Handling Unknown Interference in Cellular Networks with Interference Coordination

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***Abstract*—We consider the downlink of a cellular network with cooperating multiple antenna base stations. On the one hand, each base stations tries to serve its associated mobile devices optimally, on the other hand, they try to minimize the interference they cause. Both goals could be achieved, if the interference channels would be zero. An adaptive beamforming based interference mitigation can only be performed for measured interference channels. To find an unachievable, but relatively tight upper bound we set the measured interference channels to zero. For such a limited cooperation, we show that the rates can be improved by predicting the interference over the unknown channels.**

I. INTRODUCTION

Intercell interference (ICI) is the strongest effect limiting the performance of today's cellular networks. It can be overcome by letting *base stations* (BSs) cooperate, but it is not proved so far that cooperation will be beneficial, if all necessary operations are taken into account. In this contribution, we restrict cooperation to interference coordination, where each *mobile device* (MD) is only served by one BS. This stands in contrast to network MIMO, which allows each MD to be served by all BSs jointly and where the network can be regarded as one huge broadcast channel [1].

In a network with interference coordination, the BSs face the conflicting goals of serving their associated MDs optimally and minimizing the interference they cause. We distinguish between ICI over known and unknown interference channels. As an adaptive, beamforming based interference mitigation can only be performed for known interference channels, the ICI over unknown channels has to be regarded as noise. In [2], we formulated an upper bound to interference coordination, where we set the known interference channels to zero. Therefore, the network decomposes into independent broadcast channels and traditional techniques can be used to optimize the precoding. The BSs can meet both of their goals, because they do not produce any ICI over known interference channels and still have all their degrees of freedom to serve the associated MDs. The upper bound is not achievable, because the cost of nulling the known interference channels is neglected. But we could show that even this loose upper bound strongly limits the possible gain of cooperation.

We do not make any assumptions on how the interference coordination is realized. It is possible, but not necessary that there are high speed links between the BSs. The BSs can employ any known technique, which is covered by interference coordination, like interference alignment [3]–[5] or interference temperature methods [6], [7]. The methods are applicable for systems with macro, micro, pico and femto cells. A crucial point of the upper bound is the acquisition and outdating of *channel state information* (CSI) [2], [8]. Resources have to be spent to measure the channels and the measurements might be perturbed by pilot contamination [9]–[11]. We could show that the possible rates deteriorate if the number of measured channels grows beyond a limit. The overhead and the available knowledge at the different participants of the communication need to be determined to assess the gain of cooperation. The system model, signaling, overhead and the details of the upper bound are specified in Section II.

For such a limited cooperation, we describe the problem of the instationarity of the ICI over unknown channels and the benefit of interference awareness in Section III. If the BSs optimize their beamforming decentralized and in parallel, the ICI over the unknown channels changes randomly the moment the beamforming is applied. The achievable rates cannot be optimized directly, merely the expectations of these rates, respectively. The supported rates are unknown and can only be made available with an additional second piloting phase, in which the updated ICI is measured [6]. But, the resources spent for the second pilot reduce the efficiency. We use a large system layout and calculate all channels between all BSs and MDs for our simulations. The ICI over the virtually unknown channels is described as a random process, where the channels are technically fixed, but the precoders at the interfering BSs need to be regarded as random. Therefore, we do not base our results on recent interference modeling, e.g. [12]–[14], but investigate the statistics of the precoders and their effects on the ICI.

In Section IV, we describe different methods how the problem of the ICI instationarity can be handled by improving the rates and approaching interference awareness simultaneously without the usage of a second pilot. An existing strategy counteracts the ICI blindness and the resulting uncertainty about the supported rates by transmitting the data at reduced rates to control the risk of assuming a rate, which is not supported and would lead to complete outage. A common backoff factor is used for the rates of all MDs after the precoders are choosen [15]. In this contribution, we propose to use either a common or individual scaling factors for the assumed interference in the process of the precoder optimization. By including the risks

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of a changing ICI in the precoder selection, the BSs allocate more resources to MDs which are critical for the utility and the expected rates are improved. Simulation results are discussed in Section V.

II. SYSTEM MODEL

We consider a cellular network with 19 three faced sites and, therefore, 57 BSs. Each BS serves the MDs of the hexagonal shaped cell it covers. A MD in the set $\mathcal{K}$ of all MDs is specified by the tuple $(b,k) \in \mathcal{K}$, where $b \in \mathcal{B}$ identifies the BS in the set $\mathcal{B}$ of all BSs and $k \in \mathcal{K}_b$ the MD in the set $\mathcal{K}_b$ of all MDs in the cell of BS b. The wrap-around method is used to treat all cells equally and the channels are found with the 3GPP MIMO urban macro cell model [16].

In this paper, each BS has N antennas and serves $K = |\mathcal{K}_b|$ single antenna MDs, respectively. The vectors $\boldsymbol{h}_{\hat{b},b,k} \in \mathbb{C}^N$ contain the channel coefficients between the antennas of BS $\hat{b}$ and MD (b,k). With $(\bullet)^{\mathrm{T}}$ and $(\bullet)^{\mathrm{H}}$ we denote the transposition and the complex conjugate transposition, respectively. The achievable, normalized rate of MD (b,k) can be expressed as

$$r_{b,k} = \xi \log_2 \left(1 + \frac{|\boldsymbol{h}_{b,b,k}^{\mathrm{T}} \boldsymbol{p}_{b,k}|^2}{\sigma_{b,k}^2 + \sum_{\hat{k}<k} |\boldsymbol{h}_{b,b,k}^{\mathrm{T}} \boldsymbol{p}_{b,\hat{k}}|^2 + \theta_{b,k}} \right), \quad (1)$$

$$\theta_{b,k} = \sum_{\hat{b} \in \mathcal{B} \setminus b} \boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}} \boldsymbol{Q}_{\hat{b}} \boldsymbol{h}_{\hat{b},b,k}, \quad (2)$$

where $\boldsymbol{p}_{b,k} \in \mathbb{C}^N$ is the beamforming vector for MD (b,k) and $\boldsymbol{Q}_b \in \mathbb{C}^{N \times N} = \sum_k \boldsymbol{p}_{b,k} \boldsymbol{p}_{b,k}^{\mathrm{H}}$ is the sum transmit covariance matrix of BS b. $\sum_{\hat{k}<k} |\boldsymbol{h}_{b,b,k}^{\mathrm{T}} \boldsymbol{p}_{b,\hat{k}}|^2$ is the variance of the intracell interference with dirty paper coding, $\theta_{b,k}$ is the variance of the received intercell interference, and $\sigma_{b,k}^2 = \sigma_\eta^2 + \sigma_{\mathrm{od},b,k}^2 + \theta_{\mathrm{bg}}$ is the sum of the variance of the thermal noise σ_η^2, the *channel state information* (CSI) outdating, and the background interference. The outdating $\sigma_{\mathrm{od},b,k}^2$ is approximated with a Gaussian noise over the serving channel and the measured interference channels, which are scaled down with the measurement error

$$\sigma_{\mathrm{od},b,k}^2 = \bar{\sigma}_e^2 \frac{P}{N} \boldsymbol{h}_{b,b,k}^{\mathrm{H}} \boldsymbol{h}_{b,b,k} + \bar{\sigma}_e^2 \frac{P}{N} \sum_{\hat{b} \in \mathcal{C}_{b,k} \setminus b} \boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}} \boldsymbol{h}_{\hat{b},b,k}. \quad (3)$$

The measurement error $\bar{\sigma}_e^2$ is derived according to correlations between channels at different times and frequencies and grows with the blocklength [2], [17]. The Gaussian background interference θ_{bg} models the BSs further away than the closest 57 BSs for a given signal variance per transmit antenna. All BSs have to satisfy the transmit power constraint $\mathrm{tr}(\boldsymbol{Q}_b) \le P$, $\forall b$. The signaling overhead reduces the rates through the efficiency ξ, which is described in the next Section.

A. Channel Measurements and Signaling Overhead

We employ a time division duplex system, where the reciprocity of the propagation channels is exploited. The channels are measured in the uplink and the gained information is then utilized in the downlink. The number of channels a BS can measure is equivalent to the length of the pilot sequences $T_{\text{pilots}} = K + L$. Each BS can measure the channels to its own K MDs and L interference channels, additionally. With the block length T_{block} and neglecting other overhead contributions, we find the efficiency of the signaling as $\xi = \frac{T_{\text{block}} - (K+L)}{T_{\text{block}}}$.

B. Upper Bound to Interference Coordination

With L measured interference channels per BS, an upper bound to interference coordination can be given, as described in [2]. The intercell interference (2) can be split into

$$\theta_{b,k} = \sum_{\hat{b} \in \mathcal{C}_{b,k} \setminus b} \underbrace{\boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}}}_{\text{known}} \boldsymbol{Q}_{\hat{b}} \boldsymbol{h}_{\hat{b},b,k} + \sum_{\hat{b} \in \mathcal{B} \setminus \mathcal{C}_{b,k}} \underbrace{\boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}}}_{\text{unknown}} \boldsymbol{Q}_{\hat{b}} \boldsymbol{h}_{\hat{b},b,k}. \quad (4)$$

The set $\mathcal{C}_{b,k}$ contains all BSs, which know the channel to the MD (b,k). Therefore, $\sum_{\hat{b} \in \mathcal{C}_{b,k} \setminus b} \boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}} \boldsymbol{Q}_{\hat{b}} \boldsymbol{h}_{\hat{b},b,k}$ is the sum of the ICI over the measured channels, which is set to zero. A residual part due to outdating is taken into account with the afore described $\sigma_{\mathrm{od},b,k}^2$. $\hat{\theta}_{b,k} = \sum_{\hat{b} \in \mathcal{B} \setminus \mathcal{C}_{b,k}} \boldsymbol{h}_{\hat{b},b,k}^{\mathrm{H}} \boldsymbol{Q}_{\hat{b}} \boldsymbol{h}_{\hat{b},b,k}$ is the sum ICI over the unknown channels. First, we assume to know the variance $\hat{\theta}_{b,k}$, but we cannot optimize over the precoding vectors transmitting over these unknown interference channels.

With the monotonic utility function $U(r_{b,k})$, the result of a joint optimization of all beamforming vectors R_{coop} with (1) is always smaller than the result of the upper bound R_{upper}, where all measured interference channels are set to zero:

$$R_{\text{coop}} \le R_{\text{upper}} = \max_{\{\boldsymbol{p}_{b,k} | \forall (b,k) \in \mathcal{K}\}} \sum_{(b,k) \in \mathcal{K}} U\left(\hat{r}_{b,k}\right),$$
$$\text{s.t. } \mathrm{tr}(\boldsymbol{Q}_b) \le P \; \forall b, \quad (5)$$

$$\hat{r}_{b,k} = r_{b,k}|_{\boldsymbol{h}_{\hat{b},b,k} = \boldsymbol{0} \; \forall \hat{b} \in \mathcal{C}_{b,k} \setminus b} \quad (6)$$
$$= \log_2 \left(1 + \frac{|\boldsymbol{h}_{b,b,k}^{\mathrm{T}} \boldsymbol{p}_{b,k}|^2}{\sigma_{b,k}^2 + \sum_{\hat{k}<k} |\boldsymbol{h}_{b,b,k}^{\mathrm{T}} \boldsymbol{p}_{b,\hat{k}}|^2 + \hat{\theta}_{b,k}} \right).$$

Problem (5) is convex and can be solved distributed at all BSs independently. The upper bound is not achievable, because the cost of nulling the L interference channels per BS is neglected, but it strongly limits the possible gain of cooperation.

III. INTERFERENCE AWARENESS

Interference mitigation can only be performed for known interference channels. The interference over the unknown channels changes the moment the BSs employ their locally computed beamforming vectors. Therefore, the interference during the transmission $\hat{\theta}_{b,k}$ and the supported rate $\hat{r}_{b,k}$ of each MD cannot be known in advance. Assumed ICI variances $\tilde{\theta}_{b,k}$ have to be utilized for the optimization of the precoders, which results in assumed rates $\tilde{r}_{b,k}$. The BSs are blind to the ICI change and stand the risk, that the ICI increases and the MD cannot decode the transmitted symbols or that the ICI decreases and valuable resources are wasted

$$\tilde{r}_{b,k} = \begin{cases} r_{b,k}|_{\theta_{b,k} = \tilde{\theta}_{b,k}}, & \text{for } \tilde{\theta}_{b,k} \ge \hat{\theta}_{b,k} \\ 0, & \text{for } \tilde{\theta}_{b,k} < \hat{\theta}_{b,k}. \end{cases} \quad (7)$$

A. ICI Statistics

Although the BSs do not know the unmeasured channels, we calculate these channels for the simulations. The ICI variance change depends only on the change of the transmit covariances of the interfering BSs. These covariances are optimized without taking the interference they produce over the unknown channels into account. Therefore, we can find the statistics of the ICI variance by looking at many independent realizations of these covariances, while the channels are constant. If a transmit covariance follows a Wishart distribution

$$\mathrm{Q}_{\hat{b}} \sim W_N\left(\frac{P}{N^2}\mathbf{I}_N, N\right) \tag{8}$$

with N degrees of freedom and scale matrix $\frac{P}{N^2}\mathbf{I}_N$, the ICI from this base station will follow a Gamma distribution

$$\Theta_{\hat{b},b,k} = \boldsymbol{h}^{\mathrm{H}}_{\hat{b},b,k}\mathrm{Q}_{\hat{b}}\boldsymbol{h}_{\hat{b},b,k} \sim \mathit{\Gamma}\left(N, \frac{P}{N^2}\boldsymbol{h}^{\mathrm{H}}_{\hat{b},b,k}\boldsymbol{h}_{\hat{b},b,k}\right) \tag{9}$$

with scale parameter $\frac{P}{N^2}\boldsymbol{h}^{\mathrm{H}}_{\hat{b},b,k}\boldsymbol{h}_{\hat{b},b,k}$ and a shape parameter N. The correct calculation of the distribution of the ICI is a difficult task, on the one hand the BSs will always transmit with the full transmit power and, therefore, the covariances cannot follow a Wishart distribution. On the other hand the sum of many Gamma distributed random variables with different scale parameters is an impasse.

Although the transmit covariances $\mathrm{Q}_{\hat{b}}$ are taken from the optimizations and we build the sum over all the ICI over the unknown channels, we can show with simulations, that the ICI variance $\hat{\Theta}_{b,k} = \sum_{\hat{b}\in\mathcal{B}\setminus\mathcal{C}_{b,k}} \Theta_{\hat{b},b,k}$ follows almost a Gamma distribution,

$$\hat{\Theta}_{b,k} \sim \mathit{\Gamma}\left(\frac{\left(\mathrm{E}\left[\hat{\Theta}_{b,k}\right]\right)^2}{\mathrm{Var}\left[\hat{\Theta}_{b,k}\right]}, \frac{\mathrm{Var}\left[\hat{\Theta}_{b,k}\right]}{\mathrm{E}\left[\hat{\Theta}_{b,k}\right]}\right), \tag{10}$$

where the scale and the shape parameter can be derived from the mean $\mathrm{E}\left[\hat{\Theta}_{b,k}\right]$ and the variance $\mathrm{Var}\left[\hat{\Theta}_{b,k}\right]$ of the ICI variance.

We assume that the mean and the variance of the ICI variances are known through a combination of longterm and instantaneous measurements at the MDs, respectively. Figure 1 shows the cumulative distribution function of the ICI with 1000 realizations of the covariance matrices and the approximation with a Gamma distribution, which takes the mean and variance from the samples.

B. Handling Unknown Interference

We consider three methods handling this risk of a changing ICI in (7). First, we can accept that risk and try to adapt with a gambling algorithm as described in [15]. With this method the BSs serve the MDs with modest rates to reduce the risk of a failed transmission.

$$r^{\text{gambling}}_{b,k} = \begin{cases} \bar{r}_{b,k} = (1-\beta)\, r_{b,k}|_{\theta_{b,k}=\bar{\theta}_{b,k}}, & \text{for } \bar{r}_{b,k} \leq \hat{r}_{b,k} \\ 0, & \text{for } \bar{r}_{b,k} > \hat{r}_{b,k}. \end{cases} \tag{11}$$

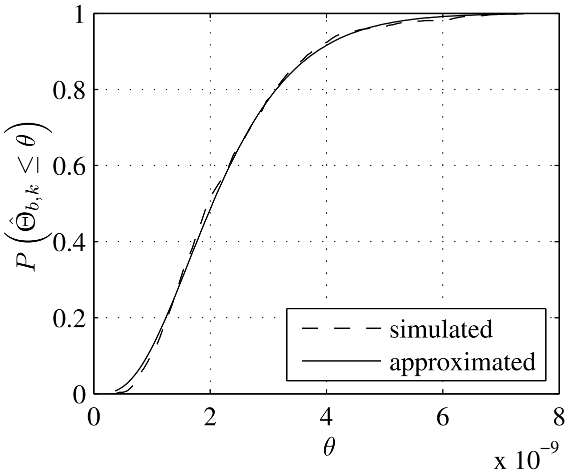

Figure 1. Cumulative distribution function of the ICI

The precoders are optimized based on the mean of the ICI variance $\bar{\theta}_{b,k} = \mathrm{E}\left[\hat{\Theta}_{b,k}\right]$ and the common backoff β is applied after the precoders are selected. The optimal backoff is found with a line search over many realizations and MDs.

Second, we can measure $\hat{\theta}_{b,k}$ with a second pilot as shown in Figure 2 and described in [2]. After the transmit covariances are optimized based on the measured channels, the BSs transmit a second pilot sequence with the calculated beamforming vectors and the MDs can measure and feedback the ICI powers. Now, the MDs can be served with the supported rates, but the increased overhead decreases the efficiency of the signaling. In the piloting phase, the MDs need to distinguish between the different precoding vectors of the BSs. An orthogonalization of all the pilot sequences for all the precoding vectors requires a very long piloting phase and if the pilot sequences are reused, pilot contamination will reduce the quality of the ICI measurements. In this contribution, we do not try to find the exact costs of the second pilot and leave this interesting task for further investigations.

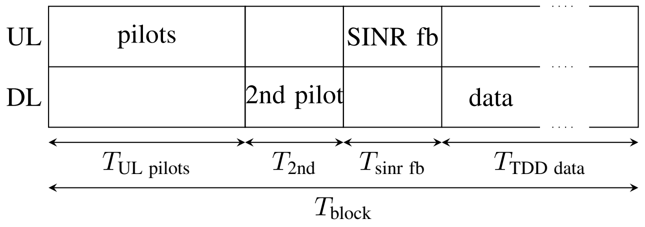

Figure 2. TDD Signaling with second pilot

Third, we can try to predict the ICI variance over the unknown channels as described in Section IV. For all methods we neglect interference, noise, quantization, and feedback errors during the pilot phase and assume all channel and ICI measurements to be perfect.

IV. PREDICTION OF THE UNKNOWN INTERFERENCE

The distributed optimizations of the beamforming vectors in (5) are based on assumed ICI variances over the unknown channels. These variances will change the moment the beamforming is applied and cannot be known in advance. Therefore, we can only optimize the expectations of the rates, with respect to the random ICI variance $\hat{\Theta}_{b,k}$,

$$\max_{\left\{\boldsymbol{p}_{b,k},\tilde{\theta}_{b,k}|\forall k\in\mathcal{K}_b\right\}} \sum_{k\in\mathcal{K}_b} \mathrm{E}_{\hat{\Theta}_{b,k}}\left[U\left(\tilde{r}_{b,k}\right)\right], \quad \text{s.t. } \operatorname{tr}(\boldsymbol{Q}_b) \leq P. \tag{12}$$

A. Common Interference Scaling

To solve problem (12) with known methods, we shift the expectation into the utility and the rate expression. We try to compensate the resulting error by scaling the mean ICI variance $\bar{\theta}_{b,k}$ with a common factor α

$$\max_{\{\alpha,\boldsymbol{p}_{b,k}|\forall k\in\mathcal{K}_b\}} \sum_{k\in\mathcal{K}_b} U\left(r_{b,k}|_{\theta_{b,k}=\alpha\bar{\theta}_{b,k}}\right), \quad \text{s.t. } \operatorname{tr}(\boldsymbol{Q}_b) \leq P. \tag{13}$$

The optimal α has to be determined with a line search in a measurement campaign. This interference scaling factor could always be transformed into a utility or rate scaling factor as well. During the optimization, the ICI variance has no influence on the direction of the beamforming vectors, only on the power distribution between different vectors at the same BS. For systems with only one MD per BS, this method is equivalent to the gambling algorithm, where the risk of an outage is reduced.

B. Individual Interference Scaling

The MDs are situated in very different interference situations [6]. Some MDs are very close to the BS, experience a strong serving channel and suffer from strong interference from the few collocated BSs at the same site. Other MDs sit in the center of the cell and see an interference floor with many comparably weak interferers. The MDs at the cell edge have the weakest channels and are disturbed by multiple strong interferers, some of those may even be as strong as the serving channel.

To account for the different interference situations, we propose to use an individual scaling factor for each MD, respectively. The expectation in (12) can be formulated as

$$\begin{aligned}\mathrm{E}_{\hat{\Theta}_{b,k}}\left[U\left(\tilde{r}_{b,k}\right)\right] &= U\left(\tilde{r}_{b,k}\right)\int_0^{\tilde{\theta}_{b,k}} f_{\hat{\Theta}_{b,k}}(\theta)\,\mathrm{d}\theta + \\ &\quad + U\left(0\right)\int_{\tilde{\theta}_{b,k}}^{\infty} f_{\hat{\Theta}_{b,k}}(\theta)\,\mathrm{d}\theta, \\ &= U\left(\tilde{r}_{b,k}\right)F_{\hat{\Theta}_{b,k}}\left(\tilde{\theta}_{b,k}\right) + \\ &\quad + U\left(0\right)\left(1 - F_{\hat{\Theta}_{b,k}}\left(\tilde{\theta}_{b,k}\right)\right)\end{aligned} \tag{14}$$

where $f_{\hat{\Theta}_{b,k}}(\theta)$ is the probability density function of $\hat{\Theta}_{b,k}$ and $F_{\hat{\Theta}_{b,k}}(\theta)$ the cumulative distribution function. Note, that the utility depends on the assumed ICI $\tilde{\theta}_{b,k}$ and not on the actual ICI realization. This leads to the optimization

$$\max_{\left\{\boldsymbol{p}_{b,k},\tilde{\theta}_{b,k}|\forall k\in\mathcal{K}_b\right\}} \sum_{k\in\mathcal{K}_b} \left(U\left(\tilde{r}_{b,k}\right) - U(0)\right) F_{\hat{\Theta}_{b,k}}\left(\tilde{\theta}_{b,k}\right), \quad \text{s.t. } \operatorname{tr}(\boldsymbol{Q}_b) \leq P. \tag{15}$$

The optimal assumed ICI variances $\check{\theta}_{b,k}$ have to fulfill the equation

$$\begin{aligned}&\left.\frac{\partial U\left(\tilde{r}_{b,k}\right)}{\partial\tilde{\theta}_{b,k}}\right|_{\check{\theta}_{b,k}} F_{\hat{\Theta}_{b,k}}\left(\check{\theta}_{b,k}\right) + \\ &+ \left(U\left(\tilde{r}_{b,k}\right)|_{\check{\theta}_{b,k}} - U(0)\right) f_{\hat{\Theta}_{b,k}}\left(\check{\theta}_{b,k}\right) = 0.\end{aligned} \tag{16}$$

For given precoding vectors, $\left(U\left(\tilde{r}_{b,k}\right) - U(0)\right) F_{\hat{\Theta}_{b,k}}\left(\tilde{\theta}_{b,k}\right)$ will have exactly one maximum, if $U\left(\tilde{r}_{b,k}\right)$ and $F_{\hat{\Theta}_{b,k}}\left(\tilde{\theta}_{b,k}\right)$ are log-convex functions. In this case, the solution can be found numerically with a bisection or Newton–Raphson method.

In the case of one MD per BS $|\mathcal{K}_b| = 1$, the optimal precoders are independent of the distribution of the ICI and have to optimize the utility alone. If there are multiple MDs associated to each BS $|\mathcal{K}_b| > 1$, the power distribution among the different beams depends on the assumed interference. A joint optimization of the precoders and the assumed interference is intractable. Therefore, we propose an alternating optimization, which optimizes the precoders and assumed interference in turns. In every step, (12) will increase and as it is bounded, it will converge to a locally optimal point.

By optimizing the expected rates, the gap between the assumed and the supported rates shrinks. The 2nd pilot, which requires air time, can be avoided by increasing the computational complexity at the BSs.

V. SIMULATIONS

Our simulations are set in a slow fading environment with a MD speed of $3\,\mathrm{km/h}$ and a delay spread of $0.5\,\mu\mathrm{s}$. We discuss the scenarios with no cooperation $L = 0$ and a small, but realistic cooperation with $L = 5$. The computed bounds are still not achievable, since we have only $N = 4$ antennas at the BSs. The actual improvement achieved by measuring some interference channels (e.g. $L = 5$) compared to not measure such channels to users in other cells at all ($L = 0$) will be even smaller if the mobility is increased to let say $30\,\mathrm{km/h}$. For the following plots, we used a blocklength of $T_{\text{block}} = 250$ symbols.

Only high SINR MDs are important for sum rate optimizations. For these MDs, the approximation with the expectation is already very good and there is almost no improvement with the interference prediction algorithms. In Figure 3 and 4 the influence of the common scaling factor α on the average cell sum rate is plotted for a sum rate maximization as the utility for $L = 0$ and $L = 5$. The plots show the supported rate, if the true ICI variance would be known after the optimization, and the rate with the common interference scaling algorithm with

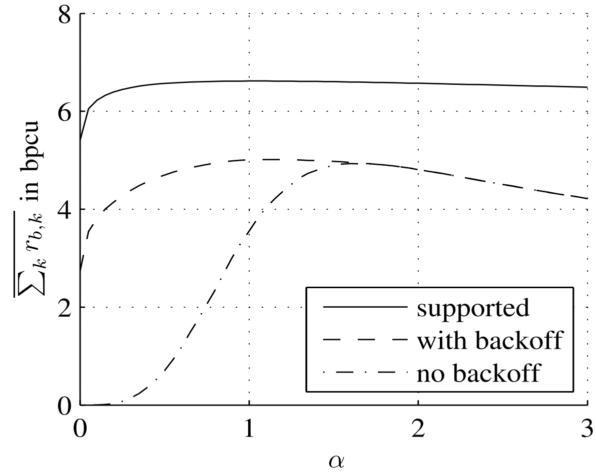

Figure 3. Influence of α, sum rate, $K = 4$, $L = 0$, $N = 4$

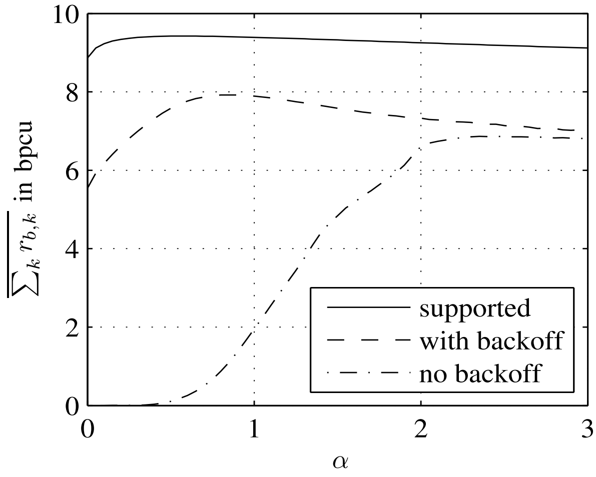

Figure 4. Influence of α, sum rate, $K = 4$, $L = 5$, $N = 4$

and without an additional backoff factor β. The backoff factor is optimized for each value of α individually and it can be seen, that this subsequent adaption is inevitable. The optimal α is very close to 1.

With the interference prediction algorithms, the BSs allocate more power to the MDs, which are critical for the utility to cope with the risk of a failed link. A large common scaling factor penalizes the MDs which have a strong ICI compared to the serving channel additionally. The BSs shift even more power to the MDs with a high mean SINR and, therefore, reduce the risk of a sudden drop in the sum rate, if a strong interference at an MD with a high mean SINR occurs. In contrast, a small common scaling factor is beneficial for fairness optimizations, as the MDs with a low mean SINR profit. The influence of the common scaling factor α on the log fairness optimization

$$\max_{\{\alpha,\boldsymbol{p}_{b,k}|\forall k\in\mathcal{K}_b\}} \sum_{k\in\mathcal{K}_b} \log\left(0.01+\left(r_{b,k}|_{\theta_{b,k}=\alpha\bar{\theta}_{b,k}}\right)\right),$$

$$\text{s.t. } \operatorname{tr}(\boldsymbol{Q}_b)\le P, \tag{17}$$

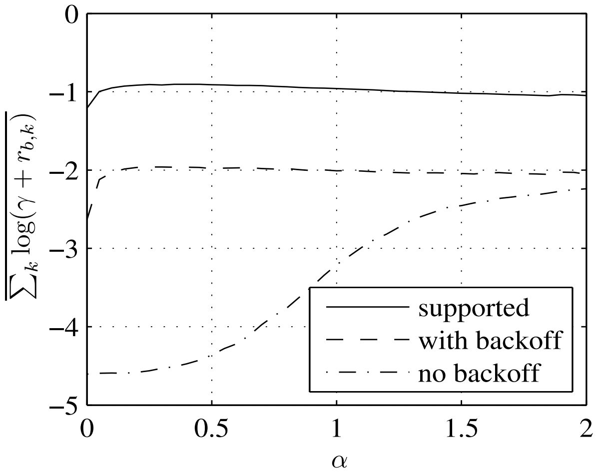

Figure 5. Influence of α, log fairness, $K = 4$, $L = 0$, $N = 4$

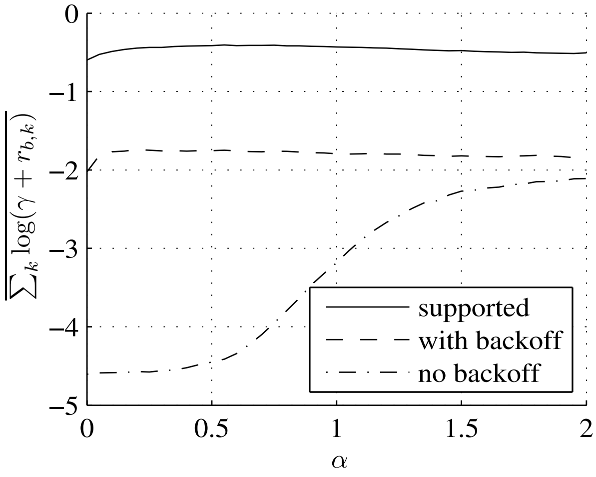

Figure 6. Influence of α, log fairness, $K = 4$, $L = 5$, $N = 4$

can be seen in Figure 5 and 6 for $L = 0$ and $L = 5$, respectively. Compared to the results with the mean interference ($\alpha = 1$), the utility can be improved by approximately 5% with an optimized α, which is 0.35 for $L = 0$ and 0.2 for $L = 5$.

Figure 7 and Figure 8 show the sum rate over the blocklength for $L = 0$ and $L = 5$, respectively. As discussed before, rates with a common scaling are not improved compared to the rates with the mean interference. The rates with the individual scaling factors introduce a slight improvement of ca. 2% for $L = 5$. The interference prediction with individual scalings has better results for the scenario with cooperation, because the strongest interferers are canceled and more MDs in unprivileged situations are served. These MDs have a wider range of channel qualities and ICI variances and an individual interference prediction has a stronger influence.

More interestingly are the results for the log fairness optimization, where the utility can be improved considerably

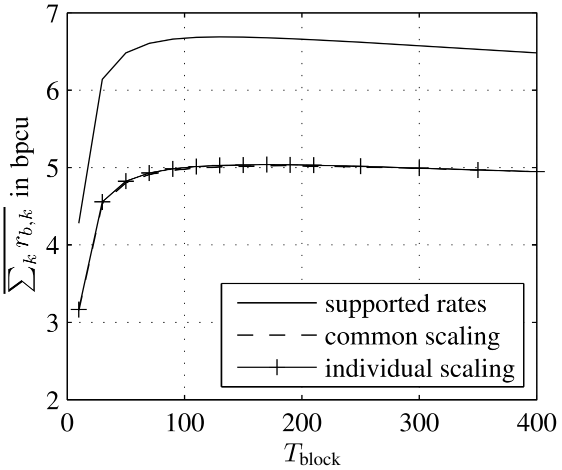

Figure 7. Sum rate, $K = 4$, $L = 0$, $N = 4$

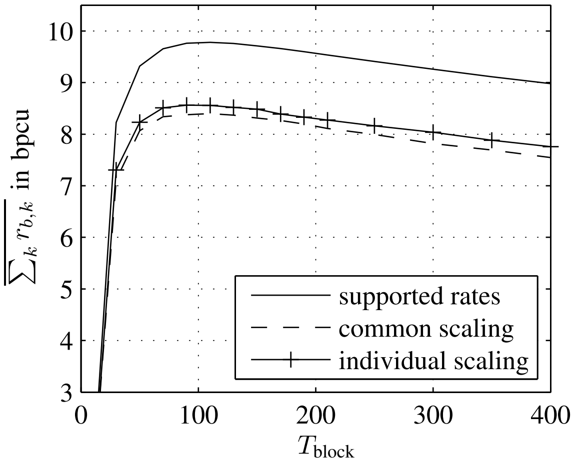

Figure 8. Sum rate, $K = 4$, $L = 5$, $N = 4$

with the individual scaling factors (See Figures 9 and 10). We also included the curves, where the mean ICI is assumed for the optimization, i.e. $\alpha = 1$. In Figure 11 and 12 the complementary cumulative distribution function of the user rates are plotted. The simulations visualize, that we can guaranty the MDs a minimal rate with an increased probability with the interference prediction algorithms and especially with the individual scaling.

VI. CONCLUSION

In a cellular network with interference coordination, the ICI has to be divided into the interference over known and unknown channels. With an upper bound to the interference over the known channels, we investigated two methods for handling the interference over the unknown channels. We either optimize the expected rates with a common or individual factors for scaling the ICI to adapt to the instationarity of the ICI. We could show, that a proper prediciton of this interference has a strong influence on systems with proportional

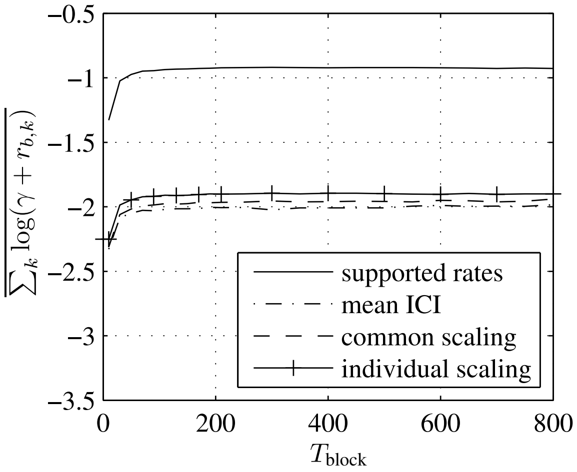

Figure 9. Log fairness, $K = 4$, $L = 0$, $N = 4$

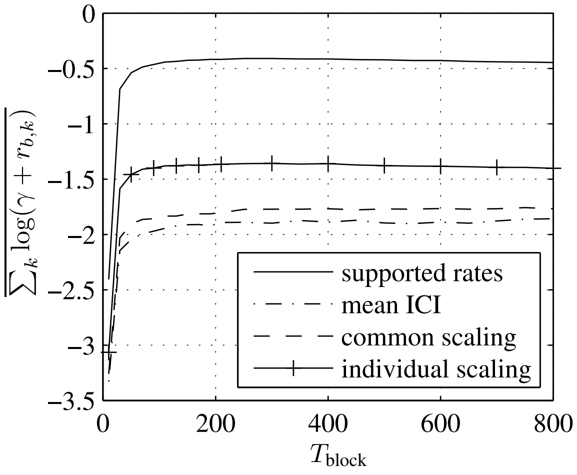

Figure 10. Log fairness, $K = 4$, $L = 5$, $N = 4$

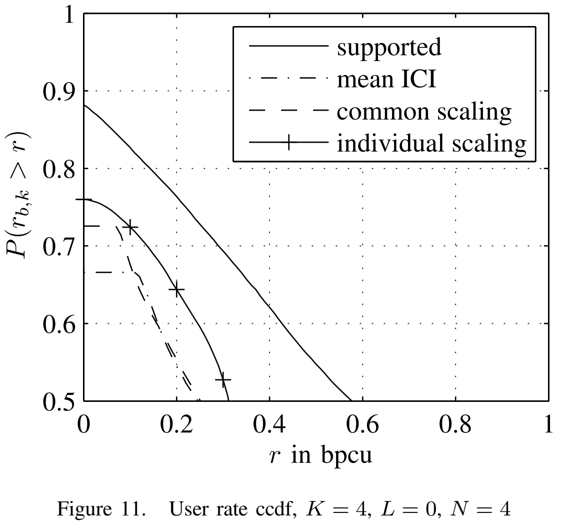

Figure 11. User rate ccdf, $K = 4$, $L = 0$, $N = 4$

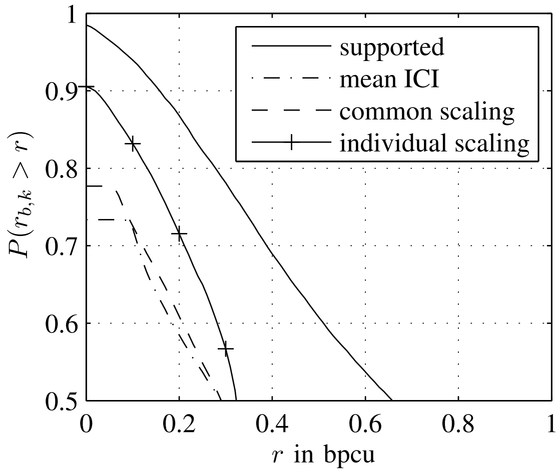

Figure 12. User rate ccdf, $K = 4$, $L = 5$, $N = 4$

fairness and can reduce the outage probability considerably. In a future work, the performance of systems with a second pilot to measure the ICI after the precoders are selected will be compared to systems without interference awareness, while the additionally required overhead for the second pilot will be taken into account.

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