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# Large Scale Field Trial Results on Uplink CoMP with Multi Antenna Base Stations

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***Abstract*—Coordinated Multi-Point (CoMP) appears to be an effective option to combat inter-cell interference in mobile communications. Previous field trials for uplink CoMP have shown that large improvements in spectral efficiency and fairness that are promised by theoretical work can also be achieved in real-world scenarios. However, these results only consider systems with single antenna base stations. We extend this work by presenting field trial results for a system with multi antenna base stations, and we show that this change of the system setup has a strong impact not only on the throughput but also on the relative performance of a cooperative compared to a non-cooperative system. Based on the presented results suggestions for further research and field trials are derived.**

## I. Introduction

The spectral efficiency of today's cellular systems is limited by inter-cell interference. Especially data rates for mobile users that are located at cell edges are strongly reduced by this effect, resulting in a lack of fairness that is identified as one of the major deficiencies of LTE Release 8 [1]. Some of the currently most promising proposals for an improved system setup consider using coordinated multi-point (CoMP) techniques for the up- and downlink. Theoretical analysis and simulations promise vast increases in spectral efficiency [2]–[4], and today's technology seems to be ready to support these concepts as previous field trial publications demonstrate [5], [6]. In [7], we show in a large scale field trial that joint detection in the cellular uplink increases the spectral efficiency by about 50 % for a setup with single antenna base stations (BSs). Additionally, the rate distribution over the measurement area was smoothed out, showing that fairness is improved strongly by using cooperation, even though the highest rate modulation scheme employed was 16QAM which resulted in a too tight constraint of the spectral efficiency. For this reason we use up to 64QAM in the here presented field trial. However, the focus of this work is the extension of the setup by using BSs that are equipped with two antennas each. The results indicate a trade-off between using more antennas per BSs and using coordinated joint detection. Furthermore, the results show the importance of a joint multi-user and multi-cell optimization in the design of future cellular systems. [1]

In the sequel, the measurement setup is described in Section II, after which details on the signal processing architecture are provided in Section III. The field trial results are presented in Section IV, followed by a summary in Section V.

[1]This paper is partially based on a more detailed description of field trial results in [8].

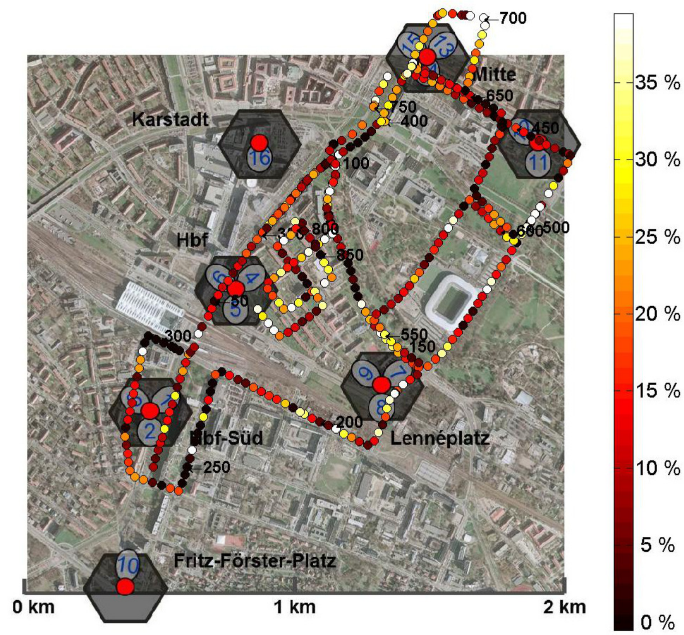


Fig. 1. Field trial setup and measurement trajectory, indicating the spectral efficiency gain of a joint detection of 2 UEs with $N_{\text{bs}} = 2$ using SIC vs. the LTE Rel. 8 baseline. Map data © Sandstein Neue Medien GmbH (http://stadtplan.dresden.de)

## II. Measurement Setup

Compared to [7], the field trial setup is increased from 12 to 16 BSs deployed at 7 UMTS sites in downtown Dresden, as shown in Figure 1. The BSs are synchronized through Global Positioning System (GPS) fed reference normals. Each BS is equipped with a cross-polarized antenna (58 degrees half-power beamwidth and 14 dBi gain), hence with two antenna elements per BS. The user equipments (UEs) share the same resources in time and frequency. Both employing one dipole antenna, transmit using orthogonal frequency division multiplexing (OFDM) and a sequence of different modulation and coding schemes (MCSs), as listed in Table II. For various further parameters refer to Table I. The signals received at all BSs are recorded for offline evaluation. Thus, the focus of the

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TABLE I
TRANSMISSION PARAMETERS.

| | |
|---|---|
| BS distance | 350 - 600 m |
| BS antenna hight | 30 - 55 m |
| distance between UEs | about 5 m |
| UE antenna hight | 1.5 m |
| Carrier frequency | 2.53 GHz |
| System bandwidth | 20 MHz |
| Num. physical resource blocks (PRBs) | 30 |
| Sub-carriers per PRB | 12 |
| UE transmit power | 18 dBm |
| Quantization resolution | 12 bit per real dim. |

TABLE II
MODULATION SCHEMES AND CODE RATES USED FOR TRANSMISSION.

| MCS# | Mod. scheme | Code rate | Peak rate (Mbps) | Bit per channel use (bpcu) |
|---|---|---|---|---|
| 1 | 4QAM | 3/16 | 1.3 | 0.375 |
| 2 | 4QAM | 1/2 | 3.46 | 1.0 |
| 3 | 16QAM | 2/5 | 5.62 | 1.6 |
| 4 | 16QAM | 4/7 | 7.99 | 2.29 |
| 5 | 16QAM | 3/4 | 10.6 | 3.0 |
| 6 | 16QAM | 6/7 | 12.3 | 3.43 |
| 7 | 64QAM | 3/4 | 16.3 | 4.5 |
| 8 | 64QAM | 7/8 | 18.72 | 5.25 |

investigation is on physical layer evaluation.

## III. SIGNAL PROCESSING ARCHITECTURE AND EVALUATION CONCEPT

We will now briefly explain the general signal processing steps performed in the offline evaluation chain mentioned before. For further details we refer to [5].

*Synchronization:* The carrier frequency of the BS is synchronized by using GPS fed reference normals that have an stability of about $10^{-9}$. The mobile terminals estimate their CFO from downlink reference signals and pre-compensate their Uplink transmission accordingly. Compared to the sub-carrier spacing, the remaining offset of less than 200 Hz is small enough to neglect residual inter-carrier interference (ICI).

*Channel Estimation:* A pilot based approach is used for channel estimation. Within each transmit time interval (TTI), pilots are mapped on all sub-carriers of the 4th and 11th OFDM symbol. Interference between pilot symbols of different UEs is avoided by a code-orthogonal design. Thus, the channel of each UE is estimated for every second sub-carrier. Time and frequency interpolation and extrapolation are carried out separately to estimate the channel for all other sub-carriers.

*Noise Estimation:* The estimation of the noise variance is based on the channel estimates $\hat{\mathbf{h}}_{m,k}$. We exploit the auto-correlation properties of $\hat{\mathbf{h}}_{m,k}$ to separate noise and signal components, and compute their respective power. Using this approach, one noise variance $\hat{\sigma}_m^2$ is determined per BS.

*Channel Equalization:* If residual synchronization errors are neglected, and we assume a flat fading channel on each sub-carrier of bandwidth $\Delta F = 15$ kHz, the received signal of each symbol on a single OFDM sub-carrier at BS $m$ can be stated as

$$\mathbf{y}_m = \mathbf{h}_{m,1}x_1 + \mathbf{h}_{m,2}x_2 + \mathbf{n}_m, \quad (1)$$

where $\mathbf{y}_m \in \mathbb{C}^{[N_{\text{bs}}\times 1]}$ are the signals received by the $N_{\text{bs}}$ antennas of BS $m$, $\mathbf{h}_{m,k} \in \mathbb{C}^{[N_{\text{bs}}\times 1]}$ denotes the channel gain vector from UE $k$ to BS $m$, $x_k \in \mathbb{C}$ is a symbol transmitted by UE $k$, and $\mathbf{n}_m \in \mathbb{C}^{[N_{\text{bs}}\times 1]}$ denotes additive, uncorrelated noise of covariance $E\{\mathbf{n}_m\mathbf{n}_m^H\} = \sigma_m^2\mathbf{I}$.

We define $E\{x_k x_k^H\} = 1$, and hence assume that the channel vectors inherently include transmit power. In the CoMP case, two BSs form a cooperation cluster which is denoted by $\mathcal{C}$ with elements $\{c_1, c_2\}$. The corresponding transmission model for the cluster is given as

$$\begin{bmatrix}\mathbf{y}_{c_1}\\ \mathbf{y}_{c_2}\end{bmatrix} = \begin{bmatrix}\mathbf{h}_{c_1,1} & \mathbf{h}_{c_1,2}\\ \mathbf{h}_{c_2,1} & \mathbf{h}_{c_2,2}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\mathbf{n}_{c_1}\\ \mathbf{n}_{c_2}\end{bmatrix}. \quad (2)$$

The signal processing architecture enables a variety of cooperation and equalization schemes:

- Independent decoding of both UEs by different BSs, using interference rejection combining (IRC).
- Both UEs are decoded by the same BS, using a linear detector (IRC) or successive interference cancellation (SIC).
- Both UEs are decoded independently by different BSs, but one BS forwards decoded data bits to the other for distributed interference subtraction (DIS).
- One BS forwards its received signal to another BS, where both UEs are detected jointly (joint detection (JD)), either using linear equalization or SIC (JD+SIC) .

Please refer to [2] for further information on these schemes and an information theoretic study of their performance.

In the following, we will consider the union of all equalization options where UEs are decoded without cooperation of BSs as the LTE Rel. 8 *baseline*.

Equalization itself is generally based on linear MMSE filters. If UE $k$ is locally detected at BS $m$, and still subject to the interference from UE $\bar{k} \neq k$ (no previous SIC, the biased MMSE filter for a particular sub-carrier is given as

$$\mathbf{G}_{\text{biased}}^{[m,k]} = \left(\hat{\mathbf{h}}_{m,k}\right)^H \left(\hat{\mathbf{h}}_{m,k}\left(\hat{\mathbf{h}}_{m,k}\right)^H + \hat{\mathbf{h}}_{m,\bar{k}}\left(\hat{\mathbf{h}}_{m,\bar{k}}\right)^H + \hat{\sigma}_m^2\mathbf{I}\right)^{-1}, \quad (3)$$

where $\hat{\mathbf{h}}$ and $\hat{\sigma}_m^2$ are estimates of the channel and noise, respectively, and $\bar{k}$ is the index of the interfering UE. Note that this implementation exploits the channel knowledge to each UE for the purpose of IRC. If the receive signals of multiple BSs are available at a joint receiver, the biased MMSE filter for UE $k$ is given as

$$\mathbf{G}_{\text{biased}}^{[k]} = \hat{\mathbf{h}}_k^H\left(\hat{\mathbf{h}}_k\hat{\mathbf{h}}_k^H + \hat{\mathbf{h}}_{\bar{k}}\hat{\mathbf{h}}_{\bar{k}}^H + \begin{bmatrix}\hat{\sigma}_{c_1}^2\mathbf{I} & 0\\ 0 & \hat{\sigma}_{c_2}^2\mathbf{I}\end{bmatrix}\right)^{-1}, \quad (4)$$

where $\hat{\mathbf{h}}_k$ denotes the channel from UE $k$ to all BSs in the considered cluster. If interference of the other UE has already

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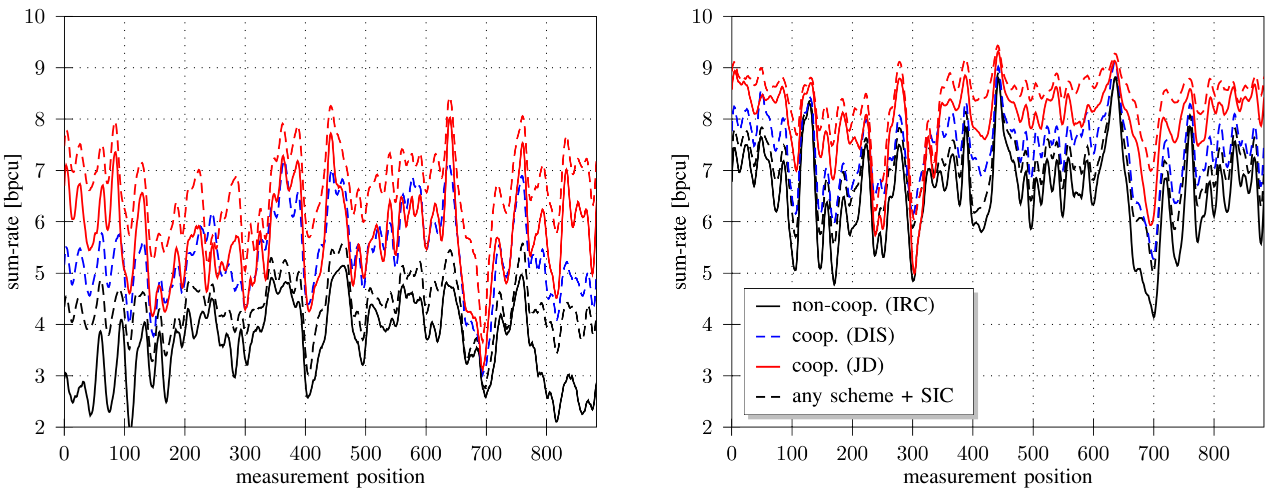


(a) $N_{\text{bs}} = 1$ antenna per BS.

(b) $N_{\text{bs}} = 2$ antennas per BS.

Fig. 2. Achieved sum-rates for considered cooperation and detection schemes along the measurement trajectory.

been canceled, filters in (3), (4) change to

$$\mathbf{G}^{[m,k]}_{\text{SIC/DIS,biased}} = \left(\hat{\mathbf{h}}_{m,k}\right)^H \left(\hat{\mathbf{h}}_{m,k}\left(\hat{\mathbf{h}}_{m,k}\right)^H + \hat{\sigma}^2_m \mathbf{I}\right)^{-1} \quad (5)$$

$$\text{and} \quad \mathbf{G}^{[k]}_{\text{SIC,biased}} = \hat{\mathbf{h}}^H_k \left(\hat{\mathbf{h}}_k \hat{\mathbf{h}}^H_k + \begin{bmatrix} \hat{\sigma}^2_{c_1}\mathbf{I} & 0 \\ 0 & \hat{\sigma}^2_{c_2}\mathbf{I} \end{bmatrix}\right)^{-1}, \quad (6)$$

respectively. To avoid demapping errors for higher order modulation schemes, the bias has to be removed from all stated filters by applying $\mathbf{G}^{[\cdot]} = (\Delta(\mathbf{G}_{\text{biased}}\hat{\mathbf{h}}_{\cdot}))^{-1}\mathbf{G}_{\text{biased}}$, where $\Delta(\mathbf{A})$ sets all off-diagonal elements of $\mathbf{A}$ to zero.

*Soft Demodulation and Decoding:* Equalization is followed by soft demodulation. The demodulator output is fed into an LTE Rel. 8 compliant decoding chain using the codes listed in Table II.

## IV. Field Trial Results

The route traversed by the measurement car, traveling at a speed of about 6 km/h, is depicted in Figure 1. Compared to [7], the length of the measurement route is extended to 17 km in total. It passes through surroundings of very different building morphology. The UEs transmitted a block of 80 codewords every 10 s, each spanning 1 TTI (1 ms), switching cyclically through all 8 MCSs given in Table II. For each loop through all MCSs, the maximum achievable rate (MCS) is determined — based on the assumption of a constant channel for at least the duration of one loop — emulating a perfect rate adaptation. The achieved rate is obtained by averaging over all loops of one measurement and denoted as $r_{k,p}$ for UE $k$ and position $p$. When SIC is used, we are able to determine the optimal MCS for each UE, because the transmitted codeword is known under field trial conditions. Thus, we can determine the MCS providing the highest rate that is successfully decoded either with or without prior SIC, and we apply the decoding order that achieves the highest sum-rate. In the field trial setup, both UEs always transmit simultaneously even though an optimal rate adaptation would assign zero transmit power to a UE that cannot be decoded at all to minimize interference and thus maximize the rate of the other UE. We handle this problem by assuming that the decodable UE achieves the SIC rate even for linear detection, because this is as close as possible to the case where only a single UE is transmitting, neglecting remaining interference due to channel estimation errors. This is a major difference when compared to the evaluation in [7], where this approach was only used for SIC receivers, leading to greater differences in the throughput achieved by linear and SIC receivers as in the results shown in the following. The BSs that are considered for non-cooperative or joint decoding of the UEs are determined by a minimum pathloss criterion. In all the plots in this section, we show only sum-rate results ($r_{\text{sum},p} = r_{1,p} + r_{2,p}$) at each position.

The achieved sum-rates for all investigated cooperation and equalization schemes are shown in Fig. 2. We smoothed out small-scale variations using a moving average filter with a length of 10 positions. We distinguish between a case where only the first antenna of each BS is used for signal processing (i.e. emulating a system with $N_{\text{bs}} = 1$, see Fig. 2(a)), or where both are used ($N_{\text{bs}} = 2$, see Fig. 2(b)). Clearly, the sum-rates of all compared schemes are significantly larger in the case of $N_{\text{bs}} = 2$ than for $N_{\text{bs}} = 1$, due to the additional degree of freedom at the BS side. While the case of $N_{\text{bs}} = 2$ is certainly the more commonly assumed setup, the former one is also interesting, as it resembles a case where the number of overall UE and BS antennas is equal if two BSs cooperate. The results obtained from this case can then be used to predict the gains in CoMP setups where multiple cooperating BSs serve two UEs *per cell* on the same resource, or where UEs with two transmit antennas each are employed. From information theory, this clearly leads to a larger sum-rate over all involved terminals or streams [2], but it is a setup which could not yet be evaluated in the test bed. The outages in Fig. 3(a) are cases where the single BS antennas were not even able to decode the lowest-rate MCS.

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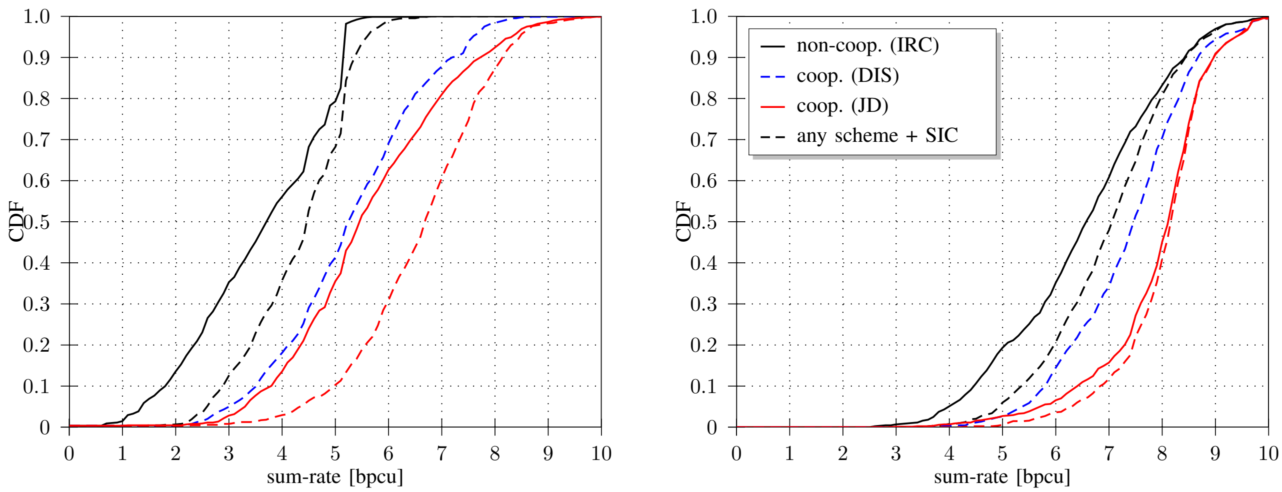


(a) $N_{\text{bs}} = 1$ antenna per BS.

(b) $N_{\text{bs}} = 2$ antennas per BS.

Fig. 3. Cumulative distribution of sum-rates observed on the measurement route.

Figure 3 shows the corresponding sum-rate cumulative distribution functions (CDFs). In the case of $N_{\text{bs}} = 1$, one can see rate improvements by applying local SIC (on average 19 %), as then one of the UEs can transmit at a low rate which is decodable despite interference, while the other can strongly benefit from interference subtraction and potentially use a high rate. Note that the good performance of SIC in this section is also due to the fact that we inherently assume perfect link adaptation as stated before, and operate in a fairly high signal-to-noise ratio (SNR) regime, as no background interference is generated. In the case of $N_{\text{bs}} = 2$ typically both UEs can already be decoded with very high rates at non-cooperating BSs because of potential spatial separation of both UEs. Local SIC gives an average gain of 7 % which shows how well the users can already be separated by linear detection.

By using DIS instead of SIC the sum-rates can be improved by an additional 23 % and 5 % on average, for the single-antenna and double-antenna BS case, respectively. Simulations show (e.g., [2], [9]) that we can expect higher gains of DIS for larger UE distances, which will be considered in future field trials. When observing the benefit of using DIS over local SIC (i.e., the Long Term Evolution (LTE) Release 8 baseline), one has to take the additional backhaul traffic that is required for the exchange of decoded bits into consideration. In this field trial, the backhaul rate required for the use of DIS was 1.4 bpcu or 5.5 Mbit/s in the case of $N_{\text{bs}} = 1$, which is low when compared to 24 (12 bits per I/Q dimension and antenna), leading to 112 Mbit/s required for JD among 2 BSs. These numbers are based on the assumption of exchanging frequency domain signals, focusing on the 360 sub-carriers on which transmission has taken place. However, no form of compression is considered (i.e. the signals forwarded to the decoding BS have the same bit resolution the analog to digital converter (ADC) uses), which would allow reducing backhaul under similar performance [10].

An additional of 30% and 13% over the non-cooperative + SIC baseline case for $N_{\text{bs}} = 1$ and $N_{\text{bs}} = 2$ can be obtained by using JD.

TABLE III
FAIRNESS, GAIN AND BACKHAUL OF THE COMPARED SCHEMES.

| Decoder | Jain index $N_{\text{bs}}$=1/ $N_{\text{bs}}$=2 | Spectral eff. gain $N_{\text{bs}}$=1/ $N_{\text{bs}}$=2 | backhaul [bpcu] |
|---|---|---|---|
| non-coop. (linear) | 0.47 / 0.87 | −19% / −7% | 0 |
| SIC (**baseline**) | 0.60 / 0.90 | - | 0 |
| DIS (2 BSs) | 0.74 / 0.92 | 23% / 5% | 1.4 / 2.4 |
| JD, (2 BSs) | 0.78 / 0.93 | 30% / 13% | 24 / 48 |
| JD+SIC (2 BSs) | 0.87 / 0.94 | 52% / 15% | 24 / 48 |

Relative sum-rate gains that allow a comparison of different detection and cooperation schemes are depicted in Fig. 4. Evaluating the gains of using JD with SIC compared to the LTE Rel. 8 baseline (detection of both UEs at different or the same BS with IRC or SIC), we see that, beside the fairly good average gain for this antenna configuration, the sum-rate gain rises over 80% in some cell-edge areas. Having a commercial usage of uplink CoMP in mind, it is interesting to see that some cases of strong cooperation gain can be obtained with inter-sector cooperation at the same site, where proprietary and inexpensive solutions are thinkable (see, e.g., the measured gains around position 200 in Fig. 4).

It is anticipated that the use of JD (or CoMP in general) leads to greater system fairness. As in [7] we use the Jain index to evaluate the aspect. The Jain index is defined as

$$\text{fairness} = \left(\sum_P \sum_K r_{k,p}\right)^2 \Bigg/ \left(PK \sum_P \sum_K r_{k,p}^2\right). \quad (7)$$

Hence, the index reflects the achievable rate distribution of both UEs over the measurement area. In the case of $N_{\text{bs}} = 1$, fairness is increased strongly by using cooperation, as shown in Table III which gives a summary of the field trial results. As the rate improvements for the case of $N_{\text{bs}} = 2$ are rather small and the Jain index is already quite high even for non-cooperative detection, we only see small improvements.

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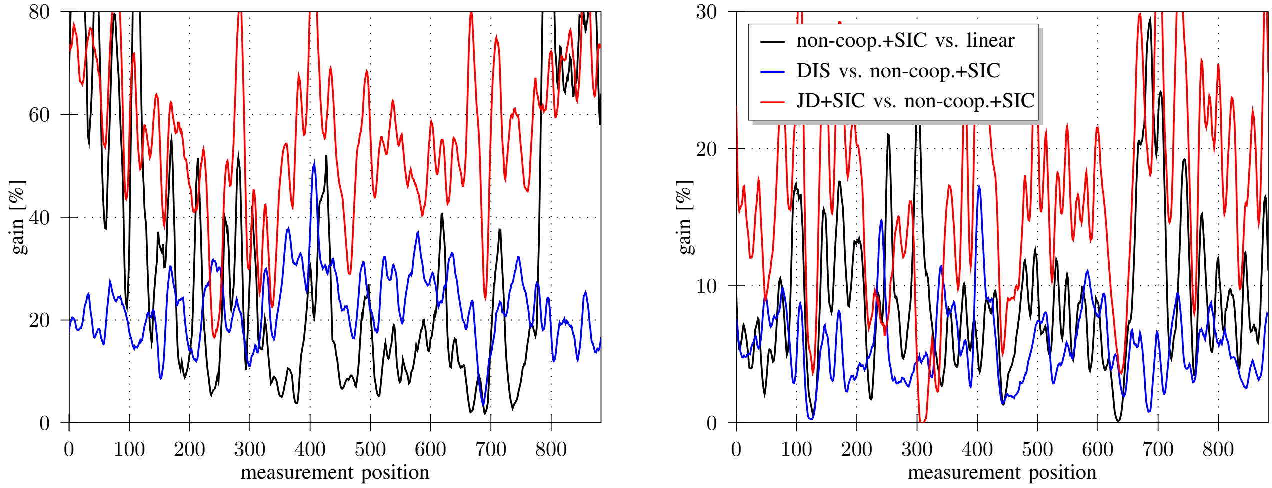


(a) $N_{\text{bs}} = 1$ antenna per BS.

(b) $N_{\text{bs}} = 2$ antennas per BS.

Fig. 4. Relative gains between different pairs of compared schemes.

In general, we point out that the field trial setup considered allows only a limited generalization of conclusions because

- UEs were located with fixed distance in close proximity,
- no background interference has been considered, and
- no power control was employed.

We expect larger gains from cooperation if an interference background is considered, as the additional spatial multiplexing and array gain provided by a larger number of virtual receive antennas then comes into play. In a field trial with more terminals, we also expect a large gain from cooperation sizes greater than two, as this allows the capture of one additional interferer in each detection process.

## V. Conclusions

In this paper, large-scale field trial results for different uplink CoMP schemes were presented, where two UEs were moved through an urban cellular test bed with a total of sixteen base stations (BSs). For the evaluation of results, either one or two antennas per BS were considered. Observing the one-antenna case allows the prediction of gains in setups with two UEs per cell served on the same resource, or UEs with two transmit antennas each. Compared to non-cooperative linear detection, local SIC already increases average spectral efficiency by about 19% or 7%, for the different antenna setups, respectively. On top of this, multi-cell joint detection yields an average gain of 52% or 15%, for one or two BS antennas, respectively. As expected, particularly strong gains are visible at cell-edges, which can in some cases already be achieved through intra-site CoMP. We assume relative gains in general to be larger if background interference is added in future field trials, as then also the array gain from cooperation will become more visible than in the before observed scenarios of high SNR. We expect the benefit from distributed interference subtraction (DIS) to be larger in cases where the terminals are spaced further apart than was possible in this measurement campaign.

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