

Autonomous Beam Coordination for the Downlink of an IMT-Advanced Cellular System

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Abstract—Cellular systems like Long Term Evolution Advanced (LTE-Advanced) aim at reusing the whole spectrum in each cell which leads to high inter-cell interference and thus low signal to interference and noise ratio (SINR) conditions for users at the cell edge. One way to utilize multiple antennas at the base station is to perform downlink transmit beamforming which besides increasing the received power at the mobile also has the potential to reduce interference when collisions of beams from different base stations are avoided. To this end we propose an autonomous coordination mechanism that allows cells to coordinate their beams in the frequency domain. In addition to increasing the SINR, it reduces interference fluctuations (the “flash light” effect) due to uncoordinated scheduling in neighbor cells thus making the interference situation more predictable. This further boosts the throughput potential. The proposed scheme is based on feedback from mobiles to their serving base station but does not require inter-cell signaling. By means of system level simulations we show that our autonomous approach converges after few iterations and yields significant cell mean and cell-edge throughput improvements.

I. INTRODUCTION

The International Telecommunication Union (ITU) has set forth ambitious performance requirements [1] that future International Mobile Telecommunications-Advanced (IMT-Advanced) compliant systems have to meet. In order to achieve these performance goals, the international standardization bodies such as the 3rd Generation Partnership Project (3GPP) within its Long Term Evolution Advanced (LTE-Advanced) project are considering, amongst others, techniques referred to as Coordinated Multi-Point (CoMP) transmission (Tx) and reception (Rx) schemes. Such schemes aim at jointly coordinating the transmissions to or from base stations at different cell sites. The primary focus is on those mobiles that experience bad signal to interference and noise ratios (SINR) because, for example, they are located at the cell edge where the SINR is negative due to the full reuse (reuse 1) of the whole spectrum in each cell.

CoMP schemes can be classified according to the complexity of the coordination and the required inter-base station communication. At one extreme, the signal processing for the links (both Tx and Rx) from the considered mobile to the participating base stations is done jointly which is sometimes also referred to as network MIMO. This approach promises the highest gains. However, it demands a lot of computational resources and also needs a huge backhaul capacity (on the order of Gigabits/s, cf. [2]). It is thus only attractive and fea-

sible in dense urban deployments where base station sites are connected by high speed fiber links. At the other extreme, the base stations might only be able to exchange few information because their backhaul resources are very limited, e.g., in a relay or femtocell deployment. Obviously, these limitations render joint signal processing infeasible, but a coordinated resource allocation with respect to the time, frequency, or spatial domain is still possible.

In this paper, we focus on the latter approach. We assume no direct communication between the cells but are able to achieve a kind of implicit coordination between downlink beamforming transmissions based on sub-band specific inter-cell interference feedback from the mobiles to their serving base station. Based on this feedback, the base station is able to (re-)assign frequency resources with low interference to the beamforming transmission towards the reporting mobile. As the base station can only choose from a small number of beams from the LTE precoding matrix codebook, it usually assigns a set of resources to all mobiles best served by a specific beam. This implies that interference feedback and resource assignments are always done for a group of mobiles. The dynamic approach allows the base stations to adapt to changes in the inter-cell interference (i.e., neighbors switching their beams) as well as to changing traffic conditions (e.g., MS movements, different QoS requirements, and traffic bursts).

The key concept for this approach to work is persistent behavior by the base stations. For a BS to rely on and adapt to the reported interference levels, its neighbors may not change their beam-to-resource allocations too much and too often as this would make the feedback information invalid. To this end, we propose to use a non-decreasing mapping of the gain that a base station could achieve by changing the allocation, to an associated probability with which that allocation is then performed. Intuitively, this will keep neighboring base stations from flip-flopping between allocations even if they always perform their re-allocations at the same point in time. In addition, the proposed probability mapping mechanism increases the chances that the gains in the own cell are not offset by bigger losses induced in neighboring cells.

The so-called “flash-light” effect that beamforming transmissions have on the inter-cell interference levels in other cells is well-known in the literature. In [3] a direct communication between two cell sectors facing each other is assumed to agree on time and frequency domain resources for all possibly

conflicting beam pairs. Besides requiring a certain signaling overhead, the proposed scheme only allows to coordinate each cell sector with one other sector even though there are typically many other sectors contributing significant interference. In [4], [5] the authors introduce a cyclic beam switching scheme that aims at making the interference fluctuations predictable by the base station's scheduler. This is achieved by introducing a system-wide fixed cycle period so that after one cycle duration, feedback measurements reflect the same beam collision situation. As the cycling is also performed in the time domain, it requires a frame-level synchronization between cells and might also add a scheduling delay if an urgent packet has to wait for an allowed slot in the cycle. The authors of [4], [5] also assume that the base stations allocate groups of users to be served by one beam based on feedback but do not discuss how such an initial allocation could be reached in a convergent way or how to adapt to changes in the traffic or interference situation. An autonomous adaptation to the inter-cell interference based on a probabilistic re-allocation of resources has also been employed in [6], [7] in a game theoretic context. Though conceptually similar, the convergence of the beam coordination process cannot be explained by the same game theoretic approach as it does not translate to the proposed beamforming system model.

The remainder of this paper is structured as follows. In Section II we discuss the system model and the adaptation scheme itself. In Section III we describe the simulation scenario and assumptions before we present and discuss the simulation results in Section IV. The paper concludes with Section V highlighting the realizable gains and the fast convergence behavior.

II. AUTONOMOUS DYNAMIC BEAM COORDINATION

A. Required intra-cell signaling

As already mentioned in the introduction, our proposed beam coordination scheme relies on sub-band specific interference feedback from the mobile stations to their serving base station. Such a dedicated feedback is currently not available directly in standards like LTE which typically only provide a channel quality indicator (CQI) per sub-band. The returned CQI value depends on the receiver's capabilities but most importantly on the instantaneous SINR value and thus allows the BS to perform fast link adaptation as well as frequency-selective scheduling. However, the base station can deduct inter-cell information also from CQI feedbacks. We assume a certain persistence of the resource-beam allocations across the system and only allow moderate re-allocations. Thus, for low-mobility mobiles an average over multiple consecutive CQI (i.e. SINR) values for a specific subband does not depend on fast fading but rather on the slowly changing pathloss and longer-term interference levels. Note that for gathering suitable interference information in the beamforming case, the SINR must be measured on (reference) symbols of the time/frequency grid for which both the serving and the interfering base station perform beamforming transmissions according to the resource-beam allocation.

Further, we assume that either by feedback from the mobiles (e.g., in form of a precoding matrix indicator (PMI) value in LTE which for rank-1 precoding basically indicates the desired beamforming weight vector) or by means of spatial processing at the base station, the base station is able to choose the most suitable beam for transmission to the mobile from a small set of fixed beams. Beamforming feedback information does not have to be frequent because it should only be necessary when the mobile moves so much that another beam has to be chosen.

B. Autonomous beam coordination scheme

1) *Initialization:* Based on the spatial processing or feedback, the base station forms groups of users that are served by the same beam. In our implementation, we use 8 different beams from the LTE rank-1 precoding codebook that cover a cell sector. Each beam group is assigned an exclusive set of sub-bands that can be used for transmissions to the users of the group. In our simulations, we assign sub-bands according to the number of users per group but different QoS requirements or longtime SINR levels could also be taken into account. The scheduler is free to schedule the users of a beam group on any of the group's subbands. That way, fast scheduling of users is possible if the necessary CQI feedback is available. Multi-user diversity gains are already achievable for a small number of users per group [8]. To improve the frequency-selectivity, the subbands for each group should be scattered across the whole spectrum to avoid correlations between adjacent subbands. Each group should only be assigned as many subbands as necessary so that surplus subbands (e.g., when the system is not fully loaded) can be assigned to a special no-beam group. That way, besides coordinating the beams, the scheme is able to avoid subbands with high interference, which leads to a self-organized fractional frequency reuse pattern [6].

2) *Adaptation process:* The adaptation process is iterative and can — but does not have to — be performed by different base stations at the same time. For each group G the base station gathers interference reports $I(j, k)$ from all mobiles j on all subbands k regardless of whether they are currently assigned to the group or not. The information from all the mobiles is aggregated and weighted so that reports from cell-edge users have a higher influence on the aggregate value for the group, cf. (1). The weighting is done based on the inverse of the achievable capacity $C(\gamma(j))$ which in turn depends on the signaled SINR (CQI) level $\gamma(j)$. An exponent α is further used to determine how strong the influence of the cell-edge interference reports is on the aggregate value. See Fig. 3 for the impact of different values.

$$I_{\text{mW}}(k, G) = \left(\sum_{j \in G} I_{\text{mW}}(j, k) \cdot C(\gamma(j))^{-\alpha} \right) / \sum_{j \in G} C(\gamma(j))^{-\alpha} \quad (1)$$

After gathering the interference feedback in the above described manner, for each group G the subbands used by that group are sorted according to their aggregate interference levels. The adaptation process now works as follows

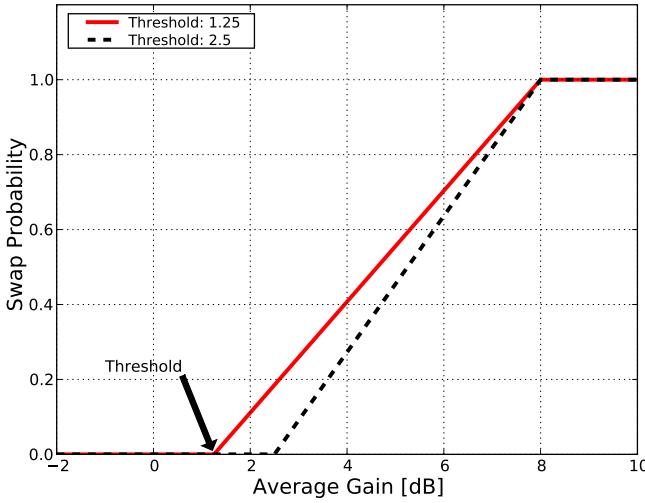


Fig. 1. Mapping the average gain to a swap probability

in a greedy way. The base station iterates over all currently assigned subbands starting with the one that has the worst interference levels. For each of the assigned subbands k per group it compares the aggregate interference $I(k, G)$ with the interference $I(l, G)$ on a subband l that is assigned to some other group or unused (i.e., it belongs to the no-beam group). If it is lower, i.e. $\Delta G = I(k, G) - I(l, G) > 0$ group G would benefit from swapping the resources. However, if the subband l is assigned to some other group G' swapping resources k and l between the groups would also lead to a change $\Delta G' = I(l, G') - I(k, G')$ in the interference of group G' . If subband l was assigned to the no-beam group then $\Delta G' = 0$. From ΔG and $\Delta G'$ the average gain $\Delta = (\Delta G + \Delta G')/2$ for the whole cell is computed and mapped to a swapping probability by a piece-wise linear function as depicted in Fig. 1. The swapping of subbands between groups is then performed with the resulting probability.

The motivation for the probabilistic method is twofold. First, swapping only with a certain probability makes the subband-beam allocation more persistent and lowers the risk that neighboring cells simultaneously switch to a previously unused resource leading to high interference [6]. Second, making the switch with a probability proportional to the potential gain and requiring a positive minimum gain threshold as depicted in Fig. 1 increases the likelihood that a gain in the cell under consideration is not offset by a bigger loss due to increased interference in other cells of the system. In Section IV we will discuss suitable parameter choices for the average gain threshold as well as for the weighting exponent α .

Besides the above described adaptation mechanism for finding better subband to beam allocations, a system should also have a mechanism that updates the number of resources available per group. For example, varying traffic loads in the cell and “hand-overs” between beams might require a transfer of subbands between groups. As the load in the cell and the inter-cell interference situation varies, resources might also be transferred to or from the no-beam group of unused resources

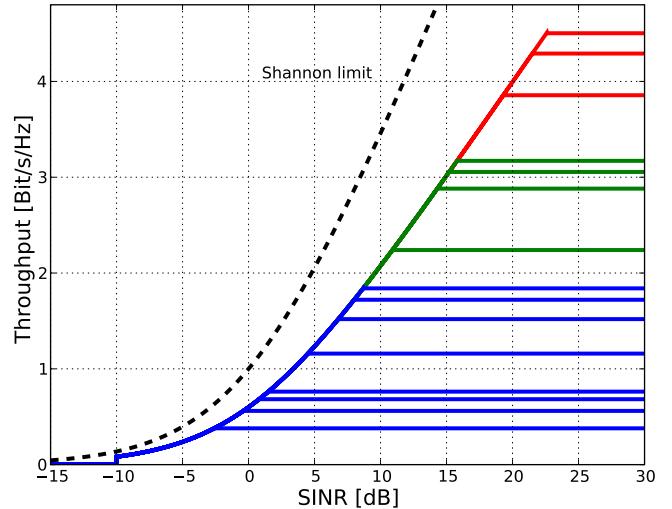


Fig. 2. Link performance model mapping SINR to throughput considering 15 different MCS levels

to find a suitable trade-off between resource reuse and inter-cell interference.

III. SIMULATION SETUP

In order to evaluate the performance of the proposed beam coordination scheme in comparison to uncoordinated reuse schemes, we conducted system level simulations using the openWNS simulator [9]. The simulation scenario consists of 19 sites with 57 cell sectors. Using a wrap-around technique to create equal interference conditions in all cells allows us to evaluate the performance in all cells. As the focus is on evaluating the performance of the beam coordination process which is supposed to happen on a longer time scale (seconds and longer), we do not model small scale effects like fast fading. Furthermore, we do not model a complete LTE protocol stack and the scheduling is done by means of a random scheduler that always allocates one of the allowed subbands to each mobile while randomly permuting the mapping of mobiles to subbands. An overview of radio simulation parameters is given in Table I.

To obtain realistic link level performance, we evaluate the achievable throughput depending on the received SINR γ and employed modulation and coding scheme (MCS) based on a model from [10] that assumes an implementation loss of 40% compared to Shannon’s capacity bound $S(\gamma) = \log_2(1+\gamma)$. It further requires a SINR of $\gamma > \gamma_{min} = -10$ dB and imposes an upper limit of $C_{max} = 4.4$ bps/Hz of spectral efficiency provided by the actual modulation and coding schemes taking certain imperfections into account [10]. We extend the model from [10] by additionally requiring that regardless of the actual received SINR γ no higher data rate is realizable than the rate of the modulation and coding scheme that was selected for the transmission by the link adaptation mechanism. The SINR requirement (including an implementation margin) for each of the 15 modulation and coding schemes shown in Fig. 2 is taken from Table 22.6 in [11]. The actual throughput of a

transmission with MCS q and received with SINR γ is thus given by the minimum of $C(\gamma)$ given by (2) and the MCS's data rate, cf. (3). Consequently, higher SINRs than estimated have only a limited beneficial impact due to the fixed MCS while lower than anticipated SINRs can be handled by the assumed HARQ-retransmission mechanism.

$$C(\gamma) = \begin{cases} 0 & : \gamma < \gamma_{\min} \\ 0.6 \cdot S(\gamma) & : \gamma_{\min} < \gamma < S^{-1}(C_{\max}) \\ C_{\max} & : 0.6 \cdot S(\gamma) \geq C_{\max} \end{cases} \quad (2)$$

$$\text{Throughput}(\gamma, q) = \min(C(\gamma), \text{Throughput}(q)) \quad (3)$$

TABLE I
RADIO SIMULATION ASSUMPTIONS

Parameter	Value
Transmission direction	Downlink
Center frequency	2 GHz
Inter-site distance	500 m
Pathloss model	$L = 128.1 + 37.6 \log_{10}(d/[km])$ [dB]
Shadowing	No shadowing
System bandwidth	24 subbands
BS Tx power	$P_{\text{Tx}} = 29$ dBm per 180 kHz PRB
Base station sector pattern [12]	$A(\Theta) = -\min \left\{ 12 \left(\frac{\Theta}{\Theta_{3\text{dB}}} \right)^2, A_m \right\}$ $\Theta_{3\text{dB}} = 70^\circ, A_m = 20$ dB
Beamforming codebook	Rank 1 precoding with beamforming vectors derived from indices 0 to 7 from Table 6.3.4.2.3-2 in [13]
Noise assumption	$N_{\text{thermal}} = -121.4$ dBm per 180 kHz PRB and 5 dB noise figure
Link performance model	Based on [10], assuming: - 2 Rx antennas - Typical urban fast fading channel model - Link adaptation between QPSK 1/8 and 64QAM 4/5 - Channel prediction and HARQ
MS distribution	Uniformly distributed over entire cell area

IV. SIMULATION RESULTS

In this section we present our simulation results. All throughput values are normalized to the system bandwidth to obtain the spectral efficiency. As metrics we use the mean cell throughput in Bits/s/Hz/cell to characterize the overall performance and the 5%-tile of the per-user spectral efficiency CDF to characterize the performance cell-edge users perceive.

A. Parameter selection and convergence behavior

The adaptation process described in the Section II depends on a set of parameters for which suitable values have to be found. In Fig. 3(a) and Fig. 3(b) we plot the influence the average gain threshold (cf. Fig. 1) and the SINR weighting exponent α have on the average cell and cell-edge user performance, respectively. The performance for different thresholds has a peak around 1.25 dB which we will use as a threshold in the following. Lower thresholds lead to a more unstable allocation as frequent re-allocations occur whereas higher thresholds do not allow enough re-allocations to happen, which, in both

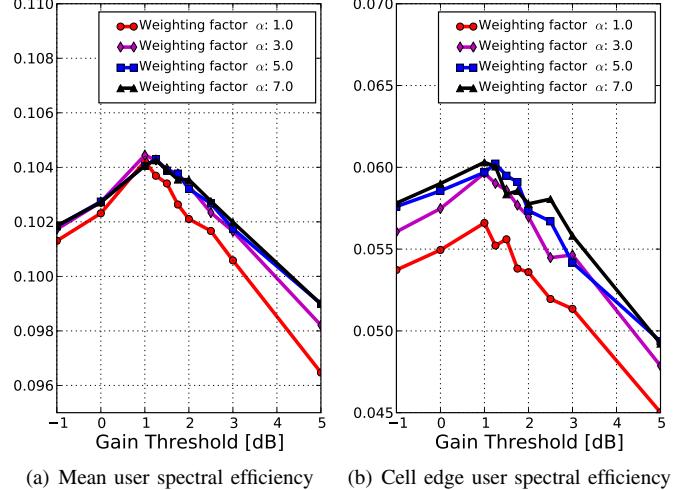


Fig. 3. User spectral efficiencies [Bits/s/Hz] for different parameter values

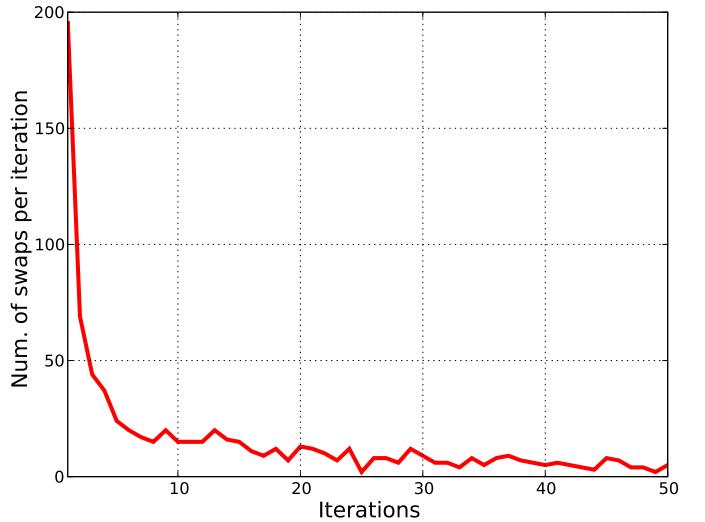


Fig. 4. Exemplary coordination convergence behavior

cases, leads to degraded performance. The weighting exponent α has most impact on the cell-edge performance where a value greater than 1 has a positive effect as shown in Fig. 3(b). For the following simulation results we have used a weighting exponent of $\alpha = 5$ and use a fixed slope as depicted in Fig. 1 because we have found that different slopes have only limited impact on the performance.

In Fig. 4 the system-wide convergence behavior is shown by plotting the total number of swapped subband-beam allocations over the simulation time. It can be seen that the total number of swaps in the 57 cells scenario quickly converges after a few iterations. Note that the algorithm does not reach complete convergence within the simulation time in this example. Due to the employed probability mapping approach, adaptations that promise a small gain above the threshold happen only with low probability and thus infrequently. However, when they happen, they can trigger adaptations in other cells

which prolong the system-wide adaptation process. As a real system will be dynamic due to fading effects, user mobility, and varying traffic conditions, a certain level of re-allocations and adaptations is to be expected anyway.

B. Performance of autonomous beam coordination

We compare the performance of the proposed beam coordination scheme to beamforming and non-beamforming variants of a frequency reuse 3, a full reuse 1, and a fractional frequency reuse (FFR) system that reserves 12 out of 24 subbands for a full reuse at the cell center, while doing a reuse 3 with 4 subbands at the cell edge. All results except those in Fig. 7 and Fig. 8 are for a fully loaded system with 24 users being scheduled on one subband each.

In Fig. 5 the SINR CDF is shown. As expected, beamforming significantly increases the SINR levels and a reuse 3 system achieves significantly better SINRs than a full reuse. The most important observation, however, is the improvement the beam coordination scheme achieves compared to the reuse 1 with beamforming. Even though both schemes do a full reuse, the SINR CDF of the beam coordination scheme shows a significant improvement especially in the low SINR, i.e. cell-edge, region. In addition to improving the SINR levels, the beam coordination scheme also significantly improves the predictability of inter-cell interference and thus SINR levels as shown in Fig. 6. In this figure, the standard deviation of experienced inter-cell interference levels across all mobiles in the system is plotted. As we do not model fast fading, these variations are solely due to the flash-light effect created by the random beam scheduling in neighboring cells. The beam coordination scheme successfully reduces these variations which allows a better link adaptation and thus higher throughputs.

The average spectral efficiency per cell for different resource utilization levels is shown in Fig. 7. Here we vary the number of mobiles from 5 to 24 while always scheduling one subband to each user. We observe that the spectral efficiency does not scale linearly with the percentage of used resources (number of users) as the inter-cell interference becomes the limiting factor. While the reuse 3 schemes perform well with very low load, they are limited by a maximum resource utilization of 1/3 and are overtaken by all other schemes beyond this mark. We note that our proposed beam coordination scheme performs best over the whole range outperforming reuse 1 with beamforming by a significant margin. Due to the combined interference avoidance and beam coordination capabilities, it even outperforms the pre-planned reuse 3 scheme at low loads.

Finally, Fig. 8 compares the schemes' cell edge user and cell mean spectral efficiencies at different resource utilization levels. We highlight that for all utilization levels, the proposed beam coordination schemes outperforms the benchmark schemes with respect to both metrics. At 100% resource utilization, the beam coordination scheme outperforms the uncoordinated full reuse by 12% in terms of mean cell spectral efficiency and by 38% in terms of cell-edge user spectral efficiency as summarized in Table II. We also note that for the non-beamforming case the reuse 1 scheme has the

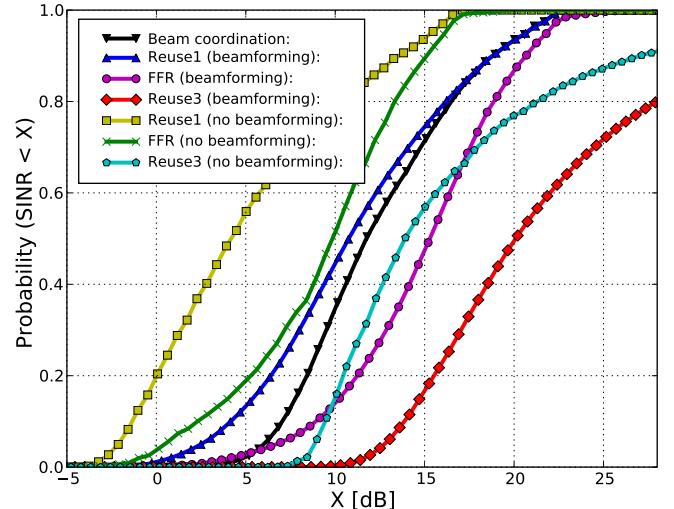


Fig. 5. SINR CDF

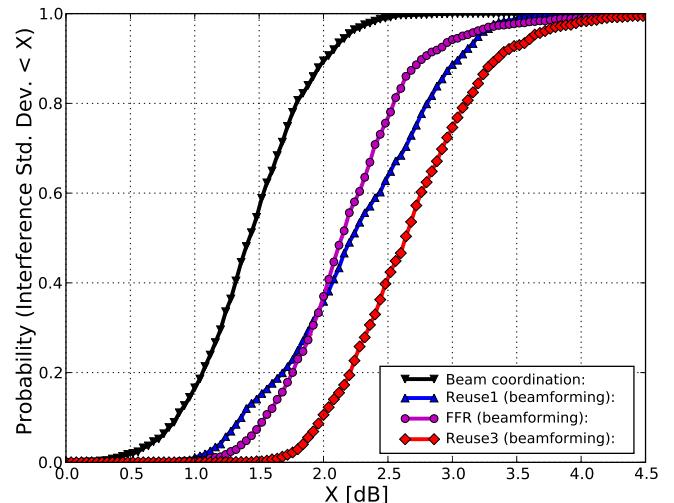


Fig. 6. CDF of MS interference standard deviation

worst cell edge performance whereas with beamforming the beamforming gain as well as the overall reduction in inter-cell interference allow reuse 1 to achieve better performance at the cell edge than reuse 3 or FFR due to its increased resource utilization.

TABLE II
PERFORMANCE COMPARISON AT FULL LOAD

	Cell mean [Bits/s/Hz]	Cell edge user [Bits/s/Hz]
Uncoordinated reuse 1	2.24	0.043
Beam coordination	2.50	0.060
Gain in %	12%	38%

V. CONCLUSION

In this paper, we proposed an autonomous beam coordination scheme for next-generation IMT-Advanced compliant systems. As it only relies on feedback from the own cell

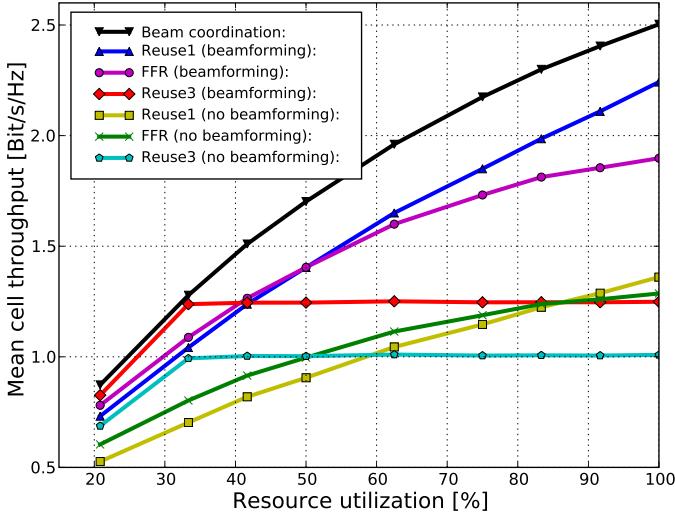


Fig. 7. Mean cell spectral efficiency at different resource utilization levels

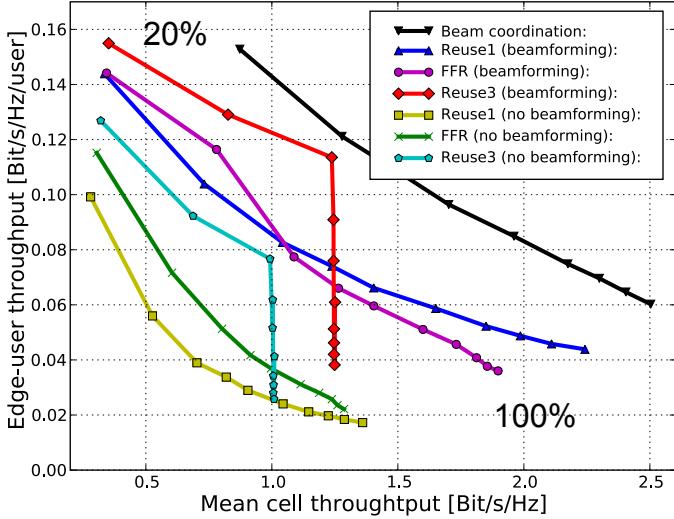


Fig. 8. Cell edge user and cell mean spectral efficiencies at different resource utilization levels

and does not need signaling between neighboring cells, it can be considered to be at the low end of currently investigated coordinated multi-point (CoMP) transmission schemes. At the same time, this makes it attractive also for scenarios with limited backhaul capacities like relay or femto-cell deployments.

Through system level simulations we showed that the algorithm converges and yields significant improvements in average cell as well as cell-edge user spectral efficiencies compared to various uncoordinated schemes and for different resources utilization levels including the 100% level. The gains are due to better SINR levels as well as a reduced “flash-light” effect which allows better link adaptation compared to uncoordinated systems.

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