Fractional Reuse for LTE-Advanced MIMO Networks

Andreas Dotzler,* Christiane Dietrich,* Guido Dietl,† and Wolfgang Utschick.*

* Associate Institute for Signal Processing, Technische Universität München, E-Mail: {c.dietrich,dotzler,utschick}@tum.de

† DOCOMO Euro-Labs and University of Applied Sciences Landshut, E-Mail: dietl@ieee.org

Introduction: Interference is a major source of performance degradation in wireless networks, which motivates to actively manage inter-cell interference in a multi-cell environment. Contrary to approaches that build on centralized coordination of the transmission strategies, we consider a rather weak form of transmitter cooperation based on fractional reuse.

For LTE-A fractional reuse by dynamic resource allocation is implicitly established via Relative Narrowband Transmit Power (RNTP) indicators. Although providing a simple protocol, avoiding explicit enumeration of reuse patterns, and allowing for large degrees of freedom for the schedulers, RNTP indicators alone may not be powerful enough.

A fundamental different approach comes from the context of advanced MU-MIMO transmission [1], which is based on active management of the resources assigned to predetermined reuse patterns. Having the rather theoretic framework at hand, the main contribution of this work is an adaption to the LTE-A system. We present practical solutions to several idealized assumptions made in the original work, thereby making a first step from theoretical research to practical solutions relevant for standards. By numerical simulations with an LTE-A system-level simulator, we are able to show significant performance gains, especially for cell-edge users.

Fractional Reuse by Scheduling of Physical Layer Modes: We briefly recapitulate the main idea of fractional reuse for advanced multi-user MIMO systems as presented in [1]. We regard a wireless cellular network with a set of eNBs $\mathcal{T}$, $T = |\mathcal{T}|$.

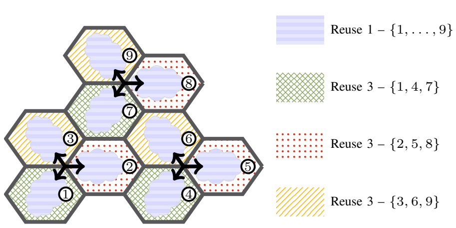

Figure 1. Illustration of Transmitter Subsets

Due to shared resources and interference the data rates $\boldsymbol{r} = [r_1, ..., r_K]^{\mathrm{T}} \in \mathcal{R}$, that can be achieved by the set of UEs $\mathcal{K}$, $K = |\mathcal{K}|$, are interdependent, which is universally modeled by the achievable rate region $\mathcal{R}$. According to [1], fractional reuse by active resource allocation can be modeled as a network utility optimization (NUM) problem, where $\mathcal{R}$ is parameterized by scheduling of physical layer modes. Conceptionally, we introduce a set of physical layer modes $\mathcal{N}$, $N = |\mathcal{N}|$, each one of them representing a subset of eNBs allowed to be active on a shared resource. For the example illustrated in Figure 1, where we have a mix of reuse one and three, we obtain $N = 4$ physical layer modes for the following subsets of $\mathcal{T}$: $\{1, \ldots, 9\}$, for reuse one and $\{1, 4, 7\}$, $\{2, 5, 8\}$, $\{3, 6, 9\}$ for reuse three. As the achievable rates depend on the interferers present, each physical layer mode has a different associated rate region $\mathcal{R}_n$ and the rates achievable by scheduling of the physical layer modes can be described by the convex hull $\mathcal{R} = \mathrm{co}\{\mathcal{R}_1, ..., \mathcal{R}_N\}$ of the individual rate regions.

The solution to the NUM can be found by solving a sequence of weighted sum rate (WSR) optimizations

$$\max_{\boldsymbol{r}} \left\{ \sum_{k \in \mathcal{K}} \lambda_k r_k : \boldsymbol{r} \in \mathrm{co}\{\mathcal{R}_1, \ldots, \mathcal{R}_N\} \right\}, \tag{1}$$

with user weights $\lambda_1, \ldots, \lambda_K$. The weights are updated by some iterative optimization algorithm, for example a dual approach as in [1] or by the well established proportional fair scheduler. The WSR optimization is decomposed into a problem per physical layer mode

$$\max_{n \in \mathcal{N}} \left\{ \max_{\boldsymbol{r}_n} \left\{ \sum_{k \in \mathcal{K}} \lambda_k r_{n,k} : \boldsymbol{r}_n \in \mathcal{R}_n \right\} \right\}, \tag{2}$$

which has an interpretation as a competition for resources among the physical layer modes.

Instead of negotiating for the reuse patterns themselves, the patterns are predefined and the best performing is selected. Limiting the attention to a fixed set of predefined patterns (instead of all possible subsets of eNBs), removes the exponential growth in complexity associated with this combinatorial aspect of the optimization. Further, we do not force a UE to be scheduled into one pre-determined pattern, which avoids a loss of performance and removes the need to classify users as cell-edge or cell-center users.

Adaptions for LTE-Advanced: Uncertainty in the interference environment of the users, which is especially challenging in MIMO systems, may lead to suboptimal decisions at the higher layers for example the resource allocation for fractional reuse. Therefore, we suggest to use robust unitary precoding [2], [3], which ensures that interference depends only on the set of interfering eNBs, but not on their scheduling decision or precoding. For unitary precoding the precoders chosen by eNB t are such that the precoding matrix $\boldsymbol{V}_t = [\boldsymbol{v}_1, ..., \boldsymbol{v}_{N_{\mathrm{tx}}}]$, which includes the precoders as columns, is unitary. As suggested in [2], a constant transmit covariance can be obtained by artificially enforcing the maximal number of $N_{\rm tx}$ data streams and an equal power allocation $\frac{P}{N_{\rm tx}}$. As a consequence, the sum transmit covariance $\boldsymbol{Q}_t$ becomes spatially white:

$$\boldsymbol{Q}_t = \frac{P}{N_{\rm tx}} \boldsymbol{V}_t \boldsymbol{V}_t^{\rm H} = \frac{P}{N_{\rm tx}} \boldsymbol{I} \quad \forall t \in \mathcal{T}. \tag{3}$$

Let $\boldsymbol{H}_{kt}$ denote the MIMO channel between UE k and eNB t, the inter-cell interference covariance matrix $\boldsymbol{C}_{{\rm inter},k}$ is given by

$$\boldsymbol{C}_{{\rm inter},k} = \sum_{t \in \mathcal{I}} \boldsymbol{H}_{kt} \boldsymbol{Q}_t \boldsymbol{H}_{kt}^{\rm H} = \sum_{t \in \mathcal{I}_n} \frac{P}{N_{\rm tx}} \boldsymbol{H}_{kt} \boldsymbol{H}_{kt}^{\rm H}, \tag{4}$$

where $\mathcal{I}_n$ is the set of interfering eNBs. We conclude that using a slightly modified version of unitary precoding interference depends only on the set of interferers but is independent of the UEs scheduled and the precoders used, which means that (2) can be split into a subproblem per eNB. Let $\mathcal{K}_t$ be the users served by transmitter t, the achievable rate region for physical layer mode n is denoted as $\mathcal{R}_{n,t} \subset \mathbb{R}^{|\mathcal{K}_t|}$ and (2) can be rewritten as

$$\max_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} \max_{\boldsymbol{r}_{n,t}} \left\{ \sum_{k \in \mathcal{K}_t} \lambda_k r_{n,t,k} : \boldsymbol{r}_{n,t} \in \mathcal{R}_{n,t} \right\}. \tag{5}$$

The weight update can be performed locally at each eNB, which implies that computing a WSR optimization can be performed locally at the eNBs (5), and there is no need to exchange channel state information or user feedback in the network. Every eNB computes a WSR optimization for each physical layer mode the eNB is allowed to be active. For every combination of transmitter and physical layer mode we define a performance indicator

$$w_{n,t} := \max_{\boldsymbol{r}_{n,t}} \left\{ \sum_{k \in \mathcal{K}_t} \lambda_k r_{n,t,k} : \boldsymbol{r}_{n,t} \in \mathcal{R}_{n,t} \right\}. \tag{6}$$

By this the competition of the physical layer modes (5) can be rewritten as

$$\max_{n \in \mathcal{N}} \sum_{t \in \mathcal{T}} w_{n,t}, \tag{7}$$

which directly leads to the following message exchange protocol:

Having computed the WSR optimizations the eNBs will exchange the performance indicators and compute the winning physical layer mode. After the message exchange among the eNBs, the winning mode is known to all eNBs and in case an eNB is allowed to be active in the winning mode, it will apply its previously computed scheduling decision for this mode.

Concerning the communication between UEs and eNBs we developed a new feedback mechanism for robust unitary precoding in fractional reuse that allows to compute the WSR optimization for every pattern. Due to space limitations it is not described in this abstract, but we would be happy to include it in the final version. Meanwhile we refer to the source code for the exact implementation of the feedback [4].

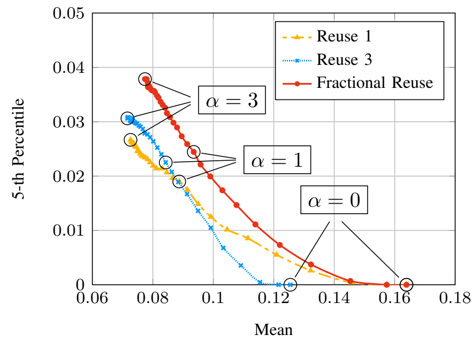

Figure 2. Mean Cell vs. Cell-Edge Throughput

Simulation Campaign: After performing the necessary adaptions of the considered theoretic framework to LTE-A, we implemented the ideas presented in the `IMTAphy` LTE-A system-level simulator [5]. The simulation results are reproducible and extendible, as the source code is publicly available under a GPL license [4].

As we want to pay particular attention to cell-edge users, we will investigate various levels of fairness and use the well known α-fairness framework to control fairness, where $\alpha = 0$ is the max-throughput scheduler, $\alpha = 1$ is the proportional fair scheduler, and for $\alpha \to \infty$ we obtain the max-min fair scheduler. Alternating the level of fairness trades off performance of the cell-edge user and the average cell performance. In order to further investigate this trade-off and the potential of fractional reuse in this context, we performed simulations for $\alpha = 0, 0.1, \ldots, 3$. For every result we compare the average cell performance, given by the mean of the empirical CDF, and the performance of the cell-edge users, given by the 5-th percentile of the empirical CDF. The complete trade-off curves are shown in Figure 2. One can see the cross-over between reuse one and reuse three for increased fairness. As expected, for all levels of fairness fractional reuse is at least as good as reuse one or reuse three. For higher levels of fairness we observe a significant gain in performance.

Outlook Full Paper: In the full paper we will provide a elaborate review of the existing literature and describe how it is related to our contribution. A more detailed description of the challenges and solutions for adapting our ideas to the LTE-A framework will be complemented by several results from our simulation campaign that will also include all information on the specific assumptions made and the scenarios investigated.

References

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