, we adopt a greedy version of the Double Proportional Fair scheduler introduced in [9]. Proportional fairness is a well-known concept that balances spectral efficiency and fairness. For single user transmissions, the user is selected for transmission that maximizes the ratio $R/R$, where $R$ is the instantaneous achievable rate $R = \log_2(1 + p_i||\mathbf{h}_i||^2/\sigma_i^2)$ and $\bar{R}$ is the average achieved rate of the considered user (for ease of notation, we do not use user indices here). In a greedy fashion, we select the first user $i$ of the group as the one that maximizes the above described ratio. Then, the second user $j$ is selected as

$$j = \arg \max_{j \in \{1, \ldots, K\} \backslash i} \frac{R_i + R_j}{R_i + R_j} = \frac{R_{i,j}}{R_i + R_j}, \quad (12)$$

where the instantly achievable sum rate is calculated using (4). The average user rates are updated after each scheduling decision. We use the common approximation

$$\bar{R}[n] = (1 - 1/t_c)\bar{R}[n-1] + 1/t_c R[n], \quad (13)$$

to calculate average rates, where the index $n$ indicates the time. $\bar{R}[n]$ in this context is the actual achieved rate of the user, which is zero if the user was not scheduled. To make
3) Greedy Max Fair Scheduling: The Max Fair scheduler (also referred to as Max Min Fair) is not channel aware. Instead, it tries to maximize user fairness solely based on the observation of average user rates. Besides neglecting instantaneous rates, its scheduling metric is very similar to that of the proportional fairness scheduling described earlier: the first user is selected to maximize the ratio $1/R_i$. The second is then chosen as

$$j = \arg \max_{j \neq i} \frac{1}{R_i + R_j}. \quad (14)$$

In general, we can observe that the Max Rate and Max Fair schedulers are based on the numerator and denominator of (12), respectively. Based on this observation, [10] proposes a framework that allows an adaptive and smooth transition between these different methods.

V. Simulation Results

In this section we present simulation results for the power control schemes and scheduling algorithms considered. For each combination of power control scheme and scheduling algorithm, we simulate 10,000 user drops where $K = 10$ users, drawn from a uniform distribution, are randomly placed in the interval $[d_0, d_{BS} - d_0]$. Depending on the user positions, the transmit powers of the users are set as described in Section III. For each user drop, we further simulate 1000 channel realizations. We assume that the channel is block static and changes for each transmit time interval (TTI) of length 1ms. The channels are correlated based on the maximum Doppler frequency. We assume that all users move at a speed of 30 km/h and the correlation behavior is modeled using the well-known Jake’s model. The scheduling decisions are updated for each TTI. Finally, we assume perfect channel knowledge and full buffer traffic (each user has data to transmit).

Figure 3 depicts the average achieved user rates based on the position in the coverage area for all power control/scheduling combinations. The depicted curves are obtained through locally averaging transmission rates in $N = 20$ bins of size 20m over the simulated TTIs. If a user is scheduled for transmission in a certain TTI, its achieved rate is considered for the bin average. If no user is located in the bin for a certain drop or none of the users in the bin are selected for transmission, the bin throughput for the TTI is zero.

Considering the Max Rate Scheduler, the average rates mainly follow the multi-cell SNR as depicted in Figure 2, which leads to a very unfair rate distribution for constant tx-power. As mostly users close to their BS are selected, cooperative detection is not very beneficial and similar results can be expected from conventional cellular transmission. Surprisingly, even though the multi-cell SNR is constant over the service area for Multi-Cell Power Control, the rate average at the cell-edge is slightly lower. From our observations, it is apparent that the Max Rate Scheduler tends to select users that are, a) from different cells and, b) have similar distances to their BSs, as this yields channel conditions where the users can be separated more easily (i.e. the user vector channels’ orthogonality is higher). This separability naturally increases as users are closer to their BSs. Thus, users at the cell-edge are slightly less likely to be scheduled in this case.

As expected, the Max Fair algorithm achieves a fair distribution of average rates over the service area. Interestingly, the average rates are slightly higher in the case of constant tx-power. Naturally, the behavior of the Proportional Fair algorithm is in between the other two schedulers. Furthermore, it is clearly visible, how the spatial fairness increases from constant, to single-cell, and Multi-Cell Power Control, which is due to the different distributions of the multi-cell SNR.

The average rates alone do not provide enough insight into the selection behavior of the different combinations of scheduling algorithms and power control schemes. Figures 7-9 depict the joint probability density of two users being selected for transmission based on their position in the service area. Considering the upper left plot, we learn, e.g., that a user at position 50m will not be scheduled with a second user at a close by location (zero probability). Instead, users closer to the other base station are preferred in the depicted case. The figures depict all combinations and allow a deeper understanding of the selection behavior of the different considered schemes. All channel aware algorithms (Max Fair, Prop. Fair) group users from different cells. The selection behavior of the prop. fair algorithm hardly changes for the different power control schemes. However, it is visible that it schedules slightly less users at the cell-edge for the case of Fixed Power Control. For the Max Fair algorithm, every user pair is almost equally likely for Single- and Multi-Cell Power Control. For fixed tx-power, users at the cell-edge are preferred as their average rates are by far the lowest. As expected, the Max Rate Scheduler mainly selects cell-center users for fixed tx-power and cell-edge users for Single-Cell Power Control. For Multi-Cell Power Control, users within the cells are selected almost equally likely with a preference for symmetric user positions. Cell-edge users are less likely to be scheduled. This is in line with our observations for the spatial average rates.

Next, we want to observe the fairness of rate distribution in the service area, based on the results in Figure 3. To measure spatial fairness, we use the Jain’s index

$$J = \frac{\left(\sum_{i=1}^{N} \bar{R}_i\right)^2}{N \cdot \sum_{i=1}^{N} (\bar{R}_i)^2}, \quad (15)$$

where $\bar{R}_i$ is the average local transmission rate in bin $i$, and $N = 20$ is the number of bins. If all rates are equal $J = 1$. In the most unfair case, if only one bin achieves non-zero rates $J = 1/N$. Figure 4 depicts the Jain’s index over the mean of the locally averaged rates. This allows us to get a feeling for the overall spectral efficiency and fairness of the different combinations considered. Clearly, Max
Rate Scheduling is spectrally most efficient with constant tx-power. Multi-Cell Power Control together with Max Rate scheduling offers a very good trade-off between fairness and spectral efficiency. The combination of constant tx-power and prop. fair scheduling seems to also achieve a good trade-off. However, looking at Figure 3, we observe that cell-center users still achieve almost double the rates of cell-edge users. As expected, Max-Fair is the least spectrally efficient algorithm.

Even though we select user powers according to position, the actual average transmit power used also depends on the scheduling decisions. If users are selected more often, their average transmit power (averaged over time) is higher than for users that do not get to transmit often. The actual average transmit powers of the different combinations are depicted in Figure 5. Interestingly, for the Proportional Fair scheduler, the average power usage in the service area follows the trend set by the power control schemes the closest. While the behavior of the other schedulers deviates from the power control trend for the constant power case, it is very aligned for single and Multi-Cell Power Control.

Given the average transmit powers, we can calculate the energy efficiency of the different schemes, which we depict in Figure 6 along with the spatial fairness. Interestingly, in terms of energy efficiency, we see an almost identical order for the different combinations as observed for the mean throughput earlier. Thus, spectral efficient combinations are also energy efficient. This is intuitive, as spectral efficient schedulers make best use of instantaneous fading conditions. Hence, the Max Fair scheduler is the least energy efficient. Likewise, we would expect the Max Rate Scheduler to be the most energy efficient. However, this is not true for all power control strategies. For Single-Cell Power Control, a significantly higher amount of power is used at the cell-edge, where the users are on average not as likely to be well separable, as explained before. Thus, this extra power spent does not translate into a high rate gain and the energy efficiency is very bad.

Overall, we can state that the combination of Multi-Cell Power Control and Max-Rate scheduling provides a good trade-off between fairness, spectral efficiency, and energy efficiency. Using Multi-Cell Power Control guarantees a fair medium access probability across the service area and Max-Rate scheduling makes best use of the instantaneous channel realizations. However, this good trade-off is not achievable for large inter-site distances, when the terminals run into their transmit power limits at the cell-edge. In this case, Multi-Cell Power Control fails to provide overall access fairness and Proportional Fair algorithms are preferable.

**VI. CONCLUSIONS**

In this contribution, we have analyzed different combinations of scheduling algorithms and power control schemes for cooperative systems that employ joint detection with respect to
throughput, fairness and energy efficiency. As we have shown, the selection of strategies has a large impact on the system behavior which needs to be well understood for system design. It was shown that a good trade-off between the different performance criteria can be achieved if the power control scheme provides for fair medium access conditions and the scheduler exploits instantaneous fading realizations.

REFERENCES