Performance of the LTE Uplink with Intra-Site Joint Detection and Joint Link Adaptation

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***Abstract*—We evaluate the performance of the uplink of a 3GPP UTRAN Long Term Evolution (LTE) system with intra-site cooperation, where different sectors belonging to the same site may cooperate with each other in order to improve the system performance. This represents an intermediate step towards general coordinated multipoint (CoMP) systems as currently under discussion for LTE-Advanced, where a cooperation might take place even between sectors belonging to different sites. In contrast to general CoMP systems, however, intra-site cooperation as considered here is already feasible with LTE Release 8 and generally does not suffer from any restrictions due to limitations of the underlying backhaul network. In this regard, we consider both joint detection as well as joint link adaptation and we investigate the achievable performance for various cases by means of extensive system-level simulations. It is shown that intra-site cooperation may yield significant performance gains compared to conventional systems at reasonable complexity, thus making it a suitable approach for implementation in real-world networks.**

I. Introduction

The performance of current wireless cellular networks is usually interference-limited and therefore the key to realizing significantly higher spectral efficiencies in next generation systems lies in finding appropriate means to efficiently overcome this problem. A rather promising approach, which has attracted a lot of research attention in recent years, is to let different base stations (BSs) cooperate with each other [1]–[3]. By doing so, it is—amongst other things—possible to perform joint transmission in the downlink, i.e., to transmit simultaneously from multiple cooperating BSs to one or multiple user equipments (UEs), and likewise to perform joint detection in the uplink by evaluating not only the signal received by a single BS, but rather jointly processing the signals received by multiple cooperating BSs in an appropriate way. Theoretically, it would be possible to completely eliminate any inter-cell interference this way by transforming the interference into useful signals, thus holding the potential to realize tremendous performance gains also in practical systems. For that reason, such BS cooperation strategies are currently also intensively discussed for next generation cellular networks such as LTE-Advanced, where this approach is commonly referred to as coordinated multipoint (CoMP) transmission/reception [4], [5].

Such CoMP techniques generally can be used to coordinate different sectors of the same BS site (what is usually referred to as intra-site cooperation) or different sectors belonging to different sites (also known as inter-site cooperation), where in the latter case relevant data has to be exchanged between the involved BSs via a fast backhaul network. In this regard, intra-site cooperation clearly exhibits several advantages over inter-site cooperation. First, this approach does not suffer from any restrictions due to limitations of the underlying backhaul network since the cooperation may take place within the same physical hardware. Hence, there are basically no limitations concerning the amount of data that might be exchanged and also the additional delay due to the cooperation stage becomes almost negligible. Besides, since all sectors belonging to the same site might be driven by the same clock, the synchronization of a certain UE to *all* cooperating sectors can be readily achieved and particularly in the uplink there is no major problem with respect to the proper adjustment of the timing advance since the propagation delay from a certain UE to the various sector antennas of the same site is virtually identical in most cases. Finally, at least in the uplink, intra-site cooperation might be already realized with state-of-the art systems such as LTE Release 8 as no backhaul signaling is involved and hence no further standardization would be required for that purpose.

While the analysis of the theoretical limits of BS cooperation strategies in general and the performance of certain schemes applied to rather simplified multi-cell systems has attracted a lot of research attention during the past few years (see for example [2], [3], [6]–[8]), a realistic and comprehensive evaluation of the gains that may be achieved with such techniques in real-world cellular systems, such as the 3GPP LTE, represents still a largely untouched yet important research area. As a first step towards this direction, we therefore investigate in the following the performance of the LTE uplink with intra-site joint processing, considering both joint detection as well as joint link adaptation. In the latter case, we take already during the link adaptation stage into account that later joint detection will be performed, thus facilitating a more adequate selection of appropriate modulation and coding schemes (MCSs). We thoroughly analyze the achievable performance of these schemes by means of extensive system-level simulations, considering different receiver types, propagation scenarios, scheduling algorithms, and antenna patterns.

The remainder of this paper is organized as follows: In Section II, we first start by elucidating the considered intra-site cooperation schemes in more detail. Afterwards, some information about the utilized system level simulator is given in Section III, followed by the actual simulation results in Section IV and finally some concluding remarks in Section V.

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II. Joint Detection and Joint Link Adaptation

We consider the uplink of a 3GPP LTE Release 8 system [9], [10], where every BS site is subdivided into K different sectors, each being equipped with N different antenna elements. In contrast to conventional cellular systems with independent processing for each sector, however, we assume that sectors belonging to the same site may cooperate with each other in order to improve the system performance. In general, this cooperation might cover various different aspects, such as the detection of the signals transmitted by all UEs associated to one of these sectors, the actual resource allocation or the adjustment of the transmit power levels of the various UEs. In this paper, we focus exclusively on joint detection and joint link adaptation as outlined before, which might be readily performed in conjunction with (conventional) sector-specific scheduling and power control. The analysis of the gains that may be achieved if also the latter two aspects are done in a cooperative fashion, in contrast, is left for further studies.

Considering only a single subcarrier and assuming that we have single-antenna UEs, the signal received by the i-th sector of a certain site generally can be expressed as

$$\mathbf{r}_i = \mathbf{h}_{i,i}\, s_i + \sum_{j=1, j\neq i}^{K} \mathbf{h}_{i,j} s_j + \mathbf{i}_i + \mathbf{n}_i, \qquad i = 1,\ldots,K \quad (1)$$

where $\mathbf{h}_{i,j}$ denotes the N-dimensional channel vector from the UE associated with the j-th sector to the antenna elements of the i-th sector, s_j denotes the symbol transmitted by the UE associated with the j-th sector, and $\mathbf{i}_i$ as well as $\mathbf{n}_i$ cover the interference caused by UEs from other sites as well as thermal noise, respectively. In conventional systems, the symbol s_i is usually detected by processing $\mathbf{r}_i$ only, for example by means of a simple diversity combiner[1]. In that case, however, UEs transmitting on the same subcarrier in the other sectors of the same site are perceived as interference. With joint detection, in contrast, all antenna elements of the sectors belonging to the same site are treated as a single large antenna array and the UEs transmitting simultaneously in each of these sectors are *jointly* detected. The effective received signal $\mathbf{r} = [\mathbf{r}_1^T \cdots \mathbf{r}_K^T]^T$, with $(\cdot)^T$ as the transpose operator, thus can be written as

$$\mathbf{r} = \underbrace{\begin{bmatrix} \mathbf{h}_{1,1} & \cdots & \mathbf{h}_{1,K} \\ \vdots & \ddots & \vdots \\ \mathbf{h}_{K,1} & \cdots & \mathbf{h}_{K,K} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix}}_{\mathbf{s}} + \underbrace{\begin{bmatrix} \mathbf{i}_1 \\ \vdots \\ \mathbf{i}_K \end{bmatrix}}_{\mathbf{i}} + \underbrace{\begin{bmatrix} \mathbf{n}_1 \\ \vdots \\ \mathbf{n}_K \end{bmatrix}}_{\mathbf{n}} . \quad (2)$$

Hence, we basically have a conventional multiple-input multiple-output (MIMO) system $\mathbf{r} = \mathbf{H}\,\mathbf{s} + \mathbf{i} + \mathbf{n}$ and we might use standard MIMO receivers for jointly detecting the symbols transmitted by all UEs in the various sectors, which are put together in the single vector $\mathbf{s}$. In the following, we particularly consider a linear minimum mean square error (LMMSE) receiver, in which case $\mathbf{r}$ is equalized with the matrix

$$\mathbf{W}_{\text{LMMSE}} = \mathbf{R}_{ss}\, \mathbf{H}^\dagger \left(\mathbf{H}\, \mathbf{R}_{ss}\, \mathbf{H}^\dagger + \operatorname{diag}\left(\mathbf{R}_{zz}\right)\right)^{-1}, \quad (3)$$

with $(\cdot)^\dagger$ as the conjugate-transpose operator, $\mathbf{R}_{ss} = \mathbb{E}[\mathbf{s}\,\mathbf{s}^\dagger]$ as the input covariance matrix, $\mathbf{R}_{zz} = \mathbb{E}[\mathbf{n}\,\mathbf{n}^\dagger] + \mathbb{E}[\mathbf{i}\,\mathbf{i}^\dagger]$ as the covariance matrix of the noise plus interference, and $\operatorname{diag}(\cdot)$ as the diagonalization operator, which sets all elements of a matrix except for its main diagonal equal to zero. Please note that we consider only the main diagonal of $\mathbf{R}_{zz}$ in (3) since we assume that a BS can only reasonably estimate the noise plus interference level per antenna element, but not the correlation between the different antenna elements. Aside from the standard LMMSE receiver according to (3), we also consider an LMMSE receiver with successive interference cancelation (SIC) in the following. In that case, first of all conventional LMMSE detection is performed and thereupon the signals of the successfully decoded UEs are subtracted from the received signals. Afterwards, LMMSE detection is performed again for the obtained reduced complexity system and this process is then continued in an iterative fashion until either all signals have been successfully decoded or until no more UEs can be canceled.

In a second step, we perform in addition to joint detection also joint link adaptation. This means that a BS takes already during the selection of appropriate MCSs into account that afterwards joint detection will be performed and estimates the signal-to-noise-plus-interference ratios (SINRs) that it expects to obtain this way. Based on these estimates, the BSs then determine the spectrally most efficient MCSs with which the imposed target block error rate (BLER) would not be exceeded and these are the MCSs that eventually will be used for the actual data transmissions. Clearly, joint link adaptation may be performed with only minimal additional complexity compared to joint detection alone and therefore it is very likely that both approaches will always be used together in practical systems. Nevertheless, we also consider joint detection alone in the following in order to be able to separately quantify the performance gains that may be obtained with either approach.

A last issue that remains to be addressed is which prerequisites have to be fulfilled so that intra-site joint detection and link adaptation actually can be realized in practice. As already mentioned before, synchronization and the proper setting of the timing advance should not represent a major problem since all sector antennas usually are co-located and connected to the same physical device. However, with intra-site cooperation we always have to estimate the channels between all UEs associated to a certain site and all sector antennas of this site. This represents a major difference to conventional systems, where usually only the channel of a certain UE to its home sector has to be estimated. In practice, this may be readily accomplished by coordinating the scheduling of sounding reference signals among the involved sectors in an appropriate way and always evaluating the demodulation reference signals received from all UEs at all antenna elements as well [10].

[1]Please note that single-carrier frequency division multiple access (SC-FDMA) is used in the LTE Release 8 uplink [10]. Therefore, s_i in (1) does not directly correspond to a certain data symbol, but rather contains contributions of all data symbols transmitted by the respective UE. However, after proper equalization of all symbols s_i of one user, the actual data symbols can easily be estimated by means of an inverse discrete Fourier transform.

Finally, please note that with intra-site cooperation different antenna patterns at the BS might be optimal compared to conventional sector-specific processing. Since intra-site interference does not exist anymore in that case, one might expect that it could be better to use wider antenna patterns in order to allow for more overlapping of the individual sectors. However, since using wider antenna patterns generally comes along with a reduced antenna gain, it is not obvious which impact is more significant for the actual system performance and therefore we will also investigate this issue in more detail in the following.

III. Simulation Methodology

We investigate the performance of the proposed intra-site cooperation schemes using a quasi-static system-level simulator, which models a 3GPP LTE Release 8 system according to [9], [10]. The most important simulation parameters are listed in Table I. In particular, we consider the Macro 1 and Macro 3 cases specified in [11], but for a carrier frequency of 2.6 GHz rather than 2 GHz. The deployment scenario corresponds to a standard hexagonal grid with 19 sites and three-fold sectorization and we make use of the wrap-around technique in order to avoid any border effects. Multipath fading is modeled by means of the 3GPP spatial channel model (SCM), where we assume that the multipath fading coefficients of a certain UE to the different sectors belonging to the same site are always uncorrelated. This assumption is likely to be fulfilled for many cases of practical interest—in particular if there is sufficient spacing between the antenna elements belonging to different sectors of the same site. Nevertheless, the development of an extended SCM model, which takes also a possible correlation between the various sectors belonging to the same site into account, is currently under way and the evaluation of its impact on the system performance that can be achieved with the proposed approach will be part of our future work.

For the scheduling at the BS side, we consider two different algorithms—a simple Round Robin (RR) scheduler, which aims at allocating an equal amount of physical resource blocks (PRBs) to all UEs in a certain sector during one transmission time interval (TTI), as well as the adaptive transmission bandwidth based proportional fair (P-FR) scheduler proposed in [14]. Please note that the RR scheduler is considered mainly as a reference, because the results obtained with it provide useful insights into the dependency of the gains offered by joint processing at the BS side on the applied scheduling algorithm. If the RR scheduler is used, no hybrid ARQ (HARQ) protocol is active whereas in case of the P-FR scheduler we employ a synchronous non-adaptive HARQ protocol with incremental redundancy. The transmit power of each UE in dBm is adjusted according to a simple open-loop power control scheme as

$$P_{\text{TX}} = \min\left\{P_{\max}, P_0 + 10\log_{10}M + \alpha\,\text{PL}\right\}, \qquad (4)$$

where $P_{\max}$ denotes the corresponding maximum transmit power, P_0 a reference power, M the number of assigned PRBs, α a constant coefficient and PL the long-term attenuation of the channel to the corresponding serving sector. Finally, we assume directional antennas at the BS side with a standard two-dimensional antenna pattern as specified in [11], where the angle-dependent attenuation $A(\theta)$ in dB is given by

TABLE I
Most important simulation parameters.

Parameter	Value
Deployment scenario	19 sites with 3 sectors per site
Inter-site distance (ISD)	500 m [Macro 1] or 1732 m [Macro 3]
Carrier freq. / bandwidth	2.6 GHz / 10 MHz
Multipath fading	3GPP SCM
Penetration loss	20 dB
User speed	3 kmph (quasi-static)
Avg. number of UEs/sector	10
BLER target	30% (instantaneous)
Traffic model	Infinite full buffer
HARQ	RR: inactive P-FR: synchronous, non-adaptive
HARQ round-trip delay	7 TTIs
Link-to-system interface	MIESM [12]
UE / BS antennas	1 (isotropic) / 2 per sector (directional)
BS antenna spacing	10 times wavelength
Receiver noise floor	17 dB
Default 3 dB beamwidth	70°
Front-to-back power ratio	20 dB
Reference antenna gain g_0	14 dBi
BS noise figure	5 dB
Power control	$P_0 = -49$ dBm, $\alpha = 0.5$ [Macro 1] $P_0 = -60$ dBm, $\alpha = 0.6$ [Macro 3] $P_{\max} = 24$ dBm
BS receiver types	MRC (w/o cooperation), LMMSE/LMMSE-SIC (w/ cooperation)
Control channel overhead	Upper and lower 4 PRBs
Reference signals overhead	According to 3GPP TS 36.211 [13]

$$A(\theta)\big|_{\text{dB}} = -\min\left\{12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, A_m\right\}, \quad -180^\circ \le \theta < 180^\circ \qquad (5)$$

with θ as the angle relative to the boresight of the antenna, $\theta_{3\text{dB}}$ as the half-power beamwidth, and A_m as the front-to-back power ratio. Clearly, different antenna patterns lead to different antenna gains and in order to take this interdependence accurately into account, we calculate the antenna gain for an arbitrary value of $\theta_{3\text{dB}}$ (assuming that A_m is fixed) as

$$g(\theta'_{3\,\text{dB}}) = \frac{\int_\theta A(\theta)\big|_{\theta_{3\text{dB}}=70^\circ}\, d\theta}{\int_\theta A(\theta)\big|_{\theta_{3\text{dB}}=\theta'_{3\text{dB}}}\, d\theta}\, g_0, \qquad (6)$$

where g_0 denotes the reference antenna gain for a half-power beamwidth of 70 degrees.

IV. Simulation Results

Figures 1 and 2 illustrate the system performance in terms of the average spectral efficiency (ASE) as well as the cell-edge throughput—which we define as the 5^{th} percentile of the UE throughput distribution—for P-FR scheduling as well as the Macro 1 and Macro 3 cases, respectively. In this regard, we consider the LMMSE and LMMSE-SIC receivers as outlined before and we compare the observed performance to the reference case without any cooperation. As can be seen from Fig. 1, joint detection alone might already facilitate significant performance gains, ranging between 11% and 18%, depending on the actual receiver type and on whether the ASE or the cell-edge throughput is considered. These gains are due to the fact that the joint detection of all users within a certain site generally improves the corresponding signal-to-interference-plus-noise ratios (SINRs) and hence for the same MCSs the observed BLERs can be considerably reduced. This is also backed up by Fig. 3, where we show the average BLERs of the first transmission attempts for the various cases as well as the distribution of the SINR values after equalization for both joint detection with an LMMSE receiver and the non-cooperative case. Clearly, for the considered scenario joint detection leads to a SINR gain of about 1.7 dB on average compared to the conventional non-cooperative case.

If in addition to joint detection also the link adaptation is done in a cooperative way, clearly considerable additional performance gains can be obtained. This is because in that case the selected MCSs generally match better to the actual SINR values after joint detection. From Fig. 3, it can also be seen that with joint link adaptation the average BLERs of the first transmission attempts are—as one would expect—higher than with joint detection only, but they are still smaller than without any cooperation at all even though the MCS selection process works exactly the same way in both cases. The reason for this is that the interference situation during the link adaptation stage is generally different from the one during the actual data transmission, but with joint processing the uncertainty about the future interference situation can be somewhat reduced since no intra-site interference exists anymore in that case.

It can also be seen from Figs. 1 and 2 that the relative performance gains in terms of the ASE are more or less the same for the Macro 1 and Macro 3 cases while the ones in terms of the cell-edge throughput are generally higher in the latter case. This is because by increasing the inter-site distance, the system is actually no longer interference-limited. Therefore, the relative gains due to intra-site cooperation generally should become higher since the fraction of the interference coming from adjacent sectors increases, but with intra-site cooperation at least part of this interference is effectively transformed into useful signals. However, the higher gains can only be observed for the cell-edge throughput and not for the ASE due to the different choice of the power control parameter α for the Macro 1 and Macro 3 cases, respectively.

Figure 4 depicts similar results as Figs. 1 and 2, but for RR scheduling and the Macro 1 case only. It can be seen that with a RR scheduler the relative performance gains over a conventional system without any cooperation are generally even higher than before, what can be intuitively explained as follows. Since the RR scheduler schedules users independently of their current channel conditions, it may often happen that the channel of a scheduled UE to its home sector is relatively poor, in which case the channels from the same UE to the other sectors of the same site are often likely to be comparable or even better, thus leading to rather high performance gains due to joint processing. In case of P-FR scheduling, in contrast, UEs are always scheduled if they have relatively good channel conditions to their home sector, so that the probability that the channels of these UEs to the other sectors of the same site are comparable or even better is considerably reduced, thus also

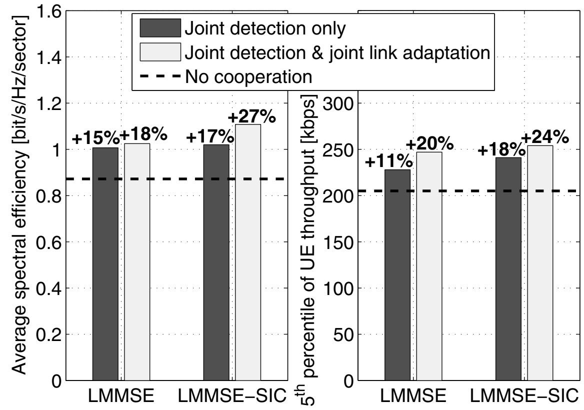

Fig. 1. Performance of joint detection as well as joint link adaptation for proportional fair scheduling with HARQ and two different receiver types for the Macro 1 case. The given percentages denote the relative performance gains compared to the reference case without any cooperation.

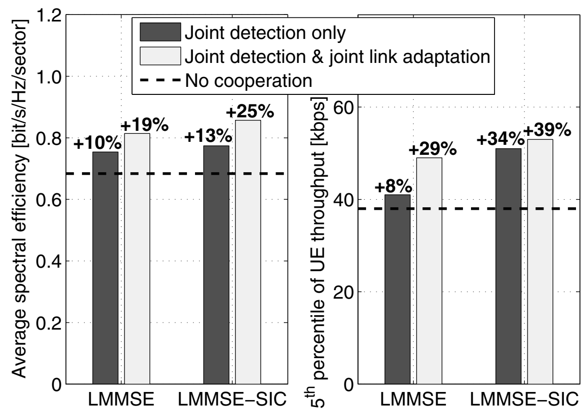

Fig. 2. Performance of joint detection as well as joint link adaptation for proportional fair scheduling with HARQ and two different receiver types for the Macro 3 case. The given percentages denote the relative performance gains compared to the reference case without any cooperation.

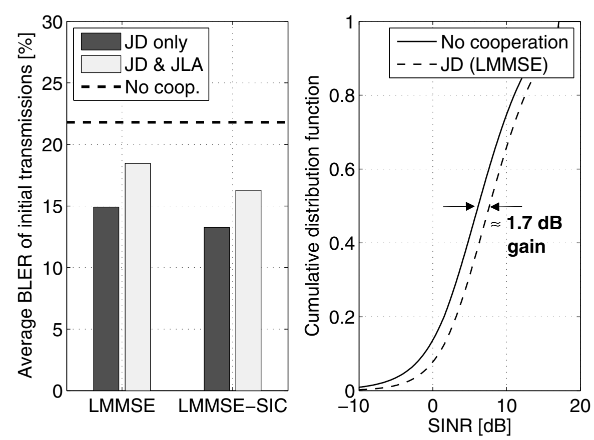

Fig. 3. Average BLERs of the initial transmission attempts for joint detection (JD) only as well as JD combined with joint link adaptation (JLA) and distribution of the SINR values after LMMSE equalization. All results are given for the Macro 1 case with proportional fair scheduling.

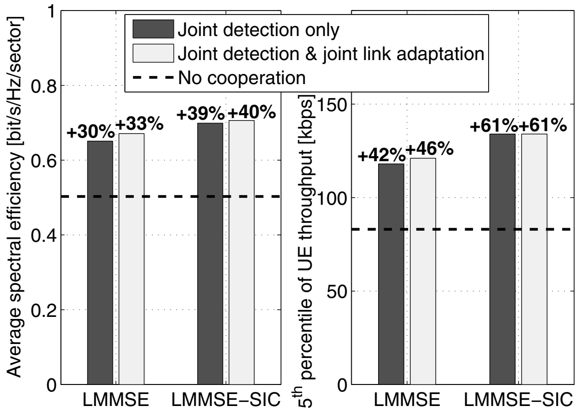

Fig. 4. Performance of intra-site cooperation for RR scheduling w/o HARQ and the Macro 1 case. The given percentages denote the relative performance gains over the reference case without any cooperation.

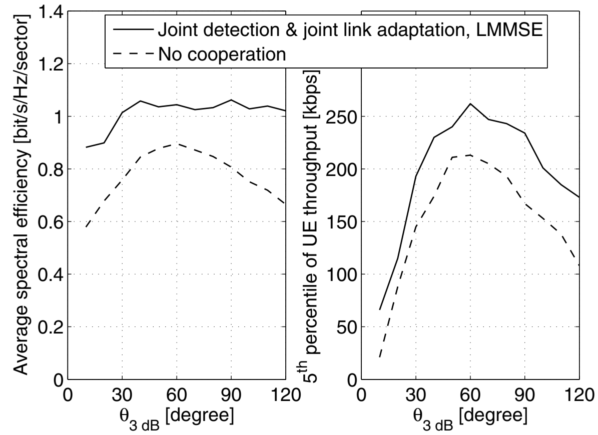

Fig. 5. Impact of the half-power beamwidth at the BS side on the system performance for the Macro 1 case with and without intra-site cooperation. In all cases, P-FR scheduling with HARQ is assumed.

reducing the actual gains due to intra-site cooperation. Hence, intelligent channel-aware scheduling reduces to some extent the theoretical performance gains that may be achieved with the proposed intra-site cooperation schemes in practice.

Figure 5 shows the impact of the half power beamwidth at the BS side on the system performance. Clearly, with intra-site cooperation the ASE is over a wide range of values almost independent of $\theta_{3\,\mathrm{dB}}$, what can be explained again by the fact that intra-site interference does not exist anymore. However, it can also be seen from Fig. 5 that the cell-edge throughput still depends significantly on $\theta_{3\,\mathrm{dB}}$, even with joint processing. Hence, this implies that the performance of the cell-center users actually improves with increasing values of $\theta_{3\,\mathrm{dB}}$, but intuitively this should be clear as only with relatively large values of $\theta_{3\,\mathrm{dB}}$ the signals of cell-center users can be received at reasonable strength by the other sectors of the same site as well whereas cell-edge users located at the original edges between different sectors of the same site can be reasonably received by at least two of them anyway. For the latter ones, however, the loss of antenna gain with increasing $\theta_{3\,\mathrm{dB}}$ becomes therefore obviously the dominant factor.

V. Conclusion

We have evaluated the performance of the uplink of a 3GPP UTRAN LTE system with intra-site cooperation, where different sectors belonging to the same site may cooperate with each other in order to improve the system performance. This represents a very attractive approach for implementation in real-world systems in the short term since no further standardization would be required for that purpose. In particular, we have considered joint detection as well as joint link adaptation combined with conventional (sector-specific) scheduling and power control and we have shown that in general significant performance gains might be obtained this way. In this regard, the actual performance gains turned out to be dependent on the applied receiver type, scheduling algorithm, and propagation scenario. For our future work, we are planning to investigate the additional gains that may be obtained if also the scheduling and power control is performed in a cooperative way.

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