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The Impact of Channel State Information Processing Delay in Optimally Scheduled OFDMA Networks

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***Abstract*—Dynamically assigning sub-carriers in the downlink of an OFDMA based cellular system has been shown to exhibit a high potential to combat co-channel interference in according systems. So far, related investigations have assumed up-to-date channel state information as input for the sub-carrier assignment mechanisms, omitting the fact that in most cases there is a significant delay between the time of channel state information acquisition and its usage for scheduling purposes. In this paper, we explore the co-channel mitigation performance of optimal sub-carrier allocation subject to the channel state information processing delay. We show that, compared to the random assignment case, large gains can be expected if sub-carriers are assigned dynamically, as long as the delay stays in reasonable bounds. Moreover, we investigate the additional usage of power masks on top of the optimized sub-carrier assignments and show that in this combination, there is hardly a chance for improvement due to power masking[1].**

I. INTRODUCTION

It is well known that *dynamically* assigning sub-carriers in the down-link of single, isolated OFDMA (Orthogonal Frequency Division Multiple Access) cells provides a significant performance increase, by taking advantage of diversity effects [1]. Generally speaking, the large gains stem from the exploitation of multi-user and frequency diversity: each sub-carrier, or small group of sub-carriers (*resource block* or *chunk*), is individually assigned to the user that can use it best in order to achieve the system optimization target (e.g. max. system throughput, or max. per-user throughput). In achieving those gains, the mechanisms, however, require up to date channel state information (CSI) values of the channel they are adapting to. Outdated information might lead to errors in the resource assignments, and, thus, to a decrease in system performance.

On the other hand, in the cellular scenario a key issue with OFDMA is co-channel interference (CCI); especially terminals located at the cell border are stronger exposed to power radiated in their communication band by the base station of neighboring cells. In legacy systems, the major alternative for mitigating CCI was *hard frequency reuse* (HFR), where neighboring cells never worked in the same frequency band. For OFMDA systems, a more sophisticated alternative has been developed: *soft frequency reuse* (SFR) [2]. The main idea with SFR is to restrict the amount of power that cells can radiate on certain frequency ranges. The access point has to respect these limitations but is otherwise free to make its scheduling decisions. Accordingly, when combining such approaches with dynamic sub-carrier assignment mechanisms, cells can use high-power sub-carriers to reach users that are far away and low-power sub carriers for users that are close to the base station. The configuration of SFR can be described in terms of cell-specific *power masks* over the system bandwidth. A power mask prescribes the fraction of the maximum transmit power that the base station may use depending at the part of the spectrum.

The configuration of the power masks has a significant impact on the system's performance. Previous work [3] shows that soft frequency reuse has a capacity advantage over the plain hard reuse. Moreover, we have addressed the question on how good the combination of SFR with optimal dynamic sub-carrier allocation provides protection against CCI, compared to the optimal approach, which individually distributes the power among the sub-carriers according to a non-linear optimization problem that minimizes the system's CCI. We have found out that the performance of the combined approach gets quite close to the optimal approach if the individual maximum throughput per user is not too high [4].

For the above studies, however, we have assumed instant channel state information to be available at any point in time and the scheduler to be able to adapt

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immediately. Obviously, in real systems these values are not instantly available. The scheduler, thus, has to work with delayed channel measurements. Note that the advantage of a highly accurate adaptation to the channel state in the optimal world might turn into a disadvantage in the real world.

Therefore, in this paper we will further investigate the impact of CSI processing delay on the performance of the dynamic sub-carrier allocation and power masking combination in multi-cell scenarios. We consider different time spans between the measurement of CSI and its actual usage for channel adaption. We first explore the CCI mitigation performance without power masking. Then, we compare the results to a similar scenario, where different standard power masks are used.

The remainder of this paper is organized as follows. In the following section, we present our system model. Then, in Sec. III, we introduce our dynamic sub-carrier scheduling goal and the according optimization model. We present our reference scenario and the according reference results in Sec. IV, and conclude our work and identify topics for further study in Sec. VI.

II. SYSTEM MODEL

Time is slotted into transmission time intervals (TTI) of duration T_{TTI} (in the order of milliseconds). During a single TTI, down-link user data multiplexing is done in frequency division multiplexing (FDM) fashion, where the smallest addressable bandwidth-unit is a *resource block*. Following the localized mapping scheme, a resource block consists of adjacent sub-carriers in the frequency domain. In the time domain, a resource block spans all OFDM symbols available for user data transmission of the respective TTI. Each resource block is expected to experience mostly flat fading throughout a single TTI. Users are uniformly distributed over the the whole system, moving with speed v according to the Manhattan grid mobility model.

A. The scheduler

For each TTI and in each cell, a scheduler assigns the resource blocks to the served terminals. We assume adaptive coding and modulation (ACM) per resource block, so the scheduler determines also the modulation type and coding, based on available channel state information (CSI). In this work, we assume different constant delays between the measurement and the usage (processing) of the individual CSI values for scheduling purposes. We refer to this time span as CSI processing delay Δ.

We use the truncated Shannon capacity of a channel (according to [5]) instead of referring to the coding and modulation type combinations actually considered for OFDMA based systems, such as LTE: for a channel with bandwidth B and a given signal-to-interference-and-noise ratio (SINR), there exists a code that achieves a throughput of

$$\text{THR} = \begin{cases} B \cdot \alpha \cdot \log_2(1 + \text{SINR}) & \text{, if SINR} \leq \gamma \\ B \cdot \beta & \text{, else.} \end{cases} \quad (1)$$

Compared to pure Shannon capacity considerations, in this case the achievable maximum throughput is bounded by threshold β, and the achieved throughput for a certain SINR is degraded by factor $0 \leq \alpha \leq 1$ in order to account for the non-idealistic performance of existing modulation and coding schemes.

We assume that the transmit power is prescribed for each resource block by a power mask. For cell i, we will denote the power mask by $p_{i,r}^{\text{mask}} \in [0, 1]$. This value denotes the fraction of the total available output power $p^{(\text{MAX})}$. On resource block r, cell i thus transmits with a power of $p^{(\text{MAX})} \cdot p_{i,r}^{\text{mask}}$. In order to stick to a consistent notation, we also assume a power mask for the original case, in which the power is uniformly distributed over the sub-carriers: the uniform power mask, where $p_{i,r}^{\text{mask}} = p^{(\text{MAX})}/|\mathcal{R}|$ for all r and i (where $\mathcal{R}$ is the set of resource blocks).

We denote the channel gain (reflecting path-loss, shadowing, and fading) in TTI t for user m, base station i, and resource block r by $\gamma_{i,m,r}^{(t)}$, and calculate the current SINR as

$$\text{SINR}_{i,m,r}^{(t)} = \frac{p^{(\text{MAX})} \cdot p_{i,r}^{\text{mask}} \cdot \gamma_{i,m,r}^{(t)}}{\sum_{j \neq i} p^{(\text{MAX})} \cdot p_{j,r}^{\text{mask}} \cdot \gamma_{j,m,r}^{(t)} + \eta_r}. \quad (2)$$

The above denominator sums up the co-channel interference from concurrently transmitting base stations $j \neq i$ and the noise power η_r.

III. SCHEDULER OPTIMIZATION

Scheduling commonly aims at maximizing system throughput, but fairness has to be taken into account, too. Solely maximizing the raw system throughput can lead to starvation of users at the cell edge and oversupply of bandwidth to users that are easy to serve. Different kinds of fairness constraints circumvent this: guaranteeing each user a certain minimum rate [6], multiplying each user's throughput by an individual proportional fair factor [7], or utility-based per-user throughput optimization [8]. Utility-based optimization is fairest, but it is highly complex.

A. Optimization model

Discussing different scheduling and fairness policies is beyond the scope of this paper. We use a simple fairness model to compare different SFR scenarios, but our approach easily adapts to other fairness notions. We assume that for each user there is a maximum throughput $\text{THR}^{(\text{MAX})}$, and that any throughput beyond $\text{THR}^{(\text{MAX})}$ is useless. In other words, we try to maximize the system throughput while assuring that none of the users gets more than a certain maximum rate. This approach corresponds to a simple piecewise linear utility function.

Formally, we can write our scheduling goal as an optimization model by introducing the binary user/resource block assignment variable $x_{m,r}^{(t)}$, which is 1 if user m obtains resource block r, and 0 otherwise [9]. The sets of all active users and of all resource blocks are denoted by $\mathcal{M}$ and $\mathcal{R}$, respectively. The task of the scheduler then is described by the following integer linear program:

$$\max \quad \sum_m \sum_r x_{m,r}^{(t)} \cdot \hat{\text{THR}}_{m,r}^{(t)} \tag{3a}$$

$$\text{s.t.} \quad \sum_m x_{m,r}^{(t)} \le 1 \qquad \forall\, r \in \mathcal{R} \tag{3b}$$

$$\sum_r x_{m,r}^{(t)} \cdot \hat{\text{THR}}_{m,r}^{(t)} \le \text{THR}^{(\text{MAX})} \quad \forall\, m \in \mathcal{M} \tag{3c}$$

The scheduling objective (3a) is to maximize the total expected throughput $\hat{\text{THR}}_{m,r}^{(t)}$ of all users m on all resource blocks r. Constraint (3b) ensures that each resource block is assigned to at most one user at a time (*i. e.,* m exclusively uses r at TTI time t). Constraint (3c) is the utility constraint that guarantees that user m does not get more than the maximum required throughput $\text{THR}^{(\text{MAX})}$.

The expected throughput $\hat{\text{THR}}_{m,r}^{(t)}$ of user m on block r depends on the expected SINR, which we will denote by $\hat{\text{SINR}}_{i,m,r}^{(t)}$. The expected SINR is derived from the latest available SINR measurement, which depends on the CSI processing delay Δ. According to Eq. (1), the expected throughput is

$$\hat{\text{THR}}_{m,r}^{(t)} = \begin{cases} \Delta f \cdot \alpha \cdot \log_2(1 + \hat{\text{SINR}}_{i,m,r}^{(t-\Delta)}) & \text{, or} \\ \Delta f \cdot \beta \end{cases} \tag{4}$$

if m is located in cell j out of the set of active cells $\mathcal{J}$; depending on whether $\hat{\text{SINR}}_{i,m,r}^{(t-\Delta)} \le \text{SINR}_{max}$ or not. Δf is the resource block bandwidth. We parameterize the truncated Shannon capacity parameters α and β according to the suggested values for the downlink of LTE systems in [5]: $\alpha = 0.6$ and $\beta = 4.4$. Note again that an according scheduler is optimal only in the sense that is optimally distributes the resource blocks among the users with respect to the optimization goal formulated above. It is not involved with optimally distributing the transmission power among the resource blocks. That's why the application of different power masking types might lead to an increase in system performance.

IV. REFERENCE SCENARIO

A. Setup

Our reference system and channel model parameterization (path loss, shadowing, and fading model) largely follows the parameters for the UTRA and EUTRA simulation case 1 as presented in Tables A.2.1.1-1 and A.2.1.1-2 of [3] with an inter-site distance of 500 m and users dropped uniformly in each hexagonal cell. Differing parameters are shown in Table I. Our OFDMA system-level simulator is based on the free timed discrete event simulation library OMNeT++ [10]. The scheduling optimization problem instances (3) have been solved using ILOG's CPLEX linear problem solver [11].

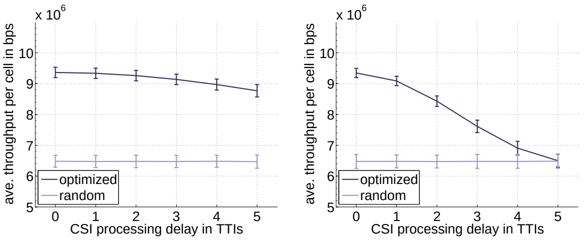
B. Methodology

We have solved 1000 instances per cell of each scheduler configuration in 5 different user deployment cases resulting in a total of 140,000 optimization problem instances solved.

1) Investigating the processing delay impact: In order to investigate the impact of the CSI processing delay Δ on the CCI mitigation performance of optimally scheduled OFDMA systems, we first compare the throughput values achieved by the optimal subcarrier assignment as described in Sec. III to the those of a scheduler that randomly distributed the subcarriers among the users. In both cases, we assume the power to be equally distributed among all subcarriers.

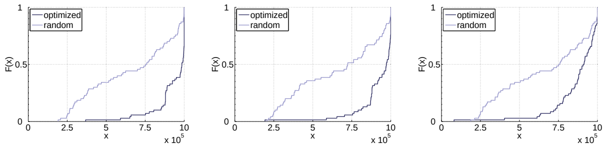
Parameter	**Symbol**	**Value**
Cells in the system	$\lvert\mathcal{J}\rvert$	7
Users	$\lvert\mathcal{M}\rvert$	70
Resource blocks	$\lvert\mathcal{R}\rvert$	25
User speed	v	{0; 10} m/s
Max. per user throughput	$\text{THR}^{(\text{MAX})}$	1 Mbps
Resource block freq. spacing	Δf	200 kHz
Max. transm. power per cell	$p_{\max}$	43 dBm
CSI processing delay	Δ	{0 …5} TTIs

TABLE I
SIMULATION PARAMETERS.

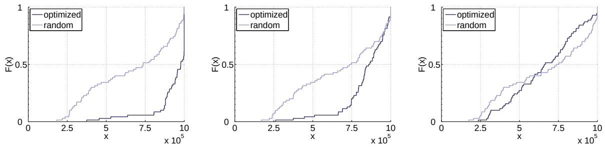


(a) $v = 0\frac{m}{s}$ (b) $v = 10\frac{m}{s}$

Fig. 1. Average per cell throughput, 90% confidence interval.



(a) 0 TTIs, $0\frac{m}{s}$ (b) 2 TTIs, $0\frac{m}{s}$ (c) 5 TTIs, $0\frac{m}{s}$



(d) 0 TTIs, $10\frac{m}{s}$ (e) 2 TTIs, $10\frac{m}{s}$ (f) 5 TTIs, $10\frac{m}{s}$

Fig. 2. Average user throughput empirical cdfs.

2) Exploring the benefit of power masking: Thereafter, we compare the performance of the equal power optimal case above to the performance of a scheduler featuring the combination of optimal subcarrier allocation and soft frequency reuse power masking. There are three different power levels: high, middle and low. Each cell uses one third of the spectrum with each power level. The parameterization follows standard power masks:

SFR$_{[1;0.5;0.25]}$: the low power level equals one forth and the medium level equals half of the high power level.

SFR$_{[1;0.1;0.01]}$: the low power level equals one hundredth and the medium level equals one tenth of the high power level.

V. RESULTS

A. Processing delay impact results

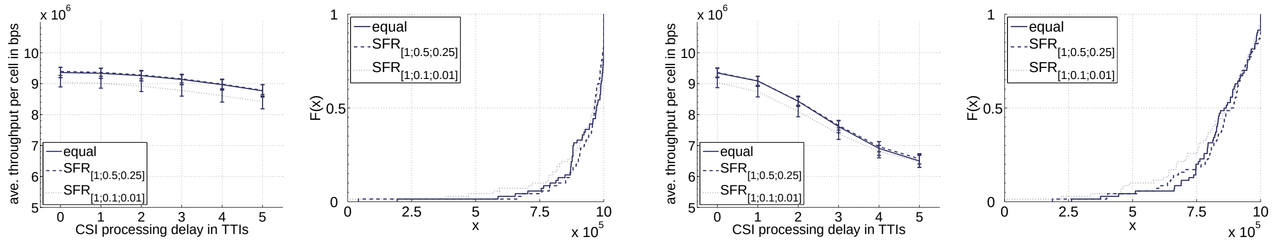
Fig. 1 shows the difference in throughput performance between the optimal and the random subcarrier allocation scheduler for the cases of static users (left) and users moving at a speed of $v = 10m/s$ (right). The graphs show the average throughput per cell values (over all cells and TTIs) subject to the CSI processing delay. As expected, the performance gain due to optimally assigning the subcarriers decreases with an increasing CSI processing delay. While the optimal curve decreases rather slowly in the case of static users, it decreases fast in the case of moving users and is completely vanished if the channel information has an age of 5TTIs. This is due to the fact that the differences in path loss, shadowing and fading add up to a large difference in SINR for the moving users, out dating the information about the channel quite fast. Bearing in mind that the sub-carrier assignments are optimally chosen - a very idealistic prerequisite, which does not hold in real systems - we have to conclude that dynamically assigning sub-carriers does not pay off in systems unable to deliver adequate CSI values in a timely manner.

For systems that can be assumed to encounter CSI processing delays of 2 to 3 TTIs, however, a large gain is achievable also with the delayed CSI values. This holds not only for the experienced per cell throughput, but - more importantly - also for the individual per user throughput as can be seen in Fig. 2. The figure shows the empirical per user throughput cumulative distribution functions (CDFs) for the static and the moving user cases with 0, 2, and 5 TTIs delay respectively. Large gains in weak user throughput performance can be observed for the 0 and 2 TTI CSI processing delay cases. In all these cases, the throughput of the weakest 25% of the users is at least doubled. For static users, the gain is achievable even when using CSI with an age of 5 TTI. We, thus, conclude that dynamically assigning sub-carriers among users according to the current channel situation has a high potential to boost the performance of weak users without harming the overall system performance.

B. Power masking results

Fig. 3 shows the results of the power mask investigations. As can be seen, power masking does not provide a gain in per-cell throughput performance. This is not surprising, since power masking takes power from the well situated users and shifts it to users in worse situations, which usually accounts rather for a decrease than an increase in system performance. Accordingly, in both the static as well as in the moving user case, the per cell throughput performance when applying the less variable power mask SFR$_{[1;0.5;0.25]}$ is comparable to the equal power case, whereas the per-cell performance of the higher variable power mask SFR$_{[1;0.1;0.01]}$ is slightly worse, as it shifts more power toward the weaker users.

In addition, there is hardly any increase in the per user throughput performance. Solely in the case of static users featuring a CSI processing of 2TTIs,



(a) ave. cell tp, $v = 0\frac{m}{s}$ (b) user tp cdf, 2 TTIs, $0\frac{m}{s}$ (c) ave. cell tp, $v = 10\frac{m}{s}$ (d) user tp cdf, 2 TTIs, $10\frac{m}{s}$

Fig. 3. The impact of power masking on per cell and individual per user throughput.

a slight improvement of the weaker users average throughput can be seen, if power mask $\mathrm{SFR}_{[1;0.5;0.25]}$ is applied (see Fig. 3b). Surprisingly, applying power mask $\mathrm{SFR}_{[1;0.1;0.01]}$ does not add any gain in per user throughput performance at all.

The disutility of the power masks is mainly due to the superiority of the scheduler, which optimally distributes the sub-carriers to mitigate CCI and maximize the system throughput. By knowing the all channel attenuation values of each user versus every base station, the scheduler is able to use the natural differences in sub-carrier attenuation (due to frequency and spatial diversity) to mitigate CCI: each user gets those sub-carriers that are highly attenuated versus other base stations, but feature good channel conditions versus the base station it is connected to. This way, the optimal scheduler exploits the same effect as power masking does, while being at the same time much more powerful than the static power masks. We must, thus, conclude that applying power masks on top of an optimal dynamic sub-carrier scheduler does not add a significant gain in the throughput performance.

VI. CONCLUSIONS

Dynamically assigning sub-carriers in the downlink of an OFDMA based cellular system exhibits a high potential to combat co-channel interference in according systems, even if the assignment decisions are based on significantly delayed channel state information. We have shown that the throughput of the weakest 25% of users can be doubled if users are static or move moderately and the channel state information stays in reasonable bounds. A gain in throughput performance is, however, not achievable, if the age of the information exceeds a certain limit, which depends on the user speed. The application of power masking in combination with optimally assigning sub-carriers among users hardly adds any extra gain in throughput performance.

The evaluation of an optimization problem requiring less channel state information as input remains as a future work issue. Moreover, a heuristic approach to dynamically distribute the sub-carriers among the users at low computational cost needs to be developed in order to approach the performance capabilities of real systems. We believe that in the latter cases, the application of power masking on top of the dynamic sub-carrier assignment process adds a more significant gain than in combination with the optimal approach presented in this paper.

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