The Effect of Out of Cluster Interference on Coordinated Beamforming in LTE-A HetNets

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***Abstract*—Coordination is foreseen to be an important component of future mobile radio networks. It is especially relevant in heterogeneous networks, where high power base stations produce strong interference to an underlying layer of low power base stations. This work investigates the impact of the interference from base stations which are not part of the cooperation. This interference is called out of cluster interference. The practical implications of out of cluster interference are investigated in a realistic implementation of cooperation through coordinated beamforming. As a key result the relationship between the amount of out of cluster interference and the performance in the network is shown. Detailed simulation analysis is presented on a realistic network layout. Comprehensive system-level LTE-Advanced simulations were used to show which network layouts are suitable for the coordination.**

I. Introduction

Coordination between base stations (BSs) of a mobile radio network (Coordinated MultiPoint - CoMP) is an important technique to improve the performance of such systems. It is under discussion for fourth as well as fifth generation systems [1] [2]. The main target of CoMP is to mitigate interference [1]. Urban deployments are typically interference limited for two reasons: A high BS density and a frequency reuse factor of one. Dense deployments with small cell sizes are required to fulfil the growing capacity demand. A frequency reuse factor of one enables all BSs to use the full system bandwidth. At the same time it causes that a BS is interfered by all active neighbours. A mitigation of interference, e.g. by means of CoMP, improves the Signal to Interference and Noise Ratio (SINR) of the mobile stations (MSs). An increased SINR directly improves the system throughput. Reducing interference is especially favourable when MSs suffer heavily from it at the so called cell-edge regions. The term CoMP refers to a set of different coordination techniques [1]. It starts with loose cooperation such as transmission point blanking. Here one BS can be muted to reduce the interference of MSs at another BS. The other extreme is a tight cooperation called Joint Transmission. In this case BSs at different locations jointly transmit to one MS which can also be seen as one large BS with distributed antennas. Coordinated Scheduling and Coordinated Beamforming lie in between the two extremes. In case of Coordinated Scheduling the BSs cooperate in the resource assignment. Coordinated Beamforming means that the BSs coordinate the beams they create (normally by means of precoding) in such a way that they don't produce interference to an MS of a neighbouring BS. The CoMP schemes especially differ in the amount of data that needs to be exchanged between the BSs [3]. The tighter the cooperation is, the higher the requirements in terms of latency and bandwidth are.

Another trend besides CoMP is the development towards heterogeneous networks [4]. A heterogeneous network in this context is a network with BSs of different transmit power. A typical case is the densification of an existing network with the help of pico BSs. Such base stations have a reduced transmit power (typically 10 to 20 dB less than traditional macro BSs). Due to the frequency reuse factor of one, each pico BS can reuse the full system bandwidth. However, it is also interfered by all other BSs in the vicinity. The resulting heterogeneous network offers a strongly increased capacity [5]. Heterogeneous networks are also a suitable deployment for CoMP [1].

Recent work underlines the importance of a correct modelling of the network topology to investigate the performance of CoMP systems [6]. The coordination takes place within a group of BSs, the so called cooperation cluster. Suitable algorithms can mitigate interference within this cluster. They operate in the BSs of a cooperation cluster or in an overarching controller. However, there is always a level of interference from BSs outside the cluster (Out Of Cluster Interference - OOCI) which cannot be controlled. As shown in [6] this fact limits the performance of CoMP systems. The limit can also be seen from two different directions in the related work: When simplified networks (e.g. with two cells only) are considered, huge gains are possible [7] [8]. On the other hand, in realistic, large scale networks, gains are difficult or impossible to obtain [9] [10].

The work presented here is positioned in-between these two directions. It contributes an analysis, under which conditions gains are feasible. This is done for a dedicated and realistic setup: Coordinated beamforming in downlink transmission for a heterogeneous network. The setup was chosen as it is a suitable environment for CoMP: In a heterogeneous network with pico and macro BSs (PBSs and MBSs) the transmit power imbalance of the two BS types leads to an unbalanced load in the network. More MSs attach to the MBSs as the received power is often higher. This is typically compensated by an offset in the handover parameters (so called cell range expansion in LTE-Advanced [11]). As a result, the MSs attach to the PBSs even if the signal received is up to a certain level lower than the one for an MBS. This leads to a more balanced load but also creates strong downlink interference at the MSs attached to Pico BSs (PMSs). Coordinated beamforming (CBF) between the MBS and the PBS should be able to reduce this interference. It is considered as a rather lightweight CoMP scheme as it does not require the sharing of user data between the BSs [12]. This reduces the effort and costs required for enhanced backhauling which is required to exchange information between BSs.

In the following it will be assessed, how much the interference situation of the PMSs can be improved by means of coordinated beamforming under different levels of OOCI. This is done in two steps: Section II studies the effect of OOCI in a network model with only three BSs. The objective is to analyse the performance of the PMS with different levels of OOCI. The idea of stressing the cooperation with additional uncoordinated interference is similar to what has been presented in [13]. [13] considers three different networks topologies, each characterized by a different level of OOCI. In contrast to [13], here a static network is burdened with a changing OOCI. The results in section II are based on simplified calculations (one MS per BS, no scheduling, frequency flat channel, throughput obtained via the Shannon capacity). This helps to focus on the effect of OOCI. The result reveals the relationship between the performance in the cooperation cluster and the level of OOCI. Section III uses the findings from section II to understand the performance results in a realistic large-scale network. For this purpose detailed 3GPP compliant system level simulations are performed including feedback, detailed antenna diagrams, scheduling, a frequency selective channel and hybrid automatic repeat request. Finally section IV presents the conclusions.

II. Three Base Stations Network Model

As mentioned before, the focus of this section is to analyse the effect of OOCI. For this reason other influences such as scheduling, feedback and so on are neglected here and will be considered in section III. Figure 1 shows the network layout which is used in this section. It consists of three BSs: One Pico BS (PBS) which cooperates with a Macro BS (MBS) and one MBS which is not part of the cooperation. Each BS serves one corresponding MS, indicated by the lines. The MSs as well as the BSs are equipped with two antennas and the MSs use maximum ratio combining. The MSs are named as follows:

- cPMS: MS attached to the cooperating PBS
- cMMS: MS attached to the cooperating MBS
- ncMMS: MS attached to the not cooperating MBS

The received signal at MS i, which is served by BS i and interfered by all other BSs, is modelled according to Equation 1.

$$y_i = \sqrt{P_i \alpha_{ii}} u_i^H H_{ii} v_i s_i + \sum_{j \neq i} \sqrt{P_j \alpha_{ji}} u_i^H H_{ji} v_j s_j + n_i \quad (1)$$

In Equation 1, $P_i \in \mathcal{R}$ represents the transmit power of BS i, $\alpha_{ii} \in \mathcal{R}$ the pathloss between BS i and MS i, $u_i \in \mathcal{C}^{2\times 1}$ the receive combining vector at MS i, $H_{ii} \in \mathcal{C}^{2\times 2}$ the radio channel between BS i and MS i, $v_i \in \mathcal{C}^{2\times 1}$ the precoder used at BS i, $s_i \in \mathcal{C}$ the symbol to be transmitted at BS i and n_i the noise power which is present in the receiver. For simplicity reasons the pathloss is here assumed to be the free space propagation loss (a more detailed modelling is also part of section III). The cooperating BSs coordinate their beams (precoders) in a zero-forcing manner such that they don't produce interference to the MS served by the other BS as described in [7]: The precoder at the cPBS v_{cPBS} is chosen to be the

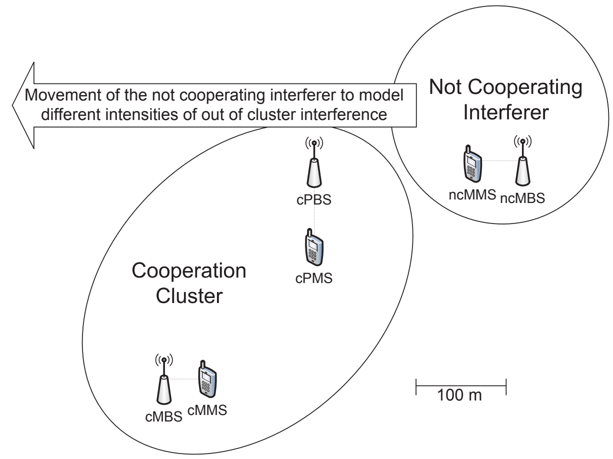

Fig. 1. Network Layout with three Base Stations

generalized eigenvector of $H_{cMBS,cMMS}^H H_{cPBS,cMMS}$ and $H_{cMBS,cPMS}^H H_{cPBS,cPMS}$. The precoder at cMBS v_{cMBS} chosen according to Equation 15 in [7]. With the help of the cooperation, the cMBS can transmit to the cMMS without interfering a simultaneous transmission on the same frequency from the cPBS to the cPMS. The ncMBS does not take into account the cooperation and uses eigen-precoding to maximize the power the ncMMS receives. By changing the location of the ncMBS and the ncMMS, the pathloss $\alpha_{ncMBS,cPMS}$ between the ncMBS and the cPMS/cMMS ($\alpha_{ncMBS,cPMS}$) and $\alpha_{ncMBS,cMMS}$ and can be varied. This is used to adjust the amount of OOCI which the cMMS and the cPMS receive. This investigation focuses on the performance of the cPMS under different levels of OOCI. Therefore in the following several performance indicators will be studied with respect to the distance between the source of the OOCI (the ncMBS) and the cPMS. The ncMBS is moved from the location where it is located in Figure 1 to the left (as indicated by the arrow). In the worst case, the distance between ncMBS and cPMS gets as low as 100 meters (when the ncMBS is located at the same position as the cPBS). After this point the situation improves again.

Figure 2 shows two basic measures of the situation at the cPMS. The red curve shows the so called geometry. It is defined as the ratio between the power the cPMS receives from the cPBS and the sum of the power it receives from cMMS and ncMMS (Equation 2).

$$G_{cPMS} = \frac{P_{cPBS}\alpha_{cPBS,cPMS}}{\sum_{i=cMBS,ncMBS} P_i \alpha_{i,cPMS}} \quad (2)$$

This value is purely based on the power level at the receive antenna of the cPMS. It does not take into account any gains that can be obtained from signal processing (precoding at the BSs, receive processing at the MS). The blue curve shows the ratio of the OOCI. This is defined as the ratio between the power the cPMS receives from the ncMMS and the cMMS (Equation 3).

$$OOCI_{cPMS} = \frac{P_{ncMBS}\alpha_{ncMBS,cPMS}}{P_{cMBS}\alpha_{cMBS,cPMS}} \quad (3)$$

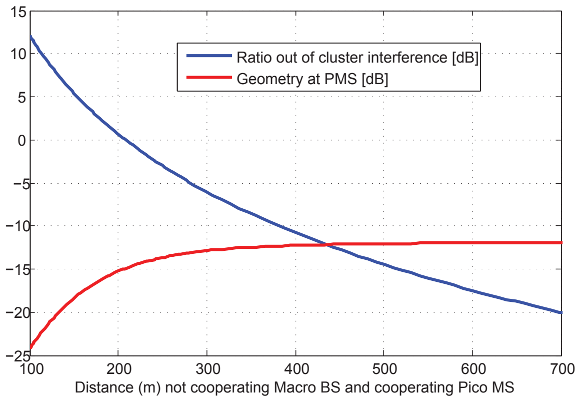

Fig. 2. Geometry and Out of Cluster Interference Ratio of the Pico MS

Again no signal processing is included in the calculation. A positive value (expressed in dB) indicates strong OOCI (more interfering power received from the not cooperating BS than from the cooperating one).

Both measures are depicted with respect to the distance between the ncMBS and the cPMS. They can be seen as a representation of the network layout from the cPMS's point of view as they describe the powers which arrive there. As mentioned before, the worst situation occurs when the distance between ncMBS and cPMS equals 100 meters. At this point the geometry is approximately -24 dB, meaning that the cPMS receives interference (from ncMBS and cMBS) which is 24 dB stronger than the power it receives from the cPBS. The OOCI is around 12 dB, meaning that the vast majority of the interference comes from outside of the cooperation cluster. As the distance between the ncMBS and the cPMS grows, the situation improves: The geometry increases and more and more of the interference originates from inside the cooperation cluster (decreasing OOCI).

Figure 3 shows the amount of interference which is present in the receiver of the cPMS when taking into account signal processing at the BSs (precoding) and receive combining at the MS (Equation 4).

$$I_{cPMS} = \sum_{i=cMBS,ncMBS} P_i \alpha_{i,cPMS} |u^H_{cPMS} H_{i,cPMS} v_i|^2 \quad (4)$$

The situation with cooperation (coordinated beamforming at cMBS and cPBS) is compared to a situation without a cooperation (cMBS and cPBS in this case use eigen-precoding as well). At a distance of 100 meters between ncMBS and cPMS the interfering power with and without cooperation is nearly equal. The reason is the high OOCI: The cooperation can only reduce interference from inside the cooperation cluster (from the cMBS) which is a small fraction at this point. The lower the OOCI gets, the higher is the difference between the interfering power with and without cooperation. This reduction in interfering power is the benefit of the cooperation. Figure 4 shows the cost of the cooperation: A reduction of the useful signal at the cPMS. The useful power is calculcated according to Equation 5.

$$S_{cPMS} = P_{cPBS} \alpha_{cPBS,cPMS} |u^H_{cPMS} H_{cPBS,cPMS} v_{cPBS}|^2 \quad (5)$$

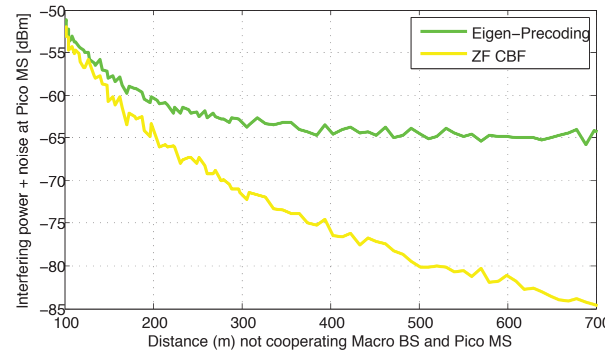

Fig. 3. Interfering Power at the cooperating Pico MS

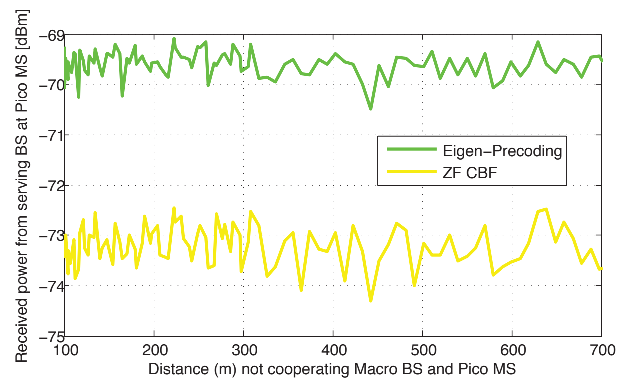

Fig. 4. Useful Power at the cooperating Pico MS

As the distance between cPMS and cPBS is constant, it does not change with a varying distance between cPMS and ncMBS. However, the useful power is reduced by 3 to 4 dB in case cooperation is active. The reason lies in the precoding at the cPBS: Without cooperation, the precoder is chosen to maximize the useful signal at the cPMS. With cooperation, it is chosen such that the interference at the cMMS is nulled out.

The combination of both effects (reduced interference and reduced useful power) can be seen in Figure 5. It shows the spectral efficiency the cPMS can achieve. The spectral efficiency is directly related to the SINR. It can be approximated through the well known Shannon-Hartley theorem (Equation 6 with C being the channel capacity, SE the spectral efficiency, B the bandwidth, S the signal power and N the noise power). As a simplification the interference is in here assumed to be independent and identically distributed such that it can be added to the noise power. A more detailed modelling of the interference is also part of section III.

$$SE = \frac{C}{B} = \frac{B \cdot \log_2(1 + \frac{S}{N})}{B} = log_2(1 + \frac{S}{N}) \quad (6)$$

For the cPMS this results in the spectral efficiency described by Equation 7 with I_{cPMS} and S_{cPMS} as described in equations 4 and 5.

$$SE = \log_2(1 + \frac{S_{cPMS}}{I_{cPMS} + N_{cPMS}}) \quad (7)$$

For distances of 100 to 200 meters between cPMS and ncMBS the spectral efficiency is very low. Additionally there

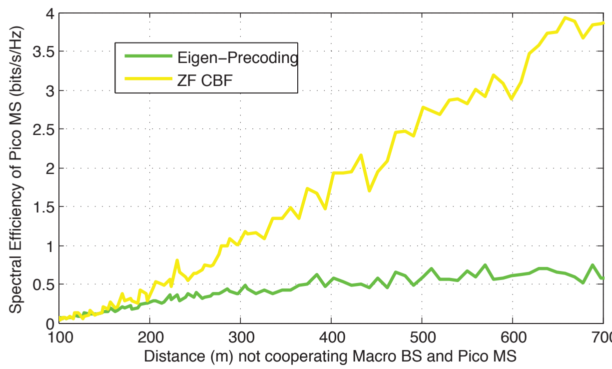

Fig. 5. Spectral Efficiency at the cooperating Pico MS

are nearly no gains from CBF in this region. For higher distances gains from CBF can be obtained. A comparison of Figure 2 and Figure 5 reveals two important points:

- With a low OOCI ratio (e.g. -15 dB) it is possible to achieve relatively high spectral efficiencies, although the geometry at the cPMS is low. This proofs the potential of CBF.
- Gains from CBF can be obtained in the regions where the OOCI ratio is negative (distance more than 200 meters).

The second finding is in line with the previous Figures and can be supported by some exemplary considerations: *The cost of the cooperation* is a constant reduction of the useful power in the order of 3 dB (Figure 4). Or in other words: In case the cooperation is used, the drop in received power reduces the SINR of the cPMS by around 3 dB. This is the case no matter how strong the OOCI is (no changes in Figure 4, although the OOCI changes as shown in Figure 2). *The benefit of the cooperation* depends on the OOCI (Figure 3). An OOCI ratio of 0 dB is the break even point: Here the interference from the cooperating BS equals the interference from the not cooperating interferer. If the interference from the cooperating BS is removed completely (as it is the case for zero-forcing beamforming), the interference is reduced by 3 dB. As a result at this point both effects (reduction of interference and reduction of useful power) sum up to zero. As soon as the OOCI ratio becomes lower than 0 dB, the benefit of the cooperation is a reduction in interference of more than 3 dB. It can then overcompensate the cost of the cooperation.

III. Detailed Simulations

The previous section analysed the impact of OOCI in an artificial and small network. The target is now to find the implications of OOCI in a realistic network. As also outlined in [6], the modelling of a larger network is required for a correct representation of the interference from inside and outside the cooperation cluster. Simulations are suitable means for investigating such complex scenarios (including tens of BSs, realistic radio channel modelling, scheduling, signal processing and channel state information feedback from the MSs). Therefore detailed LTE-Advanced system level simulations were carried out here. A complete network of 21 MBS sectors and an equivalent number of PBSs was used (Figure 6, the red points

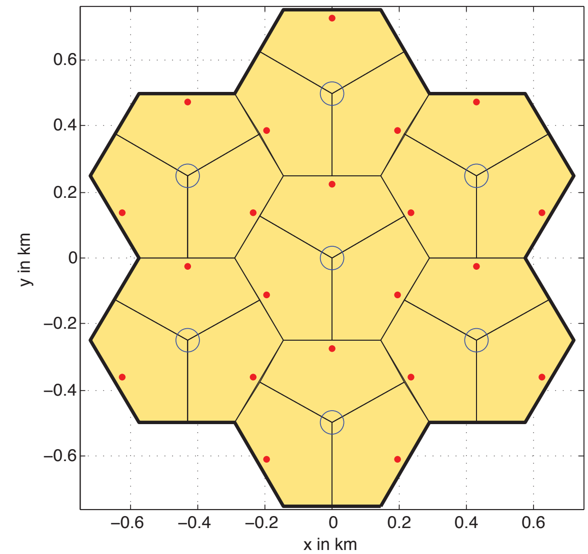

Fig. 6. Network Layout with Pico Base Stations at the Edge of Macro Sectors

indicate the PBSs). They are located at the edges of the MBS sectors and cooperate with the MBS sector they are placed in. The so called hotspot distribution of the MSs is used, meaning that two third of the MSs are placed in the vicinity of the PBSs. This scenario is typically considered as very beneficial for heterogeneous networks for three reasons:

1) The PBSs are placed in areas where two or more MBSs can be received with a similar power (the so called cell edge). Thus the PBSs can serve MSs which would have suffered from a low SINR otherwise.
2) As the hotspot distribution is used, many MSs are close to the PBSs. A good balance between MSs at the PBSs and the MBSs can be achieved.
3) Due to the distance between MBS and PBS the interference which the PMSs receive from the MBSs is relatively low.

Table I shows the detailed simulation assumptions. In contrast to section II the interference is explicitly calculated and not assumed to be independent and identically distributed. The throughput is then obtained by selecting a suitable modulation and coding scheme in the link adaptation for each MS and transmission.

TABLE I. System Level Simulation Parameters

Parameter	Value
Inter Site Distance	500 m (3GPP case 1)
System Bandwidth	10 MHz, DL (50 PRBs)
Number of Subcarriers	12 per PRB (180 kHz)
MBS transmit power	46 dBm
Antennas at BS and MS	2
MBS antenna pattern	3GPP 2D ant. model with 14 dBi max. gain
PBS transmit power	30 dBm
PBS antenna pattern	Omni directional with 10 dBi gain
Channel and Propagation Model	ITU-R M.2135 Urban Micro (PBS) / Urban Macro (MBS) [14]
MS receiver type	Maximum Ratio Combining
Transmission scheme	Transmit beamforming with 2 antennas
Traffic Model	Full buffer

Figure 7 shows the OOCI ratio which occurs for PMSs in this network layout. As there are many PMSs now, a

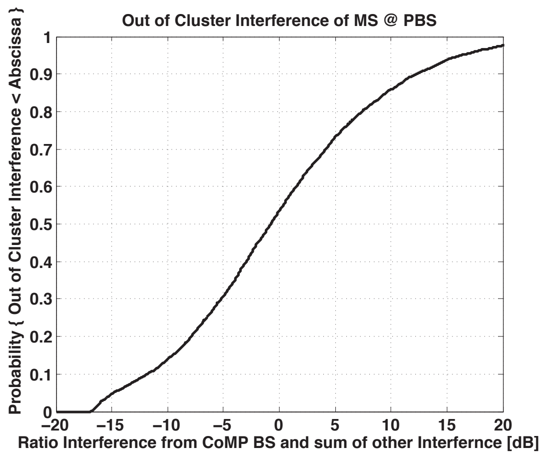

Fig. 7. Amount of Out of Cluster Interference for Pico BS at Cell Edge of Macro BS Network

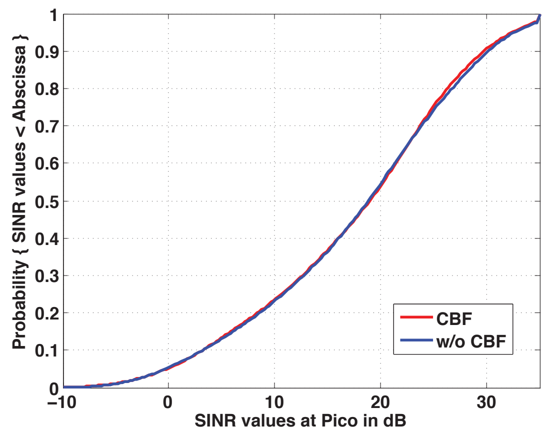

Fig. 8. SINR of Pico MSs for Pico BSs located in Figure 6

distribution is depicted. The OOCI ratio is again defined as the ratio of the interfering power from the not cooperating BSs and the one from the cooperating BS (without taking signal processing at MS or BS into account). From the results shown previously, gains from CBF can be expected at an OOCI ratio below 0 dB while significant gains should start below -5 dB. This would be the case for around 53% (0 dB) and 30% (-5 dB) of the PMSs.

However, the corresponding simulation results (Figure 8) show no gains from CBF in terms of SINR of the PMSs at all. There are two important differences of the detailed simulation used here and the assumptions used in section II. The first one is in channel knowledge: The investigations in section II are based on perfect channel knowledge at the BSs. In the detailed simulations, the process of measuring the channel at the MS and providing quantized CSI to the BS is modelled. The feedback type is explicit channel information, meaning that the channel transfer function is provided to the BS. This is a common requirement for CoMP algorithms. [15] mentions explicit channel feedback for future implementation in LTE-Advanced. Details on the feedback method that was used can be found in [16]. A reporting sub-band size of one Physical Resource Block (PRB) is used which means that the MSs report one value for amplitude and phase per 180 kHz. The number of feedback bits is not restricted (the exact information is used with double precision). This is a very detailed feedback, which would have to be reduced for a practical implementation (e.g. one value per 5 or 10 PRBs with lower precision). But even under the assumptions made here it implies a degradation of the CBF performance as it now acts based on imperfect information. The second difference is related to scheduling: In section II a single frequency-flat channel between the BS and the connected MS is assumed. As there is only one MS per BS there is no scheduling is required. In the detailed simulation a frequency selective radio channel is used in combination with a proportional fair scheduling procedure. The result is a frequency selective scheduling: For each PRB the scheduler chooses an MS which achieves a high performance. Thus, in case of a single dominant interferer, the scheduler even without CBF will select PRBs for an MS where the interferer is weak due to fading. As a result the advantages of CBF over the conventional scheduling reduces.

In total the combination of both effects eliminates the advantages of CBF in this network layout. Under the interference conditions which exist in this network layout, it is not beneficial to coordinate the beams by means of zero-forcing beamforming. The interference conditions can be characterized by the OOCI ratio in Figure 7. A situation where only in 30% of the cases a dominant interferer (5 dB stronger than the sum of all other interferers) is present, is not suitable for this type of cooperation.

It was mentioned previously that the positioning of the PBSs in the considered layout (Figure 6) is beneficial for heterogeneous networks. It assumes that an accumulation of MSs occurs at a specific location (the area between to MBS sectors). The PBS is then paced at this location and improves the situation of the clustered MSs. In reality accumulations of MSs can occur at any point in the network. It is therefore also important to consider an accumulation of MSs at other locations. Positioning a PBS there is not be as beneficial as the scenario considered as the reasons 1 and 3 listed above do not apply any more. This reduces the throughput the PMSs can achieve. In consequence the amount of additional capacity which the PBSs can provide decreases. But still significantly gains in terms of sum network capacity are achievable. A different location of the PBSs also changes the OOCI ratio of the PMSs, as the interference situation at their locations changes. In the following a scenario is considered where an accumulation of MSs occurs at the center of the MBS sectors such that a PBS is placed there (Figure 9).

The OOCI ratio at the PMSs in this network is described by Figure 10. The PMSs and the PBSs are now located at a place where the cooperating MBS is dominant. In 65% of the cases, the cooperating MBS is 5 dB stronger than the sum of all other interferers. This improves the preconditions for coordinated beamforming. Figure 11 shows that now a gain in the SINR at the PMSs can be obtained. As a higher SINR enables the usage of higher modulation and coding schemes, a significant increase in throughput is achieved (Figure 12). The throughput of the five-percentile, indicating the users with the lowest performance, increases from 301 to 421 kbps (40% gain). The mean throughput advances from 2.3 Mbps to 2.8 Mbps (22% gain).

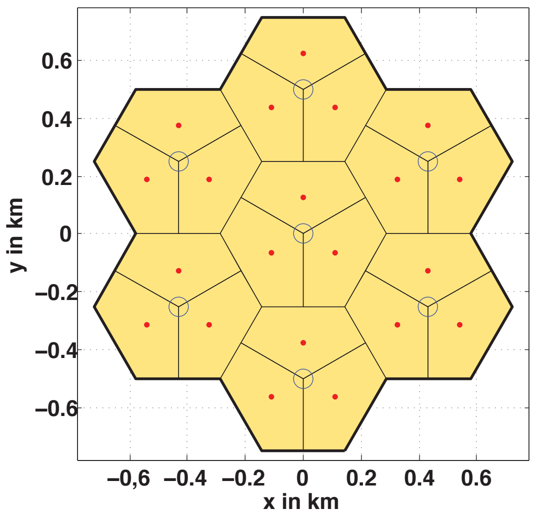

Fig. 9. Network Layout with Pico Base Stations at the Center of Macro Sectors

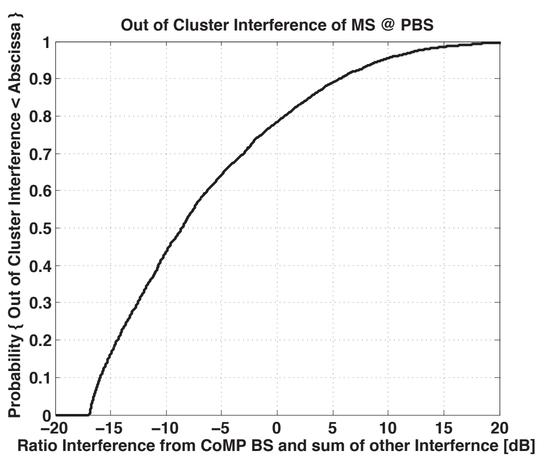

Fig. 10. Amount of Out of Cluster Interference for Pico BSs at the Center the of the Macro Cells

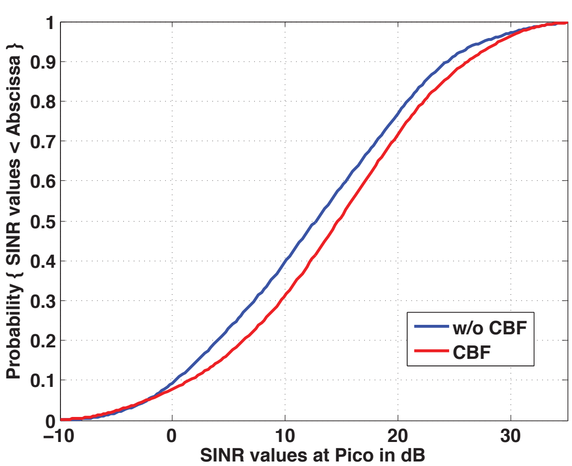

Fig. 11. SINR of Pico MSs for Pico BSs at the Center the of the Macro Cells

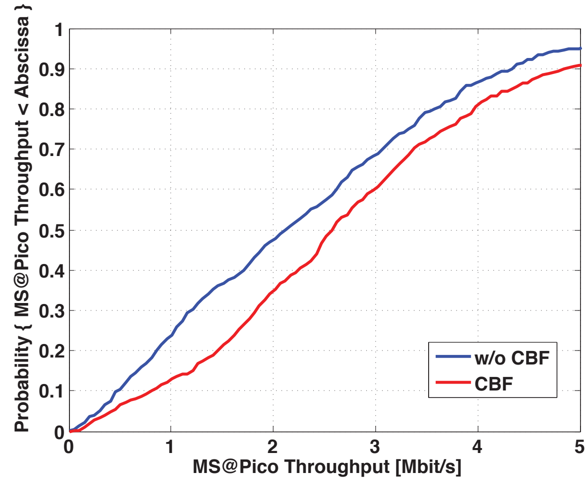

Fig. 12. Throughput of Pico MSs for Pico BSs at the Center the of the Macro Cells

IV. Summary and Conclusions

The work presented here underlines the influence of out of cluster interference on the performance of coordinated beamforming. With a simplified network model it was shown that a dominant interferer (significantly stronger than then sum of all other interferers) is a prerequisite for a benefit from coordination in the considered scenario. Two realistic scenarios show that such conditions are not necessarily present in dense interference limited networks. Additionally, the conditions suitable for coordination (the presence of a dominant interferer) are also beneficial for frequency selective scheduling which is the baseline for a non-cooperative scheme. This fact additionally limits the gains from coordinated over uncoordinated techniques. As a result, the coordination considered here is only beneficial when a level of out-of-cluster interference is not exceeded. To quantify this effect, a measure, called the out of cluster interference ratio, was introduced. It was shown that for networks with a low out of cluster interference ratio, significant throughput gains (20% to 40%) are possible. Networks characterized by a higher out of cluster interference ratio are shown to be unsuitable for the considered type cooperation. Naturally these results are only valid under the assumptions which have been made (especially the precoding technique). They should therefore be reinforced by investigating other schemes. However, as also outlined in [2], out of cluster interference is factor which limits all kinds of cooperation in mobile radio networks.

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