Linear Successive User Allocation in the Multi-Cell MIMO Environment

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***Abstract*—An interference management method for coordinating downlink transmission in a Multiple-Input Multiple-Output (MIMO) cellular network is proposed. The problem is to efficiently manage inter-cell interference in a multi-cell environment, by so-called transmitter cooperation, in order to reduce the diminishing effects of interference on the networks performance. To allow for application in deployable networks, an utmost concern of the presented algorithm is to provide a low-complexity solution avoiding costly combinatorial or non-convex optimization problems. The problem is solved by a network wide successive allocation of data streams and choosing linear transmit and receive filters for each data stream, such that interference is completely avoided. By embedding our new algorithm in a more general framework for interference coordination, we can show relevant gains for network performance where especially the cell-edge users profit.**

I. INTRODUCTION

In the downlink of a cellular network inter-cell interference (ICI) can be a severely limiting factor, especially users at the cell edge are affected and might be excluded from network service. A possible solution to completely eliminate ICI is the joint encoding of information over multiple transmitters [1], [2], so-called network MIMO. In case full channel state information (CSI) and all data is available at a central controller, joint encoding over geographically distributed antennas renders the network into a super-cell, and network MIMO can efficiently exploit all spatial degrees of freedom to eliminate ICI. Network MIMO requires a huge amount of additional complexity and signaling compared to single cell signal processing and might be difficult to implement in practice. Therefore, methods aiming at elimination of interference by cooperation of the transmitters, while every user is served by a single transmitter, are attractive for deployable networks. In order to cancel interference, user signals are orthogonalized in the signal space constituted by the available resources, for example time, frequency, and space. A simple scheme that completely removes ICI is to exclusively allocate frequency bands to transmitters and apply any single cell algorithm on the allocated carriers, which corresponds to the classical frequency reuse planning, a very simple form of interference management, missing the opportunity for cooperation in the spatial domain. The availability of multiple antennas at transmitter and receiver allows multiple users to be served interference free at the same time on the same frequency by spatial multiplexing. Interference coordination by adjusting the transmission space of each user is well understood and can be solved optimally for a single cell [3], [4]. In conventional cellular network design, signal processing in the spatial domain is only performed per cell, but interesting research towards extending spatial multiplexing over multiple transmitters is emerging. For networks where the transmitters have multiple antennas and the receivers are equipped with a single antenna (MISO), the optimal solution is known [5], however the presented algorithm has prohibitive complexity for larger networks. Methods based on pricing for the interference caused [6], thresholds for a forbidden interference direction [7], or so-called interference temperatures [8] have potential for implementation with reasonable complexity.

Coordinated transmission strategies for full MIMO systems are mainly available for smaller scenarios, for example two or multiple interfering point-to-point transmissions [9], [10]. In [11] a gradient projection method on the covariance matrices of the input signals to interfering point-to-point MIMO links is used to compute a local maximum. Recent results on the maximum available degrees of freedom in interference networks [12], and interference alignment as technique to achieve them [13], appear to be a promising research direction. However existing algorithms to compute transmit and receive filters such that interference is aligned, for example the maxSINR algorithm [14], do not provide a user selection method, which is an important feature of our algorithm. In our method every user is served by a single cell and transmitters cooperate by jointly adjusting the transmission space of each stream in order to eliminate or reduce interference. By choosing linear transmit and receive filters for each data stream, interference can be completely avoided. The data streams transmitted are determined by a network wide successive allocation, inspired by the LInear Successive Allocation (LISA) [15], [16]. Depending on the network regarded, complete cancellation of interference by zero-forcing is not desired as it drastically reduces the number of active data streams. After showing encouraging results in a small network, we embed our algorithm in a framework [17], that enables to apply the algorithm only to these users that benefit enough from removing interference, leading to a significant improvement of the network performance, especially for the cell-edge users. We summarize the main features of our algorithm:

- linear receive and transmit filter to avoid the high computational complexity of Dirty Paper Coding
- successive user allocation to avoid costly combinatorial optimization problems
- reduced data exchange compared to network MIMO by coordination of single-cell transmission strategies

II. SYSTEM MODEL AND PROBLEM FORMULATION

The cellular system is given by a set of transmit arrays $\mathcal{S}, S = |\mathcal{S}|$, and a set of users $\mathcal{K}, K = |\mathcal{K}|$ distributed throughout the covered area. User assignment to a transmitter is done by a cell selection scheme formally described by a mapping $f : \mathcal{K} \rightarrow \mathcal{S}$. We usually assume the assignment to a transmitter to be fixed for each user and therefore f partitions the users such that

$$\mathcal{K} = \mathcal{K}_1 \cup \mathcal{K}_2 \cup \ldots \cup \mathcal{K}_S \text{ and } \mathcal{K}_i \cap \mathcal{K}_j = \varnothing \text{ if } i \neq j.$$

$M_{\text{TX},s}$ is the number of transmit antennas of a transmitter s and $M_{\text{RX},k}$ is the number of receive antennas of user k. Although not a prerequisite for our algorithm, we assume the same number of antennas for each transmitter and each user and therefore

$$M_{\text{TX},s} = M_{\text{TX}},\ \forall\ s \in \mathcal{S},$$

and

$$M_{\text{RX},k} = M_{\text{RX}},\ \forall\ k \in \mathcal{K}.$$

The channel matrices are

$$\{\boldsymbol{H}_{ks}\}^{k\in\mathcal{K},s\in\mathcal{S}} \in \mathbb{C}^{M_{\text{RX}}\times M_{\text{TX}}},$$

where $\boldsymbol{H}_{ks}$ is the channel matrix between transmitter s and user k. The received signal of user k consists of the desired signal, intra-cell, and inter-cell interference and can be expressed as

$$\boldsymbol{y}_k = \boldsymbol{H}_{kf(k)}\boldsymbol{x}_k + \underbrace{\sum_{i\in\mathcal{K}_{f(k)}\setminus k} \boldsymbol{H}_{kf(k)}\boldsymbol{x}_i}_{\text{intra-cell interference}} + \underbrace{\sum_{i\in\mathcal{K}\setminus\mathcal{K}_{f(k)}} \boldsymbol{H}_{kf(i)}\boldsymbol{x}_i}_{\text{inter-cell interference}} + \boldsymbol{\eta},$$

where $\boldsymbol{x}_i \in \mathbb{C}^{M_{\text{TX}}}$ is the transmit signal for user i and $\boldsymbol{\eta} \sim \mathcal{CN}(\boldsymbol{0}, \sigma^2\boldsymbol{I}_{M_{\text{RX}}})$ represents white Gaussian noise, where $\boldsymbol{I}_{M_{\text{RX}}}$ denotes the $M_{\text{RX}} \times M_{\text{RX}}$ identity matrix and σ^2 is the power of the noise received by every antenna. Assuming Gaussian modulation, the covariance matrix of the transmit symbol $\boldsymbol{x}_i$ is $\mathrm{E}\{\boldsymbol{x}_i\boldsymbol{x}_i^{\mathrm{H}}\} = \boldsymbol{Q}_i$. As we assume linear precoding, the covariance matrix of the noise plus interference for user k is given by

$$\boldsymbol{Z}_k = \sigma^2\boldsymbol{I}_{M_{\text{RX}}} + \sum_{i\in\mathcal{K}\setminus k} \boldsymbol{H}_{kf(i)}\boldsymbol{Q}_i\boldsymbol{H}_{kf(i)}^{\mathrm{H}},$$

and the information theoretic rate for user k is given by

$$r_k = \log_2\left(\frac{\left|\boldsymbol{H}_{kf(k)}\boldsymbol{Q}_k\boldsymbol{H}_{kf(k)}^{\mathrm{H}} + \boldsymbol{Z}_k\right|}{|\boldsymbol{Z}_k|}\right).$$

In the work presented, communication in the network is carried out by transmitting data streams over scalar channels that are established by linear transmit and receive filters. An operation point of the network is therefore defined by the set of data streams $\mathcal{D}, D = |\mathcal{D}|$,

$$\mathcal{D} = \{(\pi(1), \boldsymbol{u}_1, \boldsymbol{v}_1, p_1), \ldots, (\pi(D), \boldsymbol{u}_D, \boldsymbol{v}_D, p_D)\},$$

where each stream d is described by the assignment to a user $\pi(d) \in \mathcal{K}$, receive filter $\boldsymbol{u}_d \in \mathbb{C}^{M_{\text{RX}}}$, transmit filter $\boldsymbol{v}_d \in \mathbb{C}^{M_{\text{TX}}}$, and power allocation $p_d \in \mathbb{R}_+$. The receive and transmit filters are chosen as normalized vectors and the rate of a data stream d can be calculated as

$$r_d = \log_2\left(1 + \frac{\left|\boldsymbol{u}_d^{\mathrm{H}}\boldsymbol{H}_{\pi(d),f(\pi(d))}\boldsymbol{v}_d\right|^2 p_d}{\sigma^2 + \sum\limits_{i\in\mathcal{D}\setminus d}\left|\boldsymbol{u}_d^{\mathrm{H}}\boldsymbol{H}_{\pi(d),f(\pi(i))}\boldsymbol{v}_i\right|^2 p_i}\right). \quad (1)$$

Our contribution is a scheme that selects the stream set $\mathcal{D}$, aiming at the maximization of a utility $U : \mathcal{D} \mapsto \mathbb{R}_+$ that measures the network performance, in our case a weighted sum of the user rates

$$U(\mathcal{D}) = \sum_{d\in\mathcal{D}} w_{\pi(d)} r_d,$$

where the user weights $\boldsymbol{w} \in \mathbb{R}_+^K$ may represent the priorities of the users, or act as an interface that can be used to establish a fair rate allocation among the users. As the scheme intends to completely avoid interference, the filters are selected under a zero-forcing constraint, meaning that

$$\boldsymbol{u}_d^{\mathrm{H}}\boldsymbol{H}_{\pi(d),f(\pi(i))}\boldsymbol{v}_i = 0\ \forall\ i \in \mathcal{D}\setminus d,$$

for all $d \in \mathcal{D}$. We define the gain of the scalar channel for each stream as

$$\lambda_d = \frac{1}{\sigma^2}\left|\boldsymbol{u}_d^{\mathrm{H}}\boldsymbol{H}_{\pi(d),f(\pi(d))}\boldsymbol{v}_d\right|^2. \quad (2)$$

The data rate of a stream is then given by

$$r_d = \log_2(1 + \lambda_d p_d).$$

Assuming that the transmit and receive filter for all data streams are fixed, the optimal power allocation is calculated per transmitter according to the water-filling rule. For a transmitter s the power allocation is given by

$$p_d = \max\left\{w_{\pi(d)}\mu_s - \lambda_d^{-1}, 0\right\},\ \forall\ d \in \mathcal{D}_s,$$

where

$$\mathcal{D}_s = \{d \in \mathcal{D} : f(\pi(d)) = s\} \quad (3)$$

is the set of streams transmitted by transmitter s and μ_s is chosen such that the complete power budget P_s of the transmitter s is used, i. e.

$$\sum_{d\in\mathcal{D}_s} p_d = P_s.$$

To facilitate more convenient notation we define a function $\mathrm{WF}(\mathcal{D})$, that updates the power allocation according to the water-filling rule,

$$\mathcal{D} \leftarrow \mathrm{WF}(\mathcal{D}). \tag{4}$$

It remains to describe how to decide for the set of data streams. The coordination algorithm is a scheme to successively allocate the data streams, aiming at the maximization of a weighted sum-rate, while the transmit and receive filters are chosen to eliminate interference.

III. SUCCESSIVE ALLOCATION OF DATA STREAMS

In a nutshell, the LISA algorithm [15], [16] is a zero-forcing beamforming scheme developed for an isolated MIMO broadcast system. In a first stage, the LISA algorithm performs a heuristic data stream allocation by successively adding the user that leads to the maximum performance increase, while being orthogonal to the previously allocated streams. The receive beamforming vectors found by the stream allocation are kept fixed and the transmit beamforming vectors of the resulting MISO system are chosen under a zero-forcing constraint. The power allocation for the interference free scalar sub-channels is found via water-filling. Based on this recipe we develop a successive zero-forcing scheme for the multi-cell scenario. In each iteration, a stream is selected by deciding for the user, the transmit filter, and the receive filter. The first stream selected is found by solving

$$\begin{aligned} \{\pi(1), \boldsymbol{u}_1, \boldsymbol{v}_1\} = \underset{k\in\mathcal{K},\boldsymbol{u},\boldsymbol{v}}{\operatorname{argmax}} \quad & \tilde{U}_k\left(\boldsymbol{u}^{\mathrm{H}}\boldsymbol{H}_{kf(k)}\boldsymbol{v}\right) \\ \mathrm{s.\,t.} \quad & ||\boldsymbol{u}||_2, ||\boldsymbol{v}||_2 = 1, \end{aligned}$$

where $\tilde{U}_k$ is a monotonic increasing function suitable to determine which datastream promises the highest performance improvement, see Section III-A. The solution is the user who's channel has the maximum principal singular value, and $\boldsymbol{u}_1$ and $\boldsymbol{v}_1$ are chosen as the corresponding left and right singular vectors. Besides finding the user to allocate the data stream, the corresponding receive filter is determined as well and is kept fixed. When continuing to allocate streams, projector matrices $\boldsymbol{P}_1, \ldots, \boldsymbol{P}_S$ per transmitter are used to assure orthogonality to the previously assigned streams. The projector matrices are initialized by identity matrices and updated after each step of the stream allocation. Assuming the m-th stream is allocated to user k and the receive filter is $\boldsymbol{u}_m$, the projection matrices are updated as follows:

$$\boldsymbol{P}_s^{(m+1)} = \boldsymbol{P}_s^{(m)} - \frac{\boldsymbol{P}_s^{(m)}\boldsymbol{H}_{ks}^{\mathrm{H}}\boldsymbol{u}_m\boldsymbol{u}_m^{\mathrm{H}}\boldsymbol{H}_{ks}\boldsymbol{P}_s^{(m)}}{\boldsymbol{u}_m^{\mathrm{H}}\boldsymbol{H}_{ks}\boldsymbol{P}_s^{(m)}\boldsymbol{H}_{ks}^{\mathrm{H}}\boldsymbol{u}_m} \ \forall\ s \in \mathcal{S}.$$

Selection of the m-th stream is done such that stream d_m does not disturb the previously allocated data streams, which is assured by the projection matrices $\boldsymbol{P}_1^{(m)}, \ldots, \boldsymbol{P}_S^{(m)}$:

$$\begin{aligned} \{\pi(m), \boldsymbol{u}_m, \boldsymbol{v}_m\} = \underset{k\in\mathcal{K},\boldsymbol{u},\boldsymbol{v}}{\operatorname{argmax}} \quad & \tilde{U}_k\left(\boldsymbol{u}^{\mathrm{H}}\boldsymbol{H}_{kf(k)}\boldsymbol{P}_{f(k)}^{(m)}\boldsymbol{v}\right) \\ \mathrm{s.\,t.} \quad & ||\boldsymbol{u}||_2, ||\boldsymbol{v}||_2 = 1. \end{aligned} \tag{5}$$

At this point of the stream allocation the power allocation is meaningless so we can set $p_m = 0$ and update the set of streams as follows:

$$\mathcal{D}'^{(m)} = \mathcal{D}^{(m-i)} \cup \left(\pi(m), \boldsymbol{u}_m, \boldsymbol{v}_m, 0\right).$$

Assume $\mathcal{D}'^{(m)}$ as the result of the stream allocation, it is clear that a stream d_n does not cause interference to the streams $d_1, \ldots, d_{n-1}$, due to the way it was selected. However, it well interferes with the streams $d_{n+1}, \ldots, d_m$ and therefore the transmit filters, $\{\boldsymbol{v}_n\}_{n\in\{1,\ldots,m-1\}}$, are updated according to a zero forcing constraint

$$\begin{aligned} \boldsymbol{v}_n = \underset{\boldsymbol{v}}{\operatorname{argmax}} \quad & \boldsymbol{u}_n^{\mathrm{H}}\boldsymbol{H}_{\pi(n),f(\pi(n))}\boldsymbol{v} \\ \mathrm{s.\,t.} \quad & \boldsymbol{u}_e^{\mathrm{H}}\boldsymbol{H}_{\pi(e),f(\pi(n))}\boldsymbol{v} = 0\ \forall\ e \in \mathcal{D}'^{(m)} \setminus d_n, \\ & ||\boldsymbol{v}||_2 = 1. \end{aligned} \tag{6}$$

Thus the MIMO system is decomposed into a system of effective interference free scalar subchannels where the gains are given in Equation (2). Now we can calculate the optimal power allocation and update the stream set

$$\mathcal{D}^{(m)} = \mathrm{WF}(\mathcal{D}'^{(m)}).$$

It is known from the single cell LISA algorithm that with each newly allocated user the number of zero-forcing constraints in Equation (6) increases and all channel gains diminish from one step to the next. It can therefore happen that the losses in channel gain for the streams already allocated leads to a stronger decrease in sum-rate than the gain through the newly allocated stream. For this reason we check in each iteration, whether the addition of another stream still leads to an increase in sum-rate, i. e.

$$U\left(\mathcal{D}^{(m)}\right) > U\left(\mathcal{D}^{(m-1)}\right).$$

If not, the algorithm terminates and $\mathcal{D}^{(m-1)}$ is the operating point of the network chosen by our algorithm. The algorithm terminates anyway, when $m = M_{\text{tx}}$, as for $m > M_{\text{tx}}$ there is no solution to (6). In Algorithm 1 we summarize the coordination algorithm.

A. Estimation Function

The intuition behind the successive stream allocation is to add the user promising the maximum increase in system performance, while being orthogonal to the previously allocated users. The performance increase is measured by a heuristic estimation function $\tilde{U}_k$, which is evaluated for each user and is a function of the expected channel gain. The channel gain is related to the maximum principal singular value $\gamma_k^{(m)}$ of the channel $\boldsymbol{H}_{kf(k)}$ projected into the subspace given by $\operatorname{range}\left(\boldsymbol{P}_{f(k)}^{(m)}\right)$, which can be calculated, together with the potential transmit and receive filters, as

$$\begin{aligned} \gamma_k^{(m)} = \max_{\boldsymbol{u},\boldsymbol{v}} \quad & \boldsymbol{u}^{\mathrm{H}}\boldsymbol{H}_{kf(k)}\boldsymbol{P}_{f(k)}^{(m)}\boldsymbol{v} \\ \mathrm{s.\,t.} \quad & ||\boldsymbol{u}||_2, ||\boldsymbol{v}||_2 = 1. \end{aligned}$$

A requirement for the estimation function is to account for the individual power constraints of each transmitter and the

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Input: $\mathcal{S}, \mathcal{K}, f : \mathcal{K} \mapsto \mathcal{S}, \{\boldsymbol{H}_{ks}\}^{k \in \mathcal{K}, s \in \mathcal{S}}, \{P_s\}^{s \in \mathcal{S}}, \sigma^2$
Output: $\mathcal{D}$
$m = 1$
$\boldsymbol{P}_s^{(m)} = \boldsymbol{I}, \ \forall \ s \in \mathcal{S}$
while $m \leq M_{\text{TX}}$ do
    $\{\pi(m), \boldsymbol{u}_m, \boldsymbol{v}_m\} = \underset{k \in \mathcal{K}, \boldsymbol{u}, \boldsymbol{v}}{\text{argmax}} \ \tilde{U}_k \left( \boldsymbol{u}^{\text{H}} \boldsymbol{H}_{kf(k)} \boldsymbol{P}_{f(k)}^{(m)} \boldsymbol{v} \right)$
        $\text{s.t.} \quad ||\boldsymbol{u}||_2, ||\boldsymbol{v}||_2 = 1$
    $\mathcal{D}^{(m)} = \mathcal{D}^{(m-i)} \cup (\pi(m), \boldsymbol{u}_m, \boldsymbol{v}_m, 0)$
    for $d \in \mathcal{D}^{(m)}$ do
        $\boldsymbol{v}_d \leftarrow \underset{\boldsymbol{v}}{\text{argmax}} \quad \boldsymbol{u}_d^{\text{H}} \boldsymbol{H}_{\pi(d), f(\pi(d))} \boldsymbol{v}$
            $\text{s.t.} \quad \boldsymbol{u}_e^{\text{H}} \boldsymbol{H}_{\pi(e), f(\pi(d))} \boldsymbol{v} = 0 \ \ldots$
            $\ldots \ \forall \ e \in \mathcal{D}^{(m)} \setminus d,$
            $||\boldsymbol{v}||_2 = 1$
    end
    $\mathcal{D}^{(m)} \leftarrow \text{WF}(\mathcal{D}^{(m)})$
    if $U\left(\mathcal{D}^{(m)}\right) < U\left(\mathcal{D}^{(m-1)}\right)$ then
        break
    else
        for $s \in \mathcal{S}$ do
            $\boldsymbol{P}_s^{(m+1)} = \boldsymbol{P}_s^{(m)} - \frac{\boldsymbol{P}_s^{(m)} \boldsymbol{H}_{\pi(m)s}^{\text{H}} \boldsymbol{u}_m \boldsymbol{u}_m^{\text{H}} \boldsymbol{H}_{\pi(m)s} \boldsymbol{P}_s^{(m)}}{\boldsymbol{u}_m^{\text{H}} \boldsymbol{H}_{\pi(m)s} \boldsymbol{P}_s^{(m)} \boldsymbol{H}_{\pi(m)s}^{\text{H}} \boldsymbol{u}_m}$
        end
        $m \leftarrow m + 1$
    end
end
return $\mathcal{D}^{(m-1)}$
```

Algorithm 1: Coordination Algorithm

weights of the users. In order to correctly account for the user performance, one has to calculate a waterfilling solution for each user and use the obtained power allocation in the estimation function. In order to keep complexity low, we assume that power is distributed uniformly between all streams sent by one transmitter, which is accurate in case of high transmit power. Assuming the power allocation the newly added stream is $\frac{P_{f(k)}}{|\mathcal{D}_{f(k)}|+1}$, we can estimate the weighted rate of the new stream as

$$w_k \log_2 \left(1 + \frac{1}{\sigma^2} \frac{P_{f(k)}}{|\mathcal{D}_{f(k)}| + 1} \left| \gamma_k^{(m)} \right|^2 \right),$$

which defines our estimation function $\tilde{U}_k$.

IV. SIMULATION RESULTS

The performance of the coordination algorithm is evaluated by Monte-Carlo-Simulations for a wrap-around configuration, following the guidelines in [18]. We use channel matrices generated for a realistic channel model, implemented as described in [19] and use the parameters in Table I. We regard sectorized cells with three antenna arrays per site. An average of 10 users per sector are uniformly distributed in the area covered by the network and we average over 20 drops.

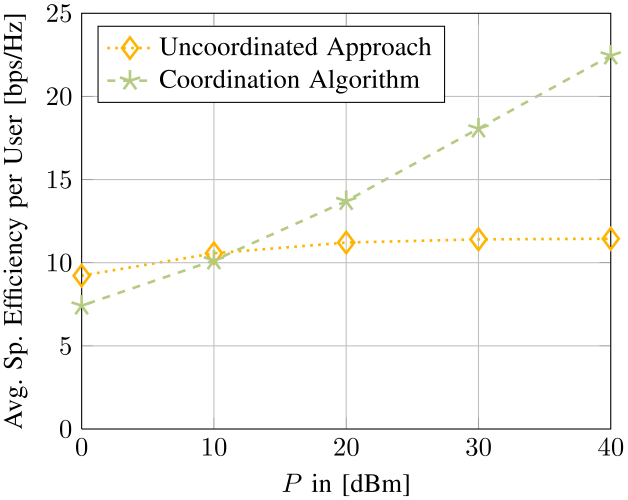

Fig. 1. Simulation Results – One Site

The spectral noise density is -174 dBm/Hz and we gradually increase the transmit power from 0 dBm to 40 dBm. As a reference, we use uncoordinated transmission in each sector, where the degradation due to the interference is accepted. We chose a linear precoding method, the LISA algorithm [15], [16], applied in each sector instead of the capacity achieving Dirty Paper Coding approaches. Unfortunately the very interesting coordination methods mentioned in the introduction, [6], [7], [8], do not easily extend to a scenario multiple receive antennas.

In a first step we regard an isolated site, with three sectors and a total of 30 users. We set the weights of all users to one and Figure 1 shows the average spectral efficiency per user. We can see that the performance of the uncoordinated approach is limited by interference, while the coordination algorithm is interference free and shows a significant gain. We will however see that these gains do not directly translate to larger scenarios: Figure 2 shows the simulation results for the full 57-sector scenario with a total of 570 users. Again, as in the small network, the LISA approach is interference limited while the performance of the coordination algorithm grows with increasing transmit power. The intersection point, where completely removing interference pays off for such a network seams to be far away from the usual operating point of a wireless network. Reducing interference comes at

scenario	urban macro-cell
inter-site dist.	500 m
center freq.	2 GHz
bandwidth	20 MHz
antenna conf.	4x4 MIMO
sectors	$19 \cdot 3 = 57$
users per sector	10

user speed	30 km/h
min dist. to site	25 m
height site	25 m
height user	1.5 m
building height	20 m
street width	20 m
antenna spacing	0.5 λ

TABLE I
SIMULATION PARAMETERS

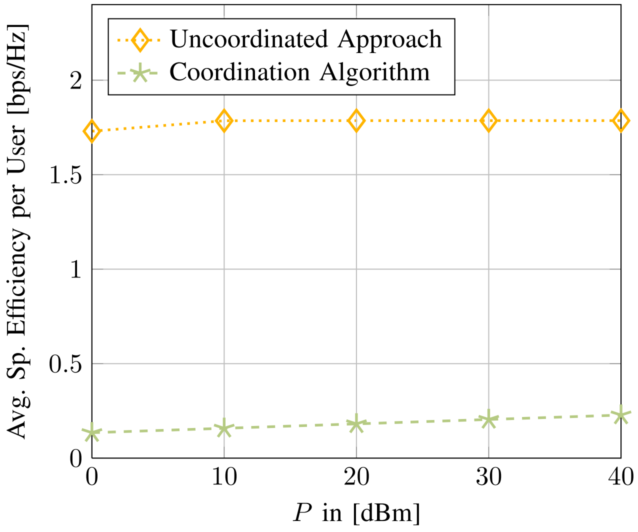

Fig. 2. Simulation Results – 57 Sectors

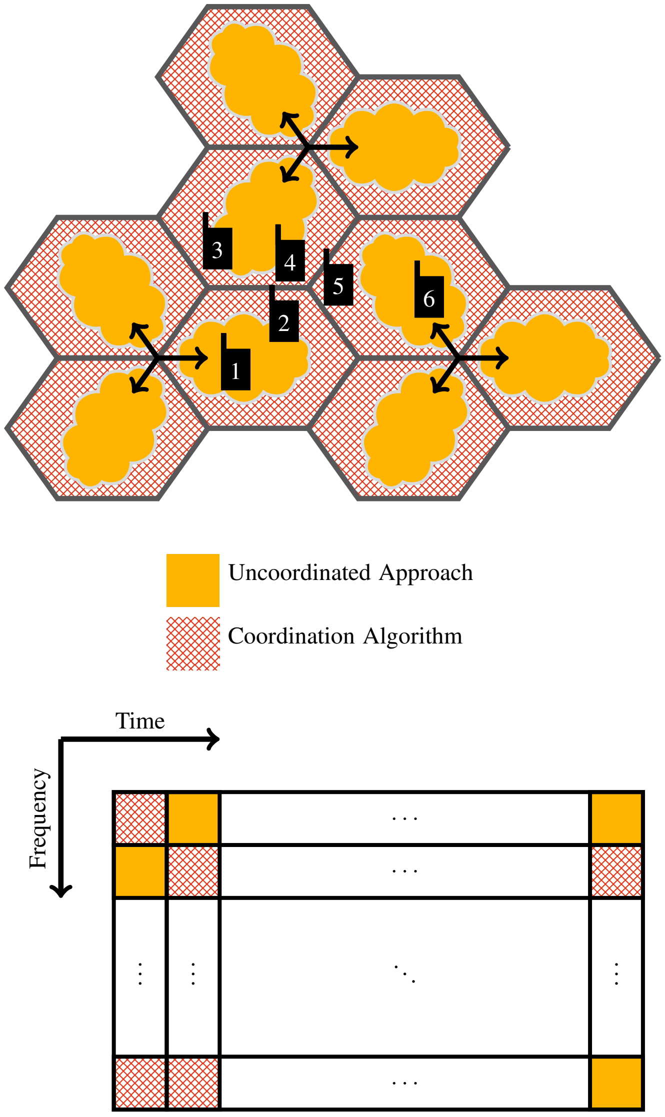

Fig. 3. Illustration Combined Approach

the price of having less users active. Or in other words, the demand of complete orthogonality of the transmission signals is too strict for larger networks. Finding the optimal cost-benefit ratio between interference avoidance and the number of active streams is essential for efficient operation of wireless networks. We therefore embed the coordination algorithm into a larger resource allocation framework [17], which assures that the coordination algorithm is only applied for those users that benefit enough. The algorithm iteratively manipulates the weights of the users, which can be interpreted as multi-user scheduling, and assigns resources to the obtained rate configurations, such that the average data rates maximize a network wide utility. Here we chose proportional fairness, which corresponds to maximize the sum of the logarithms of the users rates, $F(\boldsymbol{r}) = \sum_{k \in \mathcal{K}} \log r_k$. The framework allows various physical layer modes to be combined optimally, by jointly selecting the rate configuration within each mode and the resources assigned to the modes. In Figure 3 we illustrate such a combined approach. Some users in favorable position, in the illustration users number 1, 3, and 6, obtain sufficiently high rates although hit by interference. Serving these users by the uncoordinated single-cell approach increases the number of active user. However, the users at the cell-edge, user number 2, 4, and 5, would be excluded from network service unless interference is reduced. Therefore, these users are served on distinct resources by a coordination algorithm, like the one introduced in this work. We combine the single cell LISA algorithm and the novel coordination algorithm such that the users located in the center of a cell are served by the LISA algorithm, while the users at the cell-edge are served interference-free by the coordination algorithm. The classification as cell-edge user or cell-center user is inherently performed by the algorithm, which combines the two strategies by optimally assigning distinct resource blocks to the two modes, for details the reader is referred to [17]. Other methods to introduce the necessary non-orthogonality might be clustering the cooperation or introducing thresholds instead of strict zero-forcing conditions, see our comments on future work in Section V.

Figure 4 shows the performance measured by the proportional fairness utility for the combined approach and shows that this approach is no more interference limited. As the absolute values of the utility $F(\boldsymbol{r})$ are difficult to interpret we include a commonly accepted performance measure: Figure 5 shows the average spectral efficiency of the 10% worst users in the system, usually users at the cell-edge. We notice a significant gain and can see that while in the uncoordinated approach these users are more or less shut off, with the combined approach the cell-edge users are able to meet the targets of future wireless systems.

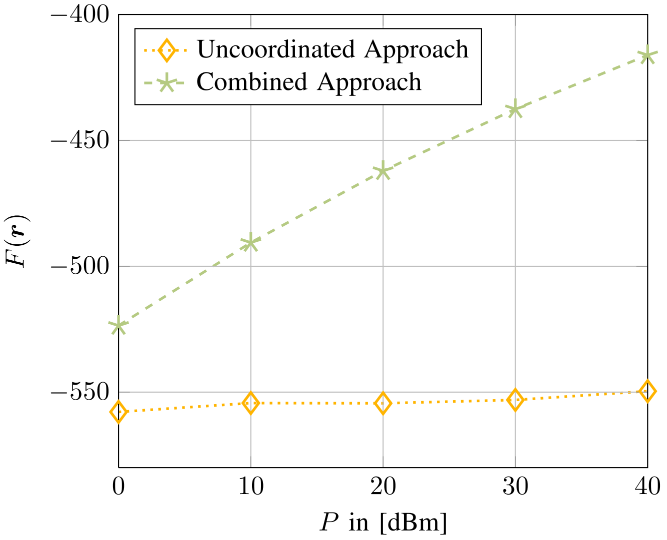

Fig. 4. Simulation Results – Proportional Fairness Utility

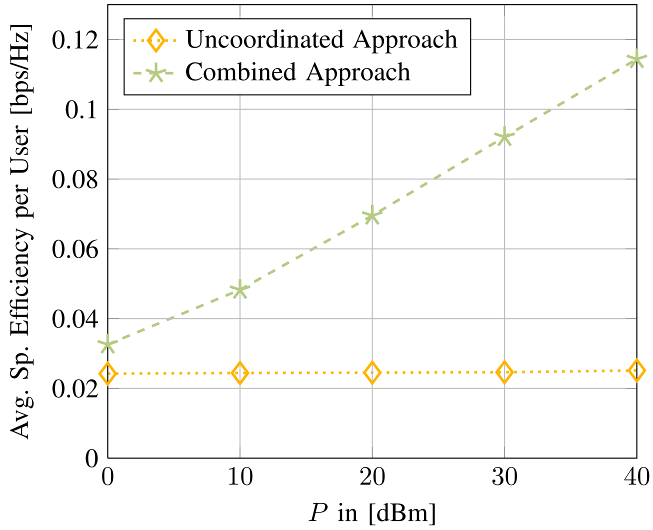

Fig. 5. Simulation Results – 10% Worst Users (Cell-Edge)

V. Conclusions and Future Work

We presented an interference coordination approach based on linear successive user allocation, where an interference free configuration is established by choosing linear receive and transmit filters accordingly. By providing system level simulations we can see, that completely avoiding interference may be to restrictive in a larger network. Therefore we use a framework that achieves a boost in performance by applying the interference coordination only to theses users that benefit enough. As a future extension we plan mechanisms to soften the strict zero-forcing constraints in the coordination algorithm, for example by setting thresholds on the interference allowed to others. We want to investigate clustered versions of the algorithm such that cooperation happens more locally in the network in order to avoid excessive coordination overhead. The signaling overhead for exchanging channel state information should be investigated and put into relation to network MIMO that also requires exchange of user data.

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