Performance Upper Bounds for Coordinated Beam Selection in LTE-Advanced

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Abstract—**Coordinated Multipoint (CoMP) transmission techniques have been considered as tools to improve cell-edge and average data throughput for LTE-Advanced. First investigations of CoMP techniques in homogeneous hexagonal macro layouts have shown that interference coordination needs to involve dominant interferers to allow significant gain. Therefore, in the present paper the application of CoMP in a heterogeneous network is considered where a planned macro deployment coexists with randomly placed femtocells resulting in a scenario where dominant interference can potentially be mitigated more effectively. The impacts of a heterogeneous layout on the interference characteristics in the downlink are evaluated by simulation and an assessment of gains achieved through coordination is provided.**

I. INTRODUCTION

The evolution of mobile wireless networks during the last decade can be characterized by an ever-increasing demand for higher data rates. This trend is ongoing and the development of current wireless network standards such as the Third Generation Partnership Project's (3GPP) High Speed Packet Access (HSPA+) and Long-Term Evolution (LTE) or WiMAX (IEEE 802.16) continue to be driven by the need to increase the data throughput for mobile users.

Due to the scarcity of available spectrum, the key to increase data rates is to improve the spectral efficiency of a wireless network. Towards this goal, several methods have been proposed, e.g., coordinated multipoint (CoMP) or network coordination [1] techniques where separate base stations no longer serve their users independently but coordinate their transmissions using either coordinated beamforming or joint transmission [2], thereby reducing received interference and/or increasing received signal power. Another approach to increase network capacity is the reduction of cell sizes using additional evolved Node-Bs (eNBs), which, if regular (also called "macro") eNBs are used, is an expensive option. The concept of femtocells (see, e.g., [3]) attempts to reduce the cost of such additional network infrastructure through the use of low-cost low-power eNBs ("femto") that are installed in the consumer's home and connected to the network backhaul via high-speed fixed connections, e.g., digital subscriber lines. The advantages of introducing these femtos are very good indoor coverage with corresponding high throughputs for their connected users, offloading of macro eNBs and better overall resource reuse in the network. On the other hand, an unplanned user-installed deployment of femtos can pose significant challenges in terms of interference caused to out-of-cell users. This can become particularly problematic if the access to a femto is restricted to a closed subscriber group (CSG), i.e., a small group of users that, e.g., live in the vicinity of the femto or own it. A femto with a defined CSG serves only those users that belong to its CSG. This restricted access could pose a serious problem to a user who is located very close to a femto but cannot connect to it because the user is not included in the corresponding CSG. Such a user may experience strong interference from the nearby femto resulting in poor downlink reception from the user's serving macro eNB.

Because of the complementary aspects of femtos (promising high throughput gains but with challenges due to interference to out-of-cell users) and coordinated beamforming (taking into account the interference to out-of-cell users) we investigate in this paper, the possible performance gains when the advantages of femtocells and CoMP are combined. We evaluate the concept in the framework of LTE and LTE-Advanced.

The remainder of this paper is organized as follows. In Section II, we present our network coordination method called Base Station Coordinated Beam Selection (BSCBS) and the corresponding evaluation method before we describe the deployment models for wireless networks with macro and femtocells in Section III. We evaluate potential gains of BSCBS in Section IV. Conclusions are presented in Section V.

II. BASE STATION COORDINATED BEAM SELECTION

In current wireless cellular networks with high system loads, interference from different transmitters can be the performance-limiting factor for the majority of users. Standard approaches to avoid intercell interference are coordinations of channel accesses either in the frequency dimension (fractional frequency reuse [4]) or the time dimension using some form of time division duplex transmission. If the transmitter (for downlink: the eNB) is equipped with several antennas, the possibility of beamforming [5] allows the steering of the radiated signal in specific directions, thereby opening up the spatial dimension for interference coordination. The general

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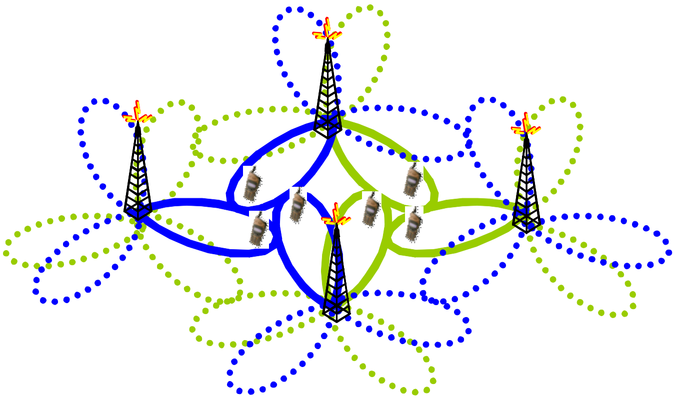

Fig. 1. Beams to users at cell-edge cause interference in adjacent cells

idea of coordinating beams in a wireless network with sectorized antennas is illustrated in Figure 1. Each mobile user is served by a corresponding beam from its serving eNB. If several mobile users are located at cell-edge and served by different eNBs, steering the beam to a particular user will create significant interference to a user served by the neighboring cell if the beams are not coordinated and cell-edge users are served from the two eNBs at the same location at the same time. The general idea of coordinated beamforming is to define an algorithm that avoids this beam "collision".

A. System Model

Assume that K users are served simultaneously from K different cells where each user is equipped with M_R and each eNB is equipped with M_T antennas. Without loss of generality, we focus on the data model for user 0. Assuming a frequency-flat fading channel, the data model

$$\mathbf{y}_0 = \mathbf{H}_0\mathbf{B}_0\mathbf{x}_0 + \sum_{i=1}^{K-1} \mathbf{H}_i\mathbf{B}_i\mathbf{x}_i + \mathbf{w} \tag{1}$$

results where $\mathbf{y}_0$ is a $M_R \times 1$ vector of received symbols, $\mathbf{x}_k$, $k = 0, \ldots, K-1$, are the $N_k \times 1$ vectors of transmitted symbols for user k drawn uniformly from a symbol alphabet satisfying

$$E[\mathbf{x}_k\mathbf{x}_k^H] = \sigma_k^2\mathbf{I}_{N_k},$$

N_k is the number of data symbols transmitted to user k, $\mathbf{B}_k$ is the $M_T \times N_k$ precoding matrix for user k and $\mathbf{w}$ is receiver noise with covariance

$$E[\mathbf{w}\mathbf{w}^H] = \mathbf{R}_w.$$

For $N_k > 1$, several data symbols are transmitted simultaneously to the user using spatial multiplexing. In this case, the data symbols are assumed to be independent. The $M_R \times M_T$ matrices $\mathbf{H}_k$, $k = 0, \ldots, K-1$, denote the channel coefficients from eNB k to user 0. For conciseness, we introduce the symbol

$$\mathbf{v} := \sum_{k=1}^{K-1} \mathbf{H}_k\mathbf{B}_k\mathbf{x}_k$$

for the intercell interference with covariance

$$\mathbf{R}_v := E[\mathbf{v}\mathbf{v}^H] = \sum_{k=1}^{K-1} \sigma_k^2\mathbf{H}_k\mathbf{B}_k\mathbf{B}_k^H\mathbf{H}_k^H.$$

The columns of each precoding matrix are also called "beams" in reference to beam-forming[5]. The specific choice of beams (or precoding matrices, respectively) has an impact on the structure ("color") of the resulting interference covariance.

In order to extract information on the transmitted data symbols from the received vector $\mathbf{y}$, a receiver filter is commonly used to mitigate the effects of the channel, interference and noise, to combine the received symbols from the receiver antennas and to separate the detection of possibly multiple transmitted data symbols if $N_0 > 1$. A common measure to assess the performance of such a linear filter is the filter output signal to noise and interference ratio (SINR). The SINR depends on the used equalizer, signal, noise and interference covariances, channel matrices and signal powers. For the purpose of illustration, we restrict the dependence of the SINR in our notation on the precoding matrices and signal powers which are under the control of the transmitters, i.e.,

$$\begin{aligned}\mathrm{SINR} = \\ \mathrm{SINR}\left(\mathbf{B}_0, \sigma_0^2, \mathbf{R}_v(\mathbf{B}_1, \ldots, \mathbf{B}_{K-1}, \sigma_1^2, \ldots, \sigma_{K-1}^2)\right).\end{aligned} \tag{2}$$

The SINR determines the supportable data rate for the transmission and, therefore, the achievable throughput for this user.

B. CoMP using Base Station Coordinated Beam Selection

If all cells perform user scheduling and precoding matrix selection independently, cell 0 chooses $\mathbf{B}_0$ and σ_0^2 and assigns transport formats based on an estimate of the expected SINR which in turn depends on an interference estimate. In *coordinated* transmission, multiple cells do not schedule users independently but select the precoding matrices and transmission powers in order to optimize a system-wide performance criterion. Several proposals for coordinated beamforming have been presented in the literature, see, e.g., [6], [7] and references therein. A common assumption is that the beamforming weights, i.e., the precoding matrices $\mathbf{B}_k$ are subject to a power constraint only and can otherwise contain arbitrary complex-valued symbols. The specific choice of these weights is then typically dependent on accurate information about the channels from the involved eNBs to the considered user. Such channel state information (CSI) is usually obtained using feedback from the mobile user to the eNB if uplink and downlink are separated in frequency. In practical systems, the uplink payload available for CSI feedback is tightly constrained, allowing only coarsely quantized information about the channel. Therefore, it could be preferable not to feedback information about the channel realization as such, but rather information about the preferred precoding matrix which is chosen from a predetermined and common codebook $\mathcal{C}$, i.e.,

$$\mathbf{B}_k \in \mathcal{C} = \{\mathbf{C}_0, \ldots, \mathbf{C}_{N-1}\} \tag{3}$$

and which results in the highest SINR together with approximate information about the expected SINR. Based on this information, the scheduler at the eNB can *select* (as opposed to “form”) the corresponding beam and transport format that the reported SINR supports. We assume this approach in the present paper together with a codebook of precoding matrices that is also used in LTE Rel.8 [8].

Without any kind of inter-cell coordination, the scheduler at each eNB will select a specific precoding matric for each user based on the precoding matrix index (PMI) obtained from this user. Since the user does not know about the impact of its serving eNB’s data transmission to other users, its specific choice of PMI cannot take into account this impact on out-of-cell users. Therefore, making such additional information available at the eNB and exploiting it using network coordination has the potential of improving performance in the entire network by reducing the intercell interference.

In the present paper, we do not consider the details of how the information about the intercell interference is obtained at an eNB or the exact optimization criterion that the scheduler applies based on this information. We focus on the impact of using a predetermined codebook $\mathcal{C}$ and the potential gains that are available when the selection from the codebook of beams is coordinated among different base stations. We call this approach base station coordinated beam selection (BSCBS). An appealing advantage of using predetermined codebooks is that the amount of required feedback information for coordinating the eNBs can be expected to be relatively moderate.

C. Upper Bounds on Performance of BSCBS

In order to investigate the achievable gains when base stations coordinate their specific choice of beam, we evaluate the gains in SINR at the user equipment (UE) under the assumption that interferers do not transmit at all or avoid specific precoding matrices that cause the largest SINR degradation. In particular, we compare the regular SINR with the resulting SINR values if one interferer had been prevented from transmitting (i.e., with transmission power zero) while all others transmit as before. We denote the interferer whose removal results in the largest SINR value at the UE as the *dominant* interferer

$$d_1 = \arg \max_{k=1,\ldots,K-1} \mathrm{SINR}\big|_{\sigma_k^2=0}.$$

Preventing interferer d_1 from transmitting implies a loss in the throughput for cell d_1. Based on the intuition that some precoding matrices used by interferer d_1 can have a worse impact on the evaluated SINR than others, it is not strictly necessary to switch off interferer d_1 completely. Instead, we only need to prevent interferer d_1 from using the most SINR-degrading codebook entries. This is beneficial because cell d_1 can then serve users where the remaining codebook is applicable with full power. Therefore, we evaluate the SINR for the entire codebook (3) and compute the set of SINR values

$$\left\{ \mathrm{SINR}\big|_{\mathbf{B}_{d_1}=\mathbf{C}_n} \right\}_{n=0}^{N-1}$$

together with the index function $i(k), k = 0, \ldots, N-1$, used for ordering the SINR values

$$\begin{aligned} \mathrm{SINR}\big|_{\mathbf{B}_{d_1}=\mathbf{C}_{i(0)}} &\leq \mathrm{SINR}\big|_{\mathbf{B}_{d_1}=\mathbf{C}_{i(1)}} \leq \cdots \\ &\leq \mathrm{SINR}\big|_{\mathbf{B}_{d_1}=\mathbf{C}_{i(N-1)}} \leq \mathrm{SINR}\big|_{\sigma_{d_1}^2=0}. \end{aligned}$$

Preventing interferer d_1 from using the p most SINR-degrading codebook entries will, therefore, result in an

$$\mathrm{SINR} \geq \mathrm{SINR}\big|_{\mathbf{B}_{d_1}=\mathbf{C}_{i(p)}}.$$

The obtained SINR in comparison with the SINR value based on no interference coordination reflects the potential gain that is achievable at the UE. Any practical scheme would require a definition of information exchange between eNBs and users in order to obtain the required information (e.g., in terms of CSI or scheduling utility) together with an assessment of the required overhead. The details of such an implementation are beyond the scope of this paper.

Note that the description above only considers a single dominant interferer. The approach can be generalized to multiple interferers when all possible combinations of precoding matrices used by the interferers are evaluated and a specific subset is excluded. We consider it more intuitive to assume that the coordination including an additional interferer is only reasonable if all other stronger interferers have been prevented from transmitting at all. In other words, we can assess the second dominant interferer with index d_2 when following the steps above assuming $\sigma_{d_1}^2 = 0$ throughout the evaluation.

In addition, it should also be emphasized that the evaluation of SINR gain is based on the instantaneous SINR which, in consecutive transmissions with a specific channel fading model, implies the optimum selection of interferer codebook entries to be removed on the shortest possible timescale. The obtained gains are therefore optimistic in the sense that for longer delays, misadjustment of the restriction of codebook entries will cause gain degradation. Moreover, the obtained throughput gains based on improved SINR are upper bounds for real system performance because the restriction of codebooks applies only to interfering cells in the calculation of the SINR, neglecting the effect that the serving cell is causing interference to other cells and therefore should also use a restricted codebook

III. HOMOGENEOUS AND HETEROGENEOUS NETWORK MODELS

Conventional wireless cellular networks consist of a number of macro eNBs providing coverage within a geographical area. The deployment of these eNBs follows careful and extensive radio planning. The coverage area of a macro eNB depends on the expected user density, channel environment, terrain, output power etc. In an effort to improve data throughput for cell-edge and indoor users by means of efficient spectral reuse and higher received power, network operators have been focusing on the introduction of low-power radio nodes (e.g., remote radio heads, micro, pico and femtos) to improve coverage.

We call a network that contains cells with significantly different maximum amplifier powers a heterogeneous network. In contrast, a conventional network containing only high-power macro eNBs is termed as a homogeneous network.

The standard model for simulating a homogeneous network places macro eNBs on a hexagonal grid. Each eNB uses sectorized antennas with possibly a three-dimensional antenna pattern, i.e., antenna downtilt effects are taken into account. The users are dispersed uniformally within the network for a given average user density. We model a heterogeneous network by deploying femtos in addition to the macro network by dispersing these nodes randomly within the coverage area of each site. A heterogeneous network, in the context of this work, contains macro eNBs and femtos. The femtos are placed in circular clusters. Within the area covered by a cluster, one or more femtos are placed with uniform distribution. Users in the heterogeneous network can be differentiated based on the type of radio access point they are allowed to connect to. Macro-only (femto-unaware) UEs are allowed to connect to a macro eNB only whereas CSG (femto-aware) UEs are allowed to connect to either a specific femto or any of the macro eNBs. Femto-aware UEs are also placed within the area covered by the corresponding cluster containing the femto node that the UE has special access to. An example heterogeneous network layout with one tier macro deployment and one cluster (with a femto and a CSG UE) per macrocell (sector) is shown in Figure 2.

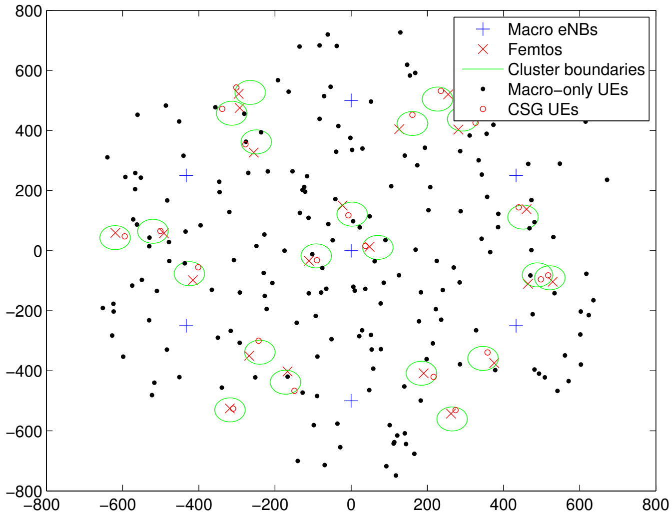

Fig. 2. An example heterogeneous network layout

We distinguish two access modes: Users that do not belong to the CSG of a femto are not allowed to connect to it (closed association) or they are allowed to connect, possibly only in some exceptional condition (open association). The modeling of a heterogeneous network layout can have a significant impact on the conclusions drawn from numerical evaluations, e.g., the radius of the cluster within which a femto and CSG UE are placed affects the probability that the CSG UE connects to the femto, not to a macro eNB.

IV. EVALUATION

We performed system-level simulations to find upper bounds on observable gains for coordinated beam selection using throughput as a performance metric. For any given number of dominant interferers prevented from transmitting and number of codebook (CB) entries suppressed of the next dominant interferer, we replaced the SINR calculated at the UE with a hypothetical SINR that can be guaranteed if the defined interferers are silent and the codebook of the next dominant interferer is restricted. The simulations were carried out assuming the codebook specified in LTE Rel. 8 [8] for a 2×2 antenna configuration, i.e., the codebook consists of 6 entries where two entries correspond to spatial multiplexing and four entries to single beams. If a user was scheduled on multiple physical resource blocks (PRBs), the hypothetical SINR was calculated assuming the same precoding matrix was used by the interferer over all scheduled PRBs. Individual SINR values in different PRBs were averaged using the mutual information effective SINR mapping (MIESM) link to system level interface [9]. The resulting SINR value was then mapped to a frame error rate based on AWGN link level results which were calibrated within WG1 of the EASY-C project [10]. Additional simulation assumptions can be found in Table I and Table II.

TABLE I
GENERAL SIMULATION ASSUMPTIONS

Network layout	19 hexagonal 3-sector sites with wrap-around
Intersite distance macro eNB	500m
Transmit power macro eNB	46 dBm
Antenna configuration (Tx × Rx)	2×2
Antenna pattern	see [2], 15° downtilt
Antenna separation macro eNB	$10\ \lambda$
Antenna separation UE	$0.5\ \lambda$
Channel model	Downlink SCME [11], 10 MHz
Channel scenario	Urban macro, 2600 MHz
Scheduling metric	Proportional fair
Scheduling granularity	1 Physical Resource Block (PRB)
Channel Estimation Loss Model	$\text{Loss}_{\text{SINR}}[\text{dB}] = \max(1, -0.35 \cdot \text{SINR}_{\text{ideal}}[\text{dB}] + 1.6)$
Equalizer	Max. Ratio Combinig
Link to System Mapping	MIESM [9]
Traffic model	Full buffer
Hybrid ARQ Retransmissions	0
Transport format selection	Ideal

The cumulative distribution functions (CDFs) of user

TABLE II
SIMULATION ASSUMPTIONS SPECIFIC TO HETEROGENEOUS NETWORKS

Pathloss model	$L = 127 + 30\log_{10}(R)$ R in km, see [2]
Femto transmit power	20 dBm
Antenna separation (femto)	0.5 λ
Cluster radius	7 m
Minimum distance (femto to CSG UE)	3 m
Maximum distance (femto to CSG UE)	Cluster diameter = 14 m
Macro-only UE access	Closed association

throughput for different combinations of silent interferers and restrictions on codebook are plotted in Figure 3 for a homogeneous network with on average 10 users per macrocell. For easier comparison, throughput values at characteristic quantiles of 5%, 50% and 95% are listed in Table III. It turns out that the gains obtained by partial restriction of the codebook are relatively small when compared to the gains where the dominant interferers are silent; for cell-center users, partial restriction does not yield any significant gain.

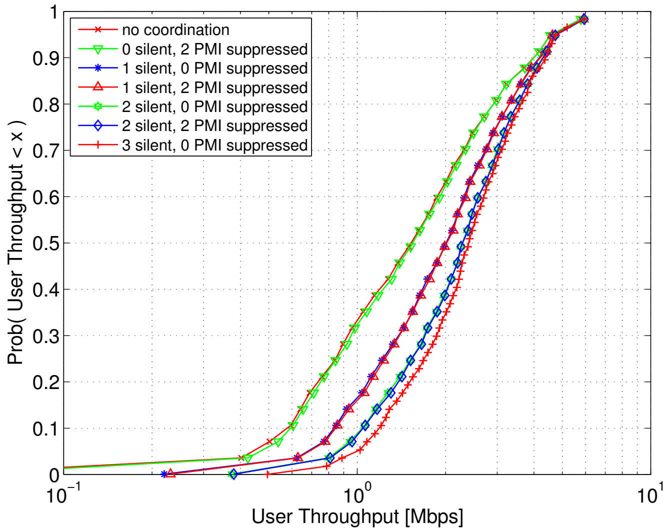

Fig. 3. Throughput CDFs in an example homogeneous layout

We are, therefore, interested in investigating how much a specific interference situation in a heterogeneous network influences our observation. For an example heterogeneous layout with 5 clusters (CSGs) per macrocell with one CSG user each and 5 macro-only UEs per cell on average, the CDFs of user throughput are plotted in Figure 4 for different coordination cases for macro users and in Figure 5 for femto users. Note that the network load is the same as in the homogeneous network, albeit split up into an equal number of macro-only and CSG users. In each case, users are differentiated based on the type of cell they are connected to and termed as macro-UEs (M-UEs) and femto-UEs (F-UEs) respectively. Note that a femto-aware UE might still be connected to a macro eNB and would be classified here as an M-UE. As for the homogeneous network, the 5%, 50% and 95% quantiles of the CDFs are also listed in Table III for M-UEs and F-UEs respectively. When comparing Figure 4 with Figure 3 (see also the numerical data in Table III), it is apparent that cell-edge macro users in a heterogeneous network suffer heavily from the interference caused by the femtos. At least three interferers need to be eliminated such that cell-edge performance for a macro-UE in a heterogeneous network is about as good as in a homogeneous network, emphasizing the need for interference coordination in such a heterogeneous deployment scenario. On the other hand, cell-center macro-UEs take advantage of the smaller load on their respective serving macrocells as compared to the homogeneous network. Even without coordination, cell-center UEs experience a performance increase of more than 90%

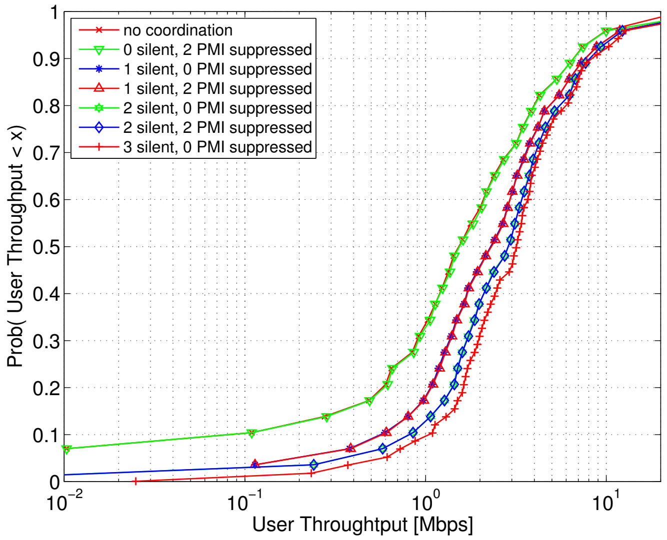

Fig. 4. Throughput CDF for M-UEs in a heterogeneous layout

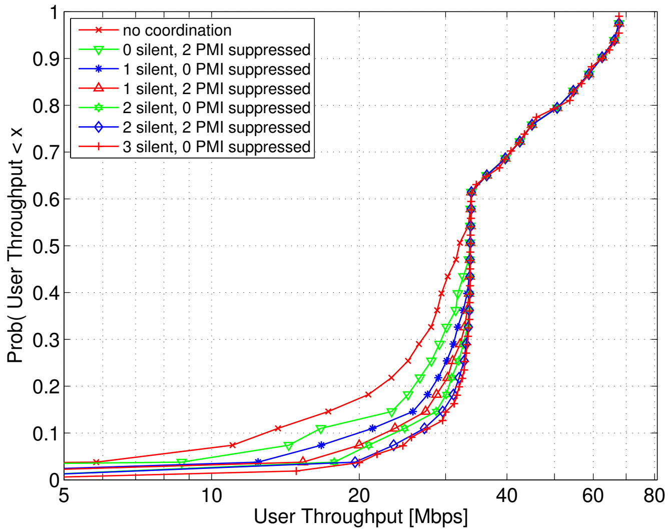

Fig. 5. Throughput CDFs for F-UEs in a heterogeneous layout

TABLE III
USER THROUGHPUT QUANTILES IN HOMOG. AND HETEROGENOUS SIMULATION LAYOUTS

Interf.	CB entries	homog. layout			M-UE in heterog. layout			F-UE in heterog. layout		
silent	suppressed	5%	50 %	95 %	5%	50 %	95 %	5%	50 %	95 %
0	0	0.4303	1.5080	4.5699	0.0053	1.5215	8.8875	8.2052	31.9059	67.3072
0	2	0.4545	1.5350	4.5699	0.0053	1.5489	9.0005	12.3460	33.5909	67.3072
0	4	0.5135	1.6234	4.6007	0.0053	1.6517	9.0005	13.7152	33.6131	67.3072
1	0	0.6912	2.0054	4.7097	0.1730	2.2434	10.5950	14.6344	33.6400	66.3072
1	2	0.7111	2.0059	4.7097	0.1873	2.2520	10.6209	17.5131	33.6661	67.3072
1	4	0.7339	2.0363	4.7097	0.2004	2.3800	10.7576	18.7246	33.6802	67.3072
2	0	0.8837	2.2932	4.7826	0.3757	2.8836	11.1243	18.9937	33.6924	67.3072
2	2	0.8951	2.3029	4.7826	0.3760	2.8836	11.1164	21.1797	33.6924	67.3072
2	4	0.9335	2.3351	4.7826	0.3796	2.8836	11.3314	21.7197	33.6924	67.3072
3	0	0.9952	2.3953	4.7826	0.5964	3.1815	12.3158	21.7408	33.7017	67.3072

which can be improved further with additional interference coordination. In both layouts, partial codebook restriction does not provide significant gains for cell-edge M-UEs compared to interferer elimination, in the heterogeneous case the gain is below numerical precision.

The femto-UEs at cell-center are in our simulation (see Figure 5) only limited by the available maximum coding rate (the throughput saturates to peak data rate). At cell edge, performance for the femto-UEs does improve significantly with codebook restriction of the dominant interferer (see Table III) illustrating the benefit of BSCBS. Shaping the color of the noise through codebook restriction of one dominant interferer can show throughout improvements of about 50% at cell-edge.

V. CONCLUSION

We have presented a simple coordinated beamforming scheme based on beam selection from a predetermined codebook. The beams from eNBs that cause significant interference to a specific out-of cell user can be prevented from being used, including the option that an interfering eNB does not transmit at all. We evaluated potential gains of this method using the LTE Rel. 8 codebook with system-level simulations and user throughput as the performance metric. In a standard homogeneous network layout, user throughput can be improved significantly by preventing interfering eNBs from transmitting, whereas partial restrictions of interferer codebooks resulted only in minor gains. Due to the different interference characteristics in a heterogeneous network with randomly placed femtocells in combination with macro eNBs, we also evaluated throughput gains available to users connected to the macro network or to a femto cell. It turned out that the user experience for users connected to the macro network varies much more in the heterogeneous setup than in the homogenous network: due to additional interference from femtocells, cell-edge users see a dramatic drop in performance that can be mitigated using interference coordination involving at least three interfering base stations. Cell-center users obtain much better throughputs because of the offloading of the macrocells to femtocells. Users connected to a femto usually obtain very high throughputs but the lower 5% quantile can be improved further by a partial restriction of interferers' codebooks.

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