Comparison of Intra and Inter Site Coordinated Joint Detection in a Cellular Field Trial

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Abstract—As it is widely known, cooperation among base stations can improve spectral efficiency, particularly at cell edges. In theory, the problem is well understood, but the application of those advanced transmission techniques in practical deployments issues multiple challenges, some of which are very difficult to model in simulation studies. In this paper we investigate the properties of intra and inter-site cooperation in the cellular uplink doing practical field measurements in an urban environment. At first we concentrate on the characterization of important channel parameters which affect the performance in cooperative networks. In particular, this includes the achievable signal-to-noise ratio as well as the synchronization accuracy. Although the results show that intra-site cooperation is less complex, especially in terms of backhaul requirements and synchronization, inter-site cooperation achieves (with higher probability) more balanced SNR levels at clustered base stations and, thus, higher spectral efficiency as well. This property was verified in the present field trial as well.

I. INTRODUCTION

The major limit of data rates in today’s cellular networks is inter-cell interference. One of the major shortcomings of LTE is that this effect reduces the quality of service of cell edge users. Some of the currently most promising proposals for increasing the spectral efficiency in future mobile communication networks involve the use of joint signal processing of multiple base stations (BSs) in the uplink and downlink which enables shaping of interference at the transmitter side or effectively handling it at the receiver (see e.g. [1]). The wide spectrum of these techniques is often referred to as coordinated multi-point (CoMP). The term joint detection (JD) refers to a wide set of receiver algorithms where received uplink signals of multiple BS are combined in a cooperation cluster for more powerful detection and decoding of information transmitted by user equipments (UEs).

Theoretical and simulation studies (e.g. [2], [3]) promise huge gains when these techniques are applied in cellular systems. Even though these results are very promising, it should also be clear that joint signal processing issues multiple challenges: besides clustering, user scheduling, and multi cell channel estimation that are much more complex when the full potential of coordination should be exploited, we face the challenge of multi-cell synchronization and the provision of large amounts of backhaul capacity for the exchange of signals in the cooperation cluster. It should be clear that most of these problems are easier to deal with when only BSs at the same site cooperate, referred to as intra-site CoMP.

The performance of intra-site CoMP certainly depends on the site deployment, mostly the number of BSs (or cells) per site and their location on the roof or radio mast and the antenna patterns (beamwidth). In general, intra-site CoMP only covers a subset of cell borders. It is, thus, expected that the performance of CoMP can be improved when cooperation clusters can be formed across sites, so called inter-site CoMP. Previous field trial results, e.g. [4], show for the uplink that inter-site CoMP is feasible as well. However, one major problem that comes up in this case is the requirement of UE timing synchronization in the whole cooperation cluster (e.g. the propagation delays in an LTE system should not exceed the cyclic prefix in order to avoid inter-symbol interference (ISI)) which degrades cooperation performance. Furthermore, the use of JD across different sites could require a costly upgrade of the backhaul network, a requirement that could be relaxed when the exchanged receive signals would be compressed, as previous theoretical and field trial publications show [3], [5].

In this paper, we provide a comprehensive comparison of intra and inter-site JD that is based on field measurements in an urban testbed. We not only address potential gains but also various challenges of both schemes. In the sequel, the measurement setup is described in Section II, after which details of the signal processing architecture are provided in Section III. The field trial results are presented in Section IV. Finally, the paper is concluded in Section V.

II. FIELD TRIAL SETUP

The field trial testbed, deployed in downtown Dresden, is depicted in Fig. 1. In total 16 BSs located on seven sites with up to three-fold sectorization are used for the measurements. Each BS is equipped with a two element, cross-polarized KATHREIN 80010541 antenna which has 58° horizontal and 6.1° vertical half power beam width. The angle between the boresight of antennas that belong to different BSs at one site is ≥120°. The basic physical layer procedures are used in close compliance with the 3GPP/LTE standard (see e.g. [6]). This concerns mainly the the control and data processing. However, as a major difference, we use OFDM instead of SC-FDMA in the uplink as well. Time and frequency synchronization of BSs, which is required for joint detection, is done through GPS fed reference normals. Other general transmission parameters are stated in Tab. I. During the field trial, two UEs were moved
on a measurement bus in 5 m distance while transmitting on
the same time and frequency resources employing one dipole
antenna each. The antennas were placed in front and behind
the bus and were tilted by about 30° to decorrelate their
channels. All UEs are configured to use the same modulation
and coding scheme (MCS), whereas the MCS is switched in a
fast sequence according to Table II. Thus, within the channel
coherence time, different transmission rates can be tested. The
superimposed signal is jointly received by all BSs which took
snapshots of 80 ms (corresponds to 80 transmit time intervals
(TTIs)) every 10 s. In total about 900 such measurements
were taken in order to observe a large number of different
transmission scenarios.

III. RECEIVE SIGNAL PROCESSING

Within the described testbed we use an offline data evaluation
approach that allows us to apply various receive signal
processing algorithms on the same recorded data. The general
receiver signal processing steps were described in [5] which
includes symbol estimation and decoding. In the following,
we focus on the algorithms for the estimation of significant
channel parameters that affects the performance of intra and
inter-site cooperation. Therefore, parameters which are influ-
enced by the different geometries of the transmission links
such as the propagation delays $\tau_d$ well as the channel gains
are of particular interest. The algorithms are applicable to the
3GPP/LTE physical layer since they are based on compliant
control signaling. It should be noted that here only estimation
algorithms for the uplink (UL) direction are discussed. 1

1) Estimation Model: As introduced above, we always
consider a system with $K$ users and $M_R$ base stations with $N_R$
receive antennas so that in total $M = M_R N_R$ observations of
the superimposed transmit signals are available. The general
underlying linear transmission model in the time domain can
be stated as:

$$ y_n^m = \sum_{k=1}^{K} \sum_{\lambda=1}^{K} h_{\lambda}^{m,k} x_{n-m,k-\lambda}^k + v_n^m, \quad (1) $$

with $x^k$ representing a known training signal of user $k$ while
$h_{\lambda}^{m,k}$ the unknown channel impulse response (CIR) of length
$\Lambda_{m,k}$ on the link between the $k$-th transmitter and the $m$-th
receiver branch. The index $n$ denotes the discrete sample index
here. In addition to the unknown CIR also the integer-valued
symbol timing offset (STO) $\mu_{n,k} = [\tau_d / T_S] \text{ is not known a-}$
priori to the receiver and must be estimated. Here, $T_S$ denotes
the sampling period.

When considering an OFDM systems (or SC-FDMA in
LTE) usually a cyclic prefix (CP) of length $N_{CP}$ is used to
ensure a circular convolution and, thus, to allow detection
in the frequency domain, which is one of the main benefits
of OFDM. Therefore, we assume that the STOs are always
less or equal than the cyclic prefix length minus the channel
delay. Due to the relatively small inter-site distances within
the testbed it can be expected that the occurring time differences
of arrival (TDOA) do not exceed the CP length which will
be validated through field trials in Section IV. Assuming
e.g. channel lengths of $\tau_C \approx 2 \mu s$ the maximum TDOA

1During the measurements all BSs are synchronized to the GPS so that a
sufficient synchronization among all local oscillators can be expected where
the caused inter-carrier interference is always below the noise power level.
The UEs are aligned in frequency by estimating the frequency mismatch in
a DL training signal and pre-compensating this estimate in the uplink.

<table>
<thead>
<tr>
<th>Table II</th>
<th>Modulation schemes and code rates used for transmission.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS#</td>
<td>Mod. scheme</td>
</tr>
<tr>
<td>1</td>
<td>4QAM</td>
</tr>
<tr>
<td>2</td>
<td>4QAM</td>
</tr>
<tr>
<td>3</td>
<td>16QAM</td>
</tr>
<tr>
<td>4</td>
<td>16QAM</td>
</tr>
<tr>
<td>5</td>
<td>16QAM</td>
</tr>
<tr>
<td>6</td>
<td>16QAM</td>
</tr>
<tr>
<td>7</td>
<td>64QAM</td>
</tr>
<tr>
<td>8</td>
<td>64QAM</td>
</tr>
</tbody>
</table>

Fig. 1. Testbed Deployment and intra-site JD sum-rate at measure-
ment locations. Map data © Sandstein Neue Medien GmbH
(http://stadtplan.dresden.de)
must not exceed \( T_{C,P} - \tau_C \approx 2.7 \mu s \) which corresponds to \( 2.7 \mu s \times c_{light} \approx 810 m \). Under these conditions the corresponding estimation model in frequency domain can be derived as:

\[
Y_q^m = \sum_{k=1}^{K} H_q^{m,k} X_k^{e^{-j2\pi q m N_{SC}}/Q} + V_q^m,
\]

where \( q \) is the sub-carrier index and \( H_q \) the sampled channel transfer function at frequency bin \( q \). Within the measurements always \( N_{SC} \) out of \( Q \) possible sub-carriers are used for pilot transmission with \( Q \) as the DFT length. For larger timing delays, as well as frequency mismatches, the stated frequency domain transmission model does not hold anymore and must be extended to account for inter-symbol and inter-carrier interference, as described e.g. in [7].

2) Symbol Timing and Delay Spread Estimation: The general time and frequency synchronization in OFDM systems is a well investigated research area in the wireless communication community. For example [8] gives a comprehensive overview on common synchronization algorithms. One main issue in our work is to obtain accurate estimates of link specific timing delays \( \mu^{m,k} \) and the CIR lengths \( \Lambda^{m,k} \) based on the uplink training signals \( X_k^{e'} \). As one can observe in (2), the linear increasing phase over the sub-carrier depends on \( X \) and \( \mu^{m,k} \) so that the STO equals the delay of the CIR w.r.t. the start of the DFT window.

In an LTE system, the UE specific uplink reference signals consists of code orthogonal Zhadoff-Chu (ZC) sequences (cf. [9]) and are distinguished by cyclic shifts in time domain which corresponds to different phase slopes in frequency domain. Thus, the user specific (delayed) CIRs are stacked in the time domain into windows of length \( Q/N_{CS} \) where \( N_{CS} \) denotes the maximum number of cyclic shifts which corresponds to the number of UEs which should transmit at the same time instant. Thus, for determining the STO for one particular UE, one needs to evaluate the CIR delay in the corresponding time window. As mentioned above, only \( N_{CS} \) available sub-carriers are usable for training. As a result, the observable CIRs are superimposed Sinc impulses due to the windowing operation in frequency domain so that the first and the last CIR tap which need to be evaluated for delay estimation cannot be determined unambiguously. With the vector CIR \( \hat{h} = [\ldots h_1 \ldots h_\lambda \ldots 0]^T \in \mathbb{C}^{Q \times 1} \) and the Fourier matrix \( \mathbf{F} = \mathbb{C}^{Q \times Q} \), the CIR filtering can be stated as:

\[
\hat{h}_n = \mathbf{F}^H \Theta \hat{h}_n + \mathbf{F}^H \Theta \mathbf{F} = \Theta \hat{h}_n + \bar{u}
\]

where \( \Theta \) is a diagonal matrix with ones on the main diagonal where the pilot subcarriers are located. With \( \kappa = l - n \) the elements of the coupling matrix \( \Theta \in \mathbb{C}^{Q \times Q} \) are given by the Dirichlet kernel:

\[
\Theta[n, l] = \begin{cases} \frac{N_{SC}}{Q} & \kappa = 0 \\ \frac{1}{Q} e^{j2\pi (2q_1 + N_{SC}) \sin(\frac{\pi}{Q} N_{SC})} & \text{otherwise} \end{cases}
\]

with \( q_1 \) as the first pilot sub-carrier index. As \( \Theta \) is always rank deficient the matrix is not invertible to simply reverse the filtering. But one can successively estimate the CIR taps by using the underlying kernel function and search the CIR which is most likely using:

\[
\hat{h}_n = \arg \min_{\hat{h}} \left\{ \frac{\| \hat{h} - \Theta \hat{h}_n \|_2^2}{\| \hat{h} \|_2^2} \right\}.
\]

Due to the shape of the Dirichlet kernels one can expect that the strongest tap of the filtered CIR is equivalent to the strongest tap of the unfiltered one. Therefore, for an initial estimate of the tap amplitudes the values of the filtered CIR are used. With \( \Theta \), denoting the \( \lambda \)-th column of the matrix \( \Theta \), the successive CIR reconstruction can formally be stated as:

\[
\hat{\mu}_\rho = \arg \min_n \left\{ \frac{\| \tilde{h}_n - \Theta_n \tilde{h}_n - \sum_{\lambda=1}^{\rho-1} \Theta_{\lambda,n} \tilde{h}_{\lambda,n} Q_{N_{SC}} \|_2^2}{\| \tilde{h}_n \|_2^2} \right\},
\]

with \( \hat{\mu}_\rho \) as the \( \rho \)-th estimated tap delay. It should be noted that a perfect reconstruction of the original CIR with correct amplitude and phase is not readily possible with this approach for common values of \( N_{SC} \). But for the CIR delay as well as length estimation this simple algorithm provides sufficient results.

Furthermore, one can either define a maximum number of taps \( \Lambda_{max} \) which are expected to be occur or search taps until a stop criterion is fulfilled. Here, the tap search is stopped if:

\[
\frac{1}{N_{CS}} \left\| \frac{1}{N_{CS}} \tilde{h}_n - \Theta_n \left( \tilde{h}_n - \sum_{\lambda=1}^{\rho-1} \Theta_{\lambda,n} \tilde{h}_{\lambda,n} Q_{N_{SC}} \right) \right\|_2^2 \leq 2\sigma_\rho^2.
\]

If multiple observations of the filtered CIRs are available, the signals can be combined with an equal gain combiner before starting the tap search to reduce the effective noise power.

3) Channel and Noise Power Estimation: The estimated link specific STOs must also be considered for the channel estimation. With \( S_{\alpha}^m = \alpha \)-th ZC root sequence the orthogonal pilot sequences \( X_k^{e'} \) in Eq. (2) are generated by \( X_k^{e'} = S_{\alpha}^m[e^{j2\pi q_k / N_{CS}}] \). The user specific cyclic shift is denoted by \( \delta_k = \{0, \ldots, N_{CS} - 1\} \). These sequences are per definition orthogonal in intervals of \( N_{CS} \) subcarriers. Defining a code matrix \( S \in \mathbb{C}^{N_{CS} \times K} \) with elements \( S[q, k] = e^{j2\pi q_k / N_{CS}} \) in total \( N_{CS} \) observed subcarriers are needed to estimate the \( K \) user channels. Assuming that the coherence bandwidth of the channel is much larger than \( N_{CS} \) the channel estimation model can also be stated as \( \hat{h}_m^m = S H_m^m + V \) with \( H_m^m \in \mathbb{C}^{K \times 1} \) as channel of the links between all transmitters and the \( m \)-th receiver branch and \( S_{\alpha}^m \in \mathbb{C}^{Q \times 1} \) as received observation of \( N_{CS} \) consecutive subcarriers. The channel estimation then simply becomes:

\[
\hat{H}_m^m = S^H \hat{R}_m^m / N_{CS} = H_m^m + S^H \hat{V}_m^m / N_{CS}
\]

But as can be derived from Eq. (2) as well, the user specific phase slopes caused by the STOs lead to an orthogonality defect of the code sequences. Thus, alternatively the code matrices can also be stated as \( S[q, k] = e^{j2\pi q / N_{CS}} e^{j2\pi q_{m,k} / Q} \). In this case one needs to apply results from the standard
estimation theory in order to reverse the coupling. As e.g. introduced in [10] by using the minimum variance unbiased filter which is also known as Gauss-Markov theorem the previous result changes to:

\[
\hat{H}^m = \left( S^H \Phi_{VV}^{-1} S \right)^{-1} S^H \Phi_{VV}^{-1} R^m
\]  

(9)

with \( \Phi_{VV} \) the noise covariance matrix which is assumed to be \( \Phi_{VV} = \sigma_V^2 I \). Consequently the minimum costs are given by

\[
\sigma_V^2 = \frac{1}{2} E \left\{ \left| \hat{H}_o - \hat{H}_{o-1} \right|^2 \right\} = \frac{1}{2} \frac{1}{E} \left\{ \left| \hat{V}_o - \hat{V}_{o-1} \right|^2 \right\} 
\]  

(10)

with \( o \) as pilot OFDM symbol index and \( \hat{V} \) as filtered noise. As it is always assumed that the transmit symbols have unit power and the noise power is fixed, the SNR which is used in the subsequent sections does only depend on the average channel power of each UE \( \hat{H}_o^m(k) \). We thus define the per UE SNR as

\[
\text{SNR}^{m,k}_{o} = \frac{E \left\{ \left| \hat{H}_o^m(k) \right|^2 \right\}}{\sigma_V^2},
\]  

(11)

as well as the sum SNR at each BS as

\[
\text{SNR}^{m} = \frac{E \left\{ \sum_{k=1}^{K} \left| \hat{H}_o^m(k) \right|^2 \right\}}{\sigma_V^2}.
\]  

(12)

In both equation \( E \{ \cdot \} \) averages over all sub-carriers and OFDM symbols. The average channel power is equal to one in the following simulation results. Thus, the SNR = 1/\( \sigma_V^2 \).

4) MSE Results of Numerical Simulations: Results in terms of the mean squared error (MSE) of the STO as well as channel estimators are shown in Fig. 2. The used parameter set for the numerical computer simulation is stated in Tab. I. The LTE standard differentiates two different kind of reference symbols (see [9] for definitions). Sounding reference signal are transmitted over a large bandwidth \( N_{SC} = 1152 \equiv 17.28 \text{MHz} \) ones every couple (second in our system) TTI. Due to the wide bandwidth (good time domain resolution) they are used for STO estimation. UL demodulation symbols, on the other hand, are used for channel estimation. They are transmitted twice per TTI over the bandwidth of the data sub-carriers (in our case \( N_{SC} = 30 \text{PRB} \cdot 12 = 360 = 5.4 \text{MHz} \)).

For obtaining results about the statistical behavior of the estimators the simulation results are averaged over different channel, noise as well as STO realizations: At this, the STO is uniformly distributed with \( \tau_d \propto \mathcal{U}(0, 4 \mu s) \). Furthermore, for the sake of simplicity it is assumed that the CIR has an uniformly distributed power delay profile of length \( \tau_C = 1 \mu s \) \( (\Lambda = 30) \) as well as that the AWGN is uncorrelated with zero mean.

In Fig. 2a the normalized MSE of the STO estimation of the first incoming path is depicted for two values of expected taps \( \Lambda_{max} \). A value of \( \Lambda_{max} = 1 \) would correspond to a conventional STO estimation algorithm. For \( \Lambda_{max} = 50 \) the stop criteria defined in Eq. (7) limits the number of estimated taps. As one can observe, the used algorithm significantly improves the estimator performance. The corresponding performance of the CIR delay estimator is shown in Fig. 2b. Again one can see that the proposed algorithm lead to more reliable results for reasonable SNR values. It should be noted that the uniform power delay profile represents the worst case for this STO and CIR delay estimator since at each sample a tap occurs. As a result the overall maximum of the filtered CIR which is used for the initial tap estimate is not necessarily the strongest path. Therefore the tap fitting becomes erroneous. In practical measurements the shapes of the observed CIRs are more 'clustered' which leads inherently to better results of the estimators. In Fig. 2c the MSE of the channel estimation is depicted. As expected the MSE decreases linearly in the log domain according to the SNR.

![Fig. 2. Mean squared error performance evaluation of the STO, CIR delay as well as channel estimators.](image-url)
IV. Field Trial Results

In this section, we compare the performance of intra and inter-site CoMP in an uplink field trial using the setup described in Section II. The route traversed by the measurement car, traveling at a speed of about 6 km/h, is depicted in Figure 1. It has a total length of about 17 km and passes through surroundings of very different building morphology. While the UEs were continuously transmitting, the received signals of the BSs were stored for a duration of 80 ms (80 TTI s) every 10 s giving a total set $L$ of 885 measurements. In the following we use the index $l$ to refer to a certain measurement.

The goal of this paper is to analyze the properties of intra and inter-site cooperation in a practical setup. While the general receive signal processing steps do not differ between both approaches, different coupling characteristics of the spatial transmission channel (in particular received power or SNR and interference levels and propagation delays) occur due to the different locations of the sites.

In Fig. 3 the measured (sum) SNR values observed at all BSs and locations are shown. The two largest SNRs measured at any BS for each measurement are depicted in the upper part of the figure. An interesting result is that rather balanced SNR values for two different BSs are observed at each location of the UEs. Since the joint signal processing is particularly beneficial in balanced coupling scenarios this result indicates that cooperation among base stations could be exploited throughout the measurement route. Furthermore, assuming that cooperation clusters were formed at the BSs with the highest SNR, and a cooperation cluster size of two, the upper row depicts whether this cluster was intra-site (which was the case in about 30% of the measurements). It should be noted that the BS antenna downtilt has a great impact on these results. In this field trial, a constant downtilt of 6° was applied at all BSs. Field trial results for different downtilts in the same testbed are reported in [11].

In the following, we evaluate the per UE SNR $\text{SNR}_{l}^m$ levels that were observed at multiple BSs during the field trial in more detail. In particular, we investigate the CDF of the minimum SNR $\text{SNR}_{\text{min,l}}^m$ that was simultaneously measured at $M_C$ BSs:

$$\text{SNR}_{\text{min,l}}^m(M_C) = \min \left\{ \text{SNR} \left| \sum_1^M \left( \text{SNR}_{l}^m \geq \text{SNR} \right) = M_C \right\} \right.$$  \hspace{1cm} (13)

where $1(\cdot) = 1$ if the condition is true and zero otherwise. This CDF is plotted in Figure 5(a) for $M_C = 1 \ldots 7$. As one can see, in 50% of the measurement positions an SNR of more than $\approx 18\text{dB}$ is seen at one BS while two BSs individually observe (at least) this SNR only in 20% of the scenarios. This is also an intuitive behavior since the different distances between one UE and several BSs lead to varying pathloss values on the links. We observe from this plot that the SNR measured at the strongest, second strongest, . . . BS differs by about 3 dB in this field trial, a value which again depends on the antenna downtilt [11].

In order to investigate this aspect in the context of intra and inter-site cooperation, we concentrated on two different sites, referred to as Hbf and Hbf-Süd (see Figure 1). Site Hbf is located in the center of the testbed and has three sectors which are mounted at different edges of the rooftop. Thus, the UEs will typically only have line-of-sight (LOS) to one (or less) of the antennas. Instead, at site Hbf-Süd, all antennas are mounted on the same radio mast. Further information on the BSs at these two sites can be found in Table III.

For each UE, we looked individually at the subsets of those measurements, where it had the best SNR $\text{SNR}_{l}^{m,k}$ at one of the BSs at Hbf $L_{Hbf,k} = \left\{ l \mid \arg \max_m \left( \text{SNR}_{l}^{m,k} \right) \in \{1, 2, 3\} \right\}$ (399 UE locations in total). The CDF of this SNR is the blue curve in Fig. 5b. The other solid curves indicate the SNR of the second and third largest SNR that was measured instantaneously at any other BS while the dashed curves indicate the SNR that was measured at the other BSs of Hbf. Clearly, we see a great advantage of inter-site CoMP due to the directive antennas which lead to a high separation of intra-site BSs and the greater diversity of potential BSs in the

We do not distinguish between the UEs in this and all following curves, i.e. stacked the values of both UEs in one vector and drew the CDF of this vector.

<table>
<thead>
<tr>
<th>BS</th>
<th>Name</th>
<th>Height Building</th>
<th>Distance to roof edge in boresight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HBF 0°</td>
<td>53 m</td>
<td>0.7 m</td>
</tr>
<tr>
<td>2</td>
<td>HBF 120°</td>
<td>49.6 m</td>
<td>3 m</td>
</tr>
<tr>
<td>3</td>
<td>HBF 240°</td>
<td>49.6 m</td>
<td>9 m</td>
</tr>
<tr>
<td>8</td>
<td>SUED 60°</td>
<td>28 m</td>
<td>7 m</td>
</tr>
<tr>
<td>9</td>
<td>SUED 180°</td>
<td>28 m</td>
<td>39 m</td>
</tr>
<tr>
<td>10</td>
<td>SUED 300°</td>
<td>28 m</td>
<td>2.5 m</td>
</tr>
</tbody>
</table>

Table III: Information on site HBF and HBF-Süd
a large percentage of the STOs are within the CP so that no ISI.

This is not possible if the cooperation cluster are formed across sites. Thus, it can be expected that the site CoMP SNR are rather similar even though the deployment of 215 UE locations. Interestingly, the results in terms of intra-site CoMP because the SNR at the strongest BS is much larger than the SNR of the third strongest BS.

The cumulative distribution function (CDF) of these rates for different intra and inter-site scenarios is plotted in Fig. 6. In Fig. 6a, we focused at the set of measurements where highest sum received power was observed at any BS of Hbf: \( L_{\text{Hbf}} = \frac{1}{l} \arg \max_m \left( \text{SNR}^m_{l} \right) \in \{1, 2, 3\} \). Only a single antenna per BS was evaluated. The rates are measured in bit per channel use (bpcu). Compared to conventional detection of UEs at individual BSs, the transmission rates could be significantly increased using JD. Compared to this baseline, intra-site CoMP gave certain gains which were increased when inter-site JD was. In particular, we see that an increase of the cluster size from two to three BSs was very beneficial in the case of inter-site CoMP while the gains of a larger cluster size was much smaller, but not negligible, for intra-site JD.

The same is basically true for a setup with two antennas per BS. However, in this case the performance gains of JD are smaller in general because spatial separation of UE signals is already possible at a single BS improving the performance of conventional detection. It should be noted, however, that the additional spatial degrees of freedom of JD could be used for spatial multiplexing of a larger number of UEs or suppression of outer cluster interference. We plan to investigate both options in future field trial campaigns.

As a final remark, we point out that the field trial is subject to the following assumptions and limitations:

- Assignment of the same resources to UEs located with fixed distance in close proximity is rather unlikely in a non-cooperative cellular system with single antenna BSs.
- No rate adaptation and hybrid automatic repeat request (HARQ) due to offline signal processing. The genie rate adaptation scheme (described above) diminishes the diversity gain of JD because each codeword can be decoded at a different BS even in the non-cooperative case.
- No background interference has been considered. Thus, an interference floor is missing, resulting in rather high SNR.
- Both UEs transmit continuously at maximum power of 18 dBm.

V. CONCLUSIONS

In this paper we investigated the characteristic differences between inter and intra site cooperation in a cellular field trial. This in particular included the channel parameters that depend on the distance between the UE and BS, namely the channel SNR as well as timing delays. After describing the general measurement setup, we presented the used timing and channel estimation algorithms which are applied to the underlying 3GPP/LTE physical layer. As shown, we used an improved STO estimator that aims at determining the delay of the first incoming path more accurately.
While being subject to much smaller implementation challenges, the performance of intra-site JD was shown to be inferior when compared to inter-site JD. At first, our evaluation showed more balanced SNR values for inter-site cooperation clusters which, finally, leads to greater user rates, as well. Clearly, large STOs can be avoided in intra-site clusters. However, our field trial showed, for an average BS distance of about 600m that inter-site cooperation between two or three sites is possible without exceeding the the cyclic prefix.

In further work we will investigate the trade-offs between channel SNRs and timing delays more closely. Furthermore, we plan to do field trials for additional setups including six fold sectorization with overlapping antenna patterns and larger number of UEs.

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