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Efficient MAC Protocol for JT CoMP in Small Cells

Moritz Lossow, Stephan Jaeckel, Volker Jungnickel
Fraunhofer Heinrich Hertz Institute
10587 Berlin, Germany
{moritz.lossow, stephan.jaeckel, volker.jungnickel}@hhi.fraunhofer.de

Volker Braun
Alcatel-Lucent Bell Laboratories
Lorenzstr. 10, 70435 Stuttgart, Germany
volker.braun@alcatel-lucent.com

***Abstract*—In this paper, we investigate an efficient MAC protocol for interference coordination in small cells embedded in a macro-cell mobile network. We perform joint transmission (JT)-coordinated multi-point (CoMP), where cells in the cluster include adjacent macro-cells as suggested by the small-cell terminal. Most gains compared to uncoordinated transmission come from selecting the right users in these macro-cells. For minimizing the feedback overhead, we propose successive channel state information (CSI) requests. Thereby we replace users in the set until all of them experience consistently enhanced performance when using JT-CoMP. Gains can be further increased by MIMO mode switching in each cell and frequency-selective scheduling. We tested our algorithms over coherently measured multi-cell channels in the LTE-Advanced testbed in Berlin where small cells were embedded at several places. Using these algorithms, performance becomes comparable to a popular bound assuming no more intra-cluster interference while feedback overhead and complexity are substantially reduced.**

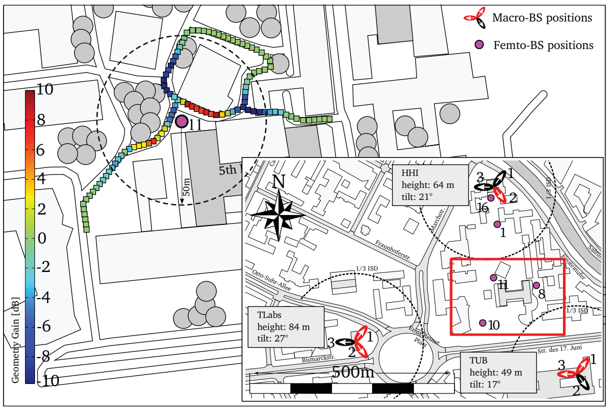

Figure 1. Measured geometry gain when inserting a small cell into a macro-cellular network. The circle has a radius of 50 m. Active base stations and the measurement area around the small cell are shown in the insert.

I. Introduction

The initial roll-out of mobile networks ends with a macro-cell network achieving full coverage. With increasing penetration of mobile devices, however, more traffic comes into the network at certain locations where the user density is high. In train stations or at big venues, traffic peaks reach the capacity limits of the mobile network easily. This has been reported for initial Long Term Evolution (LTE) networks rolled out recently in Asia, already shortly after sufficient devices were available enabling rich mobile multimedia content delivery.

A classical approach to manage this problem is to increase the density of base stations. Small cells are embedded into the existing macro-cell network at places where the user density is high. In case of full frequency reuse, small and macro cells experience mutual interference. The situation is illustrated in a measurement at 2.6 GHz in the Berlin LTE-Advanced testbed in Berlin (Fig. 1) where we inserted a small cell into a network consisting of 5 macro-cells. The colored trace shows the ratio of the geometry factor with and without adding the small cell. Geometry is the expectation of serving cell power divided by the expectation of interference plus noise power.

Geometry is higher near the small cell site, but smaller at larger distance where the macro-cell is serving but the small cell contributes additionally to the interference. In practice, the area of increased interference is often comparable or larger than the small-cell coverage area. Introducing a small cell is obviously harmful for macro-cell users nearby.

Indoors, the additional interference may be harmless due to the attenuation of walls. But for mobile outdoor use, interference management is crucial. An enhanced inter-cell interference coordination (eICIC) scheme is enabled in LTE Rel. 10. Almost blank sub-frames are introduced at macro-cells for avoiding the interference. While orthogonal signaling is straightforward, it causes a penalty for the macro-cell.

A promising new technique is network coordination [1]. Antennas of multiple base stations are considered as inputs and terminals in jointly served cells as outputs of a distributed multiple-input multiple-output (MIMO) system. By exchange of channel state information (CSI) and user data between the cells, interference can be efficiently eliminated. For joint transmission coordinated multi-point (JT-CoMP), a joint precoder is computed using CSI feedback from the terminals in all cells. The precoder is applied to all user data in a cluster of cells so that the desired signals interfere constructively and interference is eliminated [2].

The coordinated multi-point (CoMP) technique has been studied widely [3, 4]. Some details are still investigated, see e.g. [5]. Here, we focus on an efficient medium access control (MAC) protocol for CoMP and test it in a heterogeneous deployment scenario. Our objective is a practical scheme approaching the potential gains of interference coordination while complexity and overhead are limited.

The paper is organized as follows. Section II contains our algorithmic framework. Section III describes how performance is evaluated. Our measurement scenario is described in section IV. In Section V, we present our main results.

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II. Adaptive Algorithms for JT-CoMP

In this section, we describe our adaptive physical and MAC layer algorithms used for interference coordination. We use zero forcing (ZF) for canceling intra-cluster interference. Since ZF is optimal only if the user channels are orthogonal [6], we describe how to identify an appropriate user set maximizing the performance. For the identified set, finally we apply MIMO mode switching [7] and frequency-selective scheduling.

A. Physical layer precoding

We assume that N_u terminals, each having N_r antennas, are served jointly by N_b base stations with N_t antennas each. The vector $\mathbf{y}$ contains the signals received at all antennas of all terminals and it has dimension $N_r \cdot N_u$ x 1. For a given radio resource in an orthogonal frequency-division multiplexing (OFDM) system, $\mathbf{y}$ can be described as

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{P} \cdot \mathbf{x} + \mathbf{n} = \mathbf{G} \cdot \mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is the $N_r \cdot N_u$ x $N_t \cdot N_b$ multicell multiuser channel matrix, $\mathbf{P}$ is the $N_t \cdot N_b$ x $N_r \cdot N_u$ precoding matrix and $\mathbf{n}$ is the $N_r \cdot N_u$x1 noise vector at all terminals. For our measured channels, $N_b = 6$, $N_t = N_r = 2$ while $N_u = N_b$ where each user is selected from several users in each cell.

In the network, we consider a distributed ZF precoder where $\mathbf{P}$ is chosen as the right-handed Moore-Penrose pseudo-inverse of the compound channel matrix

$$\mathbf{P} = \mathbf{H}^{\dagger} = \mathbf{H^H}(\mathbf{HH^H})^{-1}. \tag{2}$$

We chose ZF as opposed to maximum eigenmode transmission or block diagonalization [8, 9] for reducing complexity. In order to avoid soft clipping, the precoder output is normalized so that the columns $\mathbf{p}^j$ of the matrix have unit Euclidic norm

$$||\mathbf{p}^j||_2 = 1, \tag{3}$$

where index j denotes the column corresponding to the user data stream. This norm has been identified as most practical for JT-CoMP in [4] since it enables individual power control per user. The desired signal is downscaled if the channel matrix is close to singular. The effective channel $\mathbf{G}$ looks similar to multi-path fading. By appropriate user selection, we try to avoid critical cases and keep the performance high.

B. MAC layer procedures for JT-CoMP

The MAC layer is mission-critical for realizing the benefits of MIMO and CoMP in mobile scenarios. For related work in homogeneous macro-cells, see [10]. Here, we consider a heterogeneous scenario. A small cell is embedded into a large macro-cell network. We assume that one (or at most a few) user(s) are served by the small cell, while in the macro-cell we can select from a large number of users. Note that the number of potential user combinations in a cluster is huge. Primarily, we need an efficient user selection approach.

1) Flexible clustering: We consider flexible cluster formation starting from the instantaneous interference situation at the small-cell terminal. We select those cells where received power averaged over all MIMO links and frequencies is within a predefined window below the power of the small cell. The window size is denoted as the cluster threshold. Here, we consider arbitrary thresholds of 6, 12 and 18 dB. Clearly, the higher the threshold, the larger is the average cluster size.

2) Feedback: Terminals measure the CSI for their assigned cluster upon a specific CSI request and feed it back to their serving base station (BS). All BSs in a cluster exchange CSI and user data and assemble the channel matrix of the cluster from CSI feedback of own and cooperative cells. Next, the joint precoder is computed. Cells outside the cluster are considered as uncoordinated interference [4]. While intra-cluster interference is removed, performance remains limited by out-of-cluster interference and noise.

3) User selection: Once a cluster is formed in the network, cooperative macro-cells identify suitable users. Feedback overhead is crucial in this step. In theory, best users have the most orthogonal channel vectors. Orthogonal channel matrices can be easily inverted and there is no loss due to linear precoding. For $N_u \to \infty$, optimal user sets can be identified [6]. Using this criterion, one would need CSI for all users in the cluster, which is impractical due to the feedback overhead.

In the following, we describe four alternative user selection schemes. In the first two approaches, user selection was confined to a radius of 50 m around the small cell since the criteria are hardly fulfilled outside this area. In the other approaches, the region of interest for user selection was expanded to the whole macro-cell area.

a) Users requesting the same cluster (US-I): In the first approach, we form a cluster only if macro-cell users request the same cluster. This approach was used e.g. in [4]. But users request the same cluster infrequently, see section V.

b) Users with partially the same cluster (US-II): In the second approach, the scheduler forms a cluster only if users request the same or partially the same cluster. Success probability is higher but the overall gain is limited. Partial cooperation implies smaller cluster size on average.

c) Random users (US-III): In the third approach, the scheduler searches for random users in the entire area served by each cooperative macro-cell. From all users positions in a macro-cell, the scheduler selects one at random. Clustering success is always guaranteed. But, in some cases, this approach increases the rate of the small-cell user at the cost of a lower data rate in the cooperative macro-cells.

d) Random users pending on gain in all cells (US-IV): Identifying the best users is prohibitively complex if the cluster is large. Here we propose a simple heuristics starting from a random set of small-cell users. Successively, we replace macro-cell users in the set so that all users benefit from cooperation at the end. Typically, if the first trial fails, it needs few more trials with randomly selected new users to end up with a win-win situation for all users.

4) Successive feedback requests: Only the small-cell terminal and randomly selected macro-cell terminals are requested to provide CSI feedback. If a trial fails, the channel of another macro-cell terminal is requested. We discard the terminal from the set having the biggest performance loss compared to uncoordinated transmission after applying JT-COMP in the cluster. Complexity and feedback scale with the number of trials until all users gain from using JT-COMP.

Note that complexity and feedback overhead is significantly reduced in this way while a consistently improved performance is reached in all cells within the cluster. Clearly, optimal performance [6] is not reached, since CSI is limited at the BS. However, the feedback overhead is significantly reduced since we terminate user selection immediately once an appropriate user set is found and no more feedback is needed.

5) MIMO mode switching: Assume that we have identified a suitable user set in this way. Still, the performance could be improved by switching off data streams in selected cells. This is denoted as MIMO mode switching in the literature. Therefore, we consider the single-user case described in [7]. MIMO mode switching is considered here for zero forcing. The channel matrix is composed of row vectors $\mathbf{h}_j$ corresponding to the j^{th} terminal antenna

$$\mathbf{H} = \begin{pmatrix} \mathbf{h}_1 \\ \ldots \\ \mathbf{h}_j \\ \ldots \\ \mathbf{h}_{N_r \cdot N_u} \end{pmatrix} \tag{4}$$

Reducing the MIMO mode in one cell is performed by removing the row vector $\mathbf{h}_j$ of the discarded data stream j from $\mathbf{H}$ and calculating the reduced precoder using (2). Afterwards, we add a zero column at the j^{th} column in the precoder corresponding to the discarded stream.

Selecting the discarded stream is done by computing a set of fictive precoders. Initially, one stream is switched off in the entire cluster. All candidates precoders are checked if there is a gain in all cells, compared to the full-rank transmission. Given this is true, the best precoder is selected having highest sum throughput in all cells. The same procedure is repeated until there is no more gain by further reducing the number of streams in the cluster. Mode switching stops typically after one or two discarded streams. Clearly, one could extend this idea for multiple users in each cell [7]. But gains are mainly due to user selection. So this is left for further research.

6) Frequency-selective scheduling: We explored also the potential of frequency-selective scheduling assuming that 1 or 4 small-cell users share the bandwidth. Each user selects the best 100 or 25% of sub-bands, respectively, having the highest cooperation gains compared to uncoordinated transmission. We ignore the competition among users since proportional fair scheduling assigns users frequently their best resources [11].

Our entire MAC protocol for JT-CoMP is shown in Fig. 2.

III. Performance Evaluation

At the terminal, we use an interference-aware MIMO receiver and evaluate the achievable signal-to-interference-and-noise ratio (SINR) directly by measuring the error vector magnitude (EVM). User throughput is then computed using a proprietary link-to-system interface.

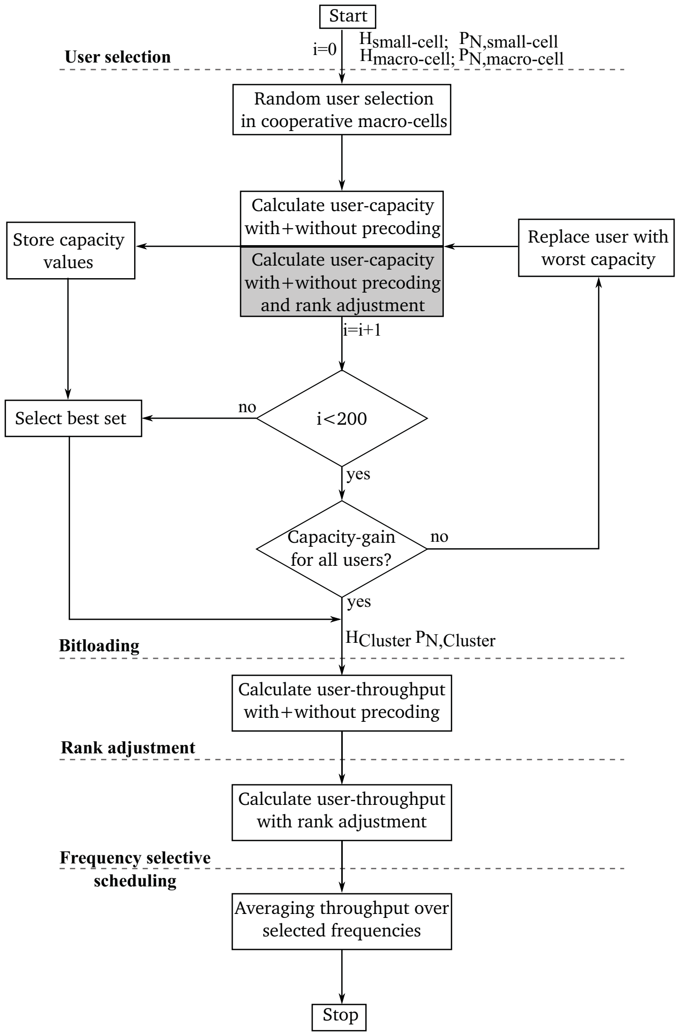

Figure 2. Flow of the MAC protocol for JT-CoMP used in small cells.

A. Interference-aware MIMO receiver

For assessing the achievable throughput, we used an interference-aware MIMO receiver in addition to distributed precoding in the cluster. Our receiver is based on the effective multi-cell channel matrix $\mathbf{G}$ of user k defined in (1). It includes knowledge of out-of-cluster interference as

$$\mathbf{W}_k = \mathbf{G}_k^H (\mathbf{Z}_k + \mathbf{G}_k \mathbf{G}_k^H)^{-1} \tag{5}$$

These weights make the receiver more robust against impairments, such as channel aging. In practice, $\mathbf{G}$ is estimated using cell-specific dedicated pilots denoted as demodulation reference signals (DRS) in LTE embedded in user data. $\mathbf{Z}$ is the interference covariance matrix of user k

$$\mathbf{Z}_k = P_N \mathbf{I} + \sum_{\forall j \neq k} \mathbf{G}_j \mathbf{G}_j^H + \sum_{\forall l \neq k \neq j} \mathbf{H}_l \mathbf{H}_l^H \tag{6}$$

The interference-aware MIMO receiver limits the noise but also scales the signal component. Therefore, the weights $\tilde{\mathbf{W}}_{k,i}$ of each stream i need to be scaled as

$$\tilde{\mathbf{W}}_{k,i} = \frac{\mathbf{W}_{k,i}}{\mathbf{W}_{k,i}\mathbf{G}_{k,i}}, \tag{7}$$

For evaluating the success of user selection pending on gain in all cells, we use the interference-limited capacity from [12]. By plugging the interference covariance matrix (6) at each subcarrier n into the capacity formula, we obtain

$$C_k = \frac{1}{N}\sum_{n=1}^{N} log_2 det\left(\mathbf{I} + \mathbf{Z}_{n,k}^{-1}\mathbf{G}_{n,k}\mathbf{G}_{n,k}^{H}\right). \tag{8}$$

B. EVM-based SINR estimation

We measure performance using the EVM after passing test data through the entire transmitter and receiver simulation chain. EVM is defined as the Euclidean distance between the reference point and the received signal in the transmitted signal space. We transmit in the serving cell the vector $\mathbf{x} = (1 - 1)^T$ as reference point while all other cells transmit pseudo-random binary sequence (PRBS) sequences. After passing signals through precoder, channel and interference-aware MIMO receiver, we obtain the reconstructed symbol vector $\mathbf{x}_{rec} = \mathbf{W}\mathbf{y}$. The difference between the reference point and the received signal is the complex error vector due to out-of-cluster interference and noise. EVM is measured as

$$\mathbf{e} = |\mathbf{W}\mathbf{y} - \mathbf{x}|^{\mathbf{2}} \qquad EVM_j = E\left(e_j\right) \tag{9}$$

for each stream j where we assume that $\mathbf{x}$ has unit power. For meaningful results, we transmit a sufficient statistics of test vectors over the same precoder and the same channel. SINR is then obtained as

$$SINR_j = \frac{1}{EVM_j}. \tag{10}$$

C. Link-to-System Interface

Achievable throughput is realized by selecting an appropriate modulation and coding scheme. In LTE, data streams may use different schemes ranging from QPSK with code rate $\frac{1}{9}$ to 64-QAM with rate $\frac{9}{10}$. A subset of 27 schemes was selected to approximate the envelope of the throughput curve over the additive white Gaussian noise (AWGN) channel. Using the SINR from above, throughput T_i is calculated as

$$T_i = \frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{N_t} 0.9 \cdot log_2(1 + 0.85 \cdot \sigma_{t,n,i}) - 0.18 \tag{11}$$

where N is the number of subcarriers, N_t the number of transmit antennas and i the channel realization.

IV. Interference-Limited Small-Cell Measurements

We evaluated these algorithms using channels measured in our macro-cell testbed. It consists of 3 multi-sector sites on the campus of the Technische Universität Berlin [13]. All BSs are interconnected by optical fibers and tightly synchronized in time and frequency using GPS-disciplined rubidium clocks. Testbed parameters are summarized in Tab. I.

Table I
Measurement parameters

Parameter	Value
Center frequency	2.68 GHz
Bandwidth (B)	18.36 MHz
Carrier (N)	144
max. excess delay	4.7 μs
MIMO capabilities	2x2 per BS
No. of BS	6
CSI update interval	10 ms
Maximal speed	2.8 m/s $\approx$ 10 km/h
ISD	500 m
Macro cell power	36.5 dBm + 18 dBi
Small cell power	24 dBm + 4 dBi
noise floor	-95 dBm

At the macro-cell sites, panel antennas with a down-tilt pointing to 0.33 times the inter-site distance (ISD) were used. At small-cell sites, omni-directional dipole antennas with crossed polarization were used. Positions of small cells (pink dots in Fig. 1) are well isolated from each other.

Pos. 1 has a good link to HHI. Surrounding area is well served from HHI. Changes of geometry due to the small cell (Fig. 1) were measured here. The area near Pos. 8 is surrounded by high buildings and subject to strong interference from HHI and TUB BSs. Pos. 10 is interfered by TUB and T-Labs sites both in direct line of sight (LOS) to the small cell BS. Pos. 11 is similar but has no LOS to any macro-site. Pos. 16 is near HHI. But the link to HHI is blocked by the rooftop edge. Area below HHI is covered by NLOS signals.

We measured a long track through the entire testbed for each small cell site. Multiuser channels were assembled from the same track using random user locations. CSI is measured using proprietary cell-specific reference signals (CRS) [14]. We used 5 CRS for macro-cells and one for the small cell. Our test mobile records six 2x2 MIMO channels coherently, i.e. a user position is represented by a 2x12 channel matrix.

V. Results

First, we study relevant factors for the performance, such as the cluster size and the success rate of clustering. Next we consider throughput both in the small cell and in all macro cells and investigate our four user selection schemes. Finally, we consider MIMO mode switching and frequency-selective

Table II
Measured statistics of the cluster size [%]

Cluster-size	Macro 6dB	Macro 12dB	Macro 18dB	Macro + Small Cell 6dB	Macro + Small Cell 12dB	Macro + Small Cell 18dB
1	53	24	8	58	27	9
2	22	18	3	25	27	16
3	22	33	28	12	20	14
4	3	12	22	4	19	33
5	0.8	13	38	0.4	4	14
6	0	0	0	0	2	14
$\overline{cs}$	1.8	2.7	3.8	1.6	2.5	3.7

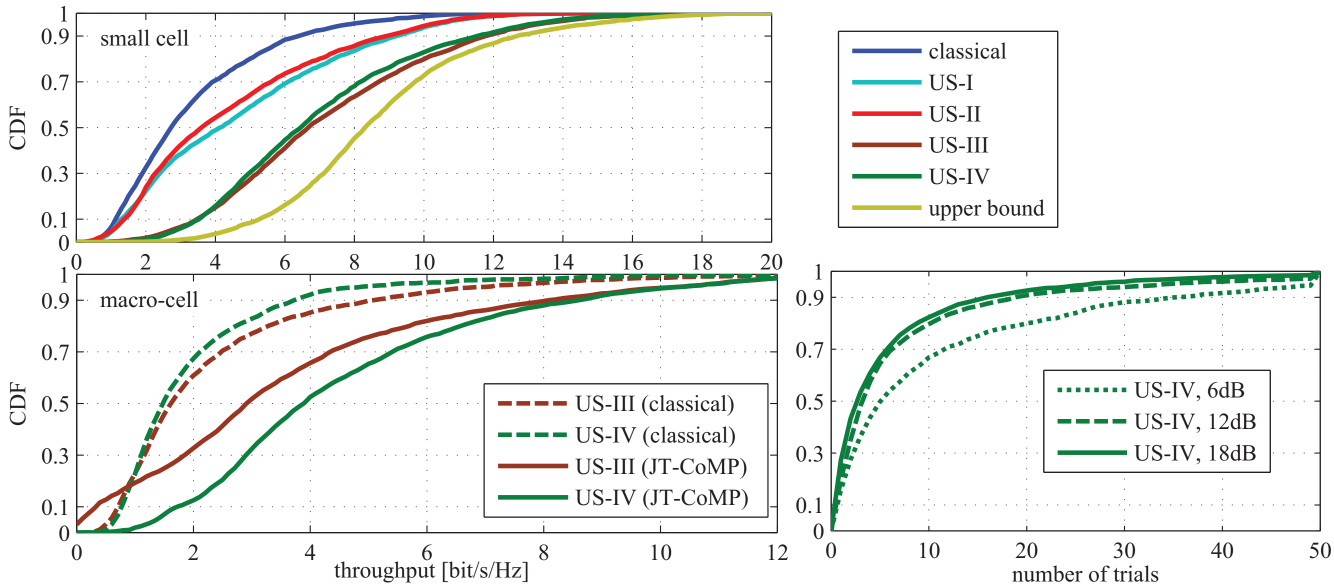

Figure 3. Throughput of small cell and and macro-cell users depending on different user selection schemes. Results are given for a threshold of 18 dB.

scheduling. Results are averaged over all 5 small-cell positions to get a better statistics.

A. Cluster Size Statistics

Cluster size statistics is considered in a radius of 50 m around the small cell. Results are listed in Tab. II. Cluster sizes are moderate indicating that interference is localized and only a few macro cells around the small cell are relevant. The higher the threshold, the larger is the cluster size. The small cell reduces the cluster size slightly when it is switched on.

B. Clustering success rate

In section II.B.3, we described our user selection schemes. Tab. III indicates the probability of clustering success, i.e. that we find users in macro-cells according to different rules in order to built the cluster as suggested by the small-cell user. Obviously, it is not as likely to find users having exactly the same desired cluster as claimed in (US-I). If we allow partially the same clusters (US-II), success rate is increased to 80.4% but the gain is reduced. Rules (US-III) to (US-V) lead always to success.

C. Impact of user selection

Fig. 3 (left) shows the throughput for the small-cell user (top) and of all macro-cell users (bottom), according to the different scheduler rules. Since the search for cooperative users suggesting the same cluster is not so likely (US-I, light blue), the achievable gain is limited.

Allowing partially the same cluster (US-II, red) has more success but it lowers the throughput since the average cluster size is then reduced.

Expanding the search region for cooperative users to the whole macro-cell area increases the chances of finding suitable users. With random users (US-III, brown), we can reach 75% of the upper bound (greenish yellow) given by (11) where we left out intra-cluster interference, see [15]. While small-cell throughput is always improved by cooperation, in around 20% of cases, the throughput of randomly selected macro-cell users is reduced, see Fig. 3 bottom (left).

If such inappropriate users are included, cooperation can lead to outage for 5% of the macro-cell users. Clearly, if we discard these users and select the next random user until all users in the set benefit from cooperation (US-IV, green), there is a consistently high gain in all cells involved in the cluster.

It is interesting to consider the number of trials needed for completing an appropriate user set, see Fig. 3 bottom (right). On average, we need few trials to find an appropriate set. If the clustering threshold is higher, number of trials is reduced. With higher threshold, average cluster size is increased. In larger clusters, it is more likely to find users sets where performance is increased. Therefore, the number of trials is reduced.

D. Impact of MIMO mode switching

We adapt the MIMO mode for realizing the best number of streams in each cell. Results are shown in Fig. 4. Decisions are based on averaging over frequency, see (8), and are thus robust against the small-scale fading. Due to MIMO mode switching, we get closer to the upper bound. The relative gain is higher in macro-cells, compared to the small cell, probably due to cell edge users randomly selected in the set.

Table III
MEASURED CLUSTERING SUCCESS RATE AT 18 DB THRESHOLD

Scheduler	Success Rate [%]
(US-I)	33.5
(US-II)	80.4
(US-III, IV, V)	100

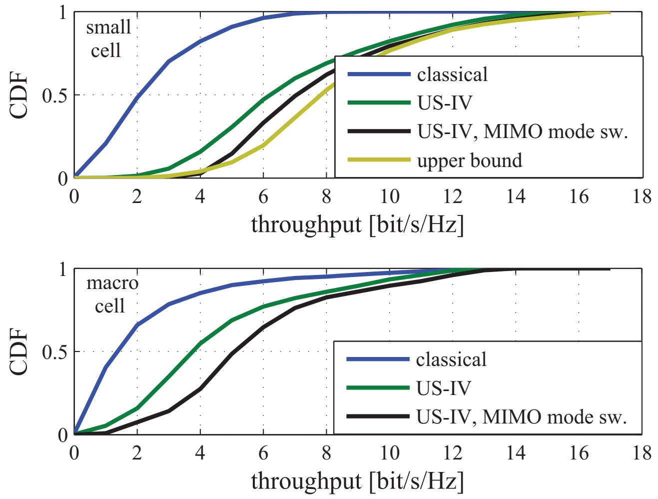

Figure 4. Throughput using MIMO mode switching on all carriers.

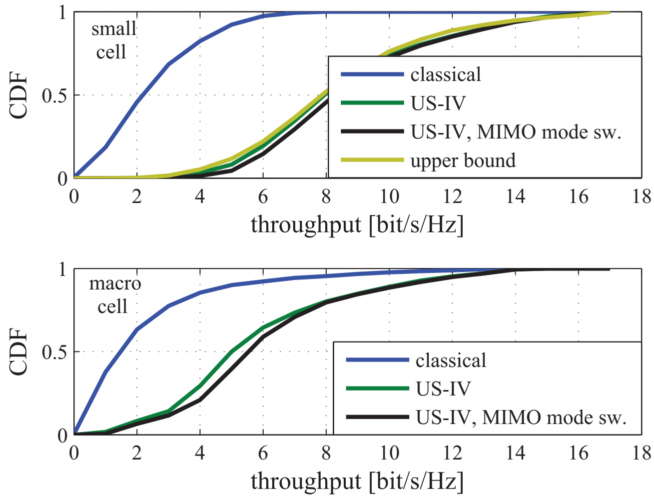

Figure 5. Throughput of users assigned to their best 25% of carriers.

E. Impact of frequency-selective scheduling

Finally, we consider the potential of frequency-selective scheduling in a simplified manner. We assume four users in the small cell. Channels of macro-cell users are often frequency-selective, due to the larger distance from the serving BS. Therefore, we can gain from using only the best carriers per user. In Fig. 5, results for 4 users in the small cell are plotted selecting their best 25% of carriers. Interestingly, the performance exceeds the bound, which is computed for the selected subcarriers only. Our bound is computed from interference-limited capacity. It ignores the precoder and thus beam-forming effects. Altogether, we increased both small and macro cell throughputs by factor around 3.7 on average in our measured scenarios.

Conclusions

In this paper, we investigated potential components of an adaptive MAC protocol for joint transmission coordinated multi-point (JT-CoMP). These are flexible cell clustering, efficient user selection, MIMO mode switching and frequency-selective scheduling. Clustering and user selection have the highest potential for reducing interference. After a first CSI feedback request addressing a random selection of cooperative macro-cell users, users can be exchanged targeting consistent gains in all cells within the cluster. MIMO mode switching and frequency-selective scheduling are efficient for single- and multiuser transmission, respectively. Performance can be improved by factors up to 3.7 altogether in our measured scenarios. Obviously, theoretical capacity bounds for cluster-based base station cooperation can be approached with both limited feedback and reduced complexity.

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